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Development of an operator model for modern additive manufacturing technologies at the Graz University of Technology

MASTER'S THESIS

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Graz, June 2015

AFFIDAVIT

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Graz, am …………………………… ………………………………..
(Signature)

Acknowledgment

I want to thank Professor Franz Haas and Professor Christian Ramsauer for establishing the cooperation between their departments during this Master Thesis which made this interdisciplinary academic project possible.

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I also want to thank my wonderful wife for joining me through all the ups and downs during the past years at the university, my unique children, my parents for their personal and financial support through the years and all my colleagues and friends who supported me.

Finally, I want to join the praise of several great scientists in the past centuries and give honour to whom honour is due – The God of the heavens and the earth!

Soli Deo gloria

Abstract

This Master Thesis deals with the technological and economic advantages and challenges that can occur when additive manufacturing technology is introduced and put into practice. In a five step approach this project gives insights on how additive manufacturing can be introduced and applied at the Graz University of Technology industry partners Magna Steyr and Ventrex Automotive.

Companies face the challenge of an increasing competitive global environment. Innovations like the additive manufacturing technologies, driven by technological research and development, are one way to gain competitive advantages in business fields by increasing economic efficiency and technological effectiveness.

Introducing a new manufacturing technology into a company leads to major changes in the entire manufacturing system. Furthermore it influences almost every department of a company. Therefore, this project is set up as an interdisciplinary work between the Institute of Industrial Management and Innovation Research and the Institute of Production Engineering. The cooperation of these two institutes allows research on economic-, technological-, process- as well as company strategy aspects, which have to be considered when introducing a new manufacturing technology.

The first phase is an analysis of the requirements to determine the attributes of possible applications for the additive manufacturing technology followed by the definition of applications at Ventrex Automotive and Magna Steyr in the second phase. In the third phase a detailed analysis of the additive manufacturing technology processes available was necessary, to choose the proper technology for the applications chosen in the previous phase.

The technological, economic and process comparison of the current prototyping fabrication processes to the potential new manufacturing technology was the objective of the fourth phase. Finally several possible operator models were evaluated to prepare the practical implementation of additive manufacturing at Magna Steyr and Ventrex Automotive.

Kurzfassung

Die vorliegende Diplomarbeit befasst sich mit den technischen und wirtschaftlichen Vorteilen sowie Herausforderungen, die bei der Einführung eines generativen Fertigungsverfahrens in die Praxis entstehen. In einem fünfstufigen Lösungsansatz gibt dieses Projekt Einblick, wie generative Fertigung verwendet werden kann, um die Leistung bei den Industriepartnern Magna Steyr und Ventrex Automotive während der Produktentwicklungsphase zu erhöhen.

Unternehmen stehen vor der Herausforderung des zunehmenden globalen Wettbewerbs. Innovationen wie die generative Fertigungstechnologie sind ein Weg um Wettbewerbsvorteile in Geschäftsfeldern durch die Erhöhung der Wirtschaftlichkeit zu gewinnen. Die Einführung einer neuen Fertigungstechnik führt zu Veränderungen in der gesamten Unternehmung. Daher ist dieses Projekt als interdisziplinäre Arbeit zwischen dem Institut für Fertigungstechnik und dem Institut für Industriebetriebslehre und Innovationsforschung organisiert, um den Einfluss über viele Aspekte wie der Wirtschaftlichkeit, technologische Anforderungen, Fertigungsprozesse sowie die Unternehmensstrategie zu beforschen.

Die erste Phase ist eine Analyse der Anforderungen, um die Eigenschaften der möglichen Anwendungen zu bestimmen. Sie dient somit als Grundlage für die zweite Phase, die Definition von Anwendungsfällen bei Magna Steyr und Ventrex Automotive. Die Analyse der bestehenden Fertigungsverfahren und der Vergleich zur generativen Fertigungstechnologie zeigen Potentiale auf um durch generative Fertigung einen Mehrwert zu lukrieren.

Die Erstellung eines Betreibermodells für eine moderne generative Fertigungsanlage an der Technischen Universität Graz soll die Möglichkeit bieten weiterhin Forschung hinsichtlich innovativer Fertigungstechnologien zu betreiben und als Fertigungsdienstleister eine Chance bieten Drittmittel zu lukrieren.

Table of Content

1 Introduction

Manufacturing companies today are facing an increasing competitive environment compared to past decades.[1] In order to prevail against competitors and to achieve sustained success, innovation becomes an important issue concerning products and processes.[2] Additive manufacturing is one of these innovative technologies to realize on one hand products with unprecedented opportunities in production and produce rational and productive on the other hand.[3]

Through the development of additive manufacturing processes, many companies now face the challenge of using these technologies cost-efficiently and trying to derive the whole range of technological advantages. The key benefits of additive manufacturing processes include the production of complex products without costly mould in a relatively short time and directly computer controlled. Due to the continuous improvements in technologies, the use of different materials in sufficient quality is now achievable. Especially in prototype and small batch production, companies can save costs by using additive manufacturing technologies.[4]

The Institute of Industrial Management and Innovation Research (IBL) conducts research in the context of Industrial Engineering and aims at achieving the optimum design of work processes in companies in terms of efficiency and effectiveness. The main objective, according to this research field, is to optimally match the individual steps in the value chain to each other and thus ensure high productivity. In the future the use of additive manufacturing processes will increase in production systems and will have enormous influence on the upstream and downstream process steps. Therefore, we need to put more emphasis in this area in order to meet the demand of industry partners and catch up with the radical changes this technology brings to Industrial Engineering.

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[1] Advanced Manufacturing in the Automotive Industry, John Mortimer, page 112
[2] Managing Technological Innovation: Competitive Advantage from Change, Frederick Betz, page 145
[3] Mass Customization: Engineering and Managing Global Operations, Fogliatto, Silveira, page 277
[4] Laser Additive Manufacturing of High-Performance Materials, Dongdong Gu, page 6

The Institute of Production Engineering (IFT) works with a 3D printer and a Fused Deposition Modelling (FDM) machine and researches in the field of technical integration for additive manufacturing processes into existing production systems.
Through the cooperation between the two institutions, the field of additive manufacturing can be viewed and researched comprehensively. This Master Thesis is supported by the “clever & smart” studentship of the faculty of mechanical engineering and economic science.

This Master Thesis should build a joint research project with two industrial partners in the automotive industry, testing the use of additive manufacturing for individual applications. In addition, an operator model should be developed, which offers the possibility to create an additive production facility, suitable for research purposes and for contract manufacturing for both industrial partners as well as for the whole industrial network of the Graz University of Technology.

1.1 Companies involved

The Graz University of Technology is very anxious to keep in touch with local and international companies in order to catch up with the trends and changes in business, offers research to the industry to meet the demand of customers, suppliers and industry partners and also helps their students on the way to their professional careers.

For this Master Thesis, two outstanding companies, who supply Original Equipment Manufacturers (OEM’s) in the automotive industry, have been chosen to efficiently and effectively introduce the innovative additive manufacturing technology.

1.1.1 Magna Steyr

Magna Steyr is part of the International Magna AG, which is one of the leading global, brand-independent engineering and manufacturing partners to automobile producers, located in Graz, Austria. Magna Steyr offers OEMs solutions for a wide range of services with highly flexible development and assembly strategies. They design and develop parts from individual systems such as door modules or roof systems to complete vehicles and manufacture small batch sizes as well as volume production.[5]

Magna International is divided into four global regions, North America, South America, Asia and Europe. Magna Europe employs over 46.000 people in 155 facilities. Magna Austria has 18 manufacturing and assembly departments as well as 9 engineering, product development and sales departments.[6] 13.075 people work currently at Magna Austria and the assembly and engineering department in Graz is the biggest facility of Magna Austria, employing more than 9500 people and raising an annually turnover of over three billion Euros in 2013.[7]

Figure 1: Magna Global Reach, source: www.magna.com

Magna Steyr has already gained experience with additive manufacturing of plastic parts and rents a 3D Printer for supportive matters in the production line. They produced glove inlays additively to protect workers whose fingers are exposed to repeated high punctual pressure. Magna Steyr has no experience with metal processing additive manufacturing technologies. Especially in the field of car body design in the prototyping

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[5] www.magnasteyr.com (05/2015)
[6] http://www.magnasteyr.com (05/2015)
[7] www.magna.com/global-reach (05/2015)

phase, the potential of reducing high tool costs for expensive formative casting processes is a potential field for technological and economic research.

1.1.2 Ventrex Automotive

Ventrex develops and manufactures high-quality compressor and valve products for the automotive industry and guarantees innovation and quality at the highest level. Headquarter of development and production of this owner-managed company is located in Graz, Austria.

Ventrex is a globally competing first tier - second tier supplier to OEMs in the automotive industry. They have major business partnerships in Slovenia, China and India, and distribute their products globally. 47% of Ventrex products are distributed to Germany and another 35% to other European countries.

Their product portfolio reaches from electronic pressure control to the tank safety valves in internal and external design. In 2014 Ventrex employed 130 people and made annual revenue of more than 50 million Euro.[8]

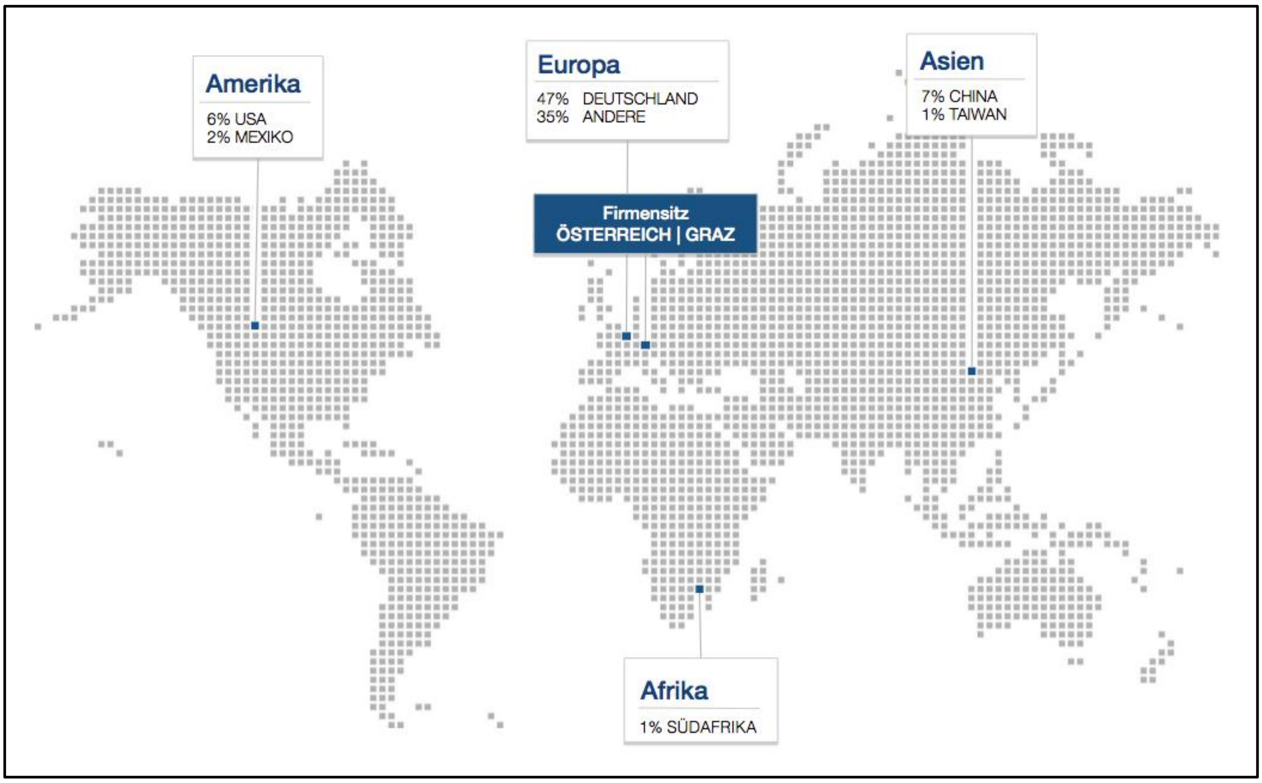

Figure 2: Ventrex Automotive Global Market Distribution, source: www.ventrex.at

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[8] http://www.ventrex.at (05/2015)

In 2014 Ventrex neither integrated any metal processing additive manufacturing technology in their production system nor did they use it for design, development or prototyping purposes. So far, Ventrex has produced some components as transparent demonstration models for their clients using stereolithography to demonstrate the functionality of their products. The metal processing additive manufacturing technologies could bring some major advantages for Ventrex, if design changes of their products could lead to a reduction of parts and therefore a reduction of sealed contact surfaces in the fluid managing valves. A reduction of costs in the prototyping phase through shorter lead times and higher variety of designs could be potential opportunities for Ventrex Automotive.

1.2 Task and Objective

The goal of this Master Thesis is to explore the use of additive manufacturing technologies through concrete case studies and thereby contribute to the introduction of these technologies at the Graz University of Technology industry partners. Furthermore, an operator model should be developed for the Graz University of Technology to have access to this cutting-edge technology for research purposes and build a way to raise external funds. This operator model should bring several advantages for the industry partners as well as for the university.

For the industry partners it is a possibility to split up the costs for acquisition and thereby lower the inventory costs compared to owning their own machines. By sharing one machine with other industry partners and the university the degree of capacity utilisation on the machine increases.

For the Graz University of Technology such an operator model brings on one hand access to the latest technology for research purposes and on the other hand it leads to an opportunity to generate external funds.

1.3 Course of Action

The project is divided into five phases. Each phase starts with theoretical research on that specific aspect to gain the knowledge necessary for the practical part of the phase. Every phase ends with a process of decision making.

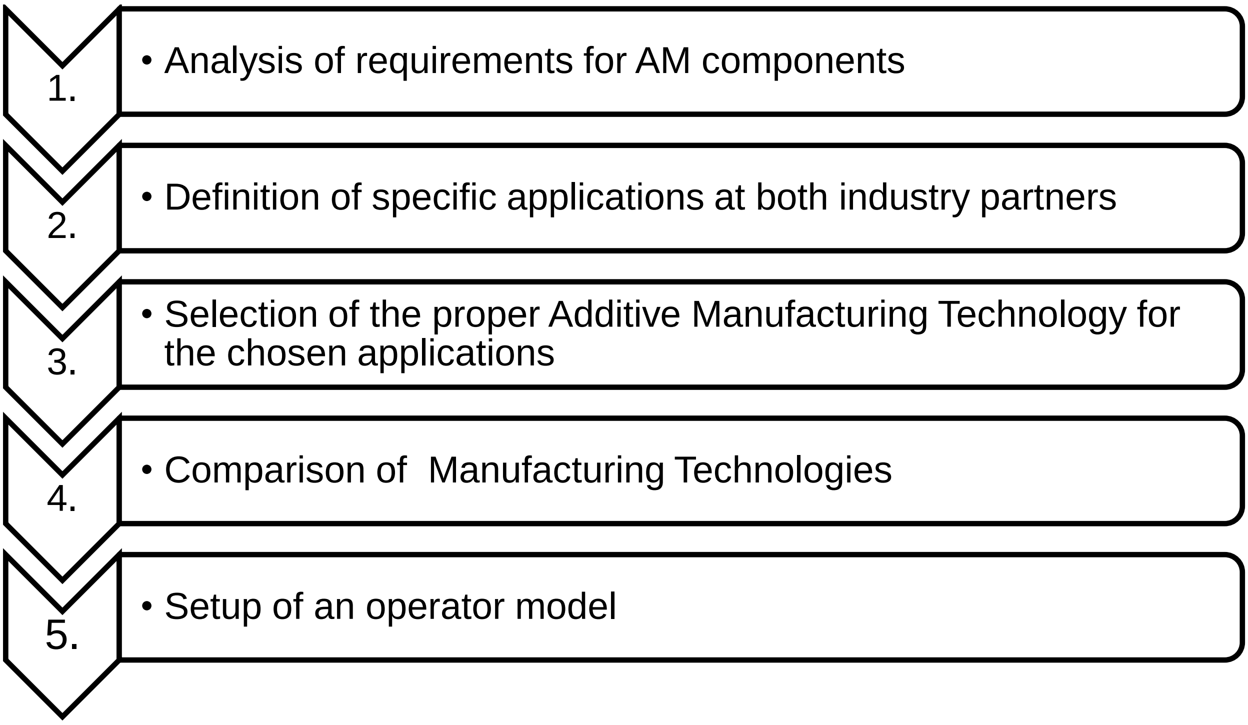

Figure 3: Master Thesis - Course of action

1. Analysis of requirements (Chapter 3.1)

The first phase is about the detailed research on the possible advantages such a new technology can bring to a company. The goal of this phase is to determine a catalogue of requirements to find fields of applications for the industry partners and therefore set the basis for the second phase of defining specific applications.

2. Definition of applications (Chapter 3.2)

After determining the requirements for the applications, the second phase is about the selection of possible parts, assemblies or applications in cooperation with our industry partners Magna Steyr and Ventrex Automotive. Focusing on the technological and economic potential of such a new manufacturing technology, specific use cases have to be selected for further investigations.

3. Selection of Additive Manufacturing Technology (Chapter 3.3)

During the past twenty years, with the rise of stereolithography as the first additive manufacturing technology, a huge amount of different processes has evolved. In this phase the accurate technology for the chosen applications should be selected, considering a possible operator model involving the Institute of Production Engineering.

4. Comparison of Manufacturing Technologies (Chapter 3.4)

After the selection of the right additive manufacturing technology, the advantages and disadvantages of the different manufacturing processes have to be determined and compared to show the technological and economic impact of such a new technology.

5. Setup of an Operator Model (Chapter 4+5)

Make or buy? How can additive manufacturing be put into practice for the industry partners? What kind of additive manufacturing machine can be used? The operator model should give answers to those questions and evaluate the possibility of a contract manufacturing and research cooperation between the industry partners and the Graz University of Technology.

2 Basics of Additive Manufacturing

“Additive manufacturing is a layer-based automated fabrication process for making 3-dimensional scaled physical objects directly from 3D-CAD data without using part-depending tools”

The development in laser technologies, materials and the computer controlled manufacturing including computer aided design (CAD) and computer aided manufacturing (CAM) during the 1960s until the late 1980s, set the basis for today’s additive manufacturing. [9] In 1986, a novel fabrication method of Charles W. Hull was patented, which should allow the direct production of physical objects from a 3D computer model. The material used was a liquid plastic that could be solidified by exposure to a laser beam. Hence, manufacturing of very complex geometries became possible. [10]

In the early 1990s selective laser sintering, laminated object manufacturing, solid ground curing and fused deposition modelling were commercialized. Those processes were basically used for prototyping production. In the mid-to-late 1990s rapid tooling was invented by the use of additive manufacturing processes for injection molding and other moulding-based mass-production processes. In the late 1990s the first metal processing additive manufacturing method was invented, the laser cladding based metal fabrication. Parallel to the laser processing technologies the electron beam melting in powder beds and ultrasonic consolidation of metal sheets was developed and commercialized successfully.[11]

The principle of all those processes is the production of layer structured 3D objects, directly evolved from a digital computer model. The produced part is built layer by layer on a platform which is maintained on a constant level by lowering the building platform after each layer is finished. Additive manufacturing processes are also called 2 ½ -D-Technology, a term derived from the NC-Technology used for processes of path generation in the x-y plane and infeed in z-direction. [12]

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[9] Materials processing handbook, Groza, Shackelford, page 26-2
[10] „Understanding Additive Manufacturing“, Andreas Gebhardt, page 2
[11] Materials processing handbook, Groza, Shackelford, page 26-2
[12] Additive Fertigungsverfahren, Berger, Hartmann, Schmid, Auflage 1, page 10

With the development of additive manufacturing a large number of different terms evolved. Since these novel manufacturing processes first seemed predestined for prototypes, the term rapid prototyping has prevailed in the first years. The development of higher performance materials increased and led to rapid tooling which is a new way to produce tools in small and medium batch sizes with high quality material within small time span.[13]

The latest developments have aimed for the production of serial identical, end user parts, produced in direct tool-free method, which is called rapid manufacturing. Production of parts without using tools and moulding forms as well as lower machine kinematics, due to layer structure, leads to high cost efficiency at rapid prototyping, rapid tooling and rapid manufacturing.[14]

The term additive manufacturing is derived from the Anglo-Saxon area and highlights the fundamental differences of these new techniques compared to traditional, subtractive or formative manufacturing processes. Stepped structures are characteristic of additive prepared surfaces. The flatter the slopes are, the more striking this structure becomes. That is the reason why the layer thickness is one of the most important factors in this technology.[15]

The expectations for additive manufacturing technologies have changed over the past thirty years. Whenever a new technology evolves, expectations increase dramatically in the first years until the so-called “peak of inflated expectations” is reached. The boundaries and limits of the technology become more visual and lead to disillusionment of these expectations.[16]

The “Gartner Hype Cycle” visualizes the development of expectations and determines that 3D printing technology, another word for additive manufacturing technology, is on its way to gain productivity and soon will be integrated to production systems all over

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[13] Rapid Tooling: Technologies and Industrial Applications, Peter Hilton, page 33
[14] „Understanding Additive Manufacturing“, Andreas Gebhardt, page 4
[15] Additive Fertigungsverfahren, Berger, Hartmann, Schmid, Auflage 1, page 14
[16] Mastering the Hype Cycle, Fenn, Raskino, page 70

the world. This is why research on this topic is very essential at this point of time and offers valuable research for the development of additive manufacturing technologies.[17]

Not only is the additive manufacturing technology itself on the rise to increase productivity, the market needs and the development towards customization of products raises the problem that mass production, like the famous Toyota Lean Production System, changes into agile production and lot size one production. Agile manufacturing is a concept where approaches and techniques like lean and flexible manufacturing are integrated to make a quick, moving, nimble and active production possible. Therefore, it aims for instant delivery of small lot sizes and meets the customers' individual needs and specifications.[18]

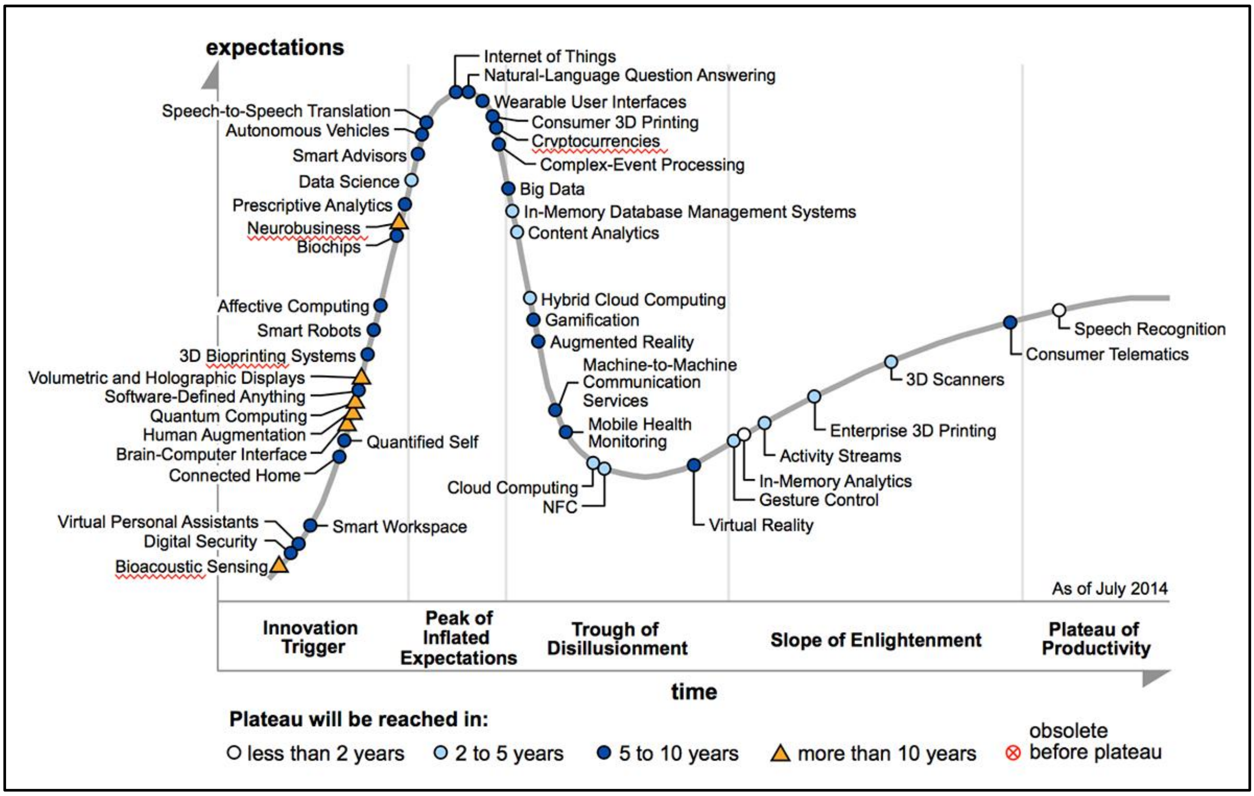

Figure 4: The Gartner Hype Cycle 2014, source: www.gartner.com

The development in BMW's product range is one example of the increasing product variety that points towards customization in the automotive industry. In 1972, BMW started with their "type 5" series. Two years later they started the "type 3" series and another two years later the "type 7" series. Today, BMW has already 12 different types of cars and more than 150 variants. Personalized interior, board computer, chassis

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[17] Mastering the Hype Cycle, Fenn, Raskino, page 6
[18] Agile manufacturing: The 21st century competitive strategy, A. Gunasekaran, Elsevier 2001, page 26

colour and additional equipment are the exact opposite of the famous Ford T-Model, available in one colour, one design and no product variety.[19]

2.1 Additive Manufacturing in context of Manufacturing Systems

The classification of manufacturing systems according to the German DIN 8580 divides all manufacturing systems into six main groups such as “master forming”, “forming”, “separating”, “joining”, “coating” and “change material properties”. [20]

Additive manufacturing systems do not fit into one of the six main groups. Hence, there are some processes that belong to the group of “master forming” like stereolithography, others fit into the “joining” processes like the 3D Printing Technology and the Chemical Vapour Deposition (CVD) process would be a part of the “change material properties” group. Therefore, a new type of classification is necessary in order to classify additive manufacturing properly into the context of manufacturing systems.

