TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

TOIMI TEELAHTI

IMPLEMENTING ADDITIVE MANUFACTURING IN MICROFACTORIES

M.Sc. Thesis

Examiners: professor Reijo Tuokko
and project manager Riku Heikkilä

Examiners and topic approved by the Faculty Council of the Faculty of Engineering Sciences on the 9th of April 2014

ABSTRACT

TAMPERE UNIVERSITY OF TECHNOLOGY
Master’s Degree Programme in Automation Technology
TEELAHTI, TOIMI: Implementing Additive manufacturing in microfactories
Master of Science Thesis, 64 pages
May 2014
Major: Factory Automation
Examiner: Professor Reijo Tuokko
Keywords: Microfactory, Additive manufacturing, 3D Printing, Solid Freeform Fabrication

This thesis presents two technologies with the potential to radically change the way we manufacture, design and recycle products in the future. The two technologies in question are additive manufacturing (also known as 3D printing, rapid prototyping, solid freeform manufacturing, and a variety of other names) and the microfactory concept. In this work, the technological basis for both these technologies and their status in industrial manufacturing is briefly examined.

The aim of the microfactory concept can be described simply: to miniaturize production equipment to roughly the same size as the product. This reduces the energy consumption and factory floor space of the production process. The benefits of the concept also include faster setup times and improved usability. On the other hand, some barriers also exist, these being mainly the lack of examples and components. TUT’s Department of Production Engineering has been active in the field, demonstrating a modular microfactory concept suitable for a variety of cases.

Additive manufacturing, or 3d printing as it is more commonly known, refers to a group of technologies which allow fabricating parts layer-by-layer, eliminating the need for subtractive shaping of the parts. A CAD model is “sliced” so that each cross-sectional slice equals one layer of the part built by the additive manufacturing machine. This allows producing parts with geometries impossible to manufacture using traditional methods, e.g. a sphere within a sphere. In practice, two types of additive manufacturing are happening currently: industrial production, characterized by expensive machines, materials and parts and low volumes, and peer production, in which consumers are purchasing or building their own low-cost machines and producing customized products at home.

Some synergies and potential applications for combining the concepts have been found. Additionally, some technical concepts were developed and presented in the thesis. Finally, the validity of these ideas is briefly discussed in the conclusion of the thesis.

TIIVISTELMÄ

TAMPEREEN TEKNILLINEN YLIOPISTO
Automaatiotekniikan koulutusohjelma
TEELAHTI, TOIMI: Ainetta lisäävän valmistuksen toteuttaminen mikrotehtaassa
Diplomityö, 64 sivua
Toukokuu 2014
Pääaine: Factory Automation
Tarkastaja: professori Reijo Tuokko
Avainsanat: Ainetta lisäävä valmistaminen, 3D-tulostus, Mikrotehtaat

Tämän diplomityön tarkoituksena on selvittää, miten mikrotehtaisiin voitaisiin integroida ainetta lisäävä valmistus eli 3D-tulostaminen. Kyseessä on siis kaksi tuotantotekniikan tulevaisuuden konseptia, jotka saattavat muuttaa radikaalisti tuotteiden suunnittelua, valmistusta ja kierrättämistä. Diplomityössä esitellään kummankin konseptin teoreettinen tausta ja lähtökohdat.

Mikrotehdas-konseptin johtoajatus on yksinkertainen: tuotantovälineitä pienennetään niin, että ne ovat samaa kokoluokkaa tuotteiden kanssa. Tämä vähentää tilantarvetta sekä energiankulutusta. Lisäksi asetusajat pienenevät ja käytettävyys helpottuu. Haasteita konseptin leviämiselle ovat muun muassa soveltuvien komponenttien vähäisyys sekä teollisten toteutusten puute. TTY:n Tuotantotekniikan laitoksella on tehty mikrotehdas-tutkimusta aktiivisesti ja useita käytännön demonstraatioita on saatu toteutettua.

Ainetta lisäävä valmistus (tunnetaan myös nimillä pikavalmistus ja 3d-tulostaminen) käsittää joukon teknologioita jotka mahdollistavat tuotteen tai osan valmistamisen kerroksittain. Tällöin valmistuksessa ei useinkaan tarvita ainetta poistavia menetelmiä. Käytännössä tuotteen CAD-malli ”viipaloidaan” siten että mallin viipaleet (poikkileikkaukset) ovat koneessa muodostuvia kerroksia. Tämä mahdollistaa mm. vaikeiden geometrioiden tulostamisen suoraan, esimerkiksi pallo pallon sisällä on mahdollinen. Tällä hetkellä on tapahtumassa kahdentyyppistä 3D-tulostusta, joita kumpaakin esitellään työssä. Perinteisessä teollisessa valmistuksessa käytetään kalliita koneita ja materiaaleja tuottamaan pieniä sarjoja lopputuotteita. Uusi ilmiö on kotikäyttäjien harrastuspohjainen tulostustoiminta, jossa koneet ovat alle tuhannen euron hintaluokassa.

Analyysin jälkeen mahdollisia sovelluksia kehitettiin osana diplomityöprosessia. Sovellukset on esitelty lyhyesti osana TTY:n mikrotehdaskonseptia. Tähän liittyen mahdollisia käyttökohteita on myös ajateltu. Työn lopussa käsitellään sovellusten toteuttamiskelpoisuutta ja alaa yleisesti.

PREFACE

I would like to thank Professor Reijo Tuokko and Riku Heikkilä for their guidance, advice and patience during the thesis process. Fernando Garcia, Ville Hautala, Ville Hämäläinen, Matias Koskela and Timo Prusi also kindly offered their comments prior to publication, for which I am very grateful. All errors and omissions are naturally my responsibility.

For several years during my studies I had the privilege of working at the Department of Production Engineering. The wholehearted support and advice I received were instrumental in my education as an engineer and indeed, as a person. I would like to take this opportunity to thank all past and present staff of the department for their kindness and encouragement. I would also like to thank the Yrjö and Senja Koivunen Foundation for their generous stipend.

Last but not least I thank my colleagues, friends and family for their continuing support, understanding and advice throughout my studies. It has been a long journey, but it was made shorter by our shared laughter, tears, and camaraderie.

Tampere 24.4.2014

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TERMS AND DEFINITIONS

3D printing	See chapter 3.
ABS	Acrylonitrile Butadiene Styrene, a thermoplastic polymer. Suitable for extrusion. *(Chapter 3.3.3)*
AM	Additive Manufacturing *(Chapter 3)*
ASTM	American Society for Testing and Materials
CAD	Computer-Aided Design
CAM	Computer-Aided Manufacturing
CNC	Computer Numerical Control, i.e. machine tools controlled by computers
DOF	Degree of freedom, i.e. how many (physical) parameters define a system’s configuration.
DLP	Digital light processing. Uses micro-sized mirrors to create an image.
FDM	Fused Deposition Modeling, a extrusion-based process commercialized by Stratasys Inc. *(Chapter 3.3.3)*
FFF	Fused Filament Fabrication. Synonymous with FDM. *(Chapter 3.3.3)*
G-Code	A numerical control (NC) programming language
LOM	Laminated Object Manufacturing, a sheet lamination process. *(Chapter 3.3.5)*
MCAD	Mechanical Computer-Aided Design
MEMS	Microelectromechanical systems. Made up of components between 0.001 and 0.1 mm in size. Example product: an accelerometer.
PCL	Polycaprolactone, a biodegradable polyester suitable for extrusion. *(Chapter 3.3.3)*

PLA	Polylactic acid, a thermoplastic polymer suitable for extrusion. *(Chapter 3.3.3)*
PLGA	Poly(lactic *co*-glycolic acid), a biodegradable and biocompatible copolymer suitable for medical applications *(Chapter 3.4.2)*
PLLA	Poly-l-lactide, a form of polylactic acid. *(Chapter 3.4.2)*
ROI	Return on investment. The net profit generated divided by the size of the invested capital.
SL or SLA	Stereolithography, a photopolymerization process commercialized by 3D Systems Inc. *(Chapter 3.3.1)*
SLS	Selective Laser Sintering, a powder bed fusion technology trademarked by 3D Systems Inc. *(Chapter 3.3.2)*
STL	Stereolithography file format, used in additive manufacturing.
Thingiverse	Website which offers community-contributed CAD models for 3D printing
TUT	Tampere University of Technology

1 INTRODUCTION

This thesis represents a confluence between two technologies which are rapidly becoming disruptive technologies, not only in the manufacturing industry, but also in everyday life. The two technologies in question are, of course, additive manufacturing (also known as 3D printing) and microfactories (also known as desktop manufacturing). Both concepts have been developed in academia and industry for more than two decades now and there have been some see exciting breakthroughs as well as a rise in viable commercial solutions.

The aim of this thesis is to attempt to illustrate some current and future possibilities of new products, production systems and processes. These possibilities are realized by combining the microfactory and additive manufacturing concepts. There are some synergies between the concepts, most notably in the typical product and machine sizes. To leverage these synergies requires in-depth knowledge, comprehensive understanding of ongoing trends and additionally some insight into future opportunities and challenges. The structure of this thesis has been adopted from the practice of technology forecasting (based on Roper et al., 2011). In practice, this means that the thesis has been divided into three stages (also known as "cold, warm and hot"). This has been illustrated below in figure 1.1:

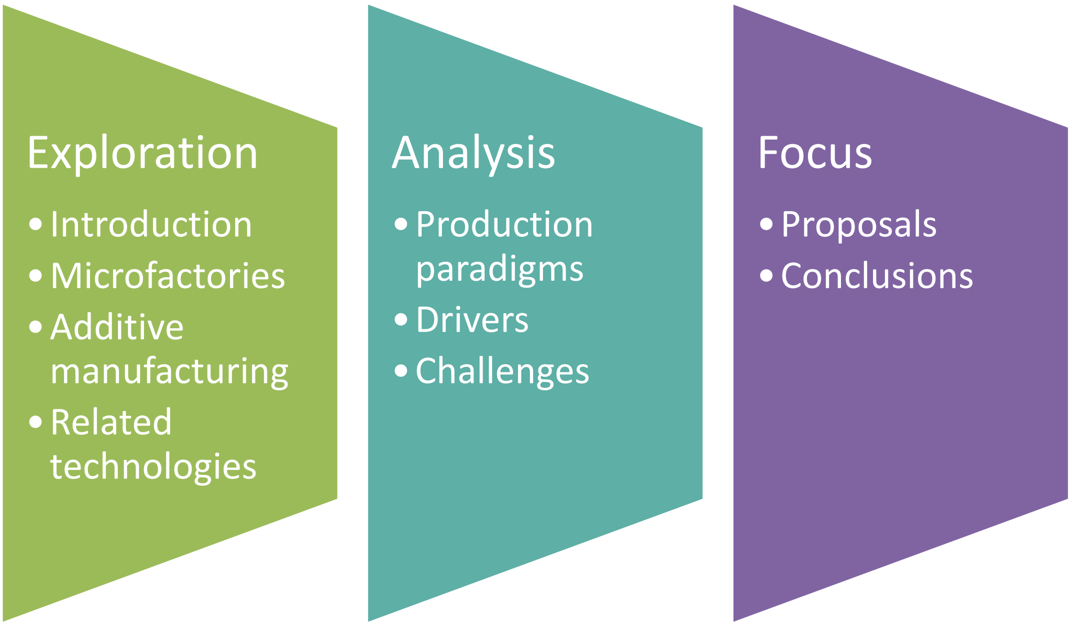

***Figure 1.1**. Content of the thesis.*

The first stage is exploration (i.e. surveying the current applications, drivers and barriers of the technology). As astutely stated by Roper et al. (2011), “the broader the sweep, the shallower the depth”. This means that exploring widely in the context of a technology always leads to a less in-depth understanding of the issues involved. This is not always a negative issue, but one must keep in mind the risks of overly broad surveying. In this thesis, defining the width has been done in the “scope of the thesis” subchapter.

