Development of Additive Manufacturing Technology

Implications on the design process and the transportation industry, moving from prototyping to production

Erik Sætre
Department of Product Design
Norwegian University of Science and Technology

ABSTRACT

As additive manufacturing continuously is gaining momentum and its technology is rapidly developing designers are being enabled to make better products faster and cheaper, without worrying about the constraints of traditional manufacturing processes. This paper reviews the development of the additive manufacturing technology with a focus on its impact on the design process, and how it is moving from prototyping into production. There will also be an emphasis on how additive manufacturing is affecting the automotive and aerospace industry. The results of this paper show that the use of AM in product development is necessary for companies to compete with industry standards. However a shift can be seen in the manufacture of production parts as 3D printing is emerging. Future implications of 3D printing are also explored.

KEYWORDS: additive manufacturing, automotive industry, design process, 3d printing, rapid manufacturing

1. INTRODUCTION

It proliferated years ago because of its usefulness in building prototypes. Ever since then, companies have increasingly used the manufacturing method to make production parts. It is rapidly changing the industry, and the way we design and manufacture. By disposal of tooling costs and reducing development time and material usage it makes for a faster turnaround and a more profitable design process.

Additive manufacturing refers to the process that automatically builds objects layer by layer from computer data, better known as 3D printing. The Technology is utilized in many sectors including Transportation, aerospace, industrial, health care, military and education. Uses include concept models, functional prototypes, factory tooling and finished goods. Materials used in 3D printing include resins, plastics and metals (Stratasys 2012). Many believe that it will shape the future of production and help to liberate the established engineering and manufacturing processes. It has been claimed that AM can cut new product costs by up to 70% and the time to market by 90% (Waterman 1994) (DDM at BMW 2013) (Stratasys 2012).

AM is enabling companies to do what otherwise would be impossible. To competitors confusion, the Aston Martin racing team managed to develop the LMP1 racing car for the 2011 Le Mans competition in just six months due to highly advanced 3D printing in the conceptual mock up stage (Rapid Prototyping 2013).

To ensure an efficient development process when designing the Mars rovers, NASA turned to 3D printing. In all, 70 AM parts where produced for its test vehicles.
Recently, a company called SelectTech Geospatial, an advanced manufacturing facility for commercial and defense applications, earned the distinction of producing the first 3D printed Unmanned aerial system (UAS) to take off and land on its own gear (Hiemenz 2013).
EADS (European Aeronautic Defense and Space Company) with their subsidiary Airbus has earmarked the prospect of growing a full sized airliner wing with AM sometime beyond 2020 (Excell 2010).

This paper will give an overview of the development of additive manufacturing technology and where it stands today. And In addition take a closer look at how additive manufacturing is continuously evolving the design process and how the technology is changing the role of the designer. An Emphasis will be put on its impact on the transportation industry, and how it´s implementation is gradually moving from prototyping and into production. Additive manufacturing also has a profound impact on the consumer market. However, this paper is solely industry focused.

2. ADDITIVE MANUFACTURING (AM)

Additive manufacturing (commonly referred to as either rapid prototyping or 3D-printing) is used to construct simple and complex geometries by fusing together very fine layers of powder or liquid. The process starts with a CAD model sliced into cross-sections. Each cross-section is mapped onto the surface of the rapid prototyping material by a laser, which fuses or cures the particles together (Thompson 2007). The layers are in the XY plane while the part is being built in the Z direction. Each of these cross-sections represents a layer in the build. The model is then tessellated and exported out as an STL file, the industry de facto file format. Having a growth of 29,4% in 2011 alone, it notched the industry's total growth over 24 years (26,4%) (Wohler 2012).

Costs	**Typical Applications**
No tooling costs SLS is cheapest and DMLS most expensive	Automotive, F1 and aerospace Product dev/testing Tooling
Quality	**Suitability**
High definition of detail and surface finish	One offs, prototypes and low volume production
Speed	**Related Processes**
Long process, but turn-around is rapid beacuse there is no tooling and data is taken directly from CAD	CNC machining Electrical discharge machining Investment casting

Figure 1: Additive manufacturing overview table (Thompson 2007).