Looking at manufacturing systems from a geometrical perspective shows that there are three different ways how parts can be manufactured – subtractive, formative and additive. This distinction also shows that additive manufacturing does not substitute an existing manufacturing technology, but is a new way to produce parts.[21]

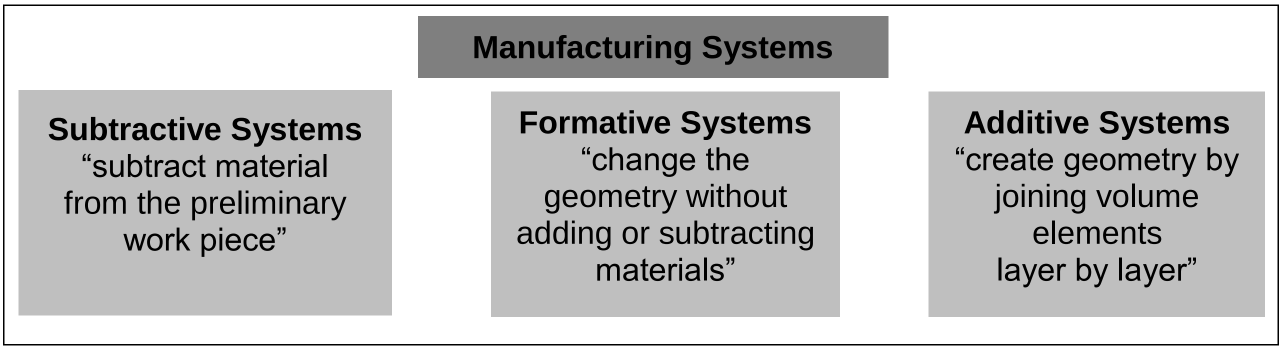

Figure 5: Classification of Manufacturing Systems, source: Generative Fertigungsverfahren, Andreas Gebhard, page 5

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[19] Wirtschaftliche Fertigung mit Rapid Technologien, Zäh, page 120
[20] „Generative Fertigungsverfahren“, Auflage 3, Andreas Gebhardt, page 3
[21] Additive Fertigungsverfahren, Berger, Hartmann, Schmid, Auflage 1, page 5

Subtractive manufacturing systems like milling or drilling subtract material from the preliminary work piece to generate a product. The volume of the produced part changes during this process.

Formative manufacturing systems change the geometry without adding or subtracting materials. Examples, such as forging or deep drawing, show that the volume is constant during this manufacturing process.

Additive manufacturing systems create geometry by joining volume elements layer by layer. The process of adding layers therefore can be based on a chemical or physical process. [22]

2.2 Classification of Additive Manufacturing Processes

Due to the fact that the number of additive manufacturing processes increased drastically in the past, it is necessary to classify the very different types of process types to get a better overview of what the different technologies and innovations are about.
A helpful way to systematically distinguish between processes is to look at the primary state of the material – solid, liquid or gaseous.[23]

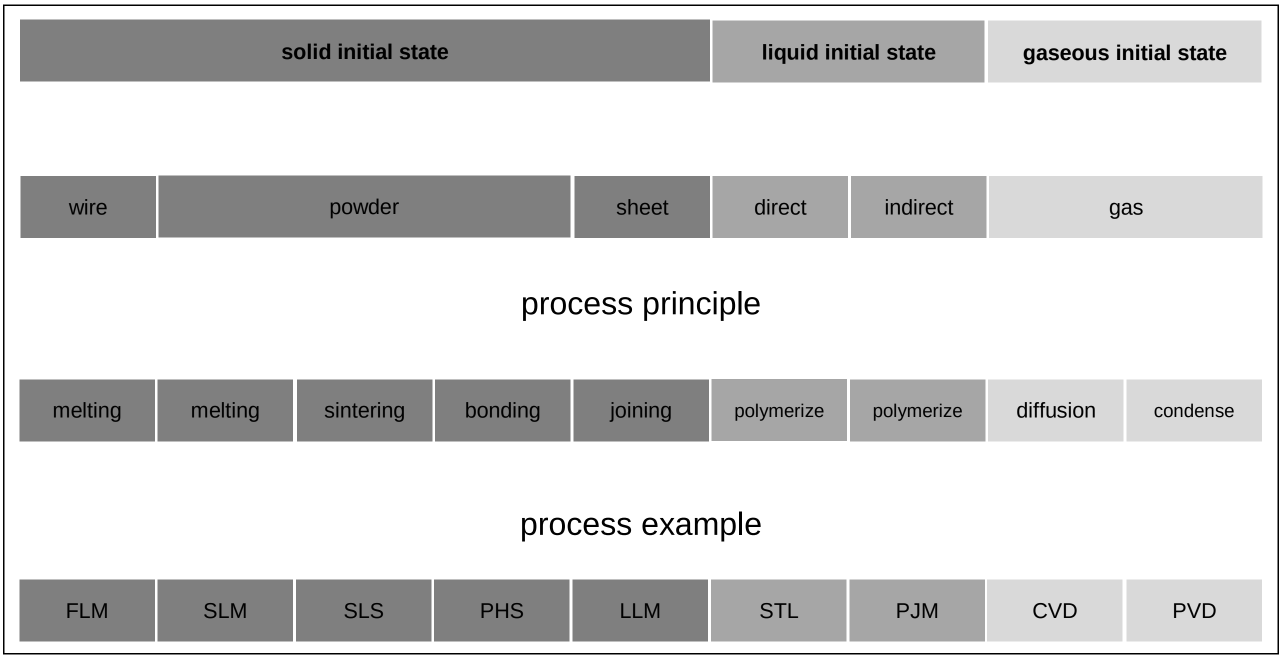

Figure 6: Classification of AM Processes, source: Generative Fertigungsverfahren, Andreas Gebhard, page 68

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[22] Generative Fertigungsverfahren, Auflage 3, Andreas Gebhardt, page 3
[23] Generative Fertigungsverfahren, Andreas Gebhard, page 68

FLM – Fused Layer Manufacturing
SLM – Selective Laser Melting (other melting method EBM – Electron Beam Melting)
SLS – Selective Laser Melting
PHS – Print Head Systems
LLM – Laminate Layer Manufacturing
STL – Stereolithography
PJM – Poly Jet Modelling
CVD – Chemical Vapour Deposition
PVD – Physical Vapour Deposition

In the following chapter one of each method will be explained to give an overview of the variety of different additive manufacturing processes and explain the fundamental differences between them. This analysis was the basis for the decision, which method could be helpful for the chosen applications at Magna Steyr and Ventrex Automotive.

2.2.1 Solid initial state

In processes based on solid initial state material components of wire, laminate/metal sheet or powder can be used. For solid materials, the greatest variety of applications is possible, because both plastics and different metals or metal alloys but also mineral materials such as sand, ceramics or even composite materials can be processed.

Compared to methods with liquid initial state, processes with solid initial state can offer a wider range in terms of material costs, material flow and material efficiency.
Several such methods can process cost efficient serial materials. Material efficiency refers to the utilization rate of the material used. It can be between 10% and 90%. The material throughput and speed of construction may be several kg/h. [24]

2.2.2 Liquid initial state

If liquid material may be applied and solidified, there is a distinction between indirect and direct constructive processes.

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[24] Additive Fertigungsverfahren, Berger, Hartmann, Schmid, Auflage 1, page 10

For indirect constructive processes, the base area of the building space is completely wetted and then selectively solidified. In direct constructive processes the base is directly and selectively wetted and then completely solidified.

The solidification of liquid or paste-like materials is carried out by polymerization. Unsaturated small hydrocarbon molecule compounds (monomers) are connected and solidified in a chemical reaction to form long molecular chains (polymers). [25]

2.2.3 Gaseous initial state

Methods that are based on the gaseous initial state of the material can be distinguished between chemical and physical principle of applying layer. Both are used in the semiconductor industry for the production of semiconducting, metallic or dielectric layers, with thickness of less than 1µm.

Layers are applied from gas phase by a chemical reaction (CVD chemical vapour deposition) or from vapor phase through a physical process (PVD physical vapour deposition) on a carrier medium (substrate). [26]

2.3 Additive Manufacturing Processes

The basis for the selection of a manufacturing technology is the detailed analysis of the technologies available in order to have solid foundation for the decision-making process.

2.3.1 FLM Fused Layer Manufacturing (solid initial state)

Besides FLM the name FDM (Fused Deposition Modelling) is also very often used in literature for this method of melting and soldering wires of thermoplastic materials. One advantage of the FLM process compared to other direct, additive methods is the good reproducibility of geometry dimensions. The accuracy of this method is about 0.2 mm. Another advantage is the possibility of engineering plastics such as ABS, PLC and high-performance plastic such as ULTEM® or any other thermoplastic material.[27]

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[25] Additive Fertigungsverfahren, Berger, Hartmann, Schmid, Auflage 1, page 15
[26] Additive Fertigungsverfahren, Berger, Hartmann, Schmid, Auflage 1, page 17
[27] Proposed Build Guidlines for Fused Deposition Modelling, G. Teitelbaum, page 9

In contrast to other methods, position controlled feed axle drives, such as machine tool drives, can be used to control the FLM-head. Thus, a higher positioning accuracy and repeatability can be achieved. The accuracy on the 3D model is limited by the nozzle mechanism on FLM – head.[28]

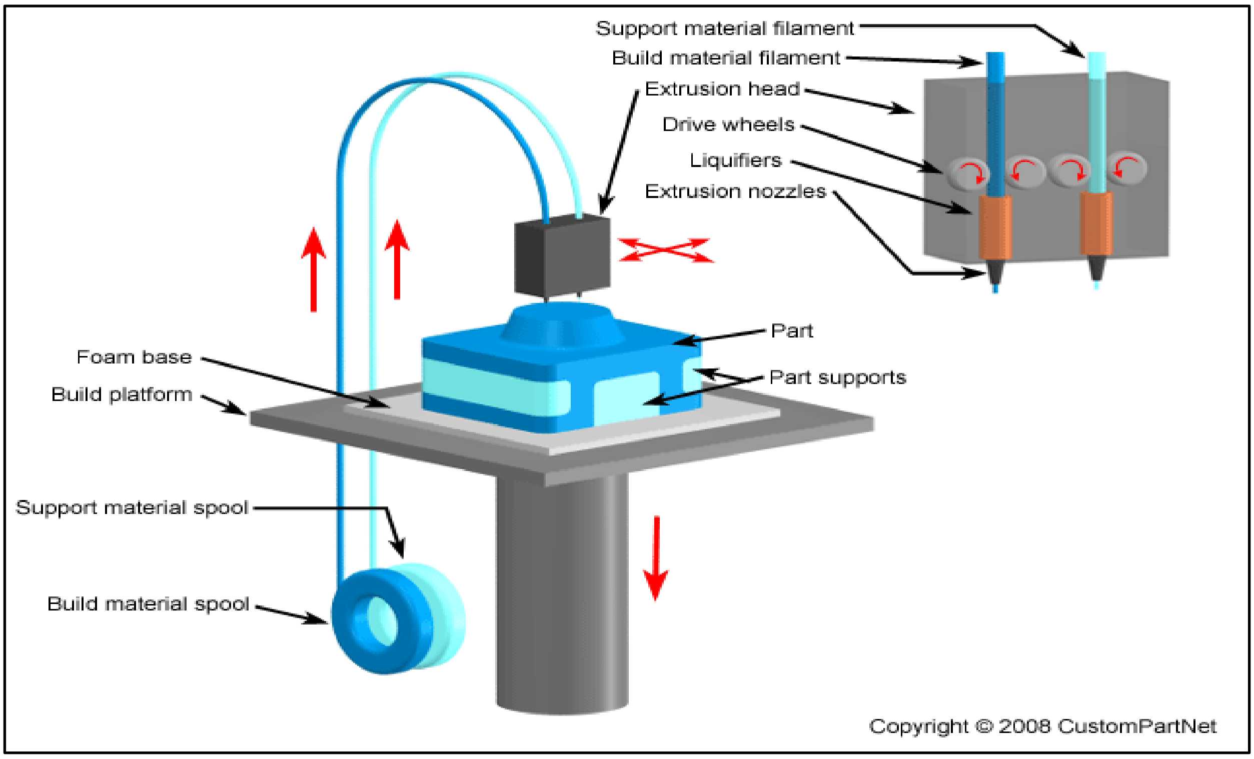

Figure 7: The Fused Deposition Modelling Process, source: www.custompartnet.com (03/2015)

The FLM system consists of the following components:[29]

1. One or more extrusion heads
2. Three translational position controlled feed axles
3. Height-adjustable, heated build platform
4. Software that controls the position of the platform, the feed axes as well as the supply of plastic wire.

In this process wires or strands of material from thermoplastic materials are melted and extruded. The extrusion die is moved, computer controlled, in the building plane through an x-y plotter mechanism. After completion of a construction, the plane is lowered one layer of thickness.

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[28] Additive Fertigungsverfahren, Berger, Hartmann, Schmid, page 131
[29] Additive Fertigungsverfahren, Berger, Hartmann, Schmid, page 133

An electrically heated nozzle is used to melt the thermoplastic material at relatively low working temperatures of 70°C for wax up to 270°C for ABS resin. Supporting structures are necessary in this process, to guarantee static stability in case of steep construction. They are built up with an interlayer so that they can be easily removed after the process of formation. The great benefits of this process are the compact small machine size, low electric power supply necessary as well as no cooling water.[30]

The material properties of FLM parts can be improved by the RP-Tempering-TM process. Thereby carbon nanotubes are sprayed or spread onto the surface of the finished part. The impact strength, compressive strength, temperature resistance or resilience of the component can be increased.

Application of the FLM method reaches from demonstration models, concept models, function models, moulding tools to end users parts. [31]

2.3.2 SLM Selective Laser Melting (solid initial state)

The SLM method and the SEBM (Selective Electron Beam Melting) are based on the development of selective laser sintering of metal powders.

The components of the system are almost identical to the SLS method. Instead of plastic or sands, metallic powder is used as building material.[32]

The basic difference is that during the process the used material gets completely melted. Thereby a local melt pool is produced and the result is a fully dense component after the process of re-solidification. The work platform is usually heated to operating temperatures of about 200°C. The layer thickness of the construction is between 20µm and 100µm.

Similar to the SLS process, powder which is not melted remains unbound and builds a supportive structure for the generated component. Still support structures are necessary for overhangs greater than 40°. Supportive elements have three basic functions. Besides the static function they are capable of the heat transfer from the produced part into the loose powder and in the solidification process they are a safety

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[30] Proposed Build Guidlines for Fused Deposition Modelling, G. Teitelbaum, page 54

[31] Additive Fertigungsverfahren, Berger, Hartmann, Schmid, Auflage 1, page 137

[32] Generative Fertigungsverfahren, Andreas Gebhardt, page 146

function against distortion through thermal shrinking or elongation. The wall thickness is limited by 80µm.[33]

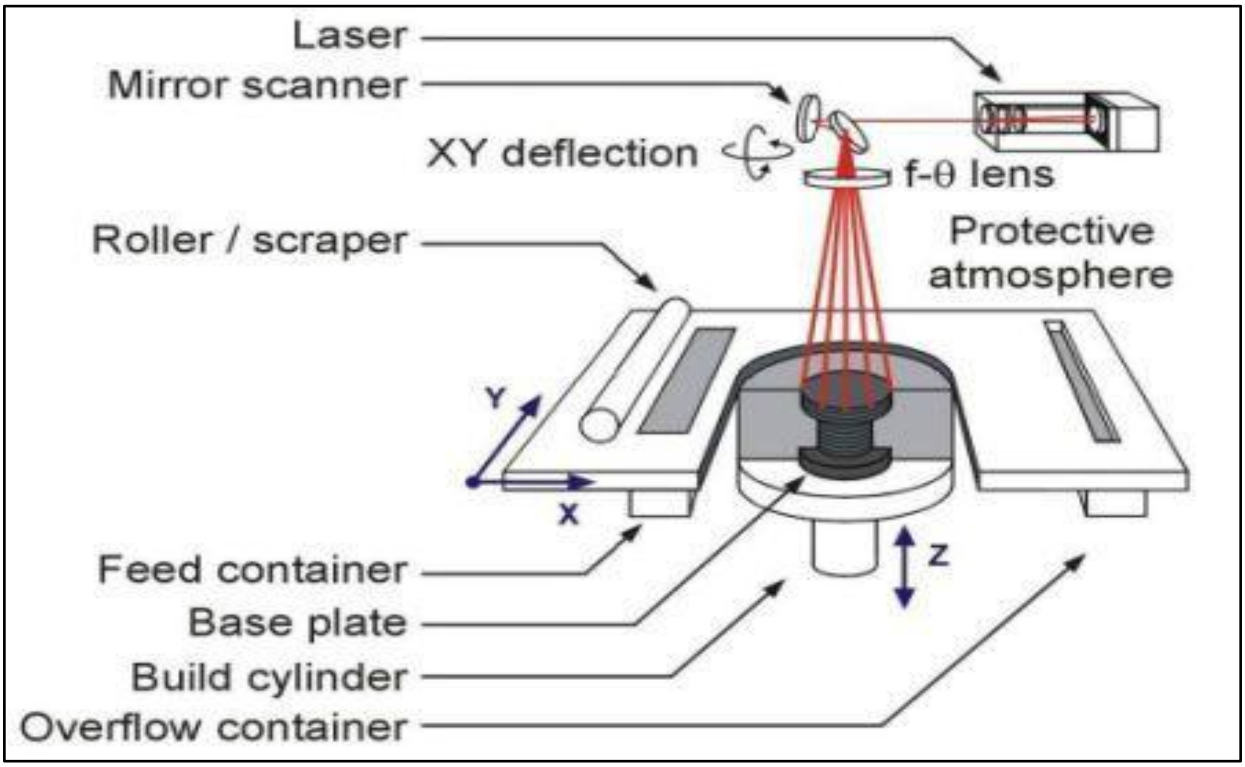

Figure 8: The Selective Laser Melting Process, source: www.custompartnet.com (03/2015)

2.3.3 SLS Selective Laser Sintering (solid initial state)

"Sintering" is also known as “laser sintering”, since its invention in the early 1990s, because all producers used a laser technology. As solidification takes place only on selected locations of the surface, the term “selective” is nowadays put in front of it.[34]

In the sintering process, densely packed and, depending on the process, easily pre-compressed granules are slightly melted or fused, using a laser beam, a directly deflected electron beam or infrared heating. Often two component powder is used with different melting points. Thereby, powder with the lower melting point fuses the particles with the higher melting point.[35]

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[33] Additive Fertigungsverfahren, Berger, Hartmann, Schmid, page 116
[34] Understanding Additive Manufacturing, Andreas Gebhardt, page 41
[35] Generative Fertigungsverfahren, Andreas Gebhardt, page 121

The SLS process can be viewed as technological consequence to the stereolithography technology, which bears the disadvantage of being limited to the material resin. Materials available for SLS processes are plastics, ceramics and moulding sand.[36]

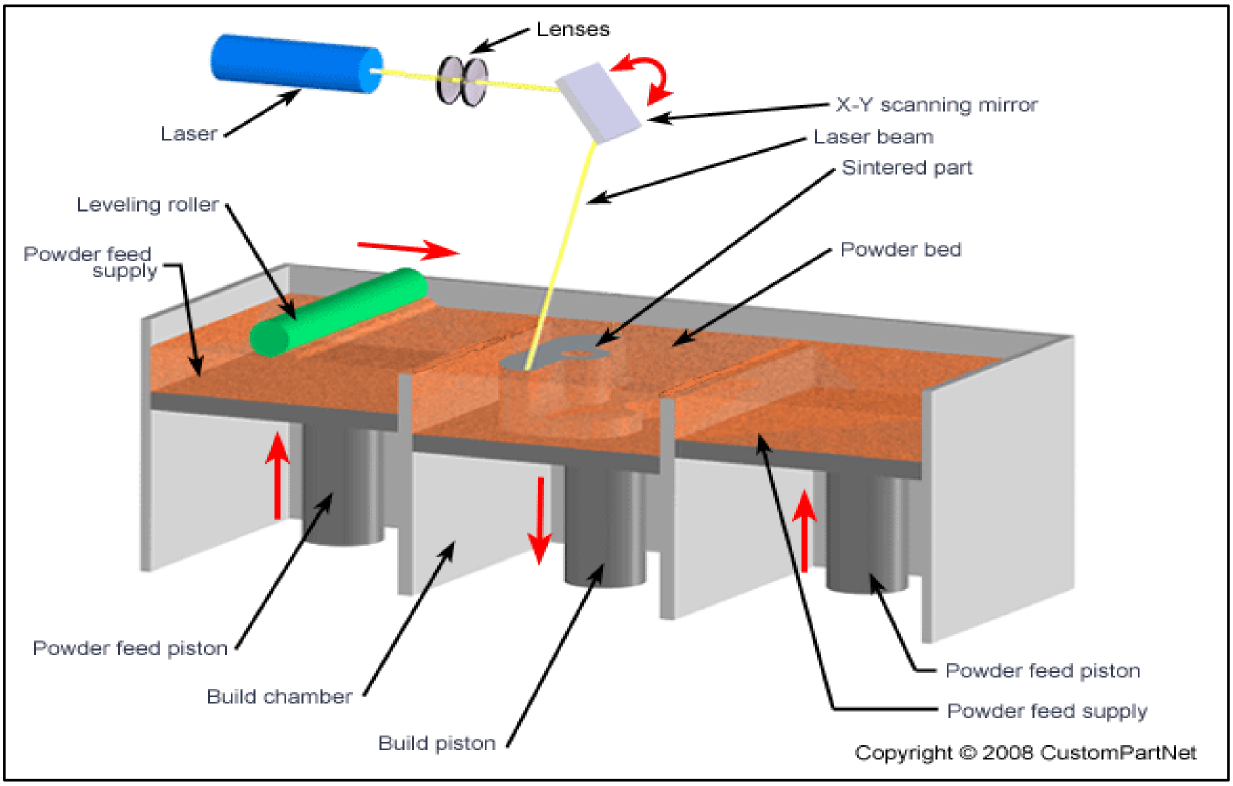

Figure 9: The Selective Laser Sintering Process, source: www.custompartnet.com (03/2015)

Just like any other additive manufacturing process the SLS construction is layers-based. The individual grains consist of semi crystalline thermoplastic; glass, sand and metal powder coated with a polymer binder which melts and after solidification holds together the material structure. The usual particle diameter is between 20µm and 100µm. The SLS method is often used for the production of sand cores and moulds for prototypes and pre-production.[37]

2.3.4 PHS Print Head Systems (solid initial state)

In 3D printing processes components are created by means of a print head. The print head corresponds in function and structure largely to the ink print heads in 2D printing processes.