The second phase, analysis, can be characterized as selecting the most promising development areas, based on the groundwork laid in the exploration phase. Selection is done based on a) qualitative data, such as expert opinions, and b) quantitative extrapolation methods, such as trend analysis. In practice, the analytical section (i.e. chapter 5) of this thesis consists of qualitative analysis of the various market areas. To maintain a wide viewpoint, several related technologies and projects are defined and analysed, the motivation being that breakthrough products (or technologies) are seldom one-dimensional. In essence, the analysis phase functions as a bridge between the exploration of the first phase and the concrete proposals of the third phase.

The third phase is focusing, where in the forecast is narrowed to focus on the most promising areas as selected in the analysis phase. In this thesis, the focusing phase has been realized as some microfactory module concepts. Due to time and budget constraints, there it was not possible to test or validate these proposals during the thesis process. Future developments will show the success of the predictions.

1.1 Background

In the modern production paradigm, manufacturers face a variety of challenges. The changing landscape of our society as we enter a digital age forces companies to adopt new methods and strategies in order to remain competitive. For example, lead times of new products must be shorter today than previously in order to challenge other products.

Okazaki (2010) states: “manufacturing is one of the most creative of human activities, and a delightful and supportive side of life”. He goes on to say that previously, manufacturing has been more closely related to customers’ needs. While mass production is a cost-effective option for producing high-quality products, Okazaki states that products which are not compatible with mass production are neglected. Even though end-users are not involved with manufacturing, they still want product variation or customized products.

Jovane et al. (2003) have listed the production paradigms of the industrial age (shown in Table 1). The production paradigm which answers the evident need for customization and variation in products is mass customisation. However, to reduce the environmental impact of industrial production, Jovane et al. envision “sustainable production” to be a viable paradigm in the future.

***Table 1.1**. Production paradigms (Jovane et al. 2003).*

Paradigm	**Craft production**	**Mass production**	**Flexible production**	**Mass customisation**	**Sustainable production**
Paradigm started	~1850	1913	~1980	2000	2020?
Society needs	Customised products	Low cost products	Variety of products	Customised products	Clean products
Market	Very small volume per product	Demand > Supply Steady demand	Supply > Demand Smaller volume per product	Globalization Fluctuating demand	Environment
Business model	Pull *sell-design-make-assemble*	Push *design-make-assemble-sell*	Push-Pull *design-make-sell-assemble*	Pull *design-sell-make-assemble*	Pull *design for environment-sell-make-assemble*
Technology enabler	Electricity	Interchangeable parts	Computers	Information Technology	Nano/Bio/ Material Technology
Process enabler	Machine Tools	Moving Assembly Line & Dedicated Machining line	Flexible Manufacturing System Robots	Re-configurable Manufacturing system	Increasing Manufacturing

Jovane et al. (2003) also explain that although the Western world has entered the era of mass customisation, the internal Chinese market had only recently adopted mass production at the time of writing. This is an example of paradigms being able to coexist, which is also stated explicitly by the authors.

Fox and Stucker (2009) present the idea of “digiproneurship”. The authors explain that they use the term to differentiate the distributed ideation, propagation and creation of physical products from digital entrepreneurship (which concerns digital content). In the digiproneurship concept, digital technology enables the product development and additive manufacturing (with other, suitable technologies) allows production. Products are distributed digitally and realized near the customer, either by the customer personally or by businesses. The digiproneurship concept shows that the gap between personal production and industrial manufacturing is “scalable”: this means that future production will encompass all product design and manufacturing modalities. For example, an end-user can download product designs for free from the internet, modify them, upload them (for others to use), and produce them either at home, at the local hardware store, at the local machine shop, or in a factory on another continent.

1.2 Research objective

The main objective of the thesis is, broadly speaking, to gain both personal and institutional knowledge of the various commercially available additive manufacturing processes for future implementation in microfactories. A key theme during the thesis process was finding suitable reasons to implement additive manufacturing in microfactories. In the author's opinion, the fact that the implementation is possible from a technical standpoint is not enough motivation. The research questions are stated below:

RQ1: What is the current state of both microfactory and additive manufacturing technology?

RQ2: What are the motivations and benefits of integrating additive manufacturing into microfactories?

RQ3: Which additive manufacturing technologies are suitable for implementation in a microfactory?

In addition, some designs are presented for future implementations.

1.3 Scope and structure of the thesis

From the very beginning it was obvious that the collective academic and industrial knowledge concerning additive manufacturing and microfactories was so vast that even obtaining a basic understanding would take up the majority of the thesis; thus, no practical work was included in the scope of the thesis process. In addition, some micro-scale and medical concepts are so theoretically complex (and far from industrial in nature) that they have also been excluded. The various exclusions have been noted in the text at the appropriate points.

Another scope-related issue is the products and production systems being considered. Obviously, while there is pressure to manufacture customized products, some products will never be suitable for customization. In the thesis, the term "product" is mainly used to describe a small-sized, relatively low-volume, hopefully high value-adding product.

The structure of the thesis is as follows: chapter 2 reviews the microfactory concept with special emphasis on the work done at TUT's Department of Production Engineering. chapter 3 discusses additive manufacturing, at first in a general sense, but the latter sections concentrate on the individual technologies in detail. chapter 4 enumerates the benefits and challenges for additive manufacturing and microfactories. Chapter 5 consists of technical analysis and some implementation examples. Some proposals for future research and commercialization are presented in chapter 6, with the conclusions forming chapter 7.

2 THE MICROFACTORY CONCEPT

This chapter introduces the microfactory concept, the current state of microfactory research and commercialization and the commonly accepted drivers and challenges in the microfactory field. The first section introduces the various types of academic microfactory, using the four categories found in Nurmi (2011). An example is presented from each of these categories. In the following section, the TUT microfactory concept is presented in a more detailed manner to provide the reader with understanding of the research done at the Department of Production Engineering. Finally, the concept's advantages and disadvantages are listed and some potential applications are presented.

2.1 Background

The basis for the microfactory concept is simple; production machines should be roughly the same size as the products they produce. Thus, for many products, e.g. mobile phones, the machinery size would be about the size of a microwave oven. The motivations for the concept in production are lower physical footprint for machines, reducing energy use and resource utilization. Challenges include the relative newness of the concept, which means that there is a distinct lack of suitable components and examples for industrial actors.

Nurmi (2012) lists four distinct types of microfactories developed in academia: a) the "traditional microfactory" consisting of fixed small-size machines, b) miniaturized machining devices such as microlathes, c) modular microfactory concepts (such as the TUT microfactory) and finally d) miniaturized assembly cells (often incorporating robots). To illustrate the differences between these concepts, a typical example of each is presented.

Tanaka (2001) presents a microfactory consisting of a microlathe, a milling machine, a press machine and assembly machines (a small manipulator and gripper). This device is shown in figure 2.1. The factory dimensions are only 625 x 490 x 380mm (LxWxH) and it weighs 34 kg. The factory fits in a suitcase. As can be seen in the figure below, the operator uses one device at a time using the two joysticks and one pushbutton. Device selection is done via the user interface by the operator. The case product was a miniature ball bearing assembly with a 900 μm diameter and 3mm shaft length.

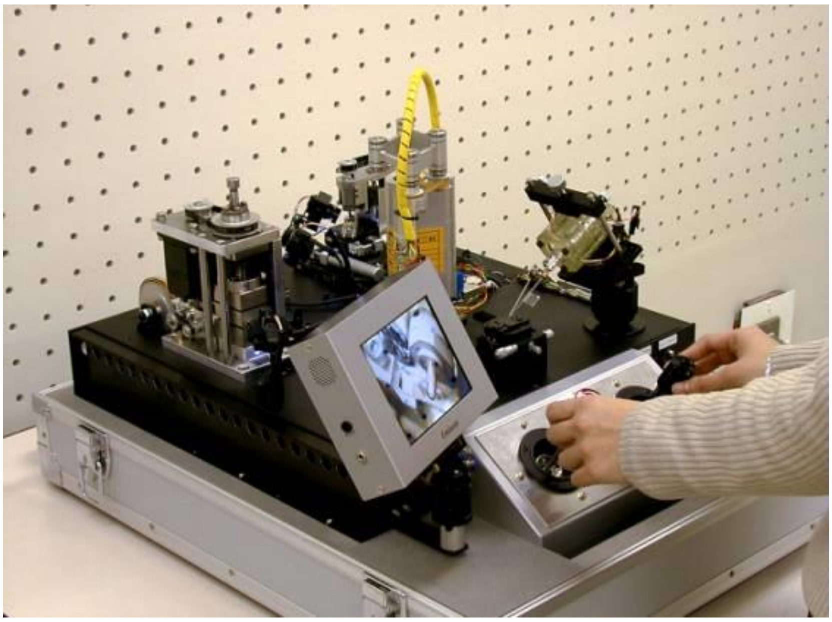

Figure 2.1. *The AIST MITI microfactory (Tanaka, 2001).*

An example of a miniaturized machining device (figure 2.2) is the Desk-Top Milling machine by Okazaki et al. (2001). Nicknamed “El Chuchito” because it looks like a Mexican church, the machine dimensions are 450 x 300 x 380 mm (W x L x H). The spindle is a high frequency AC motor with 60W rated power. The spindle’s maximum rotation speed is 200000 rpm. The machine was successfully tested on hard aluminium alloy and pre-hardened steel.

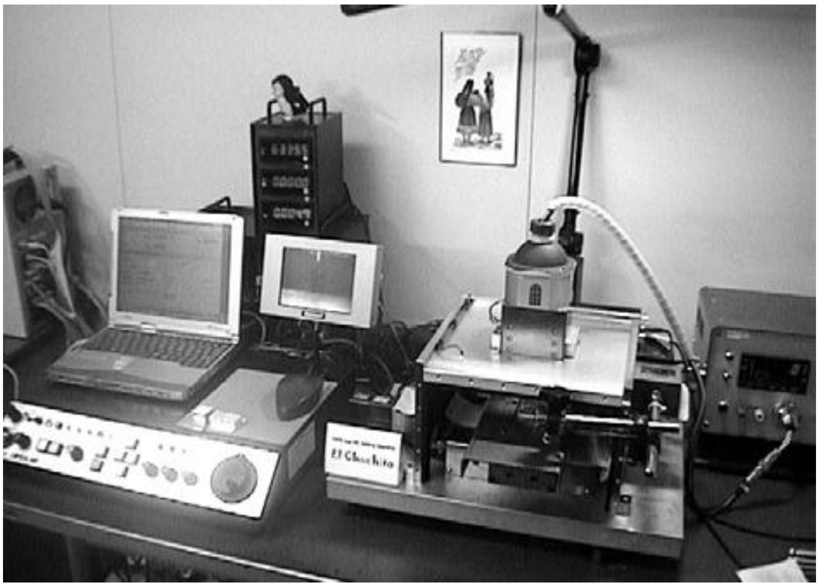

Figure 2.2. *“El Chuchito” Desk-Top NC Milling machine (Okazaki et al., 2001).*

An example of a modular microfactory concept is the Pocket-Factory (figure 2.3), developed by Verettas et al. (2006) at EPFL (Ecole Polytechnique Fédérale de Lausanne). The motivation was reducing the size of the cleanroom environment. The prototype system developed can use MEMS industry standard trays (50 x 50 mm). A goal of the project was to have high modularity in the system, and therefore a modular structure was adopted. The production system consists of individual cells called "microboxes". Verettas et al. (2006) state that the size of the microbox is adapted to the size of the product being assembled. The prototype system shown below has a usable volume of about 1 dm^3 .