2.1 Stereolithography

SLA is built one layer at the time by an UV laser beam directed by a computer-guided mirror onto the surface of the UV sensitive liquid epoxy resin. The UV light solidifies the resin it touches and each layer is applied by submersion of the build platform into the resin. SLA is the technique that produces the finest surface finish and dimensional accuracy. It requires a support structure under production, which has to be removed post-production.

2.2 Selective Laser Sintering (SLS)

SLS is a similar powder-based process where a CO_2 laser fuses fine nylon powder in layers, directed by a computer-guided mirror. The build platform progresses downwards as each layer is built. Delivery chambers rises to provide a roller with fresh powder that is being uniformly spread over the build area. The non-sintered powder encapsulates and supports the sintered model.
This eliminates the need for support material being printed along with the part.

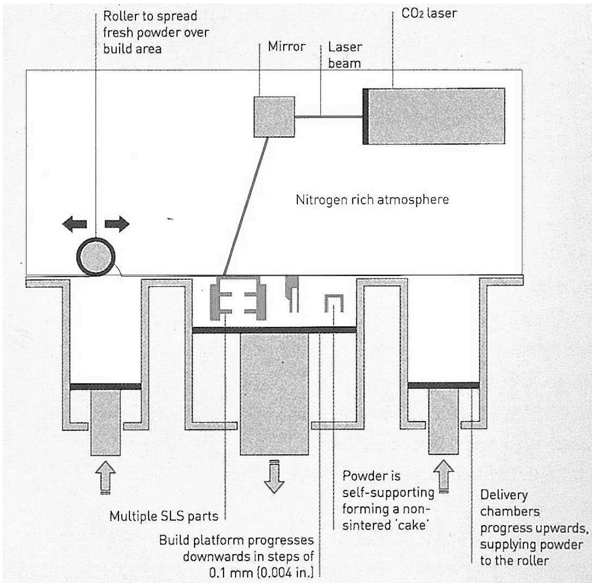

Figure 2: SLS process (Thompson 2007)

2.3 Direct metal laser sintering (DMLS)

Similar to SLS, a CO_2 laser is used to sinter metal alloy powder. An expendable first layer of the part is anchored to a steel plate to stop distortion, which makes for easier removal when the build is complete.

2.4 Fused deposition modeling (FDM)

FDM produces 3D parts by melting and advancing a fine ribbon of production grade thermoplastic materials through a computer controlled extrusion head, producing parts that are ready to use. This extrusion nozzle moves in the horizontal XY plane while the build platform moves down, building the part layer by layer. This method requires a supportive structure to be printed, but the strength to weight ratio is very high. Raw FDM parts have visible layer lines, which can be removed with several post processes.

2.5 Jetting Systems

Utilizes Inkjet technology by jetting layers of liquid photopolymer onto a build tray and then curing them with UV light. Fully cured models can be handled and used immediately, without additional post-curing. The 3D printer also jets a gel-like support material specially designed to uphold overhangs and complicated geometries. It is easily removed by hand and with water. Multi-material printing is possible.

Figure 3: 3D printed models shown with soluble support material (dark) intact, and after removal.

3. AM IN PRODUCT DEVELOPMENT

With an increasingly competitive market, getting products out faster is crucial. The longer a product stays in the design cycle, the longer It takes to get it to market, meaning less potential profit for companies. For that reason AM has become standard practice for product development across manufacturing sectors and continents. Prototyping is an essential part of the product development and manufacturing cycle required for assessing the form, fit and functionality of a design before a significant investment in tooling is made (Pham 1997). Additive manufacturing is an enabler for designers and it is changing the way design is being designed. The process of adding material layer by layer allows designers and engineers to develop complex geometries, which would be prohibitively expensive or physically impossible to produce with other manufacturing methods (Lane 2013). The technology is giving designers close to limitless freedom, removing the constraints of traditional manufacturing methods (Excell 2010).