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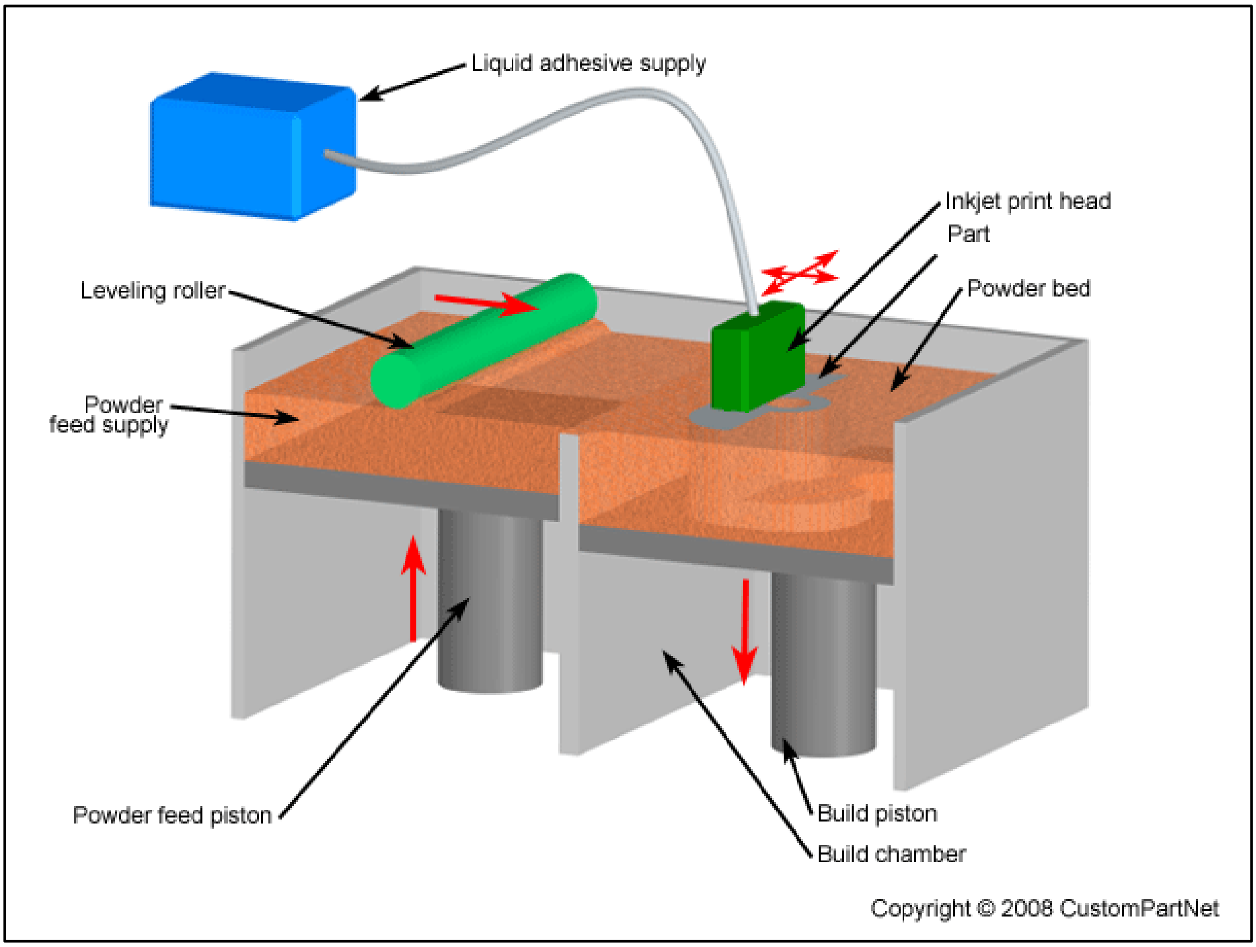
[36] Additive Fertigungsverfahren, Berger, Hartmann, Schmid, page 105
[37] Understanding Additive Manufacturing, Andreas Gebhardt, page 40

In the construction process, the print head moves horizontally, relative to a layer-wise lowered building platform. On the build platform, the print head spreads, according to the geometry of the component, fine droplets of a liquid material. The build platform is lowered by a layer thickness and the process is repeated.[38]



Copyright © 2008 CustomPartNet

Figure 10: The Binder Jet Printing Process, source: www.custompartnet.com (03/2015)

3D printing methods are divided into two categories:

1. Powder processing systems, where the print liquid is used as a bonding component in a bed of loose-applied powder.

2. Direct printing processes where the print head carries the liquid material directly to the building platform.[39]

Since the print head is responsible for the proper application of the conglutinating liquid or the building material it is the crucial feature of print head systems. One advantage of

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[38] Additive Fertigungsverfahren, Berger, Hartmann, Schmid, page 72
[39] Additive Fertigungsverfahren, Berger, Hartmann, Schmid, page 74

PHS is the possibility to apply different materials in one process, each material is processed in a separate nozzle. Another benefit of PHS is that the process speed can be increased by adding a high number of nozzles in one print head. Compared to laser sintering or laser melting systems, which scan the construction field line by line, the processing time of PHS is relatively short.[40]

The detail resolution of a print head is rated by the point density which is the number of points per area unit. The usual unit ”dots per inch” (dpi) describes the number of points that can be printed within a square of one inch (25.4mm). The frequency in which a drop of material can be generated is one of the decisive factors for the print speed of the system. Another major advantage of PHS is the possibility to produce prints in colour. The print-head works with at least three, but usually four separate channels with their own print tanks for the coloured binder in the primary colours cyan, magenta, yellow and black. (CMYK colour system) [41]

2.3.5 LLM Layer Laminate Manufacturing (solid initial state)

In the LLM process films, sheets or plates are joined in layers on a single platform. The required contour of the component is individually cut out of each layer. In automated LLM processes the excessive material is removed only after the construction process and builds the support function for the produced part.[42]

Since this process consists of several work steps such as joining, cutting and removing of material, it is also called a hybrid process. A great variety of materials such as paper, plastic, metal or ceramic can be processed. Depending on the base material, layer thickness between a few micrometres up to 80 µm is possible. The accuracy in xy-direction depends on the used tool. In automated processes parts are cut in a so called vector process. Thereby geometric accuracy until 0.05 mm can be achieved.[43]

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[40] Generative Fertigungsverfahren, Andreas Gebhardt, page 210
[41] Understanding Additive Manufacturing, Andreas Gebhardt, page 49
[42] Additive Fertigungsverfahren, Berger Hartmann Schmid, page 120
[43] Additive Fertigungsverfahren, Berger Hartmann Schmid, page 121

LLM - components show properties of the material in the direction of the layer. The behaviour of the components transverse to the layer direction depends on the respective joining process.[44]

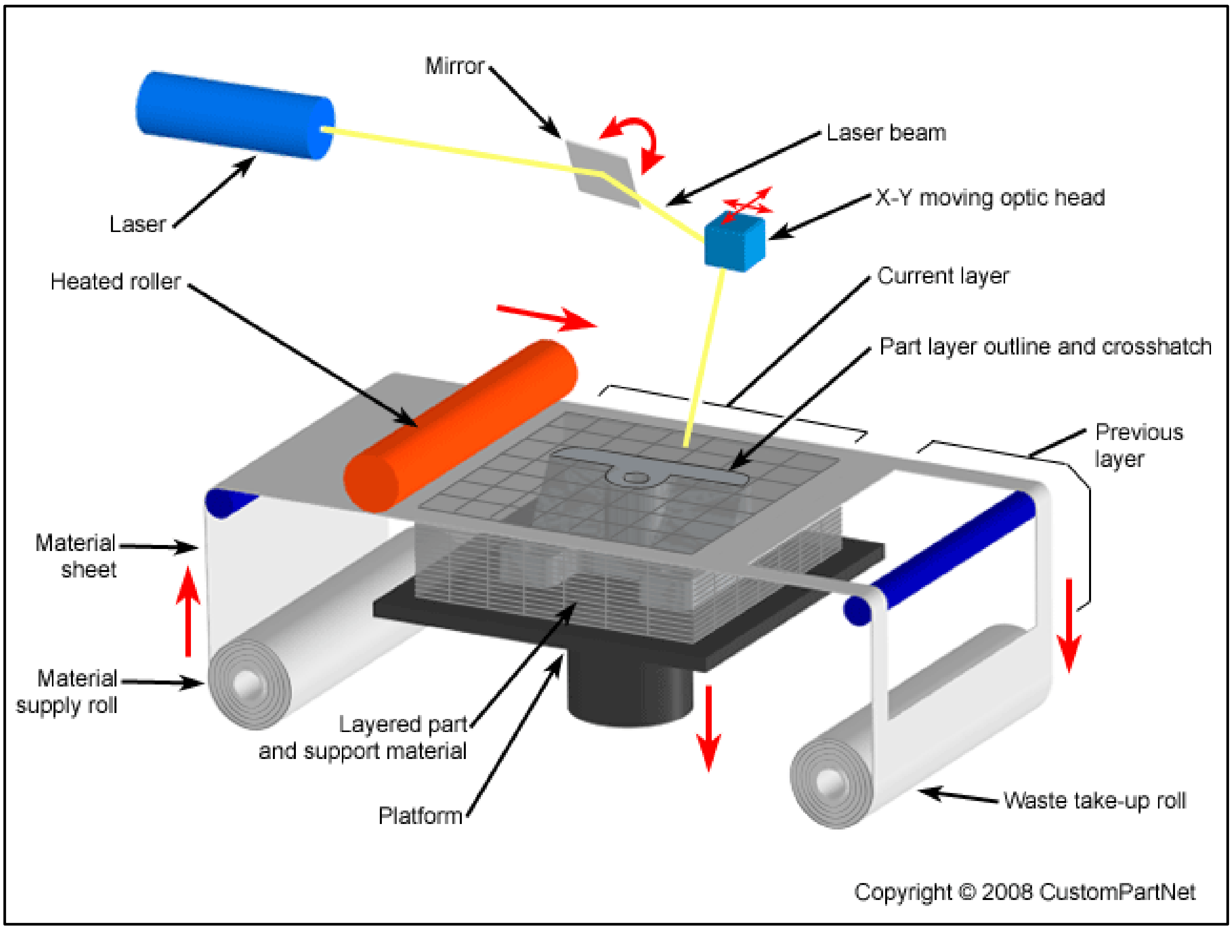

Figure 11: The Layer Laminate Manufacturing Process, source: www.custompartnet.com (03/2015)

A vertically retractable construction platform is covered with material in layers. The contours are cut with cutting plotters, laser scanners and routers. After that the fully automated joining or laminating of the sheets takes place. The joining process can be done on the entire surface or selectively to facilitate the subsequent unpacking of the left over material. There are several different variances of LLM processes such as Laminated Object Modelling (LOM), Paper Laminated Technology (PLT), MCOR-method, PVC Laminated Technology, Layer Milling Process (LMC) or Ultrasonic Additive Manufacturing which all follow the same principle but differ in the material used or use different a cutting method or joining technology.[45]

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[44] Additive Fertigungsverfahren, Berger Hartmann Schmid, page 121

[45] Additive Fertigungsverfahren, Berger, Hartmann, Schmid, page 123

2.3.6 STL Stereolithography (liquid initial state)

Stereolithography is the solidification of liquid monomers by polymerization. It is the oldest and most detailed additive manufacturing process. [46] The STL machine consists of a storage container with liquid monomer (resin bath), in which the building platform is located.

By scanning the surface of the resin bath with a UV laser, the monomer is photo-polymerized. The laser beam is guided by a computer-controlled mirror. The building platform is lowered layer by layer as the model is built up. After every layer, in an intermediate step, photopolymer is added to the resin bath surface and gets smoothened. The laser does not polymerize the whole photo-polymer and so - depending on the way you decide to scan the surface - completed uncured areas can be built within the model (cavities). [47]

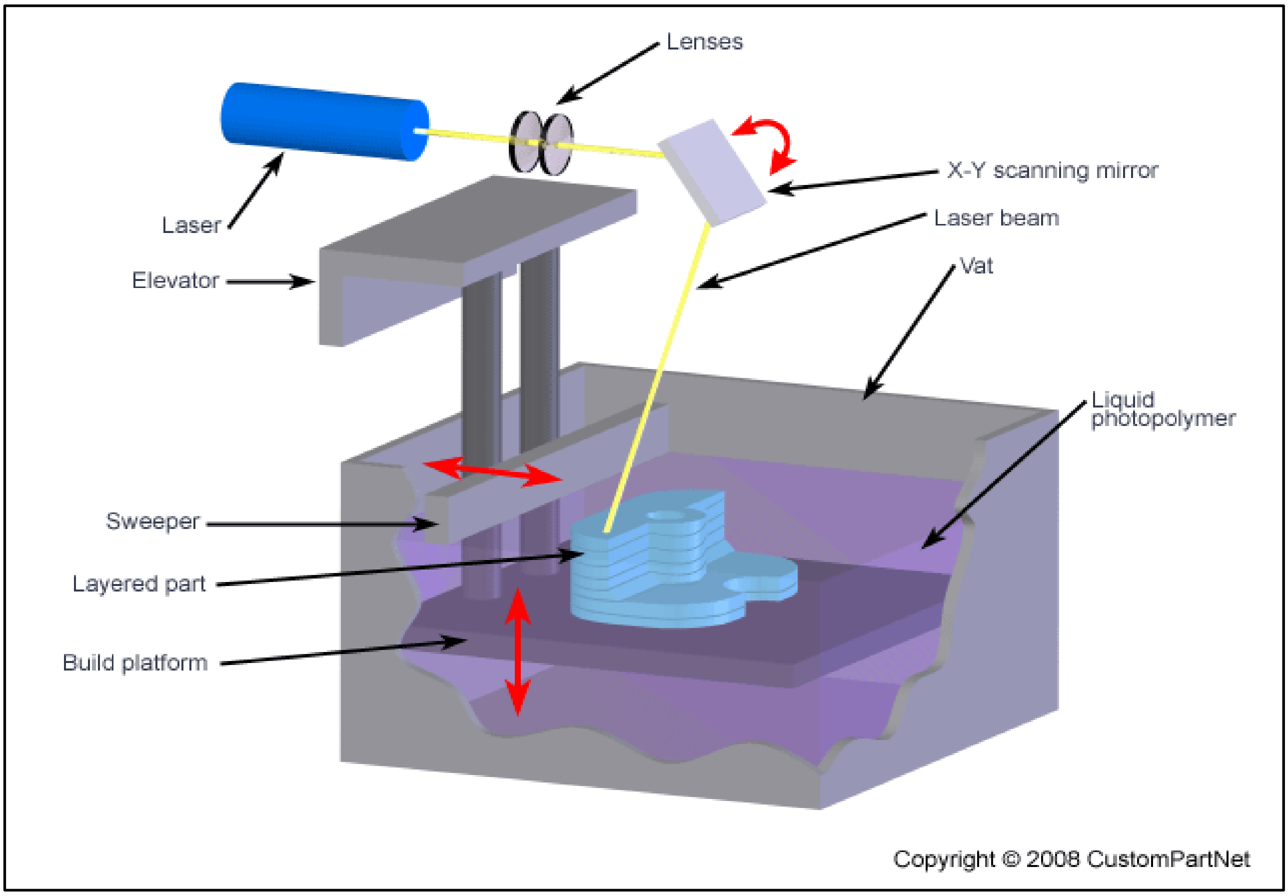

Figure12: The Stereolithography Process, source: www.custompartnet.com (03/2015)

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[46] vgl. „Understanding Additive Manufacturing“, Andreas Gebhardt, page 34
[47] vgl. Fachrichtung Maschinenbau – Kunststofftechnik, page 342

After all layers are built up, the parts have to be cured in a UV-cabinet otherwise they would be fragile. This process of curing leads to shrinkage and delay of the material which lowers surface quality.[48]

The SL process needs supporting structures for static reasons which can also be built during the process. Most common materials are epoxy-, vinyl- or acrylic resin.

2.3.7 PJM Poly Jet Modelling (liquid initial state)

In direct printing processes a print head applies selectively liquid building material directly on a construction platform which can be lowered in z-direction. The solidification process of the construction material is then carried out by chemical or thermal processes across the entire construction platform.[49]

With liquid building material very thin layers of up to 12 µm can be achieved and which results in particularly high resolution in the z-direction. Therefore, these methods are especially suitable for small parts with fine structures used in the jewellery industry or the dental medical field. The components are mainly produced as fusion models for precision casting moulds.

There are two different bonding methods:

1. Photochemical processes in which a liquid material is directly (sometimes with thermal heating unit support) printed up and chemically curing on the construction site under UV exposure. Example: Poly Jet Modelling

2. Thermal processes in which a wax or a thermoplastic material before printing is thermally liquefied and solidified by cooling on the construction site.
   Example: Thermo Jet Modelling or 3D Wax Printing.[50]

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[48] Fachrichtung Maschinenbau – Kunststofftechnik, page 342
[49] Additive Fertigungsverfahren, Berger, Hartmann, Schmid, page 86
[50] Additive Fertigungsverfahren, Berger, Hartmann, Schmid, page 88

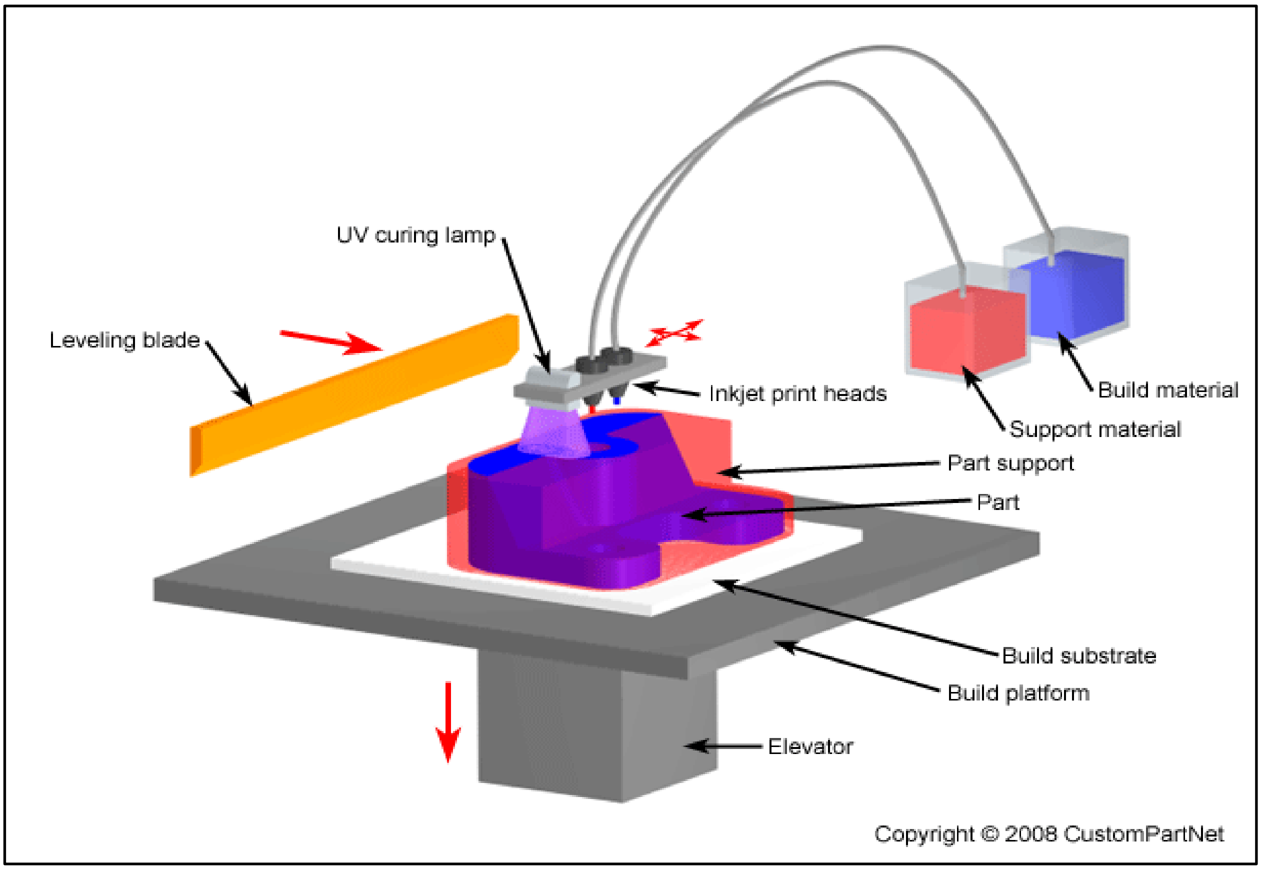

Figure 132: The Poly Jet Modelling Process, source: www.custompartnet.com (03/2015)

A high variety of different materials with different properties can be processed, so that prototypes of plastic parts and customer specific parts for the medical industry, such as hearing aids, are produced.

2.3.8 CVD Chemical Vapor Deposition (gaseous initial state)

In the chemical vapor deposition method, material is applied from a gaseous initial state by a chemical reaction on a carrier medium (substrate).

The active principle of CVD is based on the chemical reaction of diffusing gas molecules on a heated surface of a substrate. Therefore, fine recesses can be coated plane, so that a conforming application of 3D structures is possible.

Applications of CVD technology are epitaxial processes in which layers, with similar crystalline lattice structure, are built on a substrate at temperatures between 900°C and 1100°C layers are built with similar crystalline lattice structure.[51]

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[51] Additive Fertigungsverfahren, Berger, Hartmann, Schmid, page 11

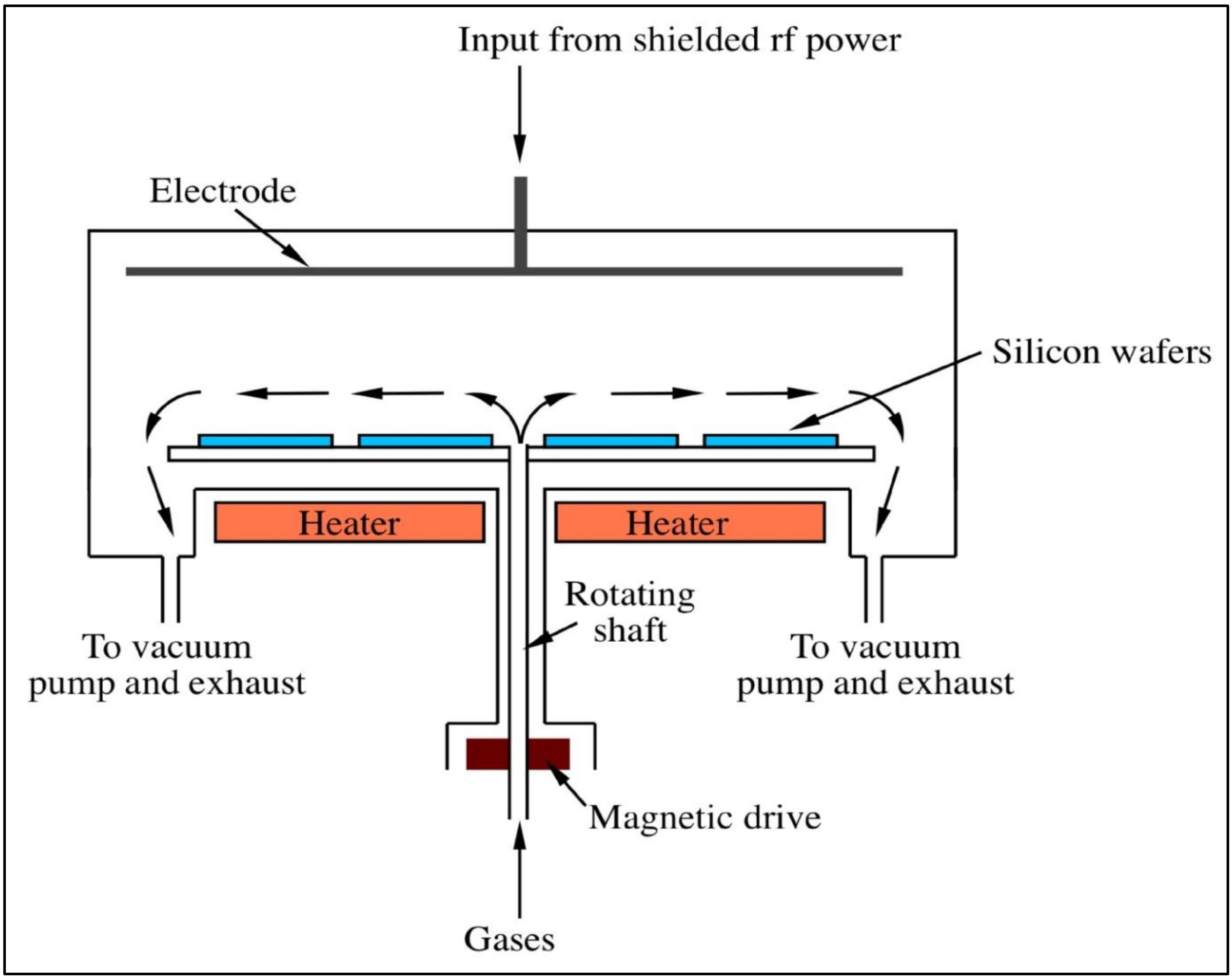

Figure 14: The Chemical Vapor Deposition Process, source: www.precisionfab.net (03/2015)

2.3.9 PVD Physical Vapor Deposition (gaseous initial state)

In physical vapor deposition processes, a component from the vapor phase or the ionized phase is applied through evaporation and later condensation on a carrier medium (substrate).
A distinction can be made between direct and indirect patterning of the produced layer.