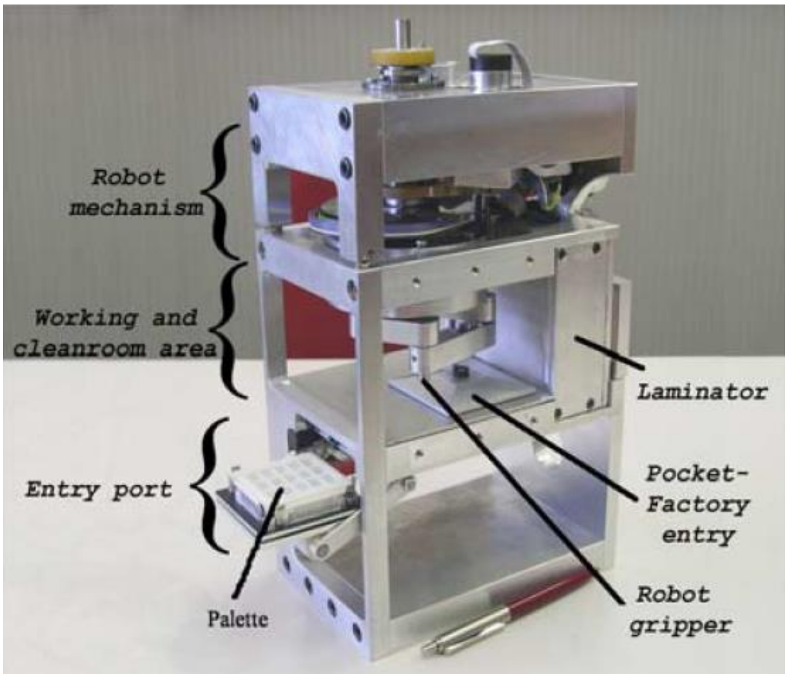

Figure 2.3. *A Pocket-Factory microbox (Verettas et al. 2006, annotations from source).*

Figure 2.4 shows an example of a miniaturized robotic system (used for assembly). The Delta Ibis robot was developed by Bouri & Clavel (2010), also from EPFL. The robot structure is parallel (i.e. the kinematic chain is closed). The robot has 2 trapezoidal screws acting as linear translations and one rotational joint. The robot payload is 250 g and the workspace is 120 x 60 x 50mm (XYZ).

Figure 2.4. *The Delta Ibis robot (Bouri & Clavel,2010).*

Commercial use of microfactories has been limited to date. Nurmi (2012) listed some European companies in the field, many of which are the result of commercialized academic research (Asyril in France, IEF Werner in Germany). In Finland, active companies in the field include MAG (Master Automation Group, which has merged with JOT Automation), Sartorius Biohit and Wegera. The MAG products targeted telecommunications applications while Sartorius Biohit is active in the laboratory liquid handling sector. Wegera are a subcontractor specializing in metal products with small lot sizes and physical dimensions. The company has developed the "Kolibri", a small-sized (roughly 50 x 50 x 100cm) 5-axis CNC machining unit. The machine is intended for subcontracting, prototyping and education. (Nurmi, 2012).

2.2 The TUT Microfactory

There have been eight microfactory-related projects at TUT from 2000 to 2014. The thrust of the research has been towards modular microfactories, resulting in the TUT microfactory (also known as the TUT µ-factory). The microfactory is shown in figure 2.5:

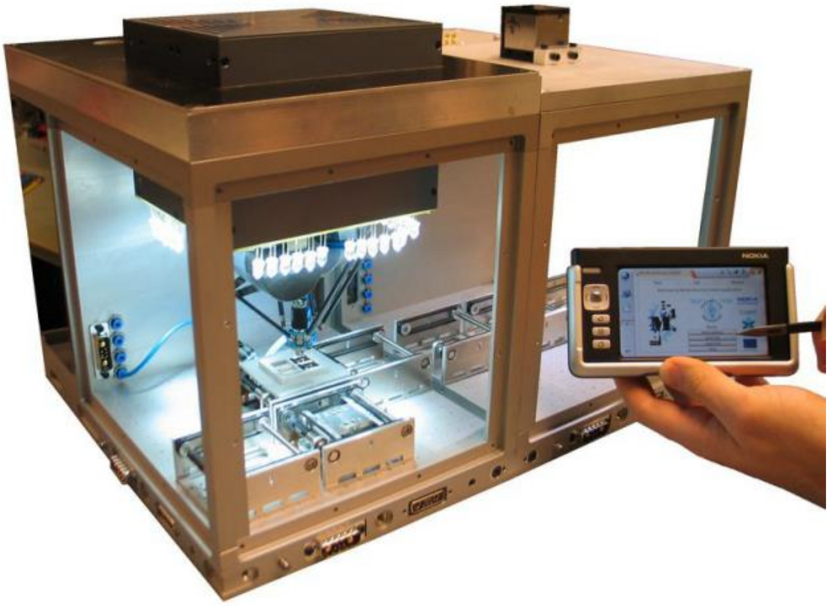

Figure 2.5. *A microfactory consisting of two TUT microfactory modules. The tablet PC is used as a user interface (Heikkilä et al.2010).*

The TUT microfactory consists of individual base modules (also called production modules). The outer dimensions of a single base module are 200 x 300 x 230 mm (W x D x L). The work space available inside the module is 180 x 180 x 180 mm. There is a segregated space behind the work space for the control PC and electronics. Additional process modules are placed on top of the production module to implement the desired functionality. The process module is shown in figure 2.6. (Heikkilä et al., 2010).

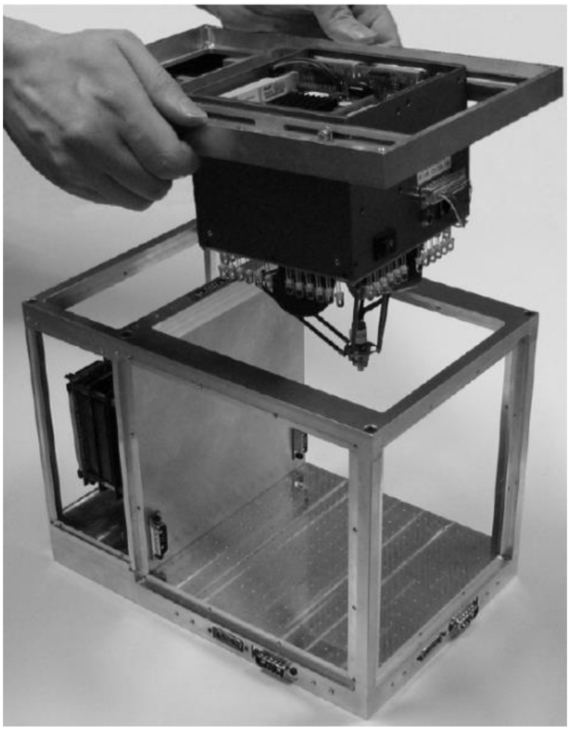

Figure 2.6. *A Pocket Delta robot process module and the base module (Heikkilä et al. 2007).*

The modularity of the system is realized by the interfaces in the bottom part of the base module. The interface between two neighboring modules consists of: two electronics connectors, pneumatic connectors (for air and vacuum) and a physical interlock. The interfaces allow a line layout with branches (loops are possible under certain conditions). Additionally, interfaces are also provided in the Y-direction, allowing modules to be placed on top of each other. Products can be transported through the system in three different ways: on pallets, on conveyors or “on air”. The “on air” option means that there is a manipulator capable of handling the part in each module. The part is then passed from one module from another. (Siltala et al. 2010a).

Heikkilä et al. (2010) state that there are several ways to feed parts. These include tray feeding, tape-and-reel feeding, bowl feeding and machine vision-based flexible feeding. The authors state that the most desirable methods for miniaturized products are tray feeding and flexible feeding. Tray feeding means that the parts are palletized on trays. Drawbacks of this approach include the space required by the trays (in storage and in production environments) and the fact that palletizing is a non-value adding activity. Flexible feeding allows feeding the parts directly into the assembly cells without palletizing. This is achieved by feeding the parts onto a well-lit conveyor and using a machine vision system to determine the parts’ location and orientation.

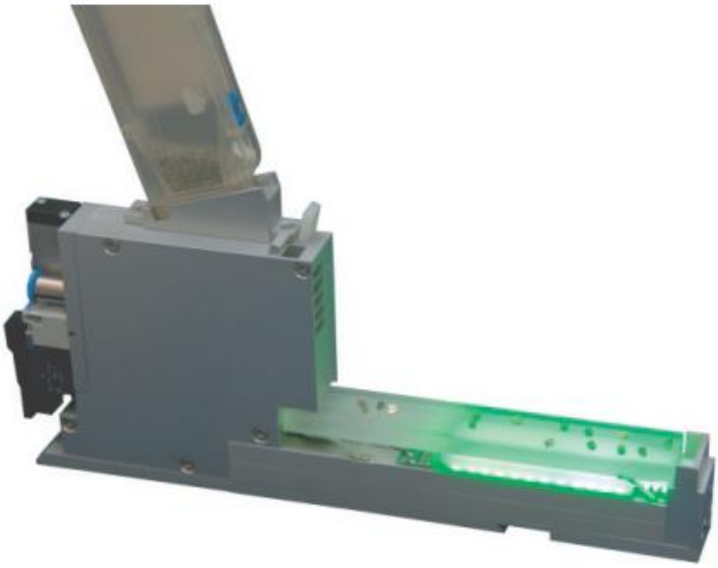

Figure 2.7. *The Wisematic minifeeder: A flexible part feeder (Heikkilä et al. 2010).*

An important research area at TUT has been miniaturized robotics for part handling. Developed robot concepts for the TUT microfactory include an H-belt robot (Vuola et al. 2010) and an H-SCARA robot (Siltala et al. 2010b). The robot is a 4-DOF (degrees of freedom) parallel kinematic manipulator. Two parallel kinematic structures are used, one vertically (the H-structure) and one horizontally (the parallel SCARA structure). The work envelope of the robot is roughly 400 x 160 x 130 mm (W x L x H). The width of the work envelope has been designed so that the robot can reach into adjacent microfactory cells, as shown in figure 2.8 below.

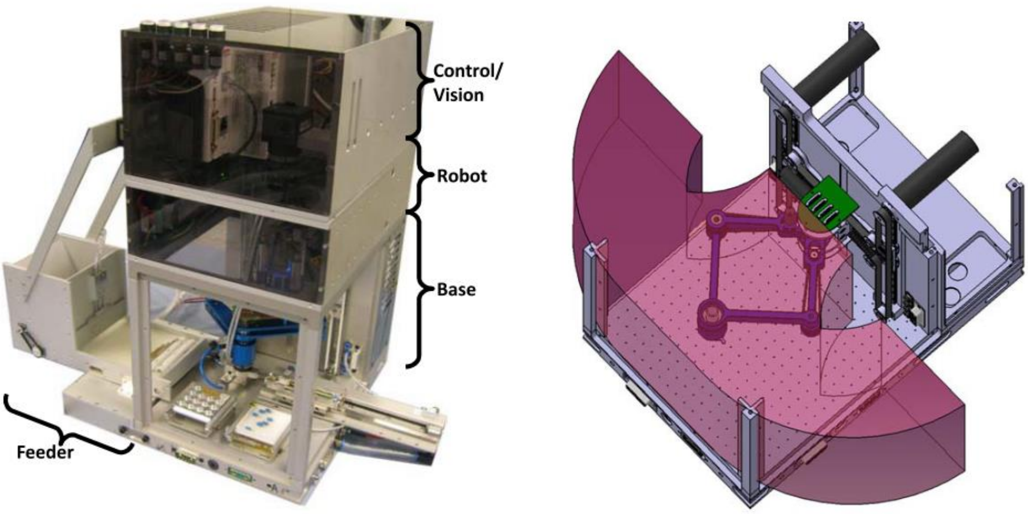

***Figure 2.8**. Left: The H-Scara robot with a feeder and case product.*
Right: The robot work envelope (Siltala et al. 2010b)

As part of the microfactory projects, several applications have been successfully demonstrated. These include an assembly cell for mobile phone loudspeakers (Heikkilä et al., 2007), a laser marking microfactory (Heikkilä et al., 2010), a modular conveyor system for microfactories (Heikkilä et al., 2010), a microfactory system for personalized hearing aids (Heikkilä et al., 2008) and a microfactory system for inserting a spring in a component (Heikkilä et al., 2010).