Cost savings alone is one of the main reasons Additive manufacturing have managed to get mainstream attention in industry. After Stratasys` key patents on FDM expired in 2009, there was an explosion of open-source FDM printers on the market. In a few years the lowest price of an FDM printer dropped from $14 000 to $300 (Mims 2013). Another significant drop in price is likely to play out again as key patents to the low-cost, high-res laser sintering is expiring in February 2014. Others claim that this turning point will not be as radical as when the FDM patents expired, it will have beneficial impact and generate a more competitive market (Lewis 2013). Only the core patents from the 1980s will expire, while the advancements made subsequent are still on the books. In addition to that, SLS is a more complex and sensitive process compared to FDM and will be harder to adopt.

There is a potential environmental benefit to 3D printing due to it being an additive manufacturing process. This is the opposite of traditional subtractive manufacturing processes, which produce objects by cutting material away from a block to create the desired shape (Hiemenz 2011). On-demand production may lead to reduced raw material requirements and a reduction in number of raw materials needed, reduced wastage originating from the process and also cuts in CO_2 emissions resulting from the savings in the distribution phase. However the process of printing is very energy consuming. Research shows that the laser process that either melts or solidifies plastics consumes up to 100 times more electrical energy than traditional mass manufacturing to make an object of the same weight. The actual energy usage per item is very high. The process does not use less energy at the production stage, it´s the material production stage that sets AM apart due to the amount of material saved (Choudhury 2013).

It is known that AM produces impressive results when it comes to part precision and complexity (Thompson 2007) (Lane 2011). Despite these qualities a major issue is the sensitivity of current machines. To be able to achieve desired material and mechanical properties they require careful optimization. Maintaining a uniform temperature is a challenge with the SLS process, which can results in variation in mechanical properties on different builds (Excell 2010).

FDM is taking on increased importance as an alternative manufacturing method for components made in small numbers. Additive components are more than strong enough to be used for highly stressed load-bearing applications. On paper, metallic additive parts printed with the DMLS technology, have mechanical properties that are better than cast and getting towards wrought standards. The limitation for expansive use is the lack of agreed standards for material and process quality. Once there will be recognized standards for testing, then people will commit to the technology and start utilizing it for load-bearing applications (Excell 2010).

An intersection of great importance is the one between AM and luxury automotive production. Noting that a company like Audi may claim it produces 7 million individual cars, there is an elaboration on the possibility for AM to make luxury design more individual and exclusive by allowing customers to create variations on interior design or entertainment components. Traditional manufacturing would make this type of customization too expensive for all but the wealthiest of customers, but AM can make the process both less expensive and faster (Lane 2013). Pointing at moldless rapid manufacturing utilizing AM, Laurens Van den Acker, at the time head of Mazda design, said that the future of car design is that everyone has his own individually styled car. (Van der Wiel 2012).

3.1 In the design studio

Trends towards affordability and ease of use are bringing professional 3D printing technology into the lives of many designers and engineers. The growing expectation that a CAD drawing can become a real three-dimensional object in a matter of hours is altering how companies see the design process (Stratasys 2012).

Purchasing a reliable 3D printer with good accuracy and low tolerance suitable for the needs of small design studio, as of today is rather expensive. Therefore outsourcing services suitable for 3D printing (conceptual form models, prototypes, tooling etc.) to a dedicated 3D printing firm is common practice. This likely ensures both competitive pricing and good print quality. On the other hand product development is dependent on the previously mentioned rapid iterative design process where designers can get immediate feedback, prevent mistakes and make design changes. Having this opportunity in house eliminates shipping delays and reduces administrative slowdowns that can accompany sourcing prototypes from external services. (Stratasys 2012)

Industry	Old Method	Time savings
Industrial design	Clay models	96%
Education	Outsourced machining	87%
Aerospace	2D laser cutting	75%
Automotive	Aluminum tooling	67%
Aerospace	Injection molding and CNC tooling	43%

Figure 4. Time saved prototyping with in-house 3D printing vs. other methods. Based on customer experience. (Stratasys 2012)

4. TRANSPORTATION INDUSTRY

4.1 Automotive sector

Additive manufacturing and its related technologies are being used by car manufacturers all over the world for their precision and ability to facilitate the creation of complex components (Brooke 2013). It is believed that with both time and the huge amount of funding the field is receiving (Atkins 2013), manufacturers will see AM making a tremendous impact on the automotive, aerospace and many other manufacturing sectors (Lane 2013).