For indirect patterning the coating material is a chemical compound in the form of a target in a vacuum chamber.
The released molecules are deposited on the substrate. The process temperatures are below 600°C. The physical action method that can be used from the vapor phase out in additive manufacturing processes include thermal evaporation, laser evaporation, evaporate arc and cathodes atomization.[52]

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[52] Additive Fertigungsverfahren, Berger, Hartmann, Schmid, page 12

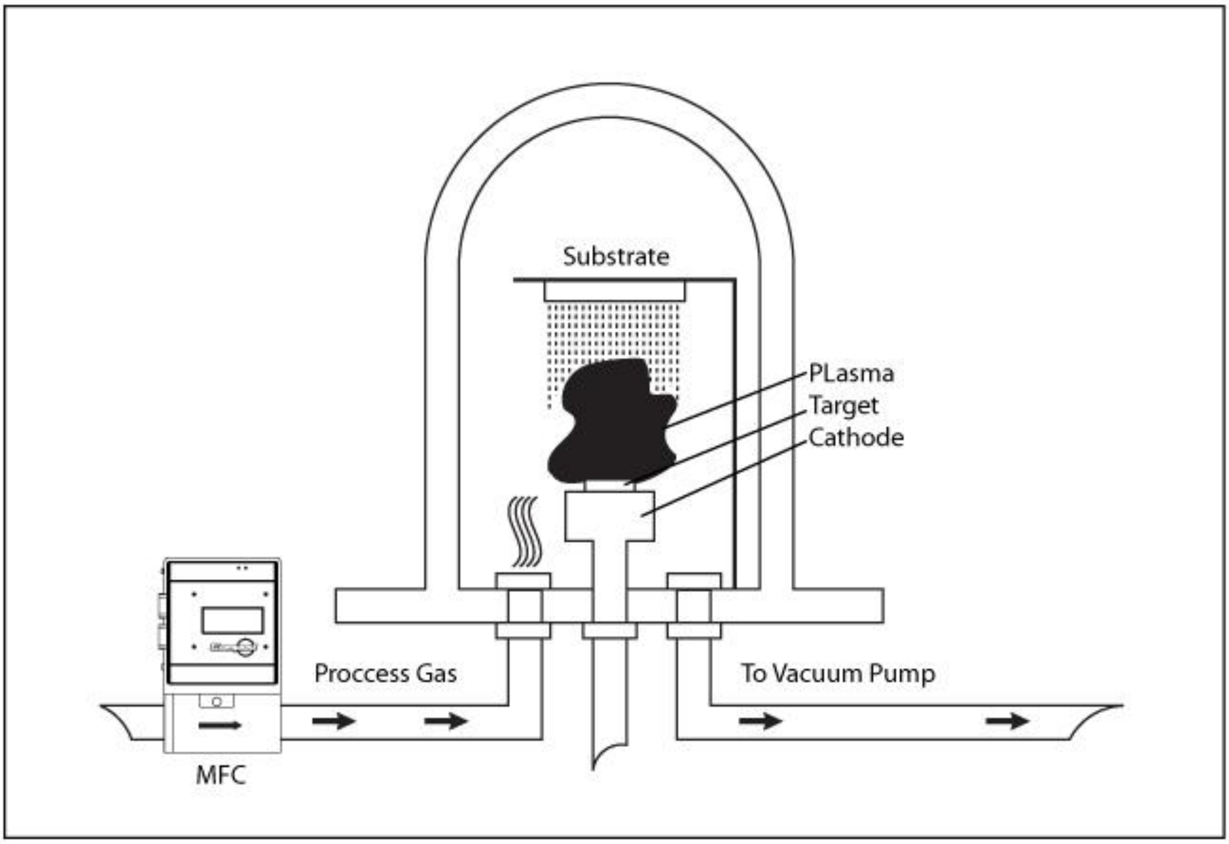

Figure 15: The Physical Vapor Deposition Process, source: www.sierrainstruments.com (03/2015)

2.3.10 Economic Advantages with Additive Manufacturing

Additive manufacturing systems do have the great advantage that the price per piece does not change by the number of produced parts or even by geometrical complexity. This is the main reason why additive manufacturing systems are basically used for small lot sizes and high complexity parts, as the following diagram from Fraunhofer Institute shows.[53]

The reason for the price consistency of the additive manufacturing technology is the process of building parts layer by layer. The processing time for one layer is the same, no matter how complex the geometries of the produced parts are but depending on the amount of processed material. The driving factor for the processing time is the layer thickness and therefore the accuracy of the produced surface as well as the mechanical properties.[54]

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[53] Additive Manufacturing: The new industrial revolution, Mangoldt, Wengerer, Fraunhofer 2014
[54] Wirtschaftliche Fertigung mit Rapid Technologien, Zäh, page 5

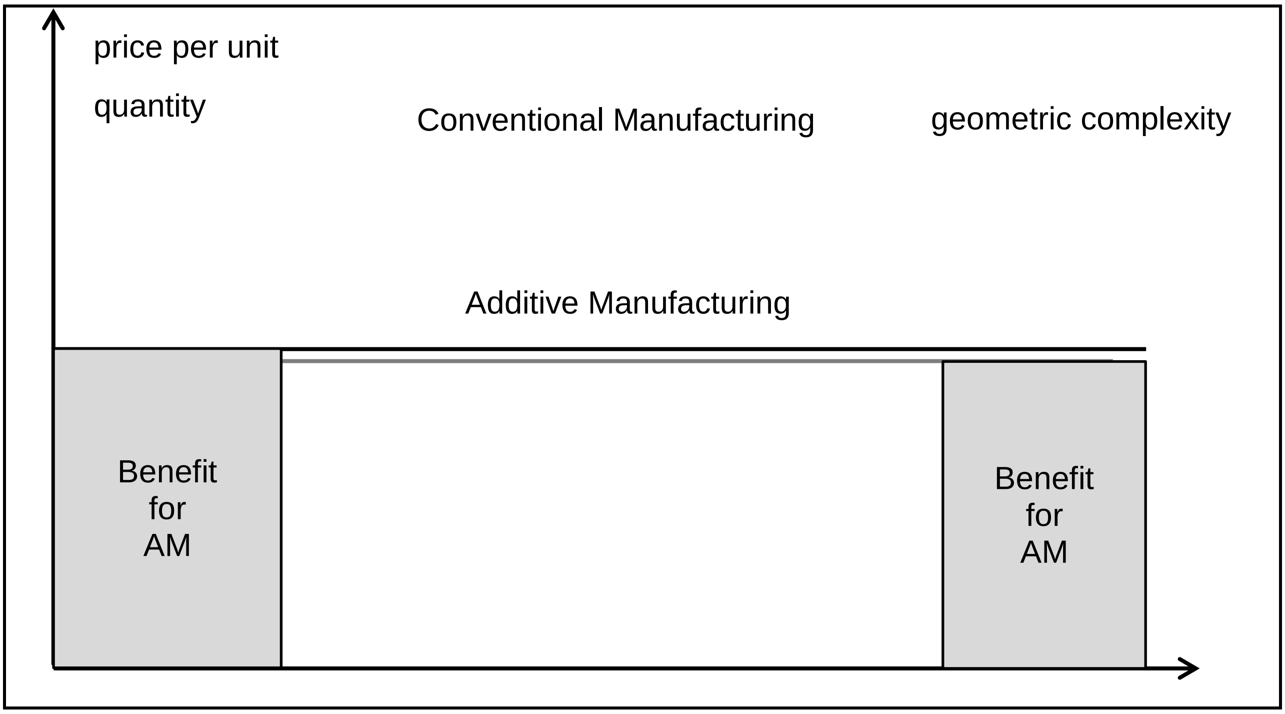

Figure 16: AM compared to conventional Manufacturing Systems, Source: Fraunhofer Institute

The diagram from the Fraunhofer Institute considers only the process of printing one part per build room in one machine. The additive manufacturing process chain including all the upstream and downstream processes needs to be considered in order to understand all the cost driving factors. The additive manufacturing process does not substitute the whole production process but it adds value to the way of generating parts. In the most chases it is followed by several post processes like drilling, milling, blasting or special heat treatment. Economic consideration of additive manufacturing shows that the isolated view of generating parts layer by layer is not precise enough to determine the overall production costs. A detailed view according to this aspect of process costs and the impact of additive manufacturing to the whole production process will be given later.[55]

Apart from constant costs per piece, there are several other economic advantages that influence the field of application. The reduction of manufacturing waste is one major benefit due to the fact that not fused powder in powder processing machines can easily be recycled and only the support structures emerge as waste.[56]

Additive manufacturing makes customization of products possible since several different designs can be processed at the same time in one building room which adds

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[55] Materials Processing Handbook, Groza, Shackelford, Lavernia, Powers, page 215

[56] Intelligent Energy Field Manufacturing: Interdisciplinary Process Innovations, Zhang W., page 439

value to the product as well as to the company's sales strategy. Compared to NC-Technology, additive manufacturing reduces the time span from the CAD model to finished parts. The reduction of production time especially in the prototyping phase leads to major competitive advantages in terms of market entry and earlier start of production (SOP). Especially in the automotive industry reduction of time until SOP is a very cost effective matter.[57]

Especially in the medical and building industry democratisation of production to reduce labour costs is discussed by several specialists. Regarding this aspect the complexity of the entire production process in the metal processing automotive industry needs to considered. Since additive manufacturing does not substitute any of the conventional production methods, workers need to understand and deal with an additional technology and its impact on the previous and subsequent processes, in addition to their general profession as manufacturing specialists.[58]

Graham Tromans from General Electric's mentions another important factor for companies like Magna: *"If you are manufacturing these parts on site then you don't need transportation, and you remove unnecessary international shipping, so manufacture is nearer to the consumer."*[59] The simplification of the supply chain and the possibility to shorten it, bears a huge advantage for cost reduction as well as for process stability.[60]

Another advantage is the tool cost and production time reduction for metal casting parts and the opportunity to gain technological benefits through the production of various different designs in one building room.[61]

2.3.11 Technological Advantages with Additive Manufacturing

The major technological advantage of additive manufacturing of course is the possibility to produce geometric complexity that could not be produced before. The fact that the complexity does not really influence the price per piece makes it much more interesting

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[57] Comprehensive Materials Processing- 13 Volume Set, Hashmi M.S.J., page 304
[58] AM Envelope: Potential of Additive Manufacturing for Façade Construction, Strauss H., page 161
[59] Plant to Print Jet Engine Nozzles in Mass Production, Graham Tromans, source: www.gereports.com/
[60] Principles of Supply Chain Management, Crandall R. Crandall W. Chen C., page 633
[61] Rapid Tooling: Technologies and Industrial Applications, P. Hilton, page 193

for designers. Cavities, undercuts, complex cool lines and possibility to produce complex geometries are the technological drivers of this new technology.[62]

The possibility to produce light-weight due to the high mechanical properties of additive manufacturing parts, is the reason why General Electrics builds their fuel nozzles for the Boing 777 additively. Thereby, they achieved a weight reduction of 25%, which is a lot in the aircraft industry. But not only the weight reduction convinces and confirms that additive manufacturing is the right choice in their case.[63]

The mechanical properties increased despite of the enormous weight reduction. Moreover, the rigidity occurs to be five times stronger than in previous versions. The weight reduction is a result of both the increase of mechanical properties and therefore smaller wall thickness, as well as the reduction of parts due to the possibility of merging assemblies, since there are no limits in terms of geometric complexity. The reduction of parts in the case of General Electrics fuel nozzle is striking. Formerly, nozzles consisted of 20 parts, now the new Direct Metal Laser Melting Technology builds it in one piece! Thereby, they also reduced the number of welds by a fifth.[64]

Credit: GE Aviation

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[62] Degamo's Materials and Processes in Manufacturing, 11th edition, Black, Kohser, page 530
[63] http://www.ge.com/stories/advanced-manufacturing
[64] http://www.ge.com/stories/advanced-manufacturing (03/2015)

Figure 17: General Electrics Fuel Nozzle for Boing 777, source: www.ge.com

The General Electrics case shows that additive manufacturing mass production is possible due to proper construction of the product. It is obvious that major technological benefits of additive manufacturing can only be achieved by changing the design of the produced part. The impact of the design changes have to be fundamental to compensate the increase of costs due to the fact that economies of scale cannot be achieved.[65]

Prof. Michael Zäh of the Munich University of Technology mentions that an additive manufacturing technology can only be integrated successfully into a company if the customers appreciate the added value of additive manufactured components.[66]

Changing the design of an existing part for serial production would be beyond the scope of a six month work for a Master Thesis. On the other hand product design is not the field of expertise of the two cooperating institutes. Therefore, this project will focus on the economic benefits we can gain for our industry partners.

3 Additive Manufacturing at Magna Steyr and Ventrex Automotive

3.1 Analysis of Requirements

Analysing the advantages as well as disadvantages of additive manufacturing was the goal of the first phase in the Mater Thesis project. The result – a catalogue of requirements – determines the attributes of the possible fields of application.

The distinction between an economic and technological perspective helps to understand and evaluate the results properly.

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[65] Additive Manufacturing: The new industrial revolution?, Mangoldt, Wengerer, Fraunhofer 2014

[66] Wirtschaftliche Fertigung mit Rapid-Technologien, Prof. Michael Zäh, page 124

3.1.1 Catalogue of Requirements

Based on the elaborated literature in chapter 2 of the maser thesis, the following catalog of requirements is derived and should build the basis for further investigations at Magna Steyr and Ventrex Automotive and help to find the right applications to add economic or other value to the processes and products in practice.

- **high geometric complexity**

The current production process of the chosen applications needs to be complex and expensive due to the geometric complexity of the parts. According to the diagram of the Fraunhofer Institute, economic benefits can be achieved for high geometric complexity of existing parts.

- **small lot size**

The second requirement of applications according to the research of the Fraunhofer Institute is the fact that economic benefits can only be achieved for small lot sizes. This is caused by the fact that additive production cannot reach economies of scale (EOS) effect.

- **existing components**

Changing the design of a product would be beyond the scope of this Master Thesis project. Research on the additive production of existing components is one basic boundary condition for this research project even if Prof. Zäh of the Munich University of Technology claims that major benefits of additive manufacturing technology can only be achieved if the change of the design is appreciated by the customers.

- **components which are expensive in small lot sizes**

The reduction of tool costs for expensive casting technology and parts with a high degree of geometric complexity produced subtractive is one potential advantage of additive manufacturing.

- **metallic components**

The Graz University of Technology currently works with three different additive manufacturing systems based on plastic or wax material. Especially the Institute of

Production Engineering is very interested in metal processing additive manufacturing systems.

- **different types of current manufacturing processes**

To compare different manufacturing processes, we want to find formative and subtractive manufactured parts to evaluate the economic and technological changes for different current manufacturing processes.

3.2 Selection of Applications

The foundation for the selection of applications at Magna Steyr and Ventrex Automotive was the catalogue of requirements setup in the previous chapter. In addition to this selection other questions and aspects of additive manufacturing came up and will be discussed here.

3.2.1 Selection of Applications at Ventrex Automotive

Ventrex Automotive as a Tier 1 – Tier 2 supplier for OEMs like Volkswagen or Mercedes, produces valves for natural gas driven vehicles. The mechanical requirements regarding density, hardness, stability or fatigue strength of fluid managing parts at temperatures differences between -40°C and 125°C as well as pressure differences of 26 N/mm² brought up the question if additive manufactured parts can be used at all.

Research at the Institute of Production Engineering shows, that the given mechanical material properties of machine manufacturers are trustworthy. There was no deviation between the given tensile strength, yield point, hardness or elastic modules and the measured values. Empirical experience from several additive manufacturing service providers also showed that parts can usually be designed with thinner walls and they can still stand the same forces, pressure or temperature they are usually exposed to. Detailed research on the mechanical differences between additive manufacturing and other manufacturing technologies will be explained later.[67]

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[67] “Charakterisierung metallischer Lasersintherstrukturen“, Brillinger, page 45

The results of research at the Faculty of Engineering at the Univeristy of Kyushun, Japan, show that the properties of Titanium alloys after an additive laser melting processes were even better than the wrought material, focusing mainly on the surface roughness and relative density of produced parts.[68]

Another question was the possibility to create magnetic, anisotropic material properties with additive manufacturing technology. Generally, it has to be mentioned that due to the process of building parts layer by layer, mechanical properties of additive manufactured parts are higher in xy-direction than in z-direction. This is caused by the fact that fusion of powder with powder (in one layer) works better than fusion with already solidified material one layer below. Anisotropy is therefore deeply connected with additive manufacturing.[69]

Ventrex builds sectional models for their customers to explain the function of their products and visualize the processes in their valves. Therefore, they produce all the necessary parts, then carefully place it into the milling machine and produce a half or a quarter sectional model and finally, assemble it again. Additive manufacturing could help a lot reducing the costs for sectional models by building it in one piece directly from the CAD model as it is commonly used in the architectural industry.[70]

According to the catalogue of requirements the following part was chosen at Ventrex Automotive for further investigations.

Electronic pressure switch EPR210

Function: pressure reduction of natural gas (CNG) in the tank to 2-12bar

Requirements:

- Fluid management in 20 – 260bar
- Operating temperature: -40°C – 125°C

Current Manufacturing Technology: milling, grinding, blasting

Annual quantity: 100.000#

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[68] Proceedings of the 8th Pacific Rim International Conference on Advanced Materials and Processing, Marquis, page 1568

[69] Proceedings of the 1st International Joint Symposium on Joining and Welding, Fujii H., page 505

[70] Advanced Customization in Architectural Design and Construction, Naboni, Paoletti, page 60

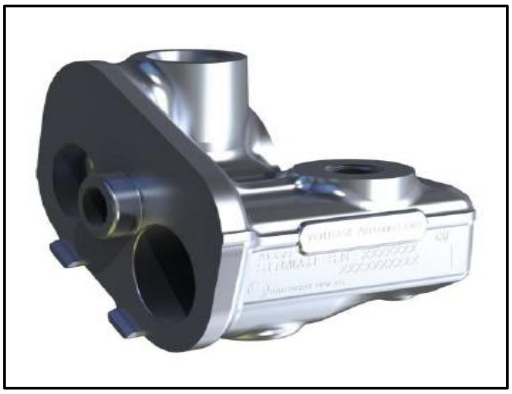

Figure 18: Ventrex Electronic pressure switch EPR210

To guarantee the density for this fluid managing part at high pressure and temperature differences a pre-forged aluminium alloy is used as a wrought material for the milling process. The deviation of surface roughness in the contact areas is limited by 1.8µm to prevent gas leakage between the sealing and the connection pin.

There is potential in reducing costs for small batch sizes, lowering the development lead time and thereby gaining more knowledge about possible solutions faster than in the milling process.

3.2.2 Selection of Applications at Magna Steyr

Magna Steyr changed their strategy being a Contract Manufacturer (CM) and only assembling cars in their line production into Contract Design Manufacturing (CDM). Therefore, the design and development, including an intense testing phase, is done in-house at Magna. They do not have a serial manufacturing site in place. Consequently all the parts for prototypes have to be supplied by other Magna companies or external suppliers.

In the department for car body construction there are several nodes connecting the pillars with each other. Those nodes are usually sand casting parts due to fact that they are exposed to high forces in case of an accident and have to guarantee the static stability of the whole car body. Unfortunately, the geometrical dimensions of the first chosen part were too big for common laser melting processes. Usually, the build room of Selective Laser Melting machines is limited by 500x500 mm in the xy-direction.

Machine producers work on the laser speed and number of processing lasers in one building room since this is the limiting factor for the build size as well. At the moment a 500x500 mm base building room has an average building time of 50 hours. The hull core laser technology of melting the contour with higher laser power and lower build rate to increase the surface quality and melt the filling with 400 W and higher build rate is an improvement towards the overall build rate in laser processing. [71]

The connection node between the car body and the wheel suspension of the Mercedes SLS Series was chosen according to the catalogue of requirements of the previous chapter. The possibility to add changes to the casting tool is very expensive and as a result one great advantage would be the chance to change the design during the testing phase.

Another benefit could be the cost reduction of the casting tool which is about 20.000 € and the time to production could be reduced dramatically since the waiting time for a casting part is several months.

Suspension node for Mercedes SLS
Function: body - fitting suspension
Material: AlSi7Mg
Current Manufacturing Technology: die casting
Quantities: 10 # of prototype tests

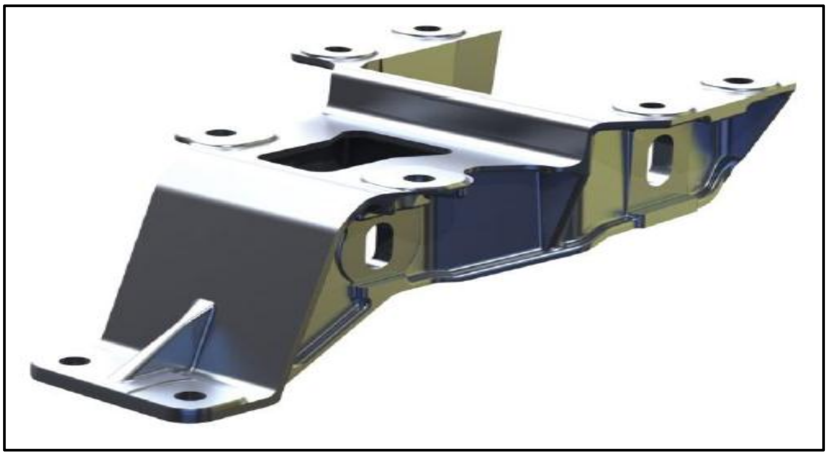

Figure 9: Magna suspension node for Mercedes SLS

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[71] Proceedings of the 37th International Matador Conference, Hinduja, Li, page 383

Regarding the car body design the following problems emerged: Aluminium alloys are commonly used to reduce weight but due to static stability e.g. the B-Pillar has to be a steel element. Currently they use a gluing technology to join the aluminium and steel parts. As a result the question arises if due to the small layer thickness and therefore lower melting energy a fusion between the aluminium alloy and the steel construction can be realized.

Since there is no machine on the market that processes two different metals at one time, this cannot be tested. However, the melting temperature would have to be reached in every material and every layer. Subsequently, even if one layer was aluminium and the following layer was steel, the fusion would only succeed by melting it with the necessary energy for steel. So the problem of different melting points will not be solved. The advantages of processing two different materials, even plastic and metal, in one building room would bring the great advantage to print electrical pipes into the car body parts.

3.3 Selection of the Additive Manufacturing Process

The manufacturing technology selection process has to be done regarding mechanical and technological requirements.[72] Subsequently the detailed analysis of the additive manufacturing technologies of the previous chapter sets the basis for the selection of the proper manufacturing technology for the chosen applications.

Both chosen applications are currently produced as an aluminium alloy AlSi10Mg. Therefore only metal processing technologies are relevant for further investigations. Three of the nine basic additive manufacturing process types are not capable of processing metal. Fused Layer Manufacturing (FLM) are processing basically thermoplastic materials.[73] The two processes that generate parts from the liquid initial state, Stereolithography (STL) and Poly Jet Modelling (PJM), cannot process metal as well. Stereolithography processes photo polymeric materials,[74] Poly Jet Modelling processes granulated thermoplastic materials.[75]

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[72] „Generative Fertigungsverfahren“, Auflage 3, Andreas Gebhardt, page 500
[73] Comprehensive Materials Processing – 13 volume set, M.S.J. Hashmi, page 37
[74] Stereolithography: Materials, Processes and Applications, P. Bartolo, page121
[75] Fertigungstechnik, Fritz, Schulze, 10th edition, page 112

The chosen applications are exposed to high mechanical forces and pressure. High density to prevent leakage of fluid managing parts and furthermore homogeneous microstructure of the processed material is an important factor and leads to further elimination of potential additive manufacturing processes.

Selective Laser Sintering processes two component metals with different melting points. Therefore, AlSi10Mg with the desired material cannot be used. In this process no fusion of the metal grains takes place which leads to an inhomogeneous microstructure of the processed material.[76]

The Layer Laminate Manufacturing process is a process of joining metal foils or sheets through conglutination or bolting connectors layer by layer.[77] In Print Head Systems (PHS) metal powder is joined by a conglutinating process of liquid glue.[78] The inhomogeneous microstructure of the processed material in both processes as well as the fact that AlSi10Mg cannot be processed separately without any joining, connecting material, are the basic arguments against the use of LLM and PHS for the chosen applications.