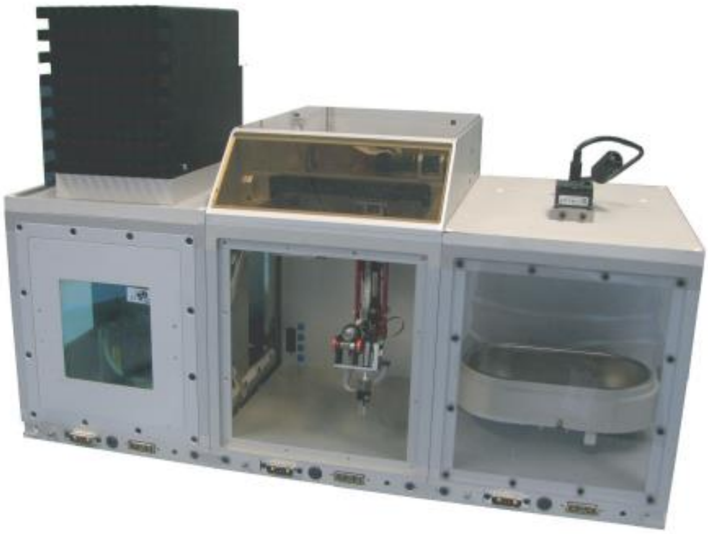

Figure 2.9. *Microfactory system for personalized hearing aids. (Heikkilä et al., 2008).*

There are several benefits of a modular microfactory structure (exemplified by the TUT microfactory) as opposed to a rigid structure with fixed tools and capabilities. Naskali et al. (2012) have developed a bi-level modular microfactory. Bi-level modularity means in this context that different process modules are used to form the production process and that these modules are formed by combining submodules, which can be changed as required. Figure 2.10 shows a robotic assembly module consisting of submodules.

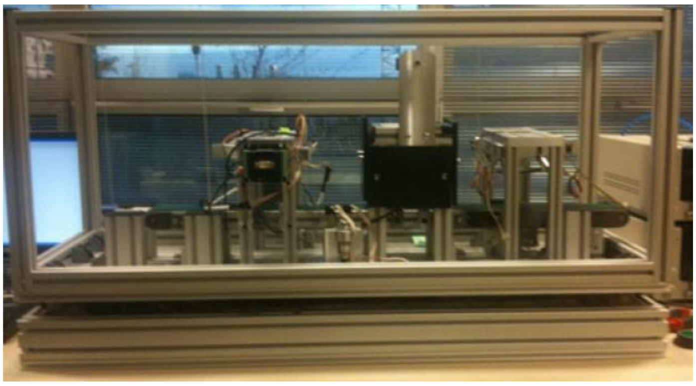

Figure 2.10. *Bi-level modular microfactory concept:*
Robotic process module(Naskali et al. 2012).

Naskali et al. (2012) state that modularity in microfactories is an important design criteria, which enhances the reconfigurability of the production system. Ease of reconfiguring is a major advantage that microfactories have over conventional systems, as the reconfiguring seldom requires heavy equipment.

2.3 Advantages and disadvantages of the microfactory concept

As stated in section 2.1, there are several compelling reasons for utilizing microfactories in production. The key motivations include the space, energy and material savings inherent in small-sized production equipment. Human factors such as ergonomics and usability also play a role as does the overall safety of the production process. Microfactories can also help reduce safety costs, for example it is much less expensive to implement a microfactory-sized cleanroom than an entire room. Table 2.1. lists some potential advantages of microfactories.

***Table 2.1**. Expected advantages from microfactory use. Compiled from Okazaki et al. (2004).*

Environmental	Economic	Technical	Human-related
• Saving energy, material • Reduced vibration and noise	• Reduced need for capital investment • Reduced running costs • Efficient utilization of space • Improved portability • Agile reconfigurability • Ubiquitous manufacturing	• Higher speed (because of reduced inertia) • Improved precision • Increased productivity • Piece-by-piece process (WIP reduced) • Shortened ramp-up • User-oriented machine design	• Machines are physically and mentally less stressful to operate • Machines can be used in educational and hobby fields

Some often-overlooked advantages envisioned by Okazaki et al. (2004) include (in the author’s opinion) ubiquitous manufacturing, the educational and hobby use of microfactories and the fact that it is less stressful for a human to operate small-sized machinery. It must be noted that these are clearly secondary to the important economic and technical considerations. The possibility of end-user microfactories is a recurring theme in the thesis and will be returned to throughout the text, whereas ubiquitous manufacturing (which is very similar to “Digiproneurship” introduced by Fox & Stucker(2009).

Nurmi (2012) identified some challenges for microfactories based on research and interviews from both industry and academic practitioners. These include the lack of examples, lack of suitable components, the attitude of production engineers and that cleanroom standards do not yet support local cleanrooms. Codourey et al. (2006)

elaborate on the reasons behind the lack of suitable components, stating (in the case of motors) that small motors often have high rotational speed and small torque, when the opposite is required for microfactory applications. Also, because the motors are quite large physically compared to the rest of the factory, parallel structures must be adopted for robots (i.e. the motor is stationary).

3 ADDITIVE MANUFACTURING

The aim of this chapter is to concisely explain the concept, execution and current possibilities of additive manufacturing. A generalized overview of the AM process is outlined and some critical phases of this process are elaborated upon. Next the main commercial technologies are explained and their various advantages, disadvantages etc. are illustrated. After this, an overview of suitable current applications for AM is presented. Finally the chapter concludes with analysis of the advantages and disadvantages inherent in additive manufacturing.

3.1 Introduction

The term “additive manufacturing” by itself is fairly new. Previously the term “Rapid Prototyping” was widely used to describe the various technologies, however, some of these have graduated from mere prototyping to several different industrial uses. Usually, professionals use the name of the technology (such as FDM, fused deposition modelling) while end-users might even use the name of the machine. This confusion of terms is why the American Society for Testing and Materials (ASTM) technical committee has recommended using the term “additive manufacturing”. Synonyms include “additive fabrication”, “additive processes”, “additive layer manufacturing” and “solid freeform fabrication”, among others. Wohlers (2012) states that, due to widespread usage by three influential groups (i.e. the mainstream press, the computer-aided design (CAD) industry and the investment community) the term “3D Printing” has become the standard term. Figure 3.1. shows how a part is obtained from the CAD file:

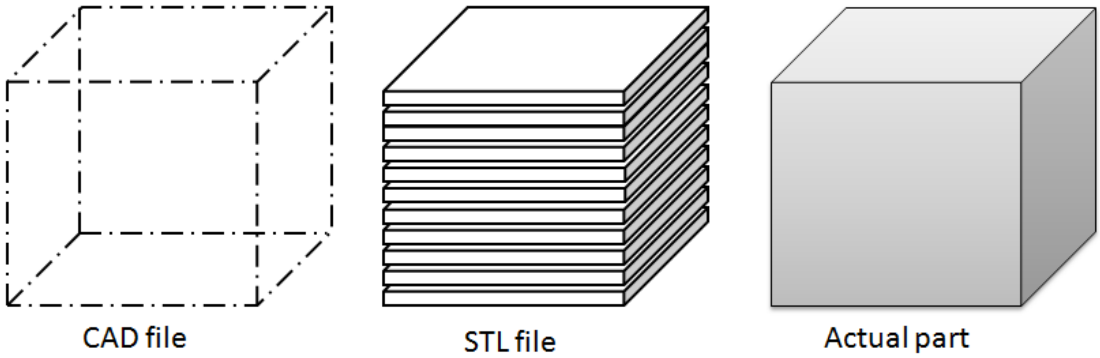

Figure 3.1. *From the CAD file to the actual part.*

The core concept of additive manufacturing is the following: products are made by adding layer upon layer of material. The layers are the cross-section of the product at given heights (obtained from the CAD model). So, in essence, the model is "sliced" into layers of a certain thickness which the additive manufacturing machine, using any of several technologies, then produces. After this the finished part is removed from the machine, post-processed (depending on the manufacturing process and intended application), and is finally ready for use. This generalized process is presented in Figure 3.2:

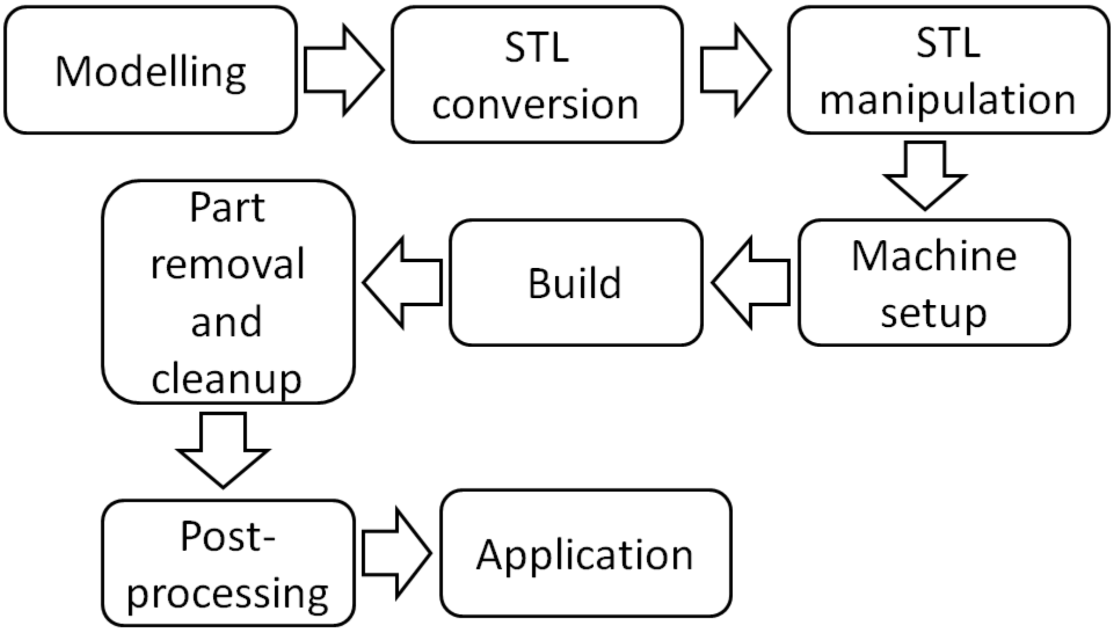

***Figure 3.2**. Generalized AM process chain (Gibson et al. 2010)*

Of these eight distinct steps in this sequence, we see that the first three (the top row in the figure above) mainly concern the CAD and STL model and are thus independent of the AM technology being used (with some exceptions). These steps will be explained in further detail in the next subchapter along with post-processing. The "build" step (i.e. the actual production of the part) is so technology-dependent that it will be covered in subchapter 3.3 "Additive manufacturing technologies".

3.2 Front- and back-end processes

This subchapter presents the non-building steps required in AM in two parts; preproduction and postproduction. Any manufacturing process begins with conceptualization. This means visualizing the intended final outcome of the production process. When using additive manufacturing, this intention is ultimately formalized as a computer-aided design (CAD) file which represents the product in a digital sense. As stated by Gibson et al. (2010), there are several ways that this CAD file might be generated: by a product designer using CAD software, by a simplified user interface, or by using reverse-engineering technology.

The operating principles and science surrounding CAD modelling are very much outside the scope of the thesis; however, a brief overview can be presented. The basic concept is representing 3D objects in a digital file format, which can be then modified, transmitted, or transferred into various production systems accordingly. Three-dimensional models are commonly created by first specifying a cross-section (in 2D), which is then extended (extruded) into 3D using user-specified parameters. Additional operations can be done afterwards, e.g. rounding the corners of the part or drilling holes in it. Currently, when using parametric CAD software, the designer can easily change the size and quantity of features in the product without having to radically change the model. The most popular mechanical CAD (MCAD) software products in use are, in order of popularity: Autodesk Inventor (Autodesk), Solidworks and CATIA (both by Dassault Systèmes) and ProEngineer (currently called Creo) from PTC. (Gibson et al., 2010, Wohlers, 2012).

The 3D data required in AM can also be generated using alternative means. The most common is called 3D scanning and it involves using a depth camera to obtain a point cloud from the scanned part. This data is then interpolated into surface data allowing use in AM processes. Tong et al. (2012) state that two main technologies exist for depth cameras currently: a) using the time-of-flight principle, in which the time delay of transmissions of a light pulse are measured, or b) light coding, wherein a specific, known pattern is projected onto the scene and the pattern deformation is analyzed to obtain the depth data. For example, the Microsoft Kinect uses a grid infrared pattern.