At Present time the first OEMs (Original Equipment Manufacturer) are starting to fit 3D printed components onto their production cars (Meadowcroft 2013).

At the BMW AG plant in Regensburg, Germany, FDM continues to be an important component in vehicle design prototyping, and beyond. BMW is extending the application of FDM to other areas and functions, including direct digital manufacturing. BMW are also utilizing AM indirectly to their automotive process. Even tools and devices that aid the workers are made with FDM (DDM at BMW 2013). BMW are in possession of internal guidelines regarding whether to utilize Additive manufacturing or not.

Both Bentley Motors Ltd. And Jaguar Land Rover (JLR) are committing to another AM technology, Jetting systems. Their studios are equipped with Objet500 and Objet30 3D printers from Stratasys. Utilizing multi-material 3D printers gives JLR a competitive advantage in the market (Modelling luxury 2013). To broaden their in-house prototyping capabilities, enhance styling and provide better testing, the use of 3D printers became the answer. This resulted in more rapid development of complex multi-material parts.

As well as producing working prototypes quickly in a single process for immediate style, fit and function testing.

The technology enables the Bentley design team to easily produce small-scale models as well as full-size parts, for assessment prior to production on the assembly line. Virtually every part is prototyped in miniature scale. 3D printing has revolutionized the design process, and enables exact simulation of how the car will look. This more or less ensures for no retooling costs (Modelling Luxury 2013).

Jim Kor, a pioneer of 3D printing within automotive design is developing a fully electric 3D printed urban city car. The goal is to design a model that can travel across the US in just 2 days by using an electric engine supplemented by 10 gallons of biofuel within 2015. Kor and his team at Kor Ecologic are utilizing 3D printing (SLA) to make the vehicle. This ensures a light, strong and safe chassis. By building the actual chassis out of molten polymer enables Kor to imagine what might be instead of worrying about limitations of materials and traditional manufacturing. Kor Ecologic are trying to develop parts that can´t be designed any other way except for on a 3D printer (Clancy 2013).

4.2 Motor sports

The Motor sport industry is using AM for direct digital manufacturing (DMM) of production parts. This demonstrates that additively manufactured parts have the quality and durability to meet some of the toughest demands there are Kreemer 2011). The motorsport sector is composed of people with a versatile background. They are used to working with high-tech processes and materials. On the other hand, the sector contains people with expertise within mass production and the concrete problems and short deadlines they deal with. It acts as a bridge between the aerospace and automotive supply chain (Excell 2010).
It is impossible to get a fully transparent image when it comes the scope of AM usage in motor sports as guarding valuable secrets is a tradition, and can give a competitive edge. Unless you are apart of the team, you wont know the full extent of additive manufacturing used for production racing.
UK-based Prodrive is one of the worlds largest vehicle technology businesses. During design and testing of their successful MINI John Cooper rally car, FDM was vital in design assessment and testing. Now that the car is racing, and the FDM parts proved strong enough, Prodrive uses its FDM machine nearly full time for production parts that include gauge pods, wheel arches and hood vents.

Figure 5: Prodrive MINI John Cooper Works RX race with over a dozen FDM parts.

Among other motor sporting branches that utilize additive manufacturing are Formula 1 and Nascar. In F1, all the teams build 60% scale models for aerodynamic testing in designated wind tunnels. For a sped-up process, all of these models are fully produced with AM. Also here minor production/race parts are starting to be manufactured additively.
The 3D printing of parts have become so essential In F1 that the Red Bull racing team in the 2011 season decided to start bringing two 3D printers around on-site to every race (Rapid prototyping 2012).

4.3 Aerospace/aviation sector

The aerospace industry, being at the forefront of technology has a long history of utilizing additive manufacturing both for prototyping and production parts. Boeing already put laser-sintered cooling ducts on the F18 10 years ago and the 787 Dreamliner also features a number of non-critical laser sintered components (Excell 2010). The most critical features of AM implementation for aerospace is the advantage of weight reduction. Equally important is the reduction in storage space for stock and material resources. The reduction in maintenance costs is also significant.