Chemical Vapour Deposition (CVD) and Physical Vapour Deposition (PVD) are complex processes due to the fact that a vacuum chamber is necessary to process the physical operation and chemical reaction.[79] Metal CVD applications are mainly used in the electronic semiconductors industry to apply thin metal layers on existing parts.[80] PVD processes are also commonly applied in the coating industry rather than building functional parts due to low build rates and expensive process costs.[81]

The Selective Laser Melting (SLM) technology can also be seen as a welding process where metal powder is totally fused through high laser energy. The mechanical properties of the processed material are comparable with the properties of wrought

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[76] Generative Fertigungsverfahren, Andreas Gebhardt, page 121
[77] Additive Fertigungsverfahren, Berger, Hartmann, Schmid, page 123
[78] Generative Fertigungsverfahren, Andreas Gebhardt, page 210
[79] Additive Fertigungsverfahren, Berger, Hartmann, Schmid, page 12
[80] The Chemestry of Metal CVD, Kodas, Hampden-Smith,page 365
[81] Modern Surface Technologies, Bach, Möhwald, Laarmann, Venz, page 29

material of subtractive and formative processes, which will be explained later. SLM processes are commonly used for functional parts in metal processing industries.[82]

3.4 Comparison of Manufacturing Technologies

Comparing the existing manufacturing methods for prototyping at Magna Steyr and Ventrex Automotive with additive manufacturing, leads to the distinction between three basic types of manufacturing systems – additive, subtractive and formative.

Ventrex' electronic pressure switch EPR210 is commonly produced in a milling process out of a pre-forked aluminium alloy wrought material. This part can be seen as the representative for the subtractive manufactured prototype.

Magna supplies their suspension node for the Mercedes SLS series from another Magna subsidiary company. This chilled casting part is the representative for the formative manufactured prototype.

In this chapter, the focus is on the individual advantages and disadvantages of additive manufacturing derived from the applications chosen. Thus, the aim is to evaluate whether an introduction of such a new manufacturing technology in their prototyping and testing phase can be done effectively in technological terms as well as on an economic level.

The technological comparison focuses on the mechanical and functional differences since the design of the parts has not been changed. The time and process comparison will give insights into the very different pre and post processes that have to take place in order to implement additive manufacturing.

The economic perspective will show the possibilities to reduce costs in the prototyping phase through the implementation of additive manufacturing.

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[82] Laser.Induced Materials and Processes for Rapid Prototyping, Lü, Fu, Wong, page 143

3.4.1 Technological Comparison

The chosen applications are exposed to high mechanical forces and pressure and so the first question was whether additively produced parts can fulfill the functional and technological requirements of those special use-cases. The used material is the aluminium alloy AlSi10Mg for both applications which made it easy to compare. It is a serial material for lightweight parts with good mechanical properties and also a common powder for additive manufacturing processes.

It can be used in subtractive processes like the milling process of the pre-forked material at Ventrex Automotive as well as for formative processes like chilled casting parts as it is done at Magna Steyr. The tendencies in the following table show that mechanical properties of additively produced parts are, in case of aluminium alloy, higher than the properties of casting (formative) parts or milling (subtractive) parts. The possible heat treatment processes are not considered but its impact on the mechanical properties will be discussed later.

Generally, it has to be mentioned that the values in the diagram below are benchmark values from producers, in case of subtractive and additive technology, or DIN standards for casting material. It would be necessary to do testing series with the actually used material to create a qualitative benchmark between the properties, but still the tendencies are obvious even if there would be a deviation of several dozen percentages.

Mechanical properties of the additive manufactured material are higher than they occur after the other manufacturing processes. The diagram also shows the anisotropic effect of additive manufactured parts which has an impact even on the elastic modulus whether you apply force in xy-direction or z-diretion.

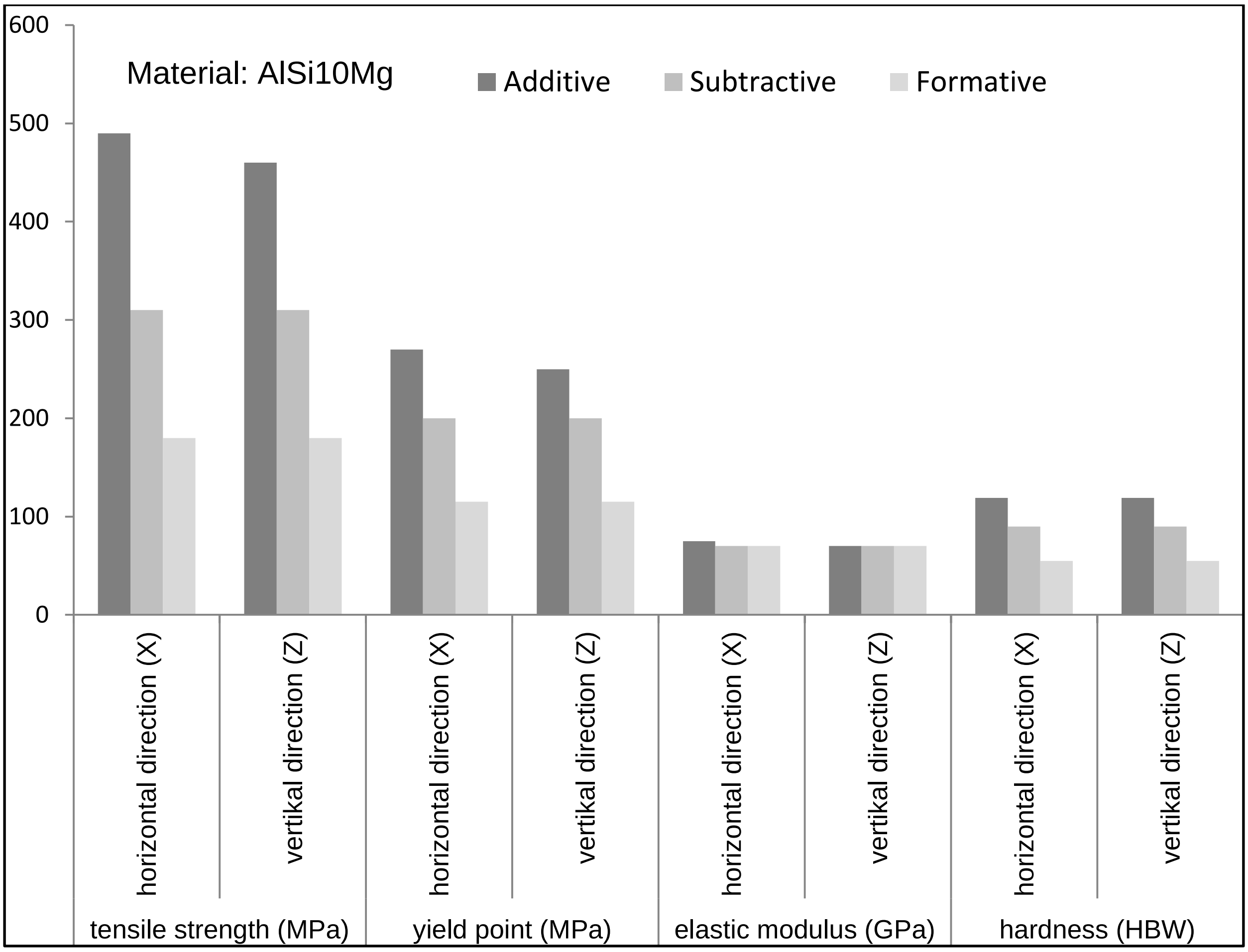

Figure 20: Mechanical Properties of different manufacturing Systems,
Source: Additive: EOS Material datasheet, Subtractive: Fa. Fuchshofer, Formative: DIN Standard

The mechanical properties of the material depend to a high degree on the fabrication processes. This has to be considered for heat treatment after production as well, because the tension in wrought material rises through pre cold forming processes. Stress relief annealing leads to lower mechanical properties such as tensile strength or elastic limit. This effect is visualized in the following diagram.

The data given from the EOS machine producer company was tested by the Institutes of Production Engineering and the Institute for Material Science and Welding. There was not a sinlge test result below the given data of the powder producers. This shows that the material data sheets are usually trust worthy. Benchmark to other material powder producers showed that the properties usually deviate a lot.[83]

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[83] Charakterisierung Metallischer Lasersintherstrukturen, Brillinger, page 45

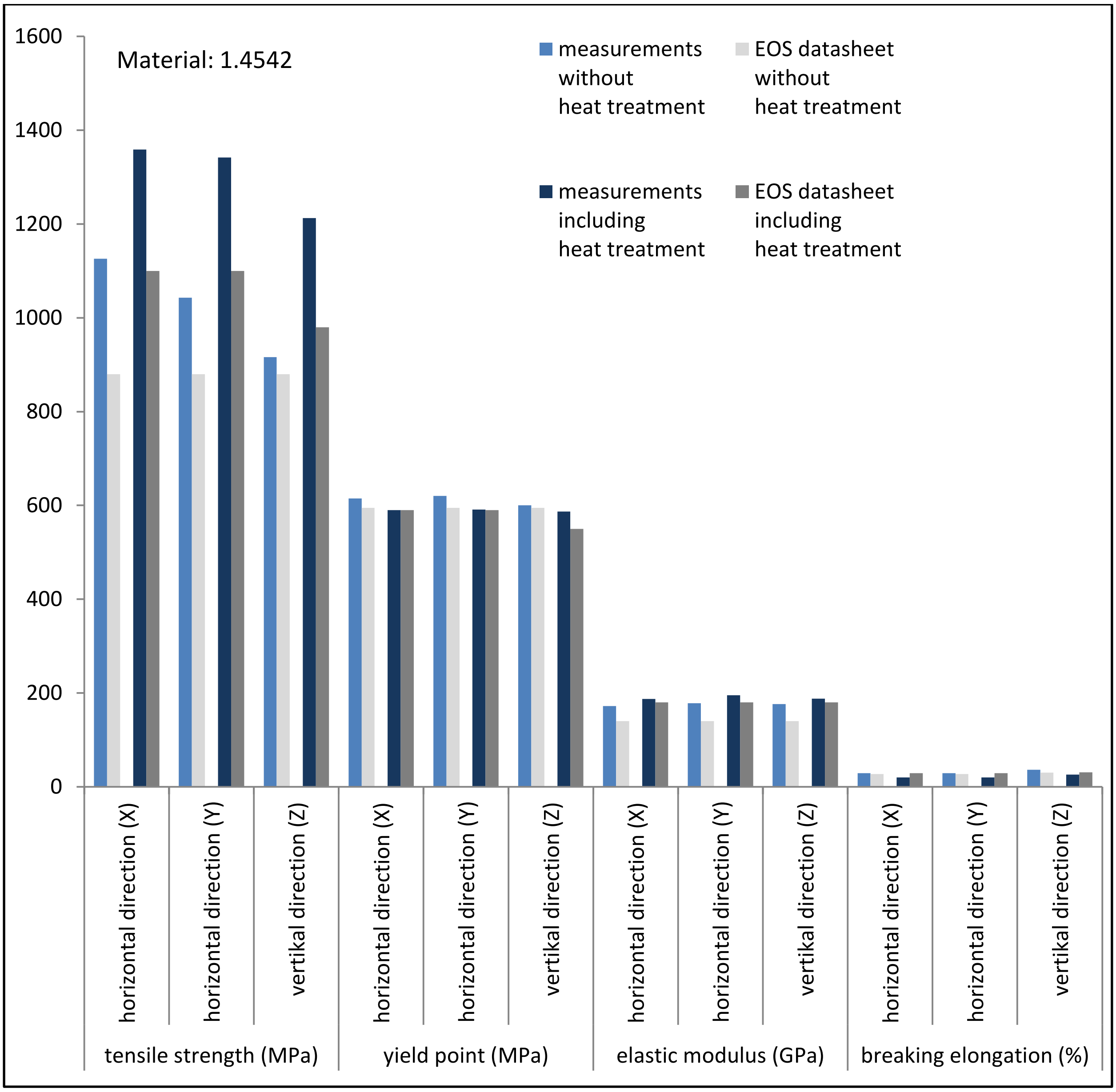

Figure 21: Mechanical Properties Comparison - Measured value and EOS datasheet,
Source: Charakterisierung Metallischer Lasersintherstrukturen, Brillinger, TU Graz, page 45

The impact of heat treatment is shown in the table and visualizes, that the heat treatment leads to higher values of strength and elastic modules, compared to the parts without heat treatment. The cold forming processes of wrought material used in the drilling Technology leads to a decrease of tension in the material through heat treatment. It is essential to determine those changes in the design phase for proper construction of the parts.

The good mechanical properties are of course a great advantage for light weight parts and leads to new opportunities in construction. For the chosen application it is obvious that we can trust the given data and we can expect to have similar material behaviour when producing additively compared to the commonly used methods.

To summarize the technical and functional evaluation of the additive manufacturing technology, it becomes obvious that the constructive dimensioning of parts for subtractive and formative manufacturing processes should be sufficient for additive produced parts as well. Several additive manufacturing service providers affirmed the experience that the wall thickness of additive produced parts can even be designed smaller than in other manufacturing systems.

3.4.2 Time and Process Comparison

Not only technological and economic aspects have to be considered when comparing the different manufacturing systems. It is essential to understand the whole process chain of each manufacturing technology to determine whether production steps can be reduced, the time span from CAD model to reality can be shorten or how to gain further benefits from the introduction of a new technology.

In this chapter different process steps of each of the three different manufacturing technologies – subtractive, formative and additive – will be discussed.

3.4.2.1 The Additive Manufacturing Process Chain

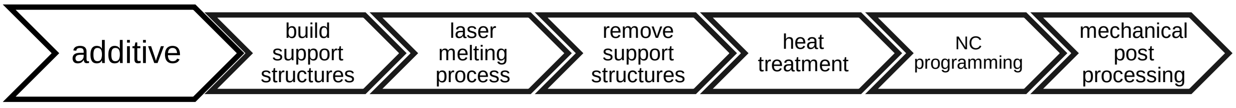

Figure 22: The Additive Manufacturing Process Chain, Additive Manufacturing Technologies: 3D-Printing, Rapid Prototyping and Rapid Maufacturing, Gibson, Rosen, Stucker, page 43

The first step of the Additive Manufacturing Process is the proper CAD construction in terms of oversize for post processing as well as support structures. Support structures have several different functions.

First of all, it has a static function for all areas of steep construction over 45° where the loose powder cannot guarantee static stability.

The second function is the evacuation of the processing energy where the support structures work as heat transfer medium. [84]

The third function of the support structures are the protection from distortion during the process of cooling down and growing stiff from the liquid to the solid phase of the metal.[85]

Reducing the amount of support structures leads to lower costs and higher material efficiency. Of course, all support structures have to be removed after the Laser Melting Process. Usually, the structures are designed by computer but, since the location of the structure influences the post processing and the position of the part in the building room influences the mechanical properties in terms of anisotropic behaviour, this process cannot be fully automated.[86]

The additive manufacturing process chain clearly shows that 'plug and play' and the very short time span from CAD model to reality is only true if the layer thickness of minimum 20 micrometres is sufficient surface quality.

In most of the cases this will not be enough and several post processing steps have to be applied after the generation of the part. Especially in the contact zones of both applications special surface treatment like milling and grinding are necessary.[87] All contact zones and drilling holes have to be designed in oversize to guarantee good drilling and milling post processes.[88]

Especially the drilling and milling steps after generation require a Computer Numerical Controlled Programming step, the setup of the machines and the manufacturing

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[84] Materials Processing Handbook, Groza, Shackelford, Lavernia, Powers, page 215

[85] Preliminary investigation on cellular support structures using SLM process, Ahmed Hussein, page 2

[86] Additive Manufacturing Technologies: 3D-Printing, Rapid Prototyping and Rapid Manufacturing, Gibson, Rosen, Stucker, page 156

[87] Enabling Manufactruing Competitiveness and Economic Sustainability, Zäh M., page 172

[88] Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing, Ian Gibson, David Rosen, Brent Stucker, page 43

processes itself. As I explained in the chapter before, the heat treatment has to be done before the final mechanical machining to guarantee geometrical consistency.

The time span from the receiving of the CAD model and start of the process chain to the finished product is about five working days. The Laser Melting Process itself in a building room of 500x500mm takes, depending on the height and quantity of melted powder, about 50 hours. Some machine producers assume that in the next five years the processing time will be reduced by one-third by optimizing the material application on the building platform and increasing the speed of laser processing.[89]

3.4.2.2 The Formative Manufacturing Process Chain

Figure 23: The Formative Manufacturing Process Chain, Globalized Solutions for Sustainability in Manufacturing, Hesselbach, Herrmann, page 318

The aluminium die casting process chain as a representative for general formative manufacturing processes, consists basically of four major production steps. The casting tool production according to a pre-designed CAD model of the produced part is the first major step. The casting process including the melting of the process metal and applying it into the casting tool is the second major production step. After solidification a heat treatment process is necessary to define the desired mechanical properties. The last step in the formative process chain is the mechanical post processing since no sufficient surface quality can be achieved in the casting process itself.[90]

The production process chain of Magnas' suspension node, as a representative for formative manufactured parts, is similar to the explained processes. Manufacturing

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[89] Pictures of the future, Nils Ehrenberg, page 33

[90] Globalized Solutions for Sustainability in Manufacturing, Hesselbach, Herrmann, page 318

process chains cannot be generalized since the requirements in terms of mechanical properties and surface quality differ for every produced part.[91]

Currently the time span from the time of CAD data transfer to the finished part at Magnas formative manufacturing service provider is six months. Reducing the time span and tool costs for the prototype production would be a huge benefit especially when it leads to a change ot the start of production (SOP).

3.4.2.3 The Subtractive Manufacturing Process Chain

Figure 24: The Subtractive Manufacturing Process Chain, Fuchshofer - subtractive manufacturing service provider

The subtractive manufacturing process used for prototype production at Ventrex Automotive is similar to the mass production process. It has to be mentioned that the pre forging process of the wrought material, to increase the material density, since this part is a fluid managing part at high pressure, is not considered here. Usually, this is done by the wrought material provider and leads to higher material costs.

The process chain itself is shorter than the other two competing manufacturing technologies and also the lead time from the moment of receiving the CAD model to the final product is close to the Laser Melting Process with about 10 working days. The longer lead time compared to additive manufacturing results from the two times mechanical processing in case of heat treatment processes.[92]

After receiving a CAD model from the customer the subtractive manufacturing service provider converts the model into a numerically controlled machining computer program. Data is transferred to the milling machine where tool and machine setting has to be

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[91] OHM Haener – Casting Manufacturing Service Provider
[92] Company Fuchshofer – Manufacturing Service Provider

done in the second phase of the manufacturing process. After the milling process is completed heat treatment and mechanical post processing has to be done to guarantee the mechanical properties and surface quality.[93]

Summarizing the differences of the process chains shows that additive manufacturing has the shortest lead time but the process chain is far more complex than assumed. Most functional parts require a higher surface quality than the machine output of 20 micrometres layer thickness. The layer thickness cannot be reduced further due to the fact that smaller particles of the powder would be respirable and the machining would have to be hermetically sealed.[94]

To gain benefits in terms of lead time and process complexity, the additive manufacturing technology can only excel formative manufacturing processes like chilled casting. Compared to subtractive manufacturing processes no major benefits concerning time or process complexity can be expected considering that no design changes are included.

3.4.3 Economic Comparison

In the current chapter manufacturing at external service providers is assumed as it is commonly done at Magna Steyr and Ventrex Automotive in their prototyping and testing phase of product development. Further investigation of operator models with in-house production will be discussed in the following chapters.

Every process step explained in the previous chapter leads to costs. The reduction of the process chain represents potential for reduction of costs. For this specific case study, the process chain was given due to the fact that certain material behaviour and surface quality are necessary, which made it impossible to eliminate steps of the process chain in each of the three different technologies used.

To compare the overall costs, manufacturing services providers for casting, milling and laser melting, placed quotes of different quantities, all produced out of AlSi10Mg wrought material and the same surface quality according to the workshop drawings.

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[93] Globalized Solutions for Sustainability in Manufacturing, Hesselbach, Herrmann, page 313
[94] Encyclopaedia of Materials, Parts and Finishes, Schwartz, page 618

The given prices exclude turnover taxes and shipping costs, since this is not considered in the price for serial production as well and it reflects the manufacturing costs best.

There are several additive manufacturing service providers that offer the laser melting process separately without the post processes necessary to realize sufficient surface quality. Cutting the manufacturing process chain bears the potential risk that each process step influences the following and manufacturing service providers will make the previous process step producer responsible for their failures. Hence, an intermediate quality control has to be implemented which leads to higher costs. Due to a statement of concealment no exact prizes can be published but an impression of the price deviation between the different technologies can be given.

Additive vs. Subtractive Manufacturing

The price per unit in serial production of approximately 100.000 pieces per year is 42,7 times cheaper than the production of one part produced a milling process. Reducing the number of produced parts for prototyping purposes shows the economies of scale effect drastically. Compared to that, the additive production of one part is 220 times as expensive as the price for serial subtractive production. The comparison shows drastically that parts produced in the laser melting process cannot compete the serial prices of subtractive production.

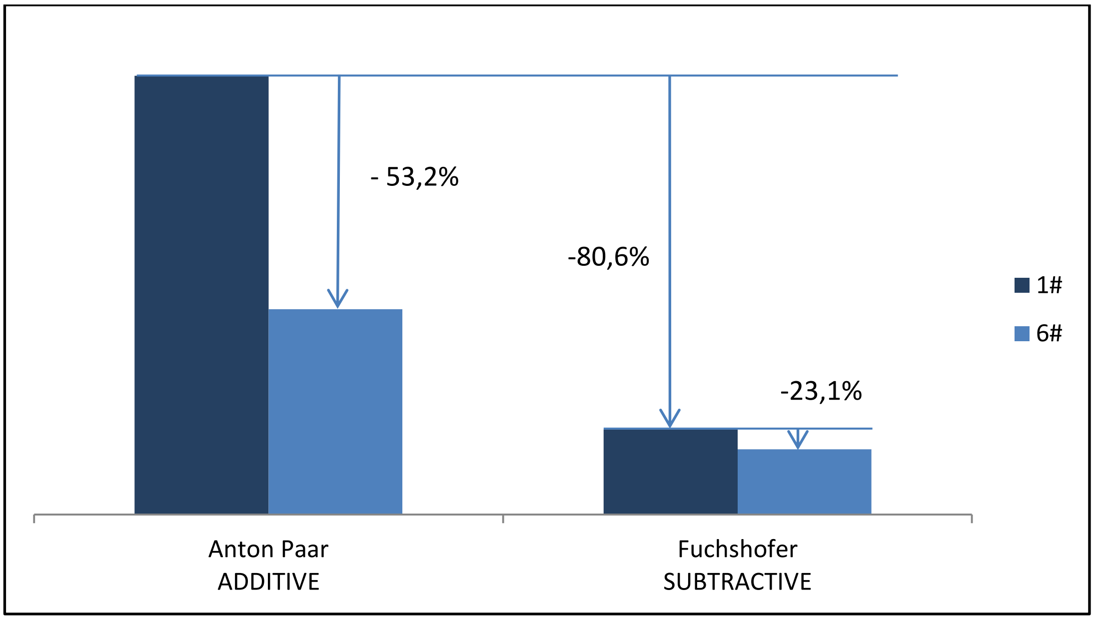

Figure 26: Total Price Comparison Additive vs. Subtractive Manufacturing of Ventrex' EPR210

The total price deviation at lot size 1 is 516 % and 290% at lot size 6 which makes clear that the introduction of an additive manufacturing technology instead of a subtractive manufacturing technology cannot be made economically efficient. The enormous scale effect of 57% at additive production is driven by the packing density in the building room and the fact that costs for CAD design as well as NC programming and post processing are divided by the number of parts produced.

In the case of subtractive production this scale effect is 23.2% which makes the impact of the packing density at additive manufacturing processes obvious and also shows that the reduction of the process chain can lead to lower costs.

The geometrical dimensions of the produced parts therefore have an enormous impact on the scale effect of additive manufactured parts. In addition to the determination of requirements of the chosen application, the part size should be small to produce economically efficient. In case of Magna's suspension node only lot size 1 was possible within one building room.

Machine producers work on bigger metal processing laser melting machines but at the moment the laser speed limits the processing time. The average time for processing a 500 x 500 mm building room is about 50 hours. The laser speed of 10 m/s leads to a build rate of - depending on the layer thickness – approximately 70 cm^3/h. Currently the biggest challenge for machine producers is to increase processing speed which results in building bigger room sizes.[95]

Additive vs. Formative Manufacturing

Magna offers design and development of cars to OEMs all around the world. In the case of Mercedes SLS they have to do a testing series to guarantee the mechanical security of the car body and construction. Ten prototypes have to be produced for this testing series. Reducing costs during this phase could be very helpful especially in the casting Technology where tool costs are the price drivers at small lot sizes.