To be able to print a CAD model, the model must be converted to the STL file format. The conversion process approximates curved surfaces using tessellation, i.e. using triangular planar faces to generate an approximation of the model. An approximation of tessellation is shown in figure 3.3. The STL file is merely a representation of these planar surfaces, to actually build the part the STL file must be sliced into layers for the additive manufacturing process and appropriate CAM paths must be generated (e.g. g-code or similar). (Jamieson & Hacker, 1995).

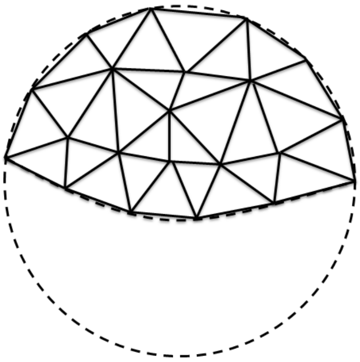

Figure 3.3. *Tessellating a spherical surface (Jamieson & Hacker, 1995).*

Post-processing is very dependent on the material and additive manufacturing process being used. Some processes require very little post-processing, while others require cleaning, post-curing and/or finishing the part along with the removal of extraneous material and supports. Obviously the degree of post-processing done to any given part is heavily dependent on the application. (Chua et al. 2010, Gibson et al. 2010)

3.3 Additive manufacturing technologies

Gibson et al. (2010) state the variety of ways additive manufacturing technologies may be classified: by baseline technology (i.e. what technology is used in the process, such as printing, lasers, etc.), by the type of raw material input, and by using various classification methods proposed by academia. Pham & Gault (1998) categorize technologies based on the form of the material the part is manufactured from. There are three categories: liquid material, sheet material and discrete particles. An example of liquid material is vat photopolymerization , an example of sheet material is sheet lamination and an example of discrete particles is powder bed fusion. This classification was originally proposed by Kruth (1991) and it is used in the Gibson et al. book (2010).

The literature in the additive manufacturing field uses a variety of more practical classifications. For example, Gibson et al. use the following: photopolymerization processes, powder bed fusion processes, extrusion-based systems, printing processes, sheet lamination processes, beam deposition systems and direct write technologies. Conversely, the ASTM standard F2792-12a uses a different system. The differences between the two are illustrated in table 3.1.

***Table 3.1**. Additive manufacturing technology names.*

Gibson et.al (2010).	ASTM standard F2792-12a	Commercial names (most common)
Powder bed fusion	Powder bed fusion	Selective laser sintering Direct metal laser sintering
Photopolymer processes	Vat photopolymerization	Stereolithography
Beam deposition	Directed energy deposition	
Sheet lamination	Sheet lamination	
Extrusion-based systems	Material extrusion	Fused deposition modeling
Printing	Binder jetting	
	Material jetting	

Gibson (2010) also refers to “Direct write” technologies. The supplied definition for this category is “technologies which are designed to build freeform structures in dimensions of 5 mm or less, with feature resolution in one or more dimensions below 50 µm.” (Gibson et al. 2010). There are a variety of approaches available: ink-based approaches, thermal-spray approaches, beam deposition approaches, beam tracing approaches etc. However, as these technologies are currently aimed at microfabrication, we will consider them outside the scope of the thesis.

Companies generally have their own, trademarked name for their process: an example is Fused Deposition Modeling (FDM) trademarked by Stratasys Inc. The term “Fused Filament Fabrication” (FFF) was coined by the RepRap project team for use as a synonymous term. (Jones et al., 2011). In this thesis, the use of company-specific terms is avoided when possible. In the following subsections, each of the six major technologies are presented in more detail. This includes the operating principle, usable materials, pricing of the machines etc. Afterwards, an overview table and some statistics are presented to aid the reader’s comprehension and to illustrate the actual use of the technologies outlined.

3.3.1 Photopolymerization

Additive manufacturing processes based on photopolymerization rely on the material properties of liquids, photopolymers or resins. To be more specific, most photopolymers react when irradiated with ultraviolet radiation to become solid. This is utilized in the various photopolymerization technologies to form parts. An overview of the process is shown in figure 3.5:

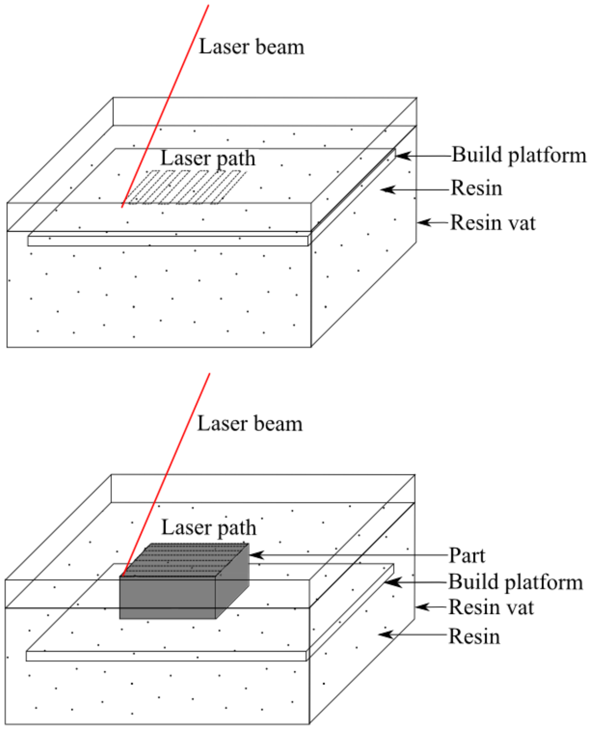

Figure 3.5. *The stereolithography process (i.e. the vector scan approach). Based on Gibson et al. (2010).*

The basic idea of photopolymerization is that a laser is used to cure the top surface of a vat of liquid photopolymer. Optics are used to direct the laser spot to the desired point in the XY-plane. Various principles of operation are possible, including vector scan (a single point is cured at a time), mask projection (an entire layer is cured at a time) and two-photon configuration (high resolution point-by-point). Stereolithography (SLA), which was the first commercialized additive manufacturingprocess, works on the principle of vector scan. Vector scan is commonly used with UV lasers. Mask projection technologies often utilize DLP micromirror arrays. Two-photon configurations are still in the research stage. (Wohlers 2012, Gibson et al. 2010)

Because the photopolymerization process is based on the fact that the material solidifies locally when irradiated, it is evident that the range of usable materials will be limited. Historically, in the early stages of development, both acrylate-based and epoxide-based materials were used. Acrylate-based resins provide high reactivity (e.g. fast solidification) but have problems with shrinkage and curling. Conversely, epoxide-based resins are slow to solidify and the resulting parts are brittle. However, they shrink and curl much less than acrylate-based materials. Today, most commercial SL resins are epoxides mixed with acrylate. These are called hybrid resins. (Gibson et al. 2010).

The advantages of photopolymerization include the part accuracy and surface finish. (Gibson et al. 2010,). Disadvantages include the limited number of resins available.

Also the restriction that only one resin can be used in a part is a limiting factor. In addition, productivity would be increased if an automated system could be developed to remove uncured resin and to replace resin reservoirs. (Melchels et al., 2010). An example of the print quality can be seen below in figure 3.6.

Figure 3.6. *Dental working model (3D Systems 2012b).*

The system costs of photopolymerization machines range from 6000€ (Asiga's Freeform Pico) to over 600 000€ for 3D Systems' large SLA machines. (Asiga, 2012. Wohlers, 2012.) A new development has been the advent of low-cost consumer machines utilizing photopolymerization such as the Formlabs Form1(further discusses in chapter 5.1.2.). The Form1 is pre-selling at ca. 2200€. (Formlabs, 2012)

3.3.2 Powder bed fusion

The powder bed fusion additive manufacturing process is basically similar to vat photopolymerization. The vat of resin is replaced by a powder bed and the light source is replaced by a beam power source (laser, electron beam) which has more power. The process functions as follows: a quantity of powder is deposited onto the build platform.
The powder levelling roller smooths the powder into a layer of even thickness. After this, the laser melts the particles corresponding with the product cross-section. The build platform is lowered and the process is repeated until the part is complete. The thickness of one layer varies by machine and manufacturer. At least one manufacturer provides layer thicknesses of 20 to 50 microns. (Wohlers, 2012). The process can be seen in figure 3.7:

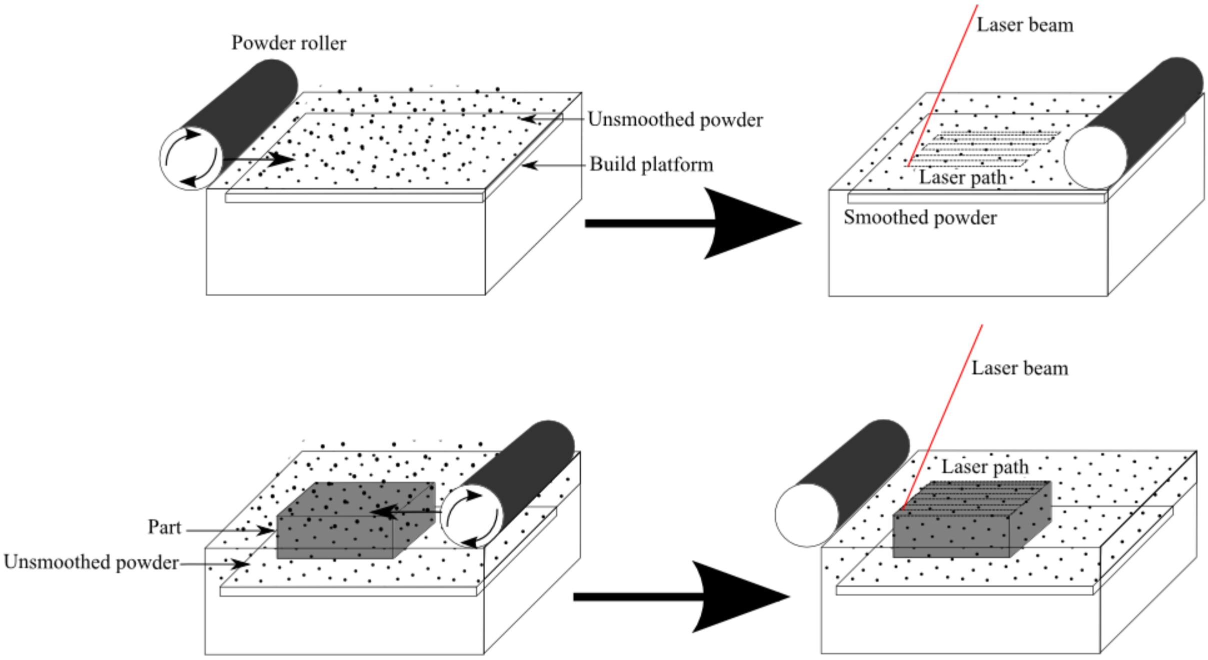

Figure 3.7. *The powder bed fusion process. Based on Gibson et al. (2010).*

Materials suitable for the powder bed process include both metals and polymers. Metal parts require supports (also called anchors) for reducing warping, part fixturing and to support down-facing surfaces. The loose powder bed provides a sufficient support in the case of polymers. (Wohlers 2012. Gibson et al. 2010)

Kruth et al. (2005) state that powder bed fusion processes can be classified into four distinct binding mechanism categories: solid state sintering, chemically induced binding, liquid phase sintering – partial melting and full melting. “Sintering” is simply a process where packed powder bonds together when heated to more than about half of the absolute melting temperature. (German, 1985). Solid state sintering means that the powder particles form “necks” between each other at a temperature between one half of the melting temperature and the melting temperature. This means, in effect, that any produced parts will be porous (i.e. there will be gaps between the particles) as the particles are only connected by the necks. Solid state sintering takes longer to achieve than melting, so not many additive manufacturing processes use solid state sintering as the primary build mechanism. It does, however, affect powder bed fusion processes in a variety of ways, some which are detrimental (unintentional powder sintering in the bed, unintentional part growth due to the sintering of extra powder) and some advantageous (porosity is decreased by post-build sintering). The sintering process is shown in figure 3.8. The figure demonstrates that with increased sintering time, the porosity is decreased. (Kruth et al. 2005. ,Gibson et al. 2010)