NASA is implementing 3D printing for more efficient manufacturing, a total of nine centers are equipped with 3D printers (Eitel 2013). NASA recently successfully tested a 3D printed rocket injector. Liquid oxygen and gaseous hydrogen passed through the component into a combustion chamber and produced 10 times more thrust than any injector previously fabricated using 3-D printing. The component was manufactured utilizing DMLS, building up layers of sintered nickel-chromium alloy. This type of injector manufactured with traditional processes would take more than a year to make, but with AM processes it can be produced in less than four months, with a 70% reduction in cost. One of the keys to reducing the cost of rocket parts is minimizing the number of components.(NASA1 2013). This injector had only two parts, whereas a similar injector tested earlier had 115 parts. Fewer parts require less assembly effort, which means complex parts made with 3-D printing have the potential for significant cost savings. NASA seeks to advance 3D printing to make every aspect of space exploration more cost-effective (NASA2 2013).

SelectTech is another innovative company that utilizes additive manufacturing. They developed a 3D printed Unmanned Aerial system (UAS) without funding or aeronautical expertise and succeeded. Additive manufacturing offered the flexibility to iterate, and was used in a trial and error approach to avoid delays for analysis and simulation (Hiemenz 2013).

5. DISCUSSION

Additive manufacturing is changing both how and what we can manufacture. It is enabling designers and engineers to create in a new way. The technology´s impact on the automotive and aerospace industry is unquestionable. Even so there are unresolved issues and challenges to overcome.

5.1 Prototyping

Research shows that by using additive manufacturing methods in the design process, designers can quickly get to a point of producing working prototypes. This serves as an effective validation tool both functionally and aesthetically, when before having a prototype would be costly early in the process. Being able to produce prototypes increases the chances of finding flaws in a design during testing, which ensures for a better product and can lead to bigger profits. If these problems were to be discovered later in the process or after market launch it could be costly or result in product failure. Additionally, AM can significantly reduce lead times through rapid turn-around cycles between design and production.
The technology allows R&D departments to make alterations quickly, refit or change the design based on digital input. This accelerates the design process by getting products to market faster.
An optimized design process with more iterations can help minimize risk of product failure (Stratasys 2012).

5.2 Cost and productivity

It is generally believed that cost and faster turnaround are among the primary drivers in industry, as for incorporating 3D printing in the product development process.
Additive manufacturing eliminates tooling, and with that the cost and time related to creating it. The amount of material used can also drastically be reduced. While traditional subtractive manufacturing processes often remove up to 95% of the raw material to arrive at a finished component, additive machines only use the material needed to make the part (Excell 2010). The savings in material usage and rapid turn-around cycle saves on additional storage and maintenance costs.

The lowering of investment cost and development time allows businesses to adapt more easily and faster to the market. This new logistics model where files are getting shipped digitally and manufactured on demand locally close to the end user, allows for fast and fairly risk free production. On the other hand these transactions of digital files and intellectual property comes with the risk of valuable information being stolen or misused illegally by others (Stratasys 2012). In house printing can eliminate that risk as well as speed up the iteration process considerably.

5.3 Complexity

The elimination of tooling also means that designers are freed from the constraints of traditional manufacturing and assembly. By creating layer by layer the geometrical complexity of printed components are almost limitless. Components that had to be manufactured in hundreds of parts can now be 3D printed into one or several-part components (NASA1 2013). The technology also allows shapes to be structurally optimized for increased performance.

5.4 Customization

It has been long known that the trend towards customized products is accelerating. Consumers are looking to have their personal taste reflect in what they are doing and using (Bryson 2011). For Instance a personal vehicle becomes your avatar, the way you portray yourself to the world around you. This becomes even more true when AM is incorporated into the product development cycle. It is believed that the technology can democratize the luxury of customized design, and make it more individual and exclusive by allowing customers to create variations on elements and design components. AM can make this process both less expensive and faster (Lane 2013). This is especially of interest to high-end luxury manufacturers, with a relative small production volume and demanding customers who want, and are willing to pay that price.