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[95] Laser Additive Manufacturing of High-Performance Materials, By Dongdong Gu, page 26

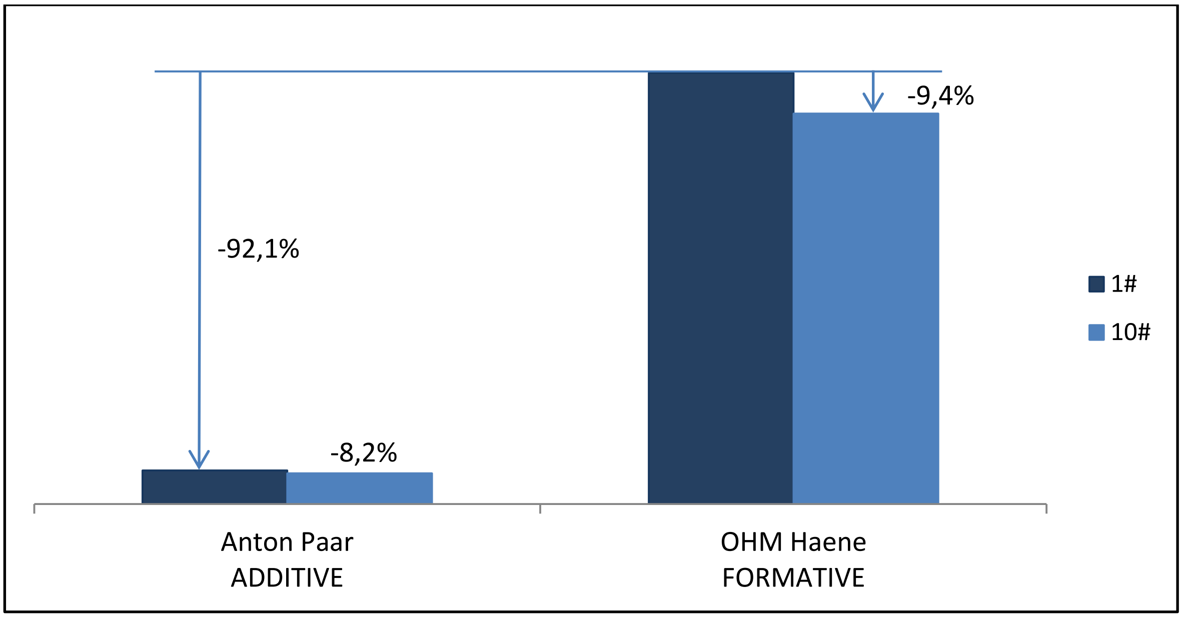

Figure 28: Total Price Comparison Additive vs. Formative of Magna’s Suspension Node

In serial production of 100.000 cars per year, the price per unit is 1.124 times cheaper than the production of one part. The direct comparison of additive and formative manufacturing shows that a casting production in small batch size is very expensive due to the high tool costs which demand 80% of the costs at lot size 1. Getting rid of those tool costs would be a real advantage for Magna during the development phase.

It is obvious that the cost deviation of 8,36% at additive manufactured parts with lot size 10 is caused by the one-off costs since only one part can be produced in one building room and therefore the packing density cannot be increased. Those one-off costs, are divided by the number of produced parts.

The overall cost comparison shows that additive manufacturing cannot compete the prices of subtractive produced parts but it can bring advantages in small batch sizes of formative manufactured parts due to the reduction of the formative tool costs.

3.5 Additive Manufacturing Process Costs

To get a better understanding of the economic behaviour of additive manufactured parts, it is important to understand the whole process chain and the effects of the single stages on the total costs. Therefore, it is helpful to consider the additive manufacturing process chain explained in the previous chapter.

According to HIC-Innotech, a German additive manufacturing service provider, there are seven cost factors in the process chain of additive manufacturing. They can be divided into variable/changeover costs and one-off/fixed costs.[96] Heat treatment after the laser melting process is not included in the process chain since it is not done in the common production of prototyping.

One – Off Costs	Changeover costs
CAD Data Preperation	Laser Melting Process
Machine Setup	Mechanical Post Processing
CNC Programming	
Equipment Costs	
Tool Costs	

Table 1: Additive Manufacturing Process Costs, HIC Innotech

One-off costs are independent from the number of produced parts and occur due to CAD data preparation, CNC programming, machine setup, tool costs and other equipment costs. They represent the fixed costs in the process chain.

Changeover costs or variable costs, generated through mechanical post processing and the laser melting process, are depending on the number of produced parts.

The diagram below shows the seven different process costs for the electronic pressure switch at lot size 1 and lot size 6. Prices cannot be published due to a statement of concealment but the influence of the different processes at different lot size is obvious.

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[96] HIC-Innotech Additive Manufacturing Process Costs, Meffle S.

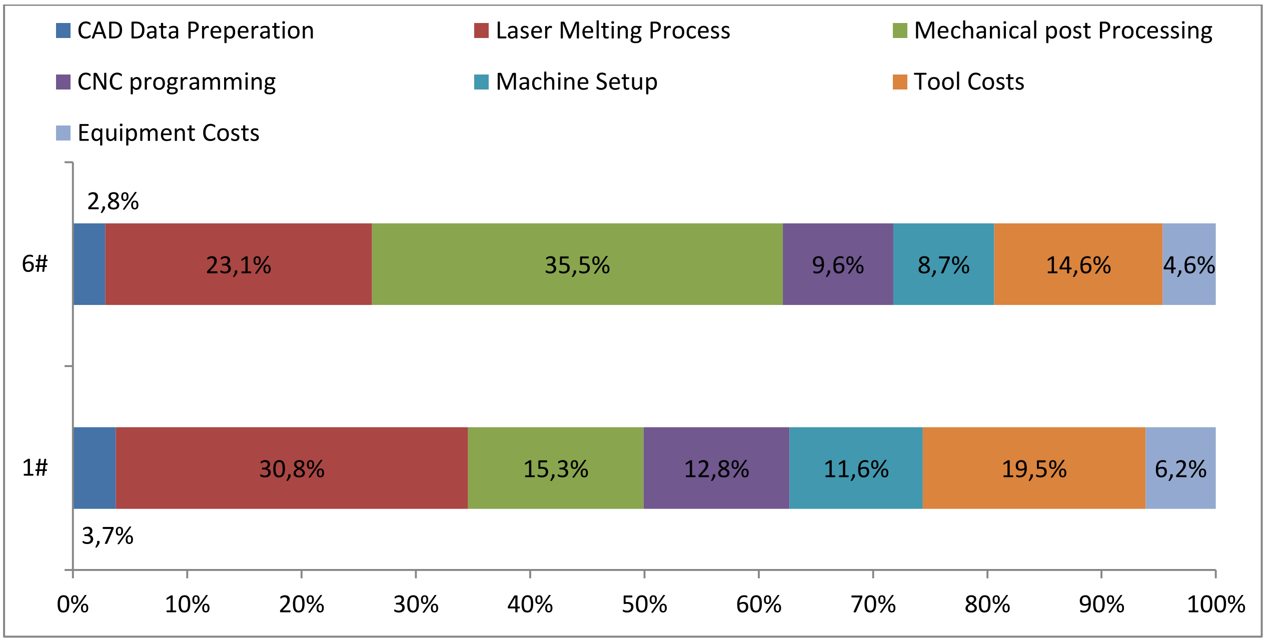

Figure 303: Process costs of Ventrex' EPR210, HIC-Innotech

The composition of the total costs per piece shows the two driving components for the economies of scale effect at additive manufactured parts. The changeover costs and the packing density in the laser melting process leads to price deviation of enormous 67,7% by a maximum lot size of 6 pieces per building room. This price deviation at factors of 1 and 6 will stay the same, no matter how many parts are produced. Therefore, the price consistency of additive manufactured parts is only given if the packing density is not considered in the calculation. The mechanical post processing has to be done separately for each part and therefore no economies of scale can be achieved.[97]

The one-off costs, which get divided by the number of parts produced, lead to a cost reduction of 33% of the total costs per piece. One-off costs amount 53,8% of the total costs at lot size 1 and only 20,8% at lot size 6. At a lot size of 30 pieces, which means 5 building rooms, the one-off costs are only 2% of the total costs.

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[97] Wirtschaftliche Fertigung mit Rapid Technologien, Prof. M. Zäh, page 176

The rapid reduction of the amount of one-off costs per piece lead to the common assumption that the price per piece is constant at additively produced parts. The following diagram shows the total cost development depending on the produced quantity.

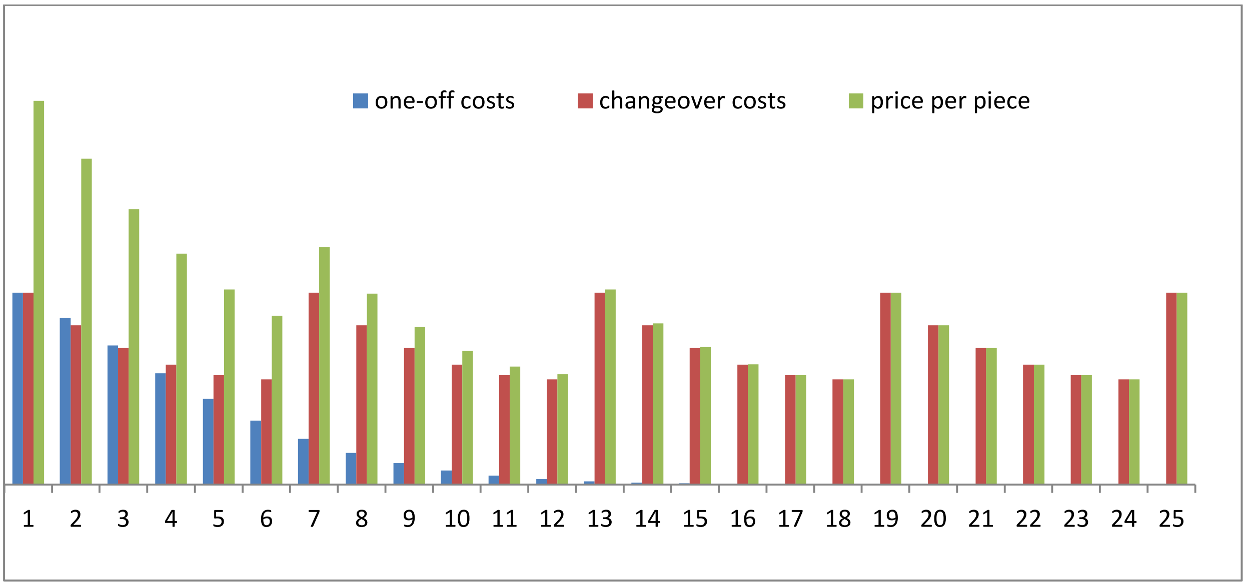

Figure 31: Cost-quantity relation for additive production of Ventrex' ERP210

The diagram below shows the seven different process costs for the suspension node at lot size 1 and lot size 10. The proportion of the one-off costs compared to the changeover costs differs drastically from the production of the electronic pressure switch. The reason for the price deviation is, on one hand on the lower surface quality requested and therefore less necessary post processing. On the other hand, the part size allows no increase of the packing density and therefore, only one part can be produced in one building room.

Literature research confirmed the data given from the manufacturing service provider HIC-Innotech. Research at the Munich University of Technology showed the same cost-stage effect due to the packing density at additive manufactured parts. Constant production costs can therefore only occur in additive manufactured parts if an increase of the packing density is impossible due to geometric dimensions and the cost drivers of upstream and downstream processes are not taken into consideration.[98]

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[98] Wirtschaftliche Fertigung mit Rapid-Technologien, Zäh, page 170

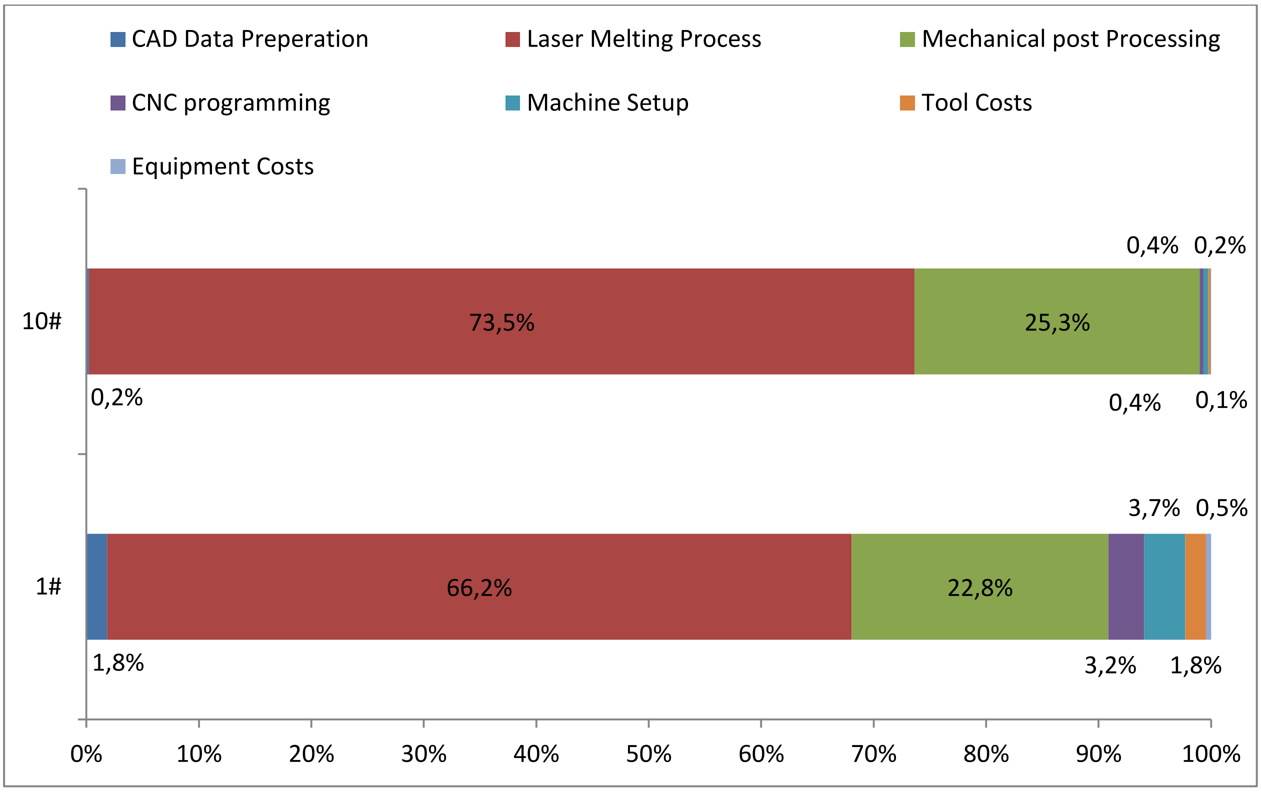

Figure 32: Process costs distribution of Magna’s suspension node

The lower total one-off costs can also be ascribed to the fact that the geometric complexity is simpler, compared to the electronic pressure switch. This results in lower costs for the design of support structures and makes complex multi-part CAD files unnecessary. Mechanical post processing costs and laser melting process costs are independent from the produced quantity, as mentioned before, which explains the small cost reduction of 8,36% between 1 and 10 parts produced. One-off costs are only 11,2% at lot size 1 and 1,2% at lot size 10.

The following diagram shows the rapid decrease of the one-off costs by the produced quantity. This price curve comes close to the curve from Fraunhofer Institute mentioned in the first chapter of this Master Thesis. The price consistency, no matter how many parts are produced only applies to cases with low upstream and downstream processes and exclusion of an increase of the packing density.

The form and positional tolerances of the suspension node are not very precise which leads to lower effort in the mechanical post processes. This comes into consideration due to the fact that the one-off costs are very low compared to the processing costs.

The price development also proofs the assumption that without consideration of packing density and pre and post processes constant costs per piece occur.[99]

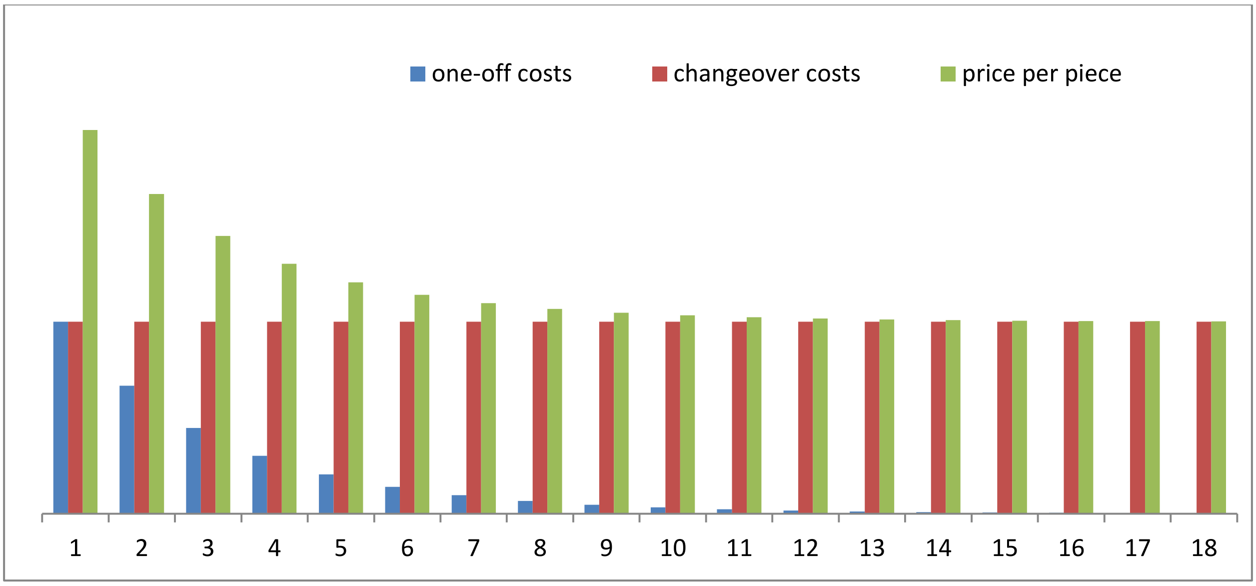

Figure 33: Cost-quantity relation of Magna's suspension node

Obviously additive manufacturing cannot compete with the common serial production since the price per produced part will almost stay the same and the current price in mass production is 1.224 times cheaper! The challenge of additive manufacturing is the radical increase of the processing performance regarding bigger building rooms, faster laser scan technique, multi laser processing and lower metal powder costs through technological research. But even if all those factors are improved Prof. Zäh's assumption that only design changes lead to a sustainable successful use of such a technology will be proofed. There is high potential in this technique but the price limits its introduction into the serial and mass production, when substituting an existing manufacturing system, not considering any design changes.

3.5.1 Summary of Comparison

To summarize the results of the technological, process-wise and economic comparison of additive, subtractive and formative manufacturing systems it has to be mentioned that we assume the production of metal parts in a laser melting process and no design changes, which would add value to the final product, are performed. Therefore, we

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[99] Additive Manufacturing: The new industrial revolution, Mangoldt, Wengerer, Fraunhofer 2014

cannot make use of the whole set of advantages of this new innovative technology explained in a previous chapter.

The electronic pressure switch, commonly produced in a subtractive process, would have better mechanical properties if it was produced additively. Moreover, the production lead time could be reduced through the laser melting process. As an economic fact, the production of one part would cost five times more than in the subtractive milling process. Even the high economies of scale effect, through the increased packing density in the laser melting process, would not be convincing enough for the introduction of this technology.

Ventrex Automotive will therefore not produce their part additively but they keep the design opportunities in mind, that occur with additive manufacturing and already work on other opportunities to implement additive manufacturing into their company in the future. As a valve producer they face challenges with interfaces between parts and ensuring density in these fluid managing parts. Therefore, the reduction of interfaces through new manufacturing possibilities seems very promising in their field of expertise.

Very different is the situation at Magna Steyr and their suspension node for the Mercedes SLS. Not only the mechanical properties and functionality of the part would be increased, if the prototyping was done additively instead of the expensive chilled casting formative manufacturing system. The reduction of the production lead time could lead to high advantages if the start of production (SOP) could be preponed. But more significantly would be the chance of cost reduction by the high casting tool costs. This especially applies to the testing phase when no contract is concluded with the OEMs.

4 Basics of Operator Model Generation

An operator model describes the business relations between the customer and the operator in the phase of planning and use of production systems. The operator purchases and operates a production facility as an economically and organisationally independent unit.[100]

In the current project the production facility is a laser melting machine considering all the necessary upstream and downstream processes regarding computer design and programming as well heat treatment and subtractive mechanical post processing. The operator should be one institute of the faculty of mechanical engineering and economic science at the Graz University of Technology.

The decision for a certain operator model of a new manufacturing technology is a mid- to long-term decision and therefore the determination of the factory of the future is very important in order to meet the demand of future customers. Because of the decreasing ability to create reliable predictions on markets, products and technologies, the logical conclusion is that future factories must be characterized primarily by an appropriate market needs and corporate strategy adaptability.[101]

4.1 The Factory of the Future

The starting points of observation, in terms of future factories, are the customer requirements in the recently turbulent markets. Functionally superior products and services with long-term customer value must be readily available. [102]

Radical changes in terms of visualisation, virtual testing and improved quality of computer simulations should be mentioned here since we are talking about a long term decision and the future development of prototyping goes into a virtual direction.[103]

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[100] Fabrikplanung und Fabrikbetrieb: Methoden für die wandlungsfähige, vernetzte und ressourceneffiziente Fabrik, 2nd edition, Schenk, Wirth, Müller, page 469

[101] Handbuch Fabrikplanung – Konzept, Gestaltung und Umsetzung wandlungsfähiger Produktionsstätten, Whiendahl, Reichardt, Nyhuis, page 39

[102] Handbuch Fabrikplanung – Konzept, Gestaltung und Umsetzung wandlungsfähiger Produktionsstätten, Whiendahl, Reichardt, Nyhuis, page 47

[103] 3D-Drucken "Wie die generative Fertigungstechnologie funktioniert", by Petra Fastermann, page 67

Research on the characteristics of the futures factory form the Fraunhofer Institute shows that flexibility, automization, computer integration and the ability to combine the advantages from the conventional manufacturing systems with new computer controlled manufacturing technologies are the key factors to sustainable success.[104] The following examples serve as future outlook of how these demands could be met and describes the attributes of the factory of the future.

4.1.1 Industry 4.0

Industry 4.0 describes the target-oriented merging of modern information- and communication technologies with the classical production and logistics processes and resources. This process takes place technologically and company comprehensively. It is the necessary reaction to move towards intelligent production and logistics facilities in order to face the increasing challenges that come up with customization, shorter lifecycles and complex business fields.[105]

The term smart factory therefore is deeply connected with Industry 4.0. It is also politically pushed forward by the German government that invests more than 200 million Euros to spread Industry 4.0 research across government, academia and business. The American version of this movement is Industrial Internet and both governments support their companies financially to gain competitive advantages on the way to the smart factory.[106]

4.1.2 Agile Production

“Agile Production aims at quick turnaround of small batch lots at competitive costs. Agile manufacturers use information technology in machine control and production planning, and leverage decision making skills and faster flow of information among all departments.” [107](Business Dictionary)

Increasing market volatility and rising insecurity of future market predictions are forcing manufacturing companies to adapt their production concept to the strongly changing

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[104] Porduktionsarbeit der Zukunft – Industrie 4.0, Spath, Ganschar, Gerlach, Hämmerle, Krause, Schlund, page 14

[105] Intellingente Produktions- und Logistiksysteme, Minichmayer, www.fraunhofer.at

[106] Germany’s vision for Industrie 4.0: The revolution will be diditised, Sara Zaske, www.zdnet.com

[107] Definition Agile Production, www.businessdictionary.com

environmental conditions. Therefore, it is necessary to anticipate volatility and proactively deal with the current changes. The orientation according to this concept of agile production may be the key to success in this environment.[108]

4.1.3 Cloud Production

There are multiple ways to make use of the additive manufacturing technology. Some people see advantages in creating a boundless production in the future and compare the 3D printed parts with a common ink jet printer were e.g. letters could be printed out in several different places around the world, through digital data management.[109]

Cloud production is a common word for such a fully automated production site where companies can get access and only a digital data transfer takes place between companies and the cloud production.[110]

Such a system guarantees several major advantages. People or companies have access to a wide spectrum of manufacturing technologies. The utilisation of the machines can be harmonized which leads to process stability and reduced costs. Furthermore, it guarantees adaptability to demand changes which is a step towards agile production.[111]

Of course, there would be a lot more operator models like the cloud production, fabrication laboratories (FabLabs) or tech centres that point towards the agile production of the future. However, they are not yet available in the area of Graz with all the necessary professional industry equipment needed for all the processes like milling, grinding, laser melting and surface blasting – all computer controlled high-tech manufacturing.

The general suggestion, in this process of analysing different operator models, is to produce parts similar to the chosen applications during this project using the Laser Melting Technology including all the necessary upstream and downstream processes.