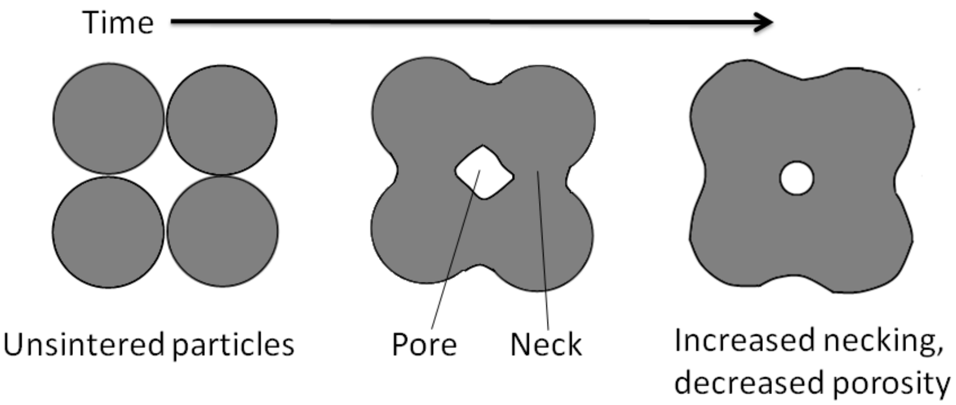

Figure 3.8. *The sintering process (Gibson et al. 2010).*

Chemically-induced sintering (or binding) is based on thermally-activated chemical reactions between the build materials and/or gases to form a by-product which acts as a binding agent. It is primarily used for ceramics. The resulting parts are porous, requiring post-processing. This is why chemically-induced sintering has not been widely adopted in commercial AM machines. (Kruth et al. 2005., Gibson et al. 2010)

Liquid phase sintering (partial melting) is a wide description including many technologies. Some utilize a structural material and a binding material (the structural material remains solid while the binding material is melted), while in others, the same material is in both phases (solid and liquid). When using two distinct materials, the process can be categorized in the following ways: 1) Separate particles, 2) Coated particles and 3) Composite particles. When using a single material, liquid phase sintering can occur when sintering particles of different sizes (common in polymers) or when a single particle type is partially melted (common in metals) or when alloys are sintered (the constituent with a lower melting temperature is melted). (Gibson et al. 2010, Kruth et al. 2005, German 1985)

Finally, the fourth binding mechanism is full melting: the particles are completely melted (at the melting temperature of the material). When the adjacent (above or next to) particles are melted, the previously melted particle is partially re-melted and thus the resulting structure is high in density.

As previously stated, powder bed fusion can be used for both metals and polymers. Resin-coated foundry sand solutions are also available commercially. Suitable applications for polymer PBF include investment patterns for metal casting (using a polystyrene-based material), flexible parts such as gaskets (using a elastomeric thermoplastic polymer) and medical applications (using biocompatible materials). An example of a medical product is shown in figure 3.9. Available metals include, for example, aluminium alloys, titanium alloys, nickel alloys, cobalt alloys and stainless steel. (Wohlers, 2012).

***Figure 3.9**. Knee implant manufactured from cobalt-chrome alloy (EOS, 2012).*

The advantages of powder bed fusion processes are mainly the wide availability of metals suitable for processing. Also, the fact that polymer parts do not require additional supports is a positive factor (metal parts require supports to eliminate warping). Disadvantages include the cost of the machines and the relatively high operating costs. Wohlers (2012) states that the cheapest machines cost about 150 000 € and the most expensive is priced around 1 million euros. On the process side, the possibility of warping, stresses and heat-induced distortion along with shrinkage are inherent to the process. The accuracy and surface finish cannot match the output of liquid-based processes, and the total part construction time is impacted by the necessary pre-heat and cool-down cycles.

3.3.3 Extrusion-based systems

Simply put, material extrusion consists of forcing semi-solid material through a nozzle using pressure. The material then solidifies after extrusion. Two approaches can be used to control the material state in extrusion: temperature control (as in polymer extrusion) or using chemical change (e.g. a reaction with air, etc.) to cause solidification. Temperature control is the more common approach. Below, a diagram illustrating the process is presented. The filament is transferred into the extruder using a feed system (various implementations exist). The extrusion head (also called nozzle, tip or die) is heated to a temperature above the melting point of the material. The end of the filament is melted when it comes in contact with the nozzle, liquefying the material. The feed system uses the unmelted filament as a piston to push the liquid material through the nozzle. The feed system usually operates with a constant speed (in additive manufacturing, the feed system can be stopped at times to facilitate the movement of the extrusion head). (Ramanath et al. 2008). The process is visualized in figure 3.10:

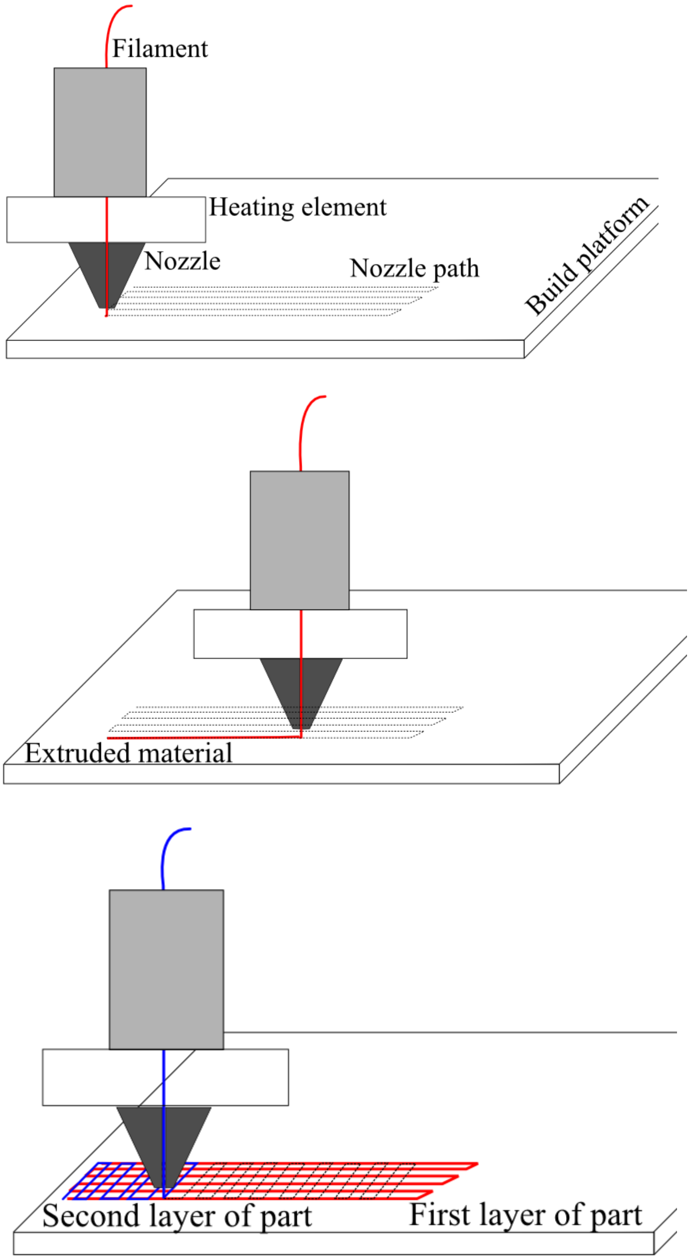

Figure 3.10. *Extrusion build process. Based on Gibson et al. (2010).*

The part is constructed on a level plate called the build platform. The build platform is moved in the Z-direction, while the extrusion head moves in the XY-directions. As shown in the figure above, the cross-section (layer) of the part is formed on the build plate by the extrusion head, after which the build plate is lowered by the layer thickness and a new layer is begun. Thus, the part is built out of layers. It is important to note that, unlike traditional extrusion production, the part layer does not correspond to the nozzle shape. The nozzle is a generic round or square shape which is used to “draw” the part outline and fill in the walls. The nozzle diameter is typically around 10-20% of the filament diameter. The nozzle diameter is constant during a single build. Some machines allow changing the nozzles between builds, thus allowing the user to decide between processing speed or accuracy. An additional support material can be used to facilitate building more complex parts.

The most common industrial additive manufacturing technology is fused deposition modelling (FDM). Wohlers (2012) states that this technology has the largest installed base, with around 18 000 units sold from 1991 to 2011 (not taking low-cost machines into account). The price of FDM systems ranges from around $9500 to $15 000.

The majority of the consumer additive manufacturing machines, mentioned repeatedly in the thesis, use extrusion technology to build parts. Traditional additive manufacturing companies are increasingly moving into this business area (e.g. the 3D Systems Cube, chapter 6.1.1). However, Wohlers (2012) states that the largest growth has been of do-it-yourself 3D printers, embodied by the RepRap (elaborated on in chapter 4.1.4). Around 23 000 machines and kits of this type were sold in 2011, estimated by Wohlers Associates. A notable fact is that some of these machines are designed to reproduce their own parts, which means that a customer buying one machine and some spare parts (the motors, extruder, controller, etc.) could produce additional machines at a very low cost. The price of these low-cost systems is from around 300 $ for basic kits to 2000$ for more complete systems like the Cube. (Wohlers, 2012).

Available materials for extrusion include various polymers (ABS, PCL, PLA, ULTEM 9085 and PPSF). Additionally, there has been academic interest in extruding metals and ceramics. Hobbyists have even used the RepRap to print chocolate and other foodstuffs. Advantages of using extrusion for additive manufacturing include the material properties and low cost of the machines. Disadvantages include the build speed, accuracy and material density. Because of the thermal nature of the process, there is a risk of warpage. Also, the circular nozzle makes producing corners somewhat inaccurate; corners and edges will be rounded to the diameter of the nozzle. (Gibson et al. 2010).

The applications of additive manufacturing using extrusion can be directly derived from the advantages and disadvantages listed above. Because the material properties of polymers such as PLA are quite good (i.e. relatively good tensile strength, durability etc.) the technology is suitable for a variety of primarily low-cost applications, including jigs, templates, fixtures and other tools used in manufacturing. An example of a fixture is presented in figure 3.11.

***Figure 3.11**. A fixture (the white part) made with FDM technology (Hiemenz, 2012).*

Other applications of extrusion-based technology in the additive manufacturing field include bioextrusion and contour crafting, to name but a few examples. Bioextrusion, as stated by Gibson et al. (2010, p. 162) is “the process of creating biocompatible and/or biodegradable components...”. These components are in turn used to create frameworks (called scaffolds) which, after being implanted in a body, host the body’s own cells while gradually being absorbed. Osteopore is using FDM to build bioresorbable scaffolds from polycaprolactone (PCL) and composites of PCL and various ceramics (Teoh et al., 2011). Medical applications of additive manufacturing are discussed also in chapter 3.4.2.