5.5 Environmental impact

It is proven that AM produces less material waste than traditional manufacturing methods, only using material needed for production of components. However there has been some discussion regarding the energy consumption of 3D printing. As the laser process consumes much more electrical energy than under traditional manufacturing, questions are raised regarding the ecological footprint. It is believed that when material production is factored into the equation, Additive manufacturing is to prefer over traditional methods for the transport industry, which is under tight environmental and emission regulations.

5.6 Moving towards production

Between design and production there are many stages were the utilization of additive manufacturing can be beneficial. The use of AM is speeding up the design process and getting products to market faster.

The implementation of 3D printed production components in motor sports and aerospace proves that additive manufacturing can move from prototyping to production, and arguably mass-production in the near future. Research shows that AM is producing parts at lighter weights than traditionally manufactured components at equal strengths (Lane 2013). Reduction in weight for the transport industry equals more effective shipping, less cost and emissions. On the other hand 3D printing is known for being a sensitive process where the slightest change in production conditions can alter the mechanical properties of manufactured components.

The limitation on build size is also a concern for many researchers. However, most believe that it´s a minor one that can be solved and should be subsequent to the likes of machine sensitivity.

Users have to be certain that components will perform. Formal types of validation and quality controls have to ensure that parts will function. At present time there are no agreed standards or regulations for material and process quality of additively manufactured parts. Once that will be in place along with general awareness of the technology´s capability, it is believed that its use within production will expand rapidly.

Another obstacle for AM to overcome is the limitations regarding materials. As of now it is improbable to produce some parts with complex geometries, since the array of materials available is more compacted than with traditional manufacturing techniques. (Lane 2013).

6. FUTURE OF AM

Many believe that 3D printing will revolutionize manufacturing and its industries. With NASA printing engine parts to rockets and Boing planning to print fully functional airplane wings it´s hard to argue. It is also easy to get carried away, imagining a futuristic sci-fi world where everything needed around us will be printed without taking the earlier addressed limitations into the equation.

The futures of additive manufacturing will likely involve significant sharing of production facilities (Eitel 2013). As files are transferred digitally, production can happen locally as close to the end user as possible. This eliminates global shipping and the damage it brings upon the environment.

Aerospace is the industry other industries look to for a glimpse of what the future might bring. They were the earliest adopter of carbon fiber and the first to integrate CAD/CAM into the design process. Both of these implementations are now commonplace throughout industries and doesn´t require financial justification (Hiemenz 2013). There are many other examples that show that trends in aerospace predict the future, which is reassuring for the additive manufacturing industry. I am confident when saying that AM will dictate manufacturing in industry in the future.

7. CONCLUSIONS

This paper has studied the impact of the rise in additive manufacturing on the design process and within the automotive and aerospace industry.

As of today AM is widely used for product development in RD departments across the mentioned industries, throughout all functions and processes. The most common uses include concept models, functional prototypes, tooling and production components. It is rapidly growing into a large-scale industry.

Additive manufacturing gives the flexibility to iterate while facilitating for faster turnaround resulting in products arriving the market sooner, while keeping costs down and thus increasing profit.

The role of 3D printing in manufacturing is an important ecological factor. Due to less material prepared and wasted in the process of manufacture, AM is beneficial to the environment when compared to traditional processes. As of today, the process of printing itself is to energy consuming and has to be developed further.

The manufacturing technology´s success and widespread use throughout the transport industry is inevitable. Aerospace and motor sports are leading the way, using AM for small production parts. The technology is producing components with good material properties at lighter weights resulting in better performance. The evolution of 3D printing won´t happen over night, as there are problems yet to figure out. Today, AM within production is used mainly for non-critical parts. For the technology to facilitate the production of load bearing components there has to be developed validation standards for material and process quality. The sensitivity of current machines is an issue and has to be dealt with. When printing a component several times the mechanical properties have to be stable from one print to the next.

Additive manufacturing might very well become the de facto method of industrial manufacture in the future. While its historical underpinnings date several decades back it´s only in recent years the technology has been widely implemented in product development, completely altering how and what can be made. The direct connection between designer and manufacturing is re-established. It is believed that we will se a remarkable shift from use limited to prototyping over to production.

REFERENCES

A New Mindset in Product Design: 3D Printing Can Help Bring Better Products to Market Faster. (2012) Stratasys Inc.