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[108] Agile Produktion, Ein Produktionskonzept für volatile Zeiten, Ramsauer, Schurig, Rabitsch, www.zwf-online.de
[109] Rapid Manufacturing – Zukünftige Wertschöpfungsmodelle generativer Fertigung, Bopp, page 42
[110] Rapid Manufacturing – Zukünftige Wertschöpfungsmodelle generativer Fertigung, Bopp, page 43
[111] Rapid Manufacturing – Zukünftige Wertschöpfungsmodelle generativer Fertigung, Bopp, page 44

4.1.4 Pay-On Production

Another new model is pay-on production which aims for more integration of the machine producers into the manufacturing process. Prof. Dr. Horst Wildemann, Professor of business administration at the Munich University of Technology, is enthusiastic about that topic: *“Operator and pay-on-production models can produce a nearly cost-neutral rehabilitation and modernization of production and infrastructure of a company."*[112]

For example the Böblingen plant manufacturer Eisenmann brought an 80 million Euros paint line into the 200 million Euros devouring modernization of the Cologne Ford plant. The system appeared not on the balance sheet of the automotive group. For Eisenmann is not only user of the system, but remains the owner. Ford bought no new plant facility, but they only pay for the final output: the painted car bodies. *”The cost of investments in operator models tend to zero"* said Wildemann. [113]

Several studies confirm that the equipment can be operated by their manufacturers much more efficiently than at the clients. Such investigations result in enormous cost reduction for the client. Thereby, production facilities up to 100% and financing expenses up to 20% of wages and salaries can be saved by this operator model.[114]

The analysis of these four “factory of the future” concepts shows that additive manufacturing, as a computer controlled full automated production process and relatively short time span from the CAD model to reality, fits perfectly into the each of the concepts.

4.2 Selection of a Laser Melting Machine

The selection of the proper machine for research purposes is driven by technological, economic and strategic aspects. Economic aspects will be discussed in the next chapter. Boundary condition for the selection process is that parts, similar to the chosen applications at Magna Steyr and Ventrex Automotive, should be produced with such a machine.

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[112] Produktion auf Rechnung und Risiko des Zulieferers, Baumgärtner, www.industrieanzeiger.de
[113] Produktion auf Rechnung und Risiko des Zulieferers, Baumgärtner, www.industrieanzeiger.de
[114] Produktion auf Rechnung und Risiko des Zulieferers, Baumgärtner, www.industrieanzeiger.de

4.2.1 Technological Aspects

The three biggest German laser melting machine vendors, EOS Manufacturing Solutions, Concept Laser and SLM-Solutions, are also the biggest players on the European metal processing additive manufacturing market.[115]

The analysis of the three machine producers’ products shows that there is a distinction of machines for serial mass production, where basically no material changes are intended and the building room is bigger to realize better scale effects through higher packing density and part sizes up to 500x500 mm building base. The second type of machines allows material changes in a relatively short time span and is characterized by smaller building rooms, as table 2 shows.

Company	Type	Building Volume (mm)	Laser	Scan Speed	Layer Thickness	Powder Application
EOS Manufacturing Solutions	EOS M 290	250x250x250	400 W	7 m/s	20 µm - 50 µm	one direction
	EOS M 400	400x400x400	1000 W			
Concept Laser	M2 cruising	250x250x280	400 W		25 µm - 45 µm	one direction
	Xline 1000 R	630x400x500	2x 400 W			
	Xline 2000 R	**800x400x500**	2x 1000 W			
SLM Solutions	SLM 280	280x280x350	**4x 400 W or 2x 1000 W**	**15 m/s**	**20 µm - 100 µm**	**two directions**
	SLM 500	500x500x350		10 m/s		

Table 2: Machine data comparison, source: www.eos.info, www.concept-laser.de, www.slm-solutions.de

According to Aziz Huskic from the Technical College in Wels, Austria, the main fields of research concerning the laser melting technology will be the optimization of the production processes, including automation of additive manufacturing processes, and the influences on the pre- and post-processes, in order to catch up with the price gap to conventional manufacturing methods. Regarding material science, research on various powder materials and their anisotropic behavior and the material optimization regarding subtractive post processes are potential fields of research. Therefore, a machine is

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[115] 3D-Druck/Rapid Prototyping – Eine Zukunftstechnologie – kompakt erklärt, Fastermann, page 153ff

necessary that handles the material change very rapidly and allows open material parameters to comprehensively research on different type of metal.[116]

Concept Laser owns the world’s biggest laser melting machine in place and also offers the greatest variety of different machine sizes.[117]

SLM has implemented a bi-directional powder application in the building process and a multi laser technology which leads to major advantages in terms of process speed. Regarding layer thickness the technology of SLM Solutions is far ahead, with minimum layer thickness of 20 micrometers. Through their Hull-Core Laser Technology they first operate the contour surfaces with two 1000 W laser and afterwards, melt the filling of the contours with a 400 W laser. The multi laser technology and the high scan speed of their machines also result in faster building rates up to 45 cm^3/h.[118]

Another advantage of SLM Solutions machines is the integrated material preparation which is handled externally at EOS and Concept. Therefore, the loose metal powder falls directly in the material post preparation space below the building room after processing and the cleaned powder is automatically replaced into the powder application unit.[119]

Finally, the research-relevant advantage of SLM material change is that it only takes two hours to clean the building room apply another material and get ready for processing.[120]

4.2.2 Strategic Aspects

Research Institutions in Austria primarily work with EOS and Concept Laser machines as the following map visualizes. No SLM-Solution machine is placed in research institutions even though they produce high quality machines with different applications in contrast to the other two competitors. Supplementing the additive manufacturing research market in Austria with a third machine producer-company should lead to increased competitiveness.

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[116] Forschung und Entwicklung der generativen Fertigung, Huskic, page 4
[117] The X line 2000R – world’s biggest laser melting machine, www.concept-laser.de
[118] SLM 280HL Produktbeschreibung, www.slm-solutions.com
[119] SLM Materialien und Pulveraufbereitung, www.slm-solutions.com
[120] Materialwechsel SLM280HL, www.slm-solutions.com

According to Prof. Haas of the Institute of Production Engineering at the Graz University of Technology the strategic goal of research is to make additive manufacturing fit for serial mass production considering all interdisciplinary aspects necessary.

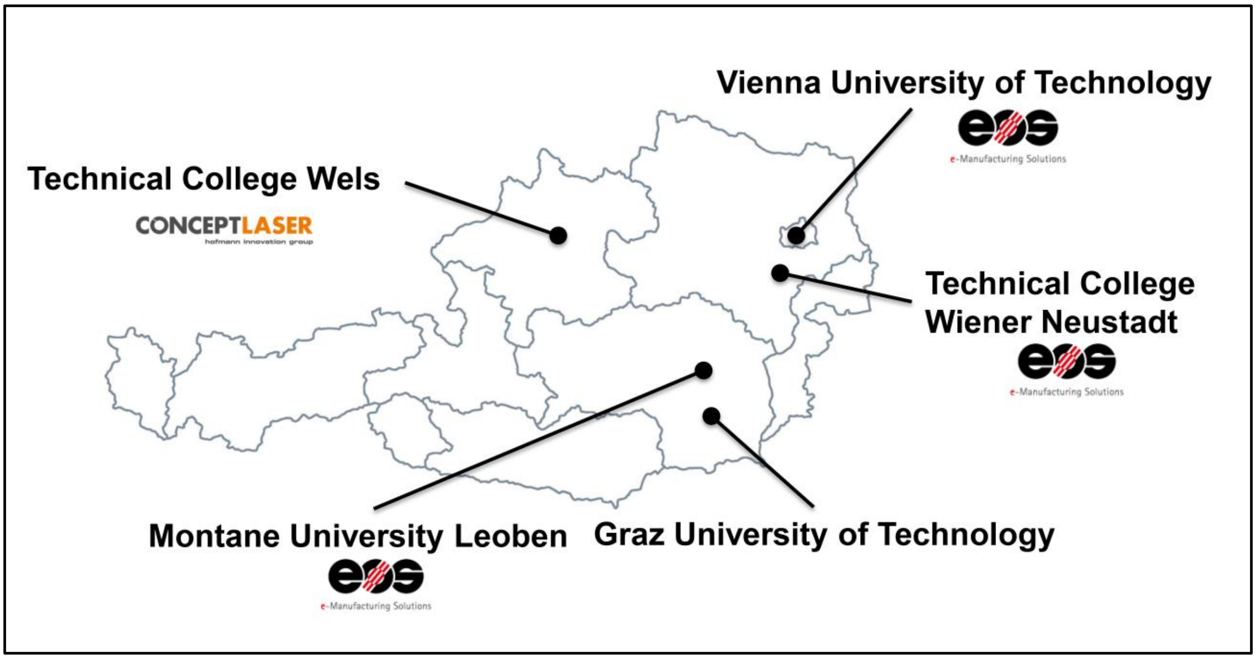

Figure 34: Additive Manufacturing Machines in Austrian Research Institutions

There are several different opportunities for both sides, the SLM-Solution company as well as the Graz University of Technology.

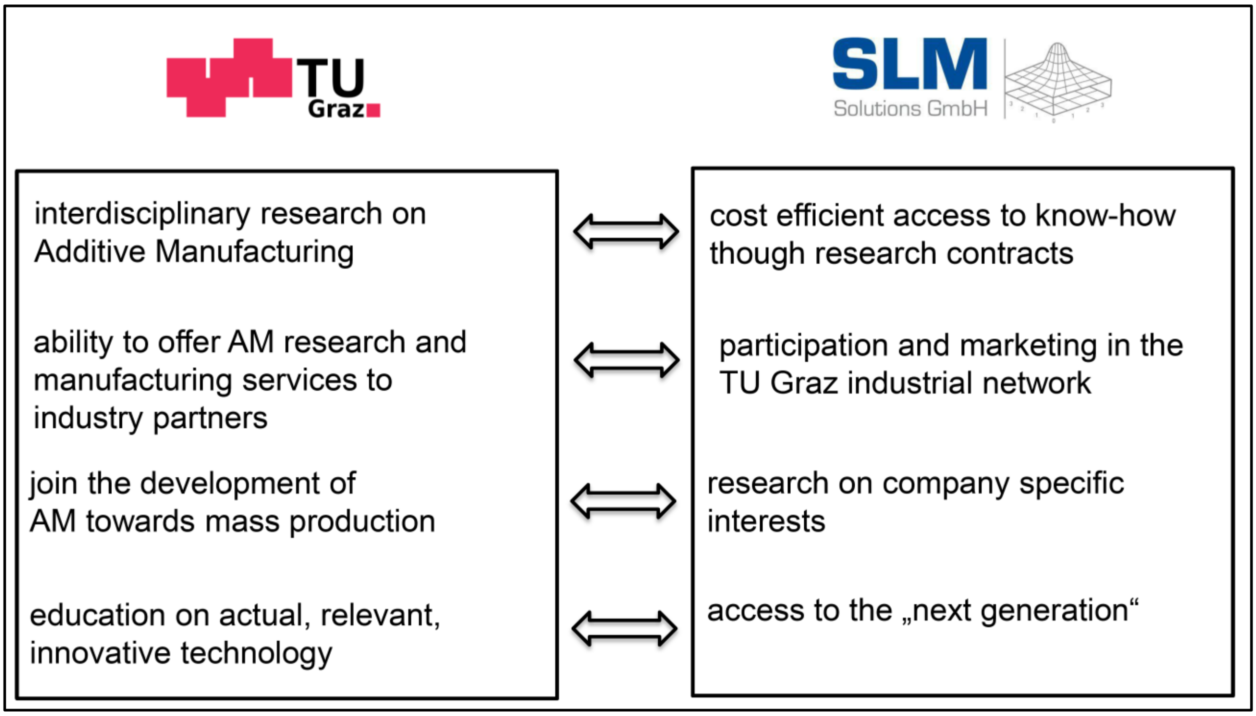

Figure 35 Opportunities of an SLM - TUGraz Cooperation

4.3 Make or Buy

Both the question of whether the additive manufacturing technology will be used at all (strategic aspect), as well as the choice of the optimal process (operational aspect) are largely independent of whether the components are produced in-house, or if they are purchased from service providers.[121]

The following diagram visualizes the company specific strategic aspects of such a ‘make or buy’ decision. “Outsourcing” describes the allocation of company internal production activities and services. The intended objectives are the reduction of fixed costs by reducing the production depth, and limitation of performance creation of the company to its core competencies.[122]

“Insourcing” describes the process of making use of company’s own resources to generate or accomplish any kind of task. This leads to reduction of logistics costs and better integration of the processes within the company. Furthermore, it leads to time advantages for product development and subcontracting.[123]

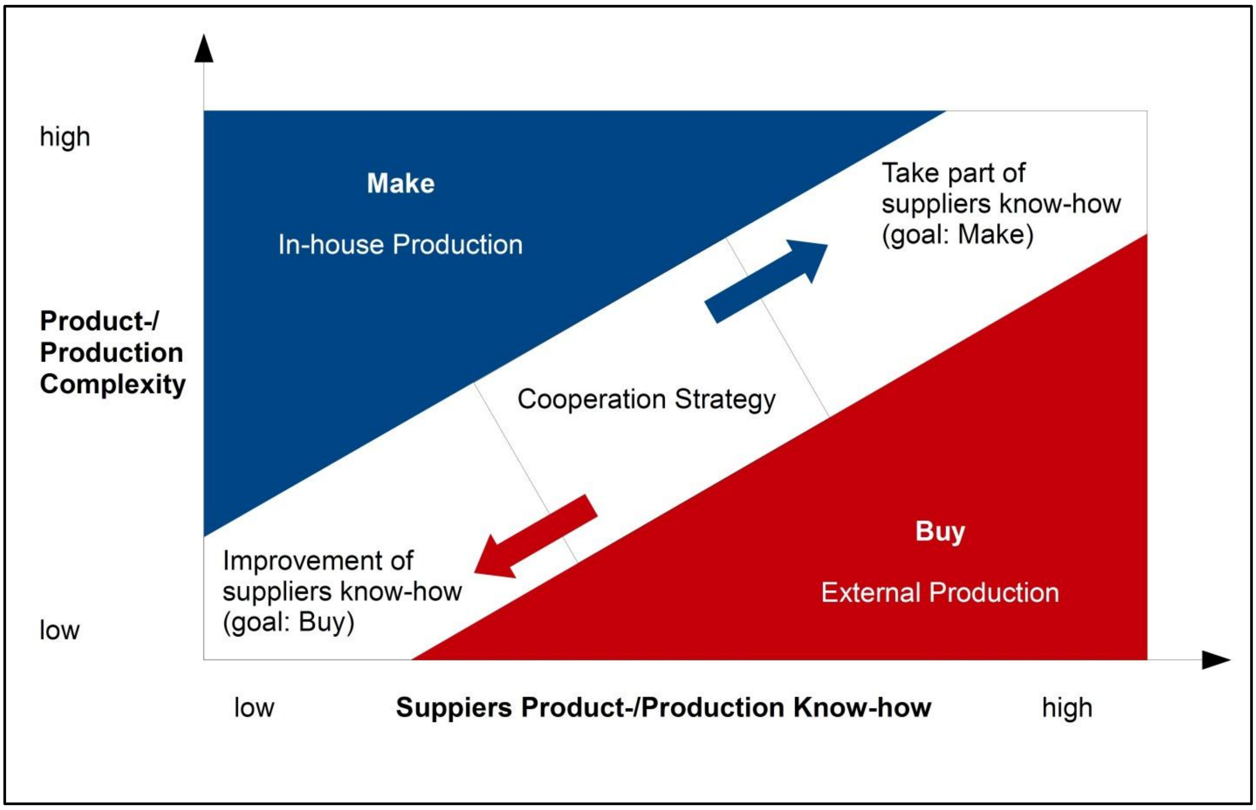

Figure 36: Strategic aspects of a make or buy decision, source: www.4wards.at

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[121] Generative Fertigungsverfahren, 4. Auflage, Andreas Gebhardt, page 513
[122] Insourcing oder Outsourcing: Risiken und Chancen, Schumann, page 4
[123] Insourcing oder Outsourcing: Risiken und Chancen, Schumann, page 5

Outsourcing of high complexity parts leads to a high dependency on the suppliers. Therefore, the goal is to keep very sensitive parts, which have direct impact on the company's success, in house.[124]

The current strategy at Magna and Ventrex is to keep the prototyping production external. Magna Steyr wants to focus on the improvement of the existing assembly line and contract design actions for the big OEMs, in order to meet their demand and stick with their core competencies.

Ventrex has a production line in place but prototyping is mostly done at external service providers to keep their manufacturing focus on the serial production of their complex valves.

Figure 35 shows various criteria that have to be considered for a “make or buy” decision. It also visualizes the impact of such a decision on the company regarding competitors, legal aspects, customer needs or even flexibility of the manufacturing system.

Figure 37:4 Criteria for the “Make or Buy” decision, Markt und Unternehmung: Eine marktorientierte Einführung in die Betriebswirtschaftslehre, Jörg Freiling, Martin Reckenfelderbäumer, page 104

All these different factors need to be considered company specifically in order to guarantee positive economic and company strategic effects through this decision. The

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[124] The Insider’s Guide to Outsourcing Risks and Rewards, Rost, page 151

following figure shows that there are opportunities in both variants and that no qualitative general answers can be given.

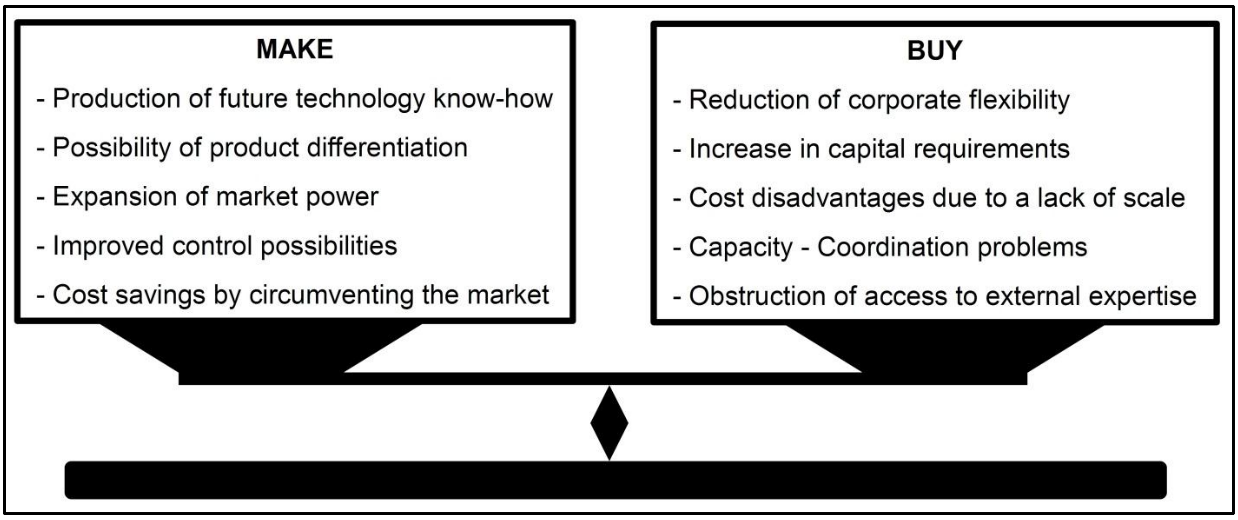

Figure 38: Make or Buy decision in marketing, Fischer, page 26

4.3.1 Make: In-house Production

The machine costs for a laser melting machine, which would be appropriate for research and low volume production purposes, depend largely on the amount of additional equipment. The basic system with a one-laser technology implemented and no material preparation unit costs approximately 500.000 Euros. Included is the computer software for part preparation and design of the supports, the installation and the training on the machine.

Additional equipment, like a second laser scanner or twin head option to increase the productivity of the process, lead to major further investment costs of 140.000 Euros up to 180.000 Euros. The Powder changing system and especially the powder preparation to recycle the infused powder after the process costs 70.000 Euros in total, as Table 3 shows.

Selective Laser Melting Machine			€ 460.000
	included:	laser 400 W	
		optical bank	
		building room 280 x 280 x 350 mm	
		build cylinder	
		powder loading system	
		powder application system	
		powder filter system	
		computer control unit	
CAM Software			€ 26.000
	included:	software for part preparation	
		software for .stl Programming	
		1 year service	
Installation and Commissioning			€ 4.200
Training per day			€ 1.200
			€ 491.400
Additional Equipment			
Two Laser Concept 400W/1000 W			€ 179.500
Twin-Head Option - productivity increase of 40%			€ 139.000
Clamping System			€ 11.500
Powder Changing System			€ 16.500
Secution Cleaning and Oscillation Sieve			€ 55.000
Vacuum Exhauster			€ 2.350
Nitrogen Generator			€ 16.900
			€ 420.750

Table 3: Machine costs including Additional Equipment,

In addition to the machine investment costs, material costs, operating costs and material costs have to be considered. Material costs are daily prices and therefore, they can only be seen as approximate value but the following table gives an impression of material prices of several different powders. Compared to a stainless steel bar (1.4404), metallic bright, milled and grinded wrought material, purchased at a common metal producer, the metal powder prices are more than 10 times as expensive. One kg of such a wrought material costs approximately € 6,5.- Euros.[125]

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[125] Preislisten-Edelstahl, www.zultner.at

Material	**Description**	**Price €/kg**
Stainless Steel	1.4404	90
Tool Steel	1.2344	80
Tool Steel	1.2709	130
Titan Alloy	TiAl6V4	520
Titan Alloy	TiAl6Nb7	680
Cobalt-Chrome Alloy	Co212f	229
Aluminium Alloy	AlSi10Mg	75
Aluminium Alloy	AlSi12	64
Inconel	625	145
Inconel	718	185

Table 4: Laser Melting Material Costs, Source: Generative Strahlschmelzanlage SLM280HL

Besides, the machine investment costs and the material costs for processing operating costs need to be considered. 180l/h nitrogen shield gas for processing is required, as well as 8 kW electricity during processing. The processing time depends on the amount of produced material and the build rate of a SLM280HL is at 70cm^3/h. The total build room size is 25.515cm^3 (270x270x350mm).[126] Therefore, operating costs have to be calculated separately for each part.

Labour costs for the worker that operates the machine and the computer design of the support structures, as well as costs for the production facility with room space of 8 m^2, have to be taken into consideration.[127]

Machine Service costs for maintaining the productivity of the laser melting machine come to account with approximately 10.000 Euros per year, depending on the type of service level.[128]

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[126] SLM 280HL Produktbeschreibung, www.slm-solutions.com

[127] Leitfaden: „Vorbereitung des Aufstellortes für den Aufbau/Betrieb einer SLM280HL

[128] Generative Strahlschmelzanlage SLM280HL, Servicekosten

4.3.2 Buy – External Production

The great advantage of an external production is the possibility to concentrate on the core competencies of a company. Furthermore, a reduction of production depth leads to reduced overhead costs by cutting management functions. The settlement from suppliers of unused land and competition of the own production with suppliers are other aspects that point towards an out-sourcing strategy.[129]

Cost reduction can be achieved by benefitting from the supplier’s cost advantages such as economies of scale and its increased experience. Performance improvement through a higher level of services quality, due to company specific service level agreements, is a further advantage of the outsourcing strategy. Flexibility by not owning and performing the whole value chain brings advantages in a rapid changing environment. The specialisation was mentioned before as an major advantage to focus on the core competences of business. Another important factor is the access to innovation through the high knowledge level of professional supplier companies.[130]

The opportunities are followed by several risks like the loss of manufacturing competence, a high dependency on external suppliers or the increased effort to ensure a smooth flow of information. Furthermore, the reduction of in-house manufacturing leads to an increase of external material flow, a demolition of the material flow at the delivery, as well as high dependency on smooth transport logistics.[131]

The basic economic analysis for the outsourcing strategy was already mentioned in the previous chapter and showed that only formatively produced parts can lead to cost advantages, compared to additive production.

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[129] Managing the Outsourcing Relationship, Langfield-Smith, smith, Stringer, page 69
[130] The Outsourcing Process: Strategies for Evaluation and Management, McIvor R., page 21
[131] 4wards Unternehmensberatung, Mag. Gerald Ludwig, source: www.4wards.at/html/make_or_buy.html

5 Operator Model for AM at the Graz University of Technology

The Graz University of Technology is interested in research on the latest technology available to meet the demand of the industry partners and stay relevant in the global competition. Therefore, this operator model should explain how the Graz University of Technology can help companies to get access to the latest technology available and also gain profit through research on various topics concerning additive manufacturing.