Contour crafting is a technology developed by professor B. Khoshnevis of the University of Southern California. It involves extruding ceramic paste or concrete and then smoothing the surface using two trowels, which function as planar surfaces. Some examples of the results can be seen in figure 3.12:

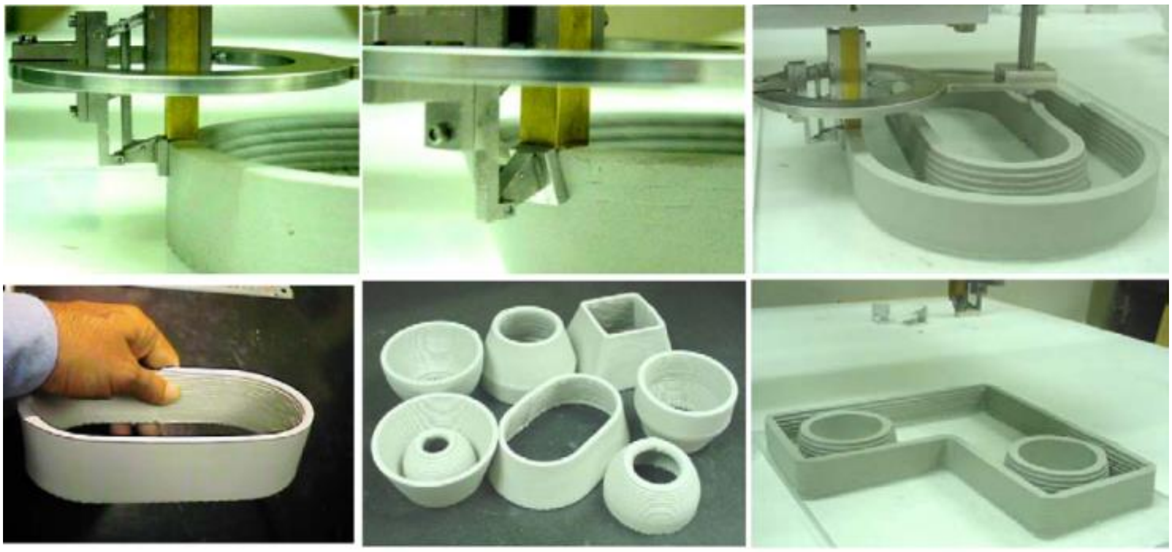

***Figure 3.12**. Contour Crafting using ceramic paste (Khoshnevis, 2004).*

In contour crafting, one trowel is used to control the top surface and one trowel controls the side surface. The side trowel can be angled, which allows the possibility of non-orthogonal surfaces. Only the outer walls are extruded, so for thicker walls, concrete or other filler material is later used to fill the gap between the walls. Potential applications include houses, extraterrestrial habitats and emergency shelter construction. (Khoshnevis 2004).

3.3.4 Printing processes

As previously stated, in this thesis the term “printing” is used to mean the various jetting technologies (as in Gibson et al., 2010). The main division is between material jetting (depositing the actual build material using print heads) and binder jetting (depositing binder material onto a powder bed etc.). In both technologies, inkjet-printing heads (or similarly structured heads) are used to deposit small droplets of material. (Wohlers 2012, Gibson et al. 2010). Figure 3.13 shows the printing process:

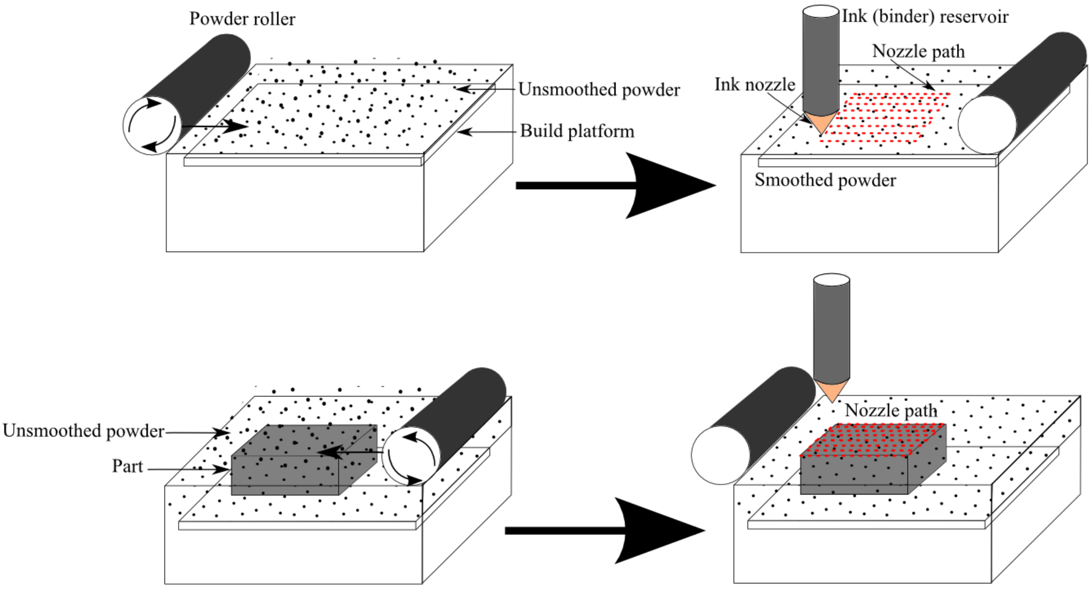

***Figure 3.13**. 3D inkjet printing process (binder jetting). From Gibson et al. (2010).*

Singh et al. (2010) state that the inkjet process consists of the ejection of a known quantity of ink through a nozzle onto the substrate (i.e. build platform or part). Once on the surface, the ink dries because of solvent evaporation. In material jetting, the print head (containing the nozzle, ejection mechanism, etc.) prints the cross-section of the part in a similar fashion to extrusion processes. Binder jetting utilizes a powder bed similar to powder bed fusion processes, the difference being that a liquid bonding agent is used to bind the particles instead of thermal energy.

Commercial material jetting machines use either waxes or photopolymers as build materials. When using photopolymers, the layer is cured by UV light after deposition. This produces fully cured models. An example is the PolyJet technology developed by

Objet Geometries. Binder jetting machines can use a variety of materials, including plaster-based powders, polymers, metals, sand and ceramics. Some of the ZPrinter machines from 3D Systems (formerly ZCorp, which was acquired in 2012), have color printing capability as shown in figure 3.14. (Fathi et al. 2012, Wohlers, 2012, Gibson et al. 2010).

Figure 3.14. *Multimeter prototype (left) and figurine (right) created using ZPrinters from 3D Systems, Inc. (3D Systems, 2012c).*

Advantages of both types printing include the relatively low cost and high speed of the process. In addition, the inkjet process is highly scalable, i.e. one can speed up build times by increasing the number of print heads. Parts can also be built using multiple materials and in color. Another factor is the maturity of the inkjet technology; Fathi et al. (2012) state that a wide range of materials can be deposited on almost any substrate in a precise manner. Also, fault recognition and quality monitoring are not difficult for inkjet technology.

Some disadvantages of printing are the limited material selection and the part accuracy. Binder printing can be faster than direct printing, as only a small part of the part volume must be dispensed. This advantage is offset by the need to recoat the powder bed. The combination of a base material and binding agent facilitates having material compositions which may not be achievable using other technologies. The build accuracy and surface finish tends to be worse than when using direct printing. Postprocessing (specifically infiltration) is required to make durable parts. (Gibson et al. 2012).

Additive manufacturing machines using print processes are inexpensive, pricing starts at about $20 000 for Objet's cheapest single material machine and extend to about $250 000 for the most expensive machines. For binder printing, the cheapest ZPrinter starts at about $15 000 and the most expensive system, ExOne's foundry sand machine, costs around $1 750 000. Common applications of printing process machines are prototyping, patterns and direct part production, as demonstrated in Figure 3.14.

3.3.5 Sheet lamination processes

Sheet lamination (in the additive manufacturing context) means that sheets of a paper-like material are cut corresponding to the cross-sections of the product. In most commercial technologies, only the outline (i.e. the edges) of the cross-section are cut, leaving the inside as-is. These cross-sections are then laminated or glued together (stacked) to form the finished product. Some processes do the stacking first and then cut ("bond-then-form") and some cut the correct cross-sections first and then stack ("form-then-bond"). (Gibson et al. 2010). The sheet lamination process is visualized in figure 3.15.

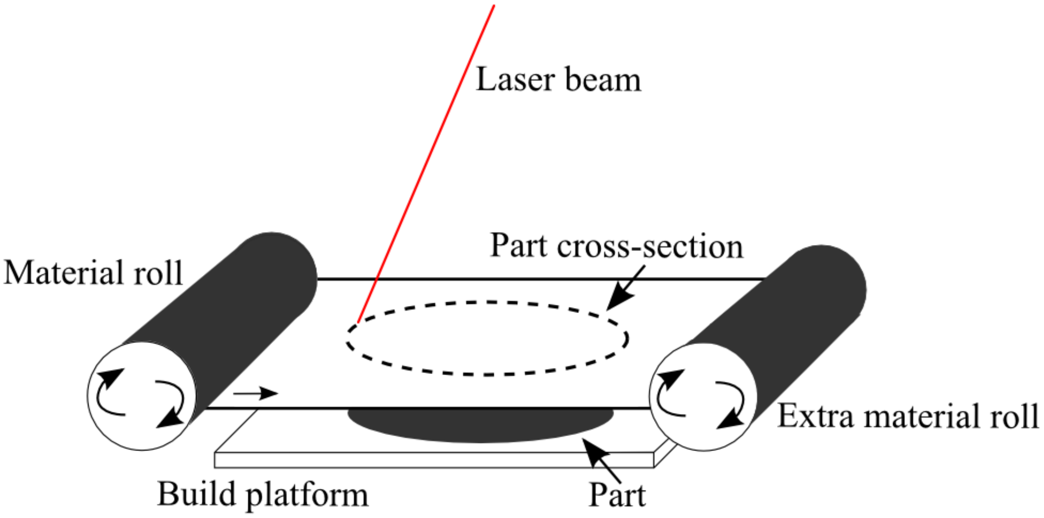

Figure 3.15*. Sheet lamination process. From Gibson et al. (2010).*

Advantages of the sheet lamination process include the processing speed; since cutting a thin layer of material can be done quickly (and only the outline of the cross-section needs to be cut) the process can be quite fast. Also, there are no difficulties with shrinkage or residual stresses and the parts can be easily finished. Finally, the operating costs and system prices are relatively low compared to other technologies. On the other hand, there are some disadvantages to using the sheet lamination process. These include the durability of the finished parts and that the usage of glue makes the properties of the finished parts inhomogenous. Materials which can be used for sheet lamination include plain paper (and variants), polymer sheets and metal or ceramic tapes. (Gibson et al., 2010).

The commercial technology most associated with paper sheet lamination is Laminated Object Manufacturing (LOM), commercialized by Helisys Inc. in 1991. Currently, Mcor technologies from Ireland is offering machines which use plain paper as the build material. The machine is available for lease at 11,500£ per annum (all materials and maintenance included). Also, Fabrisonic from the U.S. is offering ultrasonic additive manufacturing (UAM) machines, which use a sheet lamination process with ultrasonic binding in conjunction with conventional machining to build parts. (Gibson et al. 2010, Wohlers 2012).