Atkins – Manufacturing a low carbon footprint. (2013) (Cited Nov 25 2013) www.atkins-project.com

Brooke, R. (2013). TCT + Personalize to demonstrate additive manufacturing role in automotive industry [cited 12 Nov 2013] http://www.tctmagazine.com/additive-manufacturing/tct-show-personalize-to-demonstrate-additive-manufacturing/

Bryson, E. Trend towards customized products accelerates [cited 13 Nov 2013] http://articles.latimes.com/2011/mar/10/business/la-fi-single-serving-20110310

Byrne, C. 3D Printing: The State of the Art [cited 12Nov 2013] http://venturebeat.com/2010/12/20/3d-printing-the-state-of-the-art/

Choudhury; Nilima (2013) How green is 3D printing [cited 23 Nov 2013] http://www.rtcc.org/2013/09/02/how-green-is-3d-printing/

Clancy, H. (2013) How Jim Kor is revolutionizing car design with 3D Printing. [Cited 14 Nov 2013] http://www.greenbiz.com/blog/2013/08/28/how-late-adopter-jim-kor-revolutionizing-automotive-design-3-d-printing

Direct digital Manufacturing at BMW (2013) (Stratasys Inc)

Eitel; E. (2013) The future of Additive Manufacturing [Cited 15 Nov 2013]

Excell, J. (2010) The Rise of Additive Manufacturing [cited 12 Nov 2013]

Hiemenz, J. Stratasys Inc. (2011), 3D printing With FDM: How It Works

Hiemenz, J. Stratasys Inc. (2013) AM Trends in Aerospace: Leading the way

Kreemer, A. Stratasys Inc. (2011) Motor Trends: AM drives production of race-ready parts.

Lewis, Michael. (2013) Selective Laser Sintering Patent Expiration Will Not Be a Game Changer. [Cited Nov 22 2013] http://news.thomasnet.com/IMT/2013/09/04/selective-laser-sintering-patent-expiration-will-not-be-a-game-changer/

Lane, B. (2013) Integrating Additive Techniques into Aerospace and Automotive Manufacturing [cited: 10 Nov 2013] http://www.thomasnet.com/journals/machining/integrating-additive-techniques-into-aerospace-and-automotive-manufacturing/

Meadowcroft, J (2013) Why 3D printing is the future car industry [cited 12 Nov 2013] http://www.motortorque.com/news/why-3d-printing-is-the-future-of-the-car-industry

Mims, Christopher. (2013) 3D printing will explode in 2014, thanks to expiring patents [cited 21 Nov 2013) http://qz.com/106483/3d-printing-will-explode-in-2014-thanks-to-the-expiration-of-key-patents/

Modelling Luxury (2013) Stratasys Inc.

NASA, Industry Test "3D Printed" Rocket Engine Injector (2013) NASA. [Cited 15 Nov 2013] (NASA 1) http://www.nasa.gov/content/nasa-industry-test-3d-printed-rocket-engine-injector/#.UoY_OJTfwSY

NASA Tests Limits of 3-D Printing with Powerful Rocket Engine Check (2013). NASA [cited 15 Nov 2013] (NASA 2) http://www.nasa.gov/exploration/systems/sls/3d-printed-rocket-injector.html#.UoY-65TfwSY

Pham, D.T. (1997) A comparison of rapid prototyping technologies.

Rapid prototyping, rapid manufacturing, 3D printing [cited 12 Nov 2013] http://www.formula1dictionary.net/rapid_prototyping.html

Ryder, Brett. The Third Industrial Revolution [cited 11 Nov 2013] http://www.economist.com/node/21553017

Standard Terminology for Additive Manufacturing Technologies, ASTM International

Thompson, R. (2007) Manufacturing Processes for Design Professionals, pp. 232-241

Top Five Reasons To Integrate 3D Printing into your PDL (2013) Stratasys

Van der Wiel, J. (2012) Future of Automotive Design & Materials. Pp. 21

Waterman, N.A. (1994) Rapid product development in the USA, Europe and Japan, World class design to manufacture.

Wohler Associates. (2012) Wohler Associates publishes 2013 Report on AM and 3D Printing