5.1 The Business Model Canvas

The business model canvas is a helpful tool to develop an operator model or business plan including all the relevant factors that have to be determined. Such an organisations business model can be described with nine basic building blocks: The customer segments, your value proposition for each segment, the channels to reach customers, customer relationships you establish, the revenue streams you create, the key resources and key activities you acquire to create value, the key partners and the cost structure of the business model.[132]

The nine building blocks

Customer Segments

Customer Segments are all the people or organisations for which you are creating value. This includes simple users and paying customers. Mass markets, niche markets, segmented and diversified markets as well as multi sided platforms need to be considered[133]

Value Proposition

For each segment you have a specific value preposition which bundles the products and services that create value for your customers. The values have to be defined by

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[132] Business Model Generation, Alexander Osterwalder & Yves Pigneur, page 32

[133] Business Model Generation, Alexander Osterwalder & Yves Pigneur, page 21

their novelty, performance compared to other competing value providers, the degree of customization, design, brand and price.[134]

Channels

Channels describe through which touch points you are interacting with customers and delivering value. Communication channels have to be chosen by factors like the awareness of the customers to reach you through this channel and the possibility to stay in touch with the customers.[135]

Customer Relationships

Customer Relationships outline the type of relationship you are establishing with the customers. Different motivations are driving these relationships, such as the acquisition or retention of potential customers or the vision to boost sales activities.[136]

Revenue Streams

Revenue Streams make clear how and through which pricing mechanisms your business model is capturing value. Definition of the value the customer is willing to pay for and a comparison of the price development as well as paying mechanisms is the objective of this building block.[137]

Key Resources

Key Resources describe the infrastructure to create, deliver and capture value and show which assets are in your business model. Determining physical, intellectual, human and financial aspect of the resources required, for the value proposition, is the goal of this building block.[138]

Key Activities

Key activities show which things you really need to be able to perform well. The most important processes that have to be done to make the business model work are defined in this part of the business model canvas.[139]

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[134] Business Model Generation, Alexander Osterwalder & Yves Pigneur, page 23
[135] Business Model Generation, Alexander Osterwalder & Yves Pigneur, page 27
[136] Business Model Generation, Alexander Osterwalder & Yves Pigneur, page 28
[137] Business Model Generation, Alexander Osterwalder & Yves Pigneur, page 31
[138] Business Model Generation, Alexander Osterwalder & Yves Pigneur, page 35
[139] Business Model Generation, Alexander Osterwalder & Yves Pigneur, page 37

Key Partners

Key Partners show who can help you leverage your business model, since you will not own all your resources yourself, nor perform all your key activities. Suppliers and other key partners need to be defined and brought into connection with the key resources they provide. Also key activities performed by the partners have to be considered [140]

Cost Structure

Once you understand your business models infrastructure, you will also have an idea about its cost structure. Costs of all key activities, key resources and other cost driving factors have to be defined. A certain cost structure needs to be put into practice, determining fixed costs and variable costs as well as potential economies of scale and economies of scope effects in the business model.[141]

Figure 39 shows the business model canvas for additive manufacturing at the Graz University of Technology. Due to space reasons each building block is described in detail on the following pages.

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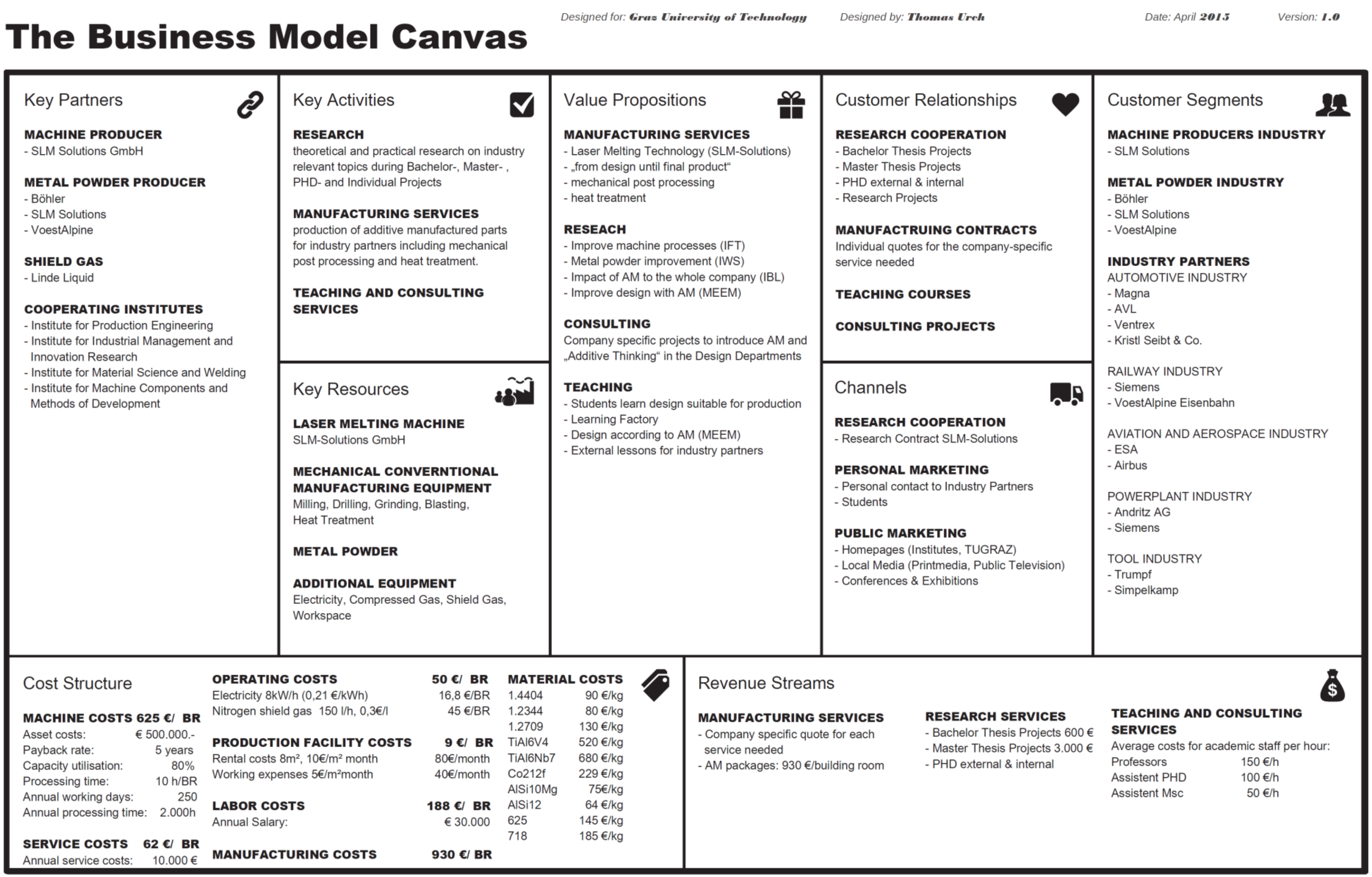
[140] Business Model Generation, Alexander Osterwalder & Yves Pigneur, page 39

[141] Business Model Generation, Alexander Osterwalder & Yves Pigneur, page 41



The Business Model Canvas

Designed for: Graz University of Technology
Designed by: Thomas Urch
Date: April 2015
Version: 1.0

Key Partners

MACHINE PRODUCER
- SLM Solutions GmbH

METAL POWDER PRODUCER
- Böhler
- SLM Solutions
- VoestAlpine

SHIELD GAS
- Linde Liquid

COOPERATING INSTITUTES
- Institute for Production Engineering
- Institute for Industrial Management and Innovation Research
- Institute for Material Science and Welding
- Institute for Machine Components and Methods of Development

Key Activities

RESEARCH
theoretical and practical research on industry relevant topics during Bachelor-, Master- , PHD- and Individual Projects

MANUFACTURING SERVICES
production of additive manufactured parts for industry partners including mechanical post processing and heat treatment.

TEACHING AND CONSULTING SERVICES

Key Resources

LASER MELTING MACHINE
SLM-Solutions GmbH

MECHANICAL CONVERNTIONAL MANUFACTURING EQUIPMENT
Milling, Drilling, Grinding, Blasting, Heat Treatment

METAL POWDER

ADDITIONAL EQUIPMENT
Electricity, Compressed Gas, Shield Gas, Workspace

Value Propositions

MANUFACTURING SERVICES
- Laser Melting Technology (SLM-Solutions)
- „from design until final product"
- mechanical post processing
- heat treatment

RESEACH
- Improve machine processes (IFT)
- Metal powder improvement (IWS)
- Impact of AM to the whole company (IBL)
- Improve design with AM (MEEM)

CONSULTING
Company specific projects to introduce AM and „Additive Thinking" in the Design Departments

TEACHING
- Students learn design suitable for production
- Learning Factory
- Design according to AM (MEEM)
- External lessons for industry partners

Customer Relationships

RESEARCH COOPERATION
- Bachelor Thesis Projects
- Master Thesis Projects
- PHD external & internal
- Research Projects

MANUFACTRUING CONTRACTS
Individual quotes for the company-specific service needed

TEACHING COURSES

CONSULTING PROJECTS

Channels

RESEARCH COOPERATION
- Research Contract SLM-Solutions

PERSONAL MARKETING
- Personal contact to Industry Partners
- Students

PUBLIC MARKETING
- Homepages (Institutes, TUGRAZ)
- Local Media (Printmedia, Public Television)
- Conferences & Exhibitions

Customer Segments

MACHINE PRODUCERS INDUSTRY
- SLM Solutions

METAL POWDER INDUSTRY
- Böhler
- SLM Solutions
- VoestAlpine

INDUSTRY PARTNERS
AUTOMOTIVE INDUSTRY
- Magna
- AVL
- Ventrex
- Kristl Seibt & Co.

RAILWAY INDUSTRY
- Siemens
- VoestAlpine Eisenbahn

AVIATION AND AEROSPACE INDUSTRY
- ESA
- Airbus

POWERPLANT INDUSTRY
- Andritz AG
- Siemens

TOOL INDUSTRY
- Trumpf
- Simpelkamp

Cost Structure

MACHINE COSTS	**625 €/ BR**
Asset costs:	€ 500.000.-
Payback rate:	5 years
Capacity utilisation:	80%
Processing time:	10 h/BR
Annual working days:	250
Annual processing time:	2.000h
SERVICE COSTS	**62 €/ BR**
Annual service costs:	10.000 €

OPERATING COSTS	**50 €/ BR**
Electricity 8kW/h (0,21 €/kWh)	16,8 €/BR
Nitrogen shield gas 150 l/h, 0,3€/l	45 €/BR
PRODUCTION FACILITY COSTS	**9 €/ BR**
Rental costs 8m², 10€/m² month	80€/month
Working expenses 5€/m²month	40€/month
LABOR COSTS	**188 €/ BR**
Annual Salary:	€ 30.000
MANUFACTURING COSTS	**930 €/ BR**

MATERIAL COSTS	
1.4404	90 €/kg
1.2344	80 €/kg
1.2709	130 €/kg
TiAl6V4	520 €/kg
TiAl6Nb7	680 €/kg
Co212f	229 €/kg
AlSi10Mg	75€/kg
AlSi12	64 €/kg
625	145 €/kg
718	185 €/kg

Revenue Streams

MANUFACTURING SERVICES
- Company specific quote for each service needed
- AM packages: 930 €/building room

RESEARCH SERVICES
- Bachelor Thesis Projects 600 €
- Master Thesis Projects 3.000 €
- PHD external & internal

TEACHING AND CONSULTING SERVICES
Average costs for academic staff per hour:

Professors	150 €/h
Assistent PHD	100 €/h
Assistent Msc	50 €/h

Figure 39: The Business Model Canvas for Additive Manufacturing at TU Graz

5.1.1 Customer Segments

The Graz University of Technology can provide additive manufacturing services for three basic customer segments.

Machine producers, like SLM Solutions, are currently focusing on the improvement of their production processes in order to meet the customer requirements of higher building rates and increased mechanical properties of the processed material. Scientific research on fields that surround their core competences of building laser melting machines is also an opportunity for the Graz University of Technology to research along the whole process chain of additive manufacturing.

The second field for research is the material development of metal powders according to customer requirements. Currently, no specific laser melting metal powder is used in the processes. Optimizing the powder regarding the laser melting process and the subtractive post processes bears potential for research and the metal producing industry partners.

The third group of customers is the industrial network of the Graz University of Technology. Manufacturing services can be offered including all the necessary subtractive post processes as well as heat treatment. On an interdisciplinary level consulting projects regarding part design and opportunities to add value through this new manufacturing technology can be offered.

5.1.2 Value Proposition

The Graz University of Technology offers research-, teaching- , consulting- and manufacturing services to their industrial network. It provides manufacturing services along the whole additive manufacturing process chain, including CAD file preparation, laser melting, various heat treatment processes and subtractive manufacturing technologies for part finishing.

Interdisciplinary research on the manufacturing processes, the metal powder processed, the design optimization as well as the management aspects that have to be determined with the introduction of such a new technology can be offered to the producers as well as the industry partners.

Teaching students the actual relevant manufacturing technologies available and learn a production suitable design of products is one central objective of the industrial engineering studies at the Graz University of Technology. Teaching sessions for students as well as industrial partners can be offered to increase “additive thinking”.

In company specific consulting projects, the University can offer its services to the industry partners to comprehensively add value through this technology.

5.1.3 Channels

There are several ways to communicate the services to the industry partners. Research contracts can be setup with the machine producer SLM Solutions to improve the processes of their machines as well as the metal powder.

Personal and public marketing are the two other channels that have to be used frequently to generate new potential business and research partners.

The heads of additive manufacturing interested institutes as well as students, who create projects for a bachelor or master thesis, are responsible for personal acquisition of research contracts and cooperation. Commonly the most effective way to create new projects and partnerships is personal contact. Additionally, manufacturing services need to be promoted publically as well.

The public television and print media should be informed as well a private people who might also be interested in manufacturing services. Websites and social networks can be used to spread the information. Conferences and additive manufacturing exhibitions in Europe are also common platforms for marketing.

5.1.4 Customer Relationships

Research cooperation’s like bachelor-, master- or PhD projects - which differ in the project time span and qualification of the student or scientific collaborator - are one common customer relationship model. In addition, research cooperation projects can be offered which have to be defined individually with the industry partners.

Manufacturing services including all the necessary pre- and post-processes will be provided at the Graz University of Technology. Therefore, detailed manufacturing quotations can be offered specifically to the local industry.

Interdisciplinary teaching and consulting projects for students and for industry partners can be offered by the universities staff.

5.1.5 Revenue Streams

Manufacturing services are offered in two distinct basic ways. Specific quotes for products according to detailed workshop drawings are placed by the machine operating institute. The Graz University of Technology thereby offers all necessary manufacturing technologies including heat treatment processes.

The second possibility is to buy additive manufacturing packages. In this case, only specific CAD design of the support structures and the laser melting process is created with fixed prices per building room according to the price structure mentioned below.

Research services are defined by the time and qualification of the researcher. A Bachelor Thesis commonly takes three months and costs 600 Euros while a Master Thesis takes six months and costs 3.000 Euros. For PhD and other projects usually no clear price is defined and each project needs to be considered separately. The price and time depends also on whether such a project is done internal at the Graz University of Technology or externally at the industry partner.

The teaching and consulting servic costs are defined by the type of staff needed. Payment for the specific staff required is regulated according to standard hourly wage rates. In addition, room costs and extra equipment could come to account depending on the type of teaching and consulting.

5.1.6 Key Resources

Key resource for the manufacturing service is a laser melting machine. Moreover, the existing conventional mechanical manufacturing equipment for milling, drilling, grinding, blasting as well as the heat treatment equipment will be required.

The metal powder, electricity, shield gas and compressed gas necessary for the production will be supplied by several partners. Metal powder from any producing company can be processed due to the open material properties of the SLM280 machine. The Argon or Nitrogen shield gas is usually supplied by Linde Liquide for other welding processes at the University.

The space to setup such a machine will be at the Institute of Production Engineering at the Graz University of Technology where several different departments will comprehensively research on the factory of the future.

5.1.7 Key Activities

There are four basic different activities regarding the additive manufacturing technology. Theoretical and practical research on industry relevant topics will be offered during Bachelor-, Master- , PhD- and individual projects.
Manufacturing services will be offered to industry partners including mechanical post processing and heat treatment.

Teaching sessions and consulting projects should help to spread the knowledge about this innovative technology to our students as well as the local industry. Teaching design including the new geometrical possibilities for students and industry partners will be a key factor for future success of this technology.

5.1.8 Key Partners

The key partners for research and manufacturing purposes will be SLM Solutions as the machine producing company and the metal powder producing companies Böhler and VoestAlpine. Metal powder can be supplied from those three companies. Another partner for the supply of the shield gas will be Linde Liquid.

The basic cooperating institutes at the Faculty of Mechanical Engineering and Business Economics will be the Institute of Production Engineering, the Institute of Industrial Management and Innovation Research, the Institute of Material Science and Welding and the Institute of Machine Components and Methods of Development. Thereby, interdisciplinary research and teaching at the highest level is guaranteed.

5.1.9 Cost Structure

The cost structure of the manufacturing services is explained in the following case to give an impression of the competitiveness of this business model compared to other manufacturing service providers.

Machine investment costs, material costs, processing costs, labour costs, production facility costs, and service costs need to be considered. To make a comparable calculation possible the production of six electronic pressure switches from Ventrex Automotive should be produced. Due to geometric dimensions the suspension node from Magna Steyr cannot be produced in the SLM280HL machine.

Additive manufacturing packages should be offered to the industry partners. That makes a calculation of the production price per building room necessary. The average processing time for one building room of 10 hours is assumed which is similar to the 50 hours processing time in a 500x500x500mm machine, as the following calculation shows.

$$\frac{270 * 270 * 350\,mm^3}{500 * 500 * 500\,mm^3} * 50\,hours = \mathbf{10,2}\ \frac{hours}{building\ room}$$

Equation 1: Processing timer per building room

Processing times strongly depend on the accuracy of the produced part, the layer thickness and processing laser power as well as other factors.[142]

The capacity utilisation on the machine, to gain productivity, is one driving factor. For this case 80% capacity utilisation at one shift per day which leads to the following calculation.

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[142] Generative Fertigungsverfahren. Additve Manufacturing und 3D Drucken, Gebhardt, page 414

$$250\,\frac{days}{year} * 8\,\frac{hours}{day} * 80\%\; utilisation = \mathbf{1600}\;\frac{hours}{year}$$

Equation 2: Processing hours per year

Considering 10 hours processing time, 160 building rooms can be processed per year with the assumed capacity utilisation.

Machine Investment Costs

The payback time for the machine investment costs is assumed with 5 years. Considering a laser melting machine with no additional equipment of 500.000 Euros leads to 625 Euros per building room.

$$\frac{500.000€}{5\; years\; payback * 160\,\frac{building\; rooms}{year}} = \mathbf{625}\;\frac{€}{building\; room}$$

Equation 3: Machine Investment costs per building room

Labour Costs

One person processing the machine with an average yearly salary of approximately 30.000 Euros[143] is assumed to calculate the labour costs for processing the machine.

$$\frac{30.000\; €/year}{160\; building\; rooms/year} = \mathbf{188}\;\frac{€}{building\; room}$$

Equation 4: Labour costs per building room

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[143] Kollektivvertrag Arbeiter Metallgewerbe, Lohngruppe 4, www.wko.at

Service Costs:

The annual service costs of 10.000 Euros[144] have to be taken into consideration as well.

$$\frac{10.000\ €/year}{160\ building\ rooms/year} = \mathbf{62}\frac{€}{building\ room}$$

Equation 5: Service costs per building room

Production Facility Costs

The costs for the production facility where the machine is setup with 8 m² minimum space[145] including rental costs and working expenses like heating, air conditioning and lightning, with 15 €/m² per month is further assumed.

$$\frac{8\,m^2 * 15\frac{€}{m^2} * 12\ months/year}{160\ building\ rooms/year} = \mathbf{9}\frac{€}{building\ room}$$

Equation 6: Production facility costs per building room

Operating Costs

The calculation of the operating costs which current electricity prices of 0,06 €/kWh[146] and nitrogen shield gas cost of 0,3 €/l[147] leads to the 46 € operating costs per building room. Shield gas is only needed during the welding process which amounts to 10% of the actual processing time.[148]

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[144] Generative Strahlschmelzanlage SLM280HL, Servicekosten

[145] Leitfaden: „Vorbereitung des Aufstellortes für den Aufbau/Betrieb einer SLM280HL

[146] Energie Graz Strompreise für Geschäftskunden, 1.4.2015

[147] Linde Liquide Preisliste Schweißgas Stickstoff

[148] SLM 280HL Produktbeschreibung, www.slm-solutions.com

$$8kW * 0{,}06\ \frac{€}{kWh} * 10h + 150\frac{l}{h} * 10h * 0{,}1 * \frac{0{,}3€}{l} = \mathbf{46}\frac{€}{building\ room}$$

Equation 7: Operating costs per building room

Production Costs per Building Room

$$625 + 188 + 62 + 9 + 46 = \mathbf{930}\ \frac{€}{building\ room}$$

Equation 8: Manufacturing costs per building room

Material Costs

The costs for the processed material AlSi10Mg is 75 €/kg.[149] One electronic pressure switch weights 428g[150], which leads to material costs of 32 €/part.

Production Price Comparison

The price for one building room, including six parts of Ventrex' electronic pressure switch, is € 7.092.- including taxes and profit margin at a undisclosed external additive manufacturing service provider. The quote from this specific manufacturer worked with a laser melting machine where six parts could be produced in one building room. (500x500x500 mm²)

Comparing this price with the five times smaller building room of this case calculation, would lead to a comparable price 5.580 Euros, considering that only one part can be produced in one building room. Material costs for the six parts have to be added which amounts another 192 Euros. A profit margin of 20% and taxes of other 20% lead to a total price of 8.312 Euros.

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[149] Laser melting material costs SLM-Solutions

[150] Datenblatt Electronic Presure Switch, Ventrex Automotive

The packing density, with its influence on the price development, was mentioned in the previous chapters. Considering that the external service provider achieved a 15% lower price for the production of six parts, with all parts produced in one building room, shows that the calculation is accurate.

6 Conclusion

Summarizing the result and major findings during this Master Thesis project leads to the following conclusions:

Additive manufacturing is an additional manufacturing technology and will not substitute conventional subtractive and formative production processes.[151] This is caused by the fact that subtractive post processes in metal processing additive manufacturing technologies are required to produce the afforded surface accuracy for functional parts. Besides, this technological argument, investigations showed that additive manufacturing cost for serial production cannot excel subtractive or formative technologies.

The relatively high costs for processing laser melting machine in-house and technological complexity to operate it effectively, is a barrier for companies today to give this new technology a chance in their existing manufacturing system.[152] Therefore, manufacturing service providers who are capable of the whole manufacturing process chain will be more important in the future. Companies can gain advantages through the outsourcing strategy such as increased flexibility, cost reduction, performance improvement and the ability to focus on the company specific core competences.[153]

Sustainable success can only be guaranteed through design changes of products according to the new technological advantages of the additive manufacturing technology. The added value to the product design must be recognized and appreciated by the customers.[154] Therefore, manufacturing suitable design and construction is the key to success. Airbus recently produces more than 1.000 parts of their A350 additively. That shows that especially lightweight construction can be performed on a better level with additive manufacturing.[155]

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[151] Generative Fertigungsverfahren, Auflage 3, Andreas Gebhardt, page 3
[152] Global Trends 2030: Alternative Worlds, National intelligence Council, page 91
[153] The Outsourcing Process: Strategies for Evaluation and Management, McIvor R., page 21
[154] Wirtschaftliche Fertigung mit Rapid-Technologien, Prof. Michael Zäh, page 124
[155] BBC Technology Report, By Dan Simmons, www.bbc.com (05/2015)

Additive manufacturing, and in this particular case the laser melting technology, can be a helpful innovative way to reduce costs in the prototyping phase especially when reducing tool costs of formative manufacturing processes. Future development of prototyping and testing phases lies in a virtual and computer simulated direction. Therefore, the future perspective for this kind of application seems not to be very promising.[156]

Research cooperations between universities and machine producers could bring advantages for both parties. Interdisciplinary research on additive manufacturing can be offered comprehensively, regarding automation and optimization of the manufacturing pre- and post-processes, material scientific research on metal powder and the welding process, design adaptation according to the new geometric possibilities and management aspects that have to be considered when introducing a new manufacturing technology. Furthermore, university activities as a manufacturing service provider are a potential to raise external funds. For machine producers, the industrial network of the university builds potential future market, because access to cost efficient and company specific research projects is available and their machine brand is part of lectures and practices for students.

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[156] 3D-Drucken “Wie die generative Fertigungstechnologie funktioniert“, by Petra Fastermann, page 67

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10 List of Tables

11 List of Equations

12 List of Abbreviations

ABS	Acrylonitrile Butadiene Styrene
AG	Stock Corporation
AM	Additive Manufacturing
BMC	Business Model Canvas
BR	Building Room
CAD	Computer Aided Design
CNC	Computer Numerical Controlled
CVD	Chemical Vapor Deposition
EOS	Economies of Scale
FDM	Fused Deposition Modelling
FLM	Fused Layer Manufacturing
GUT	Graz University of Technology
IBL	Institute for Industrial Management and Innovation Research
IFT	Institute for Production Engineering
LLM	Layer Laminated Manufacturing
LOM	Layer Object Manufacturing
NC	Numerically Controlled
OEM	Original Equipment Manufacturer
PHS	Print Head Systems
PJM	Poly Jet Modelling
PVD	Physical Vapor Deposition
STL	Stereo Lithography
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
SOP	Start of Production