3.3.6 Beam deposition systems

In beam deposition (also referred to as directed energy deposition), energy is focused into a beam which is used to melt a material while the material is being deposited. Usually a laser is the energy source while metal in powder or wire form is the deposited material. A robotic arm or 4/5-axis motion system (similar to a CNC machine) can be used for positioning the deposition head. During the process, the actual metal addition is done by creating a very small (0.25-1mm in diameter and less than 0.5mm in depth) molten pool on the surface. When the feedstock enters the pool it melts and when the energy source is moved it solidifies, thus creating the new layer. (Gibson et al. 2010). The beam deposition process is shown in figure 3.16:

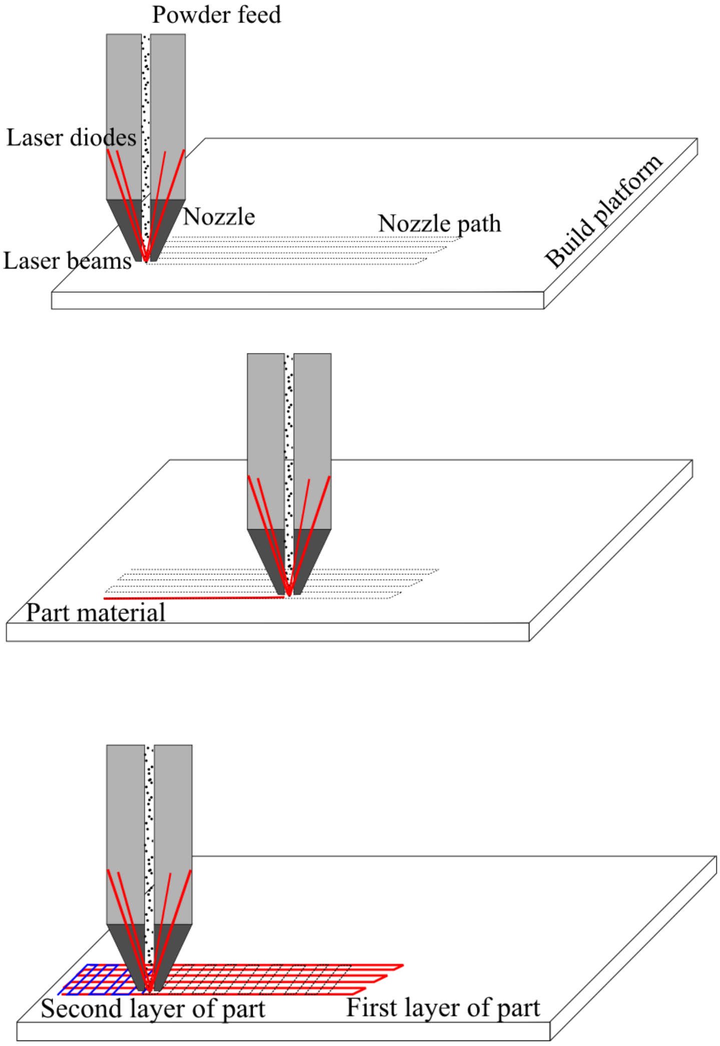

***Figure 3.16**. Beam deposition process. From Gibson et al. (2010).*

Typically, in a beam deposition process, the material is deposited at a high speed, making the effect of gravity on the material minimal. This means that nonvertical deposition is possible. Also, the surface being printed on (commonly referred to as the substrate) can be an existing metal part, which allows adding new geometry to existing parts. Obviously the option to fabricate completely new parts using beam deposition is also viable, although the positioning system might be different in the two cases. (Gibson et al. 2010., Wohlers 2012).

Beam deposition is a very similar process to laser cladding. At TUT, some research has been done using a coaxial direct diode laser. The laser diodes are arranged in sectors around the optical axis leaving a tool opening of 20mm diameter throughout the laser. This allows coaxial wire or powder feeding, monitoring, heating etc. The laser head is very compact and weighs approximately 2 kg. (Vihinen et al. 2009).

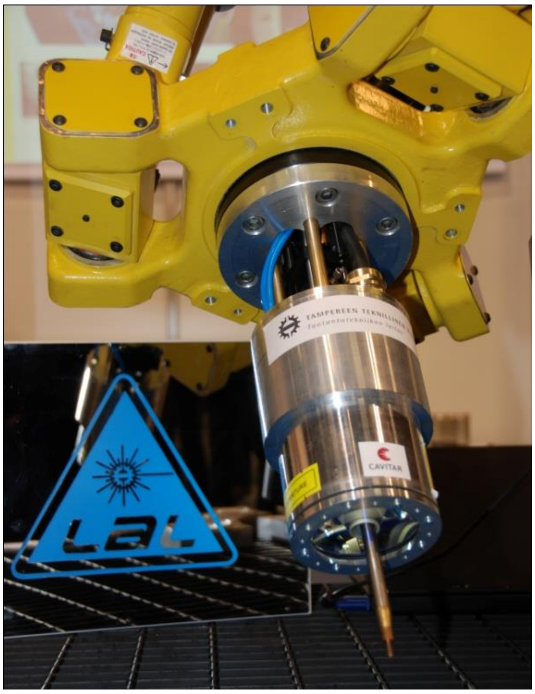

Figure 3.17. *The CAVIPRO direct diode coaxial laser mounted on a FANUC robot. (Vihinen et al. 2009).*

3.3.7 Summary

This subsection summarizes the previously presented information about the various technologies. Data about unit sales and system costs is also presented.

Table 3.2. *An overview of additive manufacturing technologies (Compiled by the author based on Wohlers, 2012., Gibson et al. 2010).*

AM technology	Operating principle	Price range (k€)	Materials
Material jetting	Similar to inkjet printing	16-200	Polymers, Ceramics, Metals Wax
Extrusion	Semi-solid material is forced through a nozzle and solidifies after extrusion	7-400	ABS, PLA, ABSplus etc.
Photopolymerization	Photopolymers solidify when irradiated	6-650	Resins
Powder bed fusion	Powder on a bed is fused using a point energy source	150-950	Metals, polymers
Binder jetting	Powder bed fusion using “glue”	12-556	Ceramics, metals, starch etc.
Beam deposition	A laser is focused on a surface so that it melts a small puddle, into which material is injected	280-810	Metals, ceramics
Sheet lamination	Sheets of paper-like material are cut & glued corresponding to the cross-sections of the product	n/a	Laminate, paper, PVC, metals

To briefly summarize, the above table shows that the additive manufacturing processes suitable for metal fabrication are material and binder jetting, beam deposition, powder bed fusion and sheet lamination. Processes suitable for polymer fabrication are extrusion, photopolymerization, powder bed fusion and sheet lamination.

Data and observations from the Wohlers State of the additive manufacturing industry progress report give us a rough indication of the “popularity” of the various technologies in industry (i.e. the amount of sold machines = the installed base).

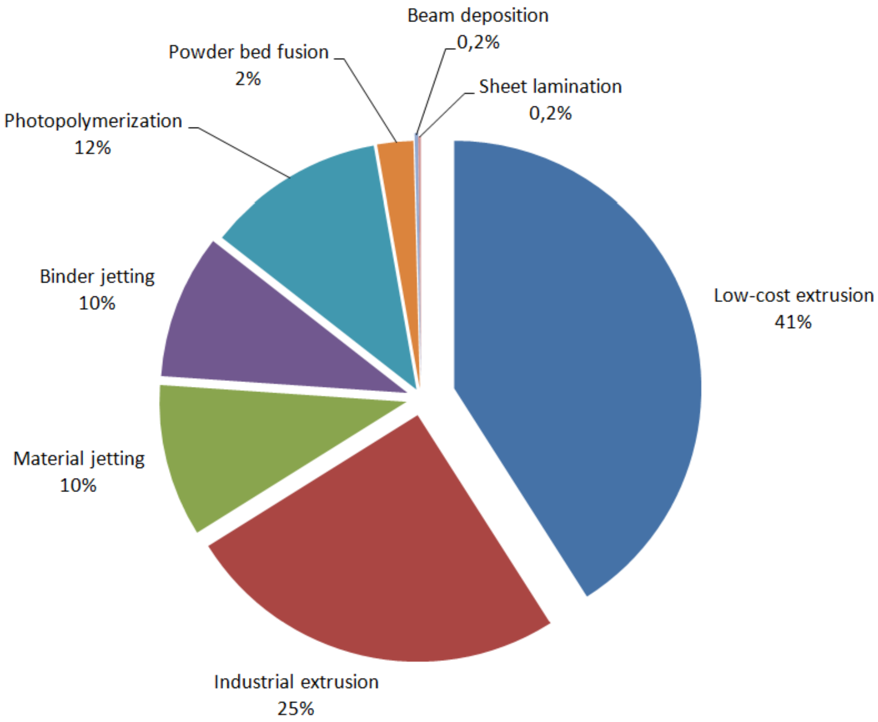

Figure 3.18. *Market share by technology, units sold from 1988 to 2011. Only companies active in 2011 included (Compiled from Wohlers, 2012).*

Figure 3.18 shows the market share of the various additive manufacturing technologies when the low-cost consumer machines are included in the data. The 41% market share is even more impressive when one considers that this type of machine has only been on the market for four years. Additionally, the first chart shows that extrusion is by far the dominant technology in additive manufacturing; the industrial and consumer categories combined have a market share of 66 %, which means two out of three units sold are using extrusion technology. If consumer machines were to be excluded, industrial extrusion (mainly FDM, chapter 3.3.3) is still in the lead but printing (material and binder jetting combined) has a 30 % market share and photopolymerization 20%.

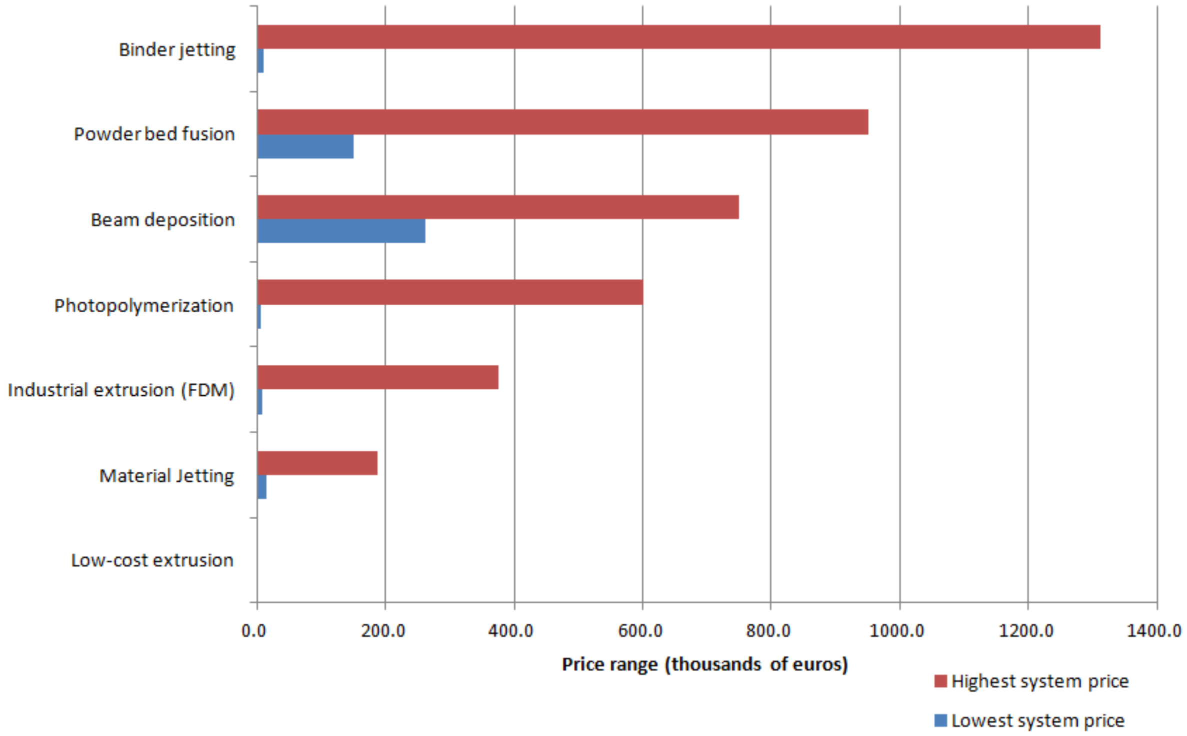

Figure 3.19*. Price range of commercial additive manufacturing machines, by technology (Wohlers, 2012).*

The above figure illustrates the typical pricing of the machines. We see that binder jetting is by far the most flexible technology in terms of pricing, while other technologies have less variation in the system prices.

3.4 Applications of additive manufacturing processes

This subchapter presents an overview of current additive manufacturing applications, divided into industrial, consumer and medical applications. Obviously the plethora of current applications make it impossible to compile a definitive list, but this subchapter should provide a reasonable illustration of what additive manufacturing is used for in today’s production environment.

Commercial applications for additive manufacturing include direct part production, modelling and prototyping, pattern production, production for tooling, jigs and fixtures and medical and architectural applications. Wohlers (2012) includes the results of a survey done in 2011 with 102 companies providing data. The survey asked the companies what the end-user (i.e. customer) use of their additive manufacturing products is. Originally, the survey included 10 answer options, ranging from direct part production to patterns for metal castings to research and education. Of these categories, the most common uses were direct part production and functional modelling. To examine the data, the data is simplified slightly by unifying categories, resulting in four categories: prototyping, direct (part) production, pattern making (i.e. molds or castings for production or prototyping purposes) and research and education. (Wohlers 2012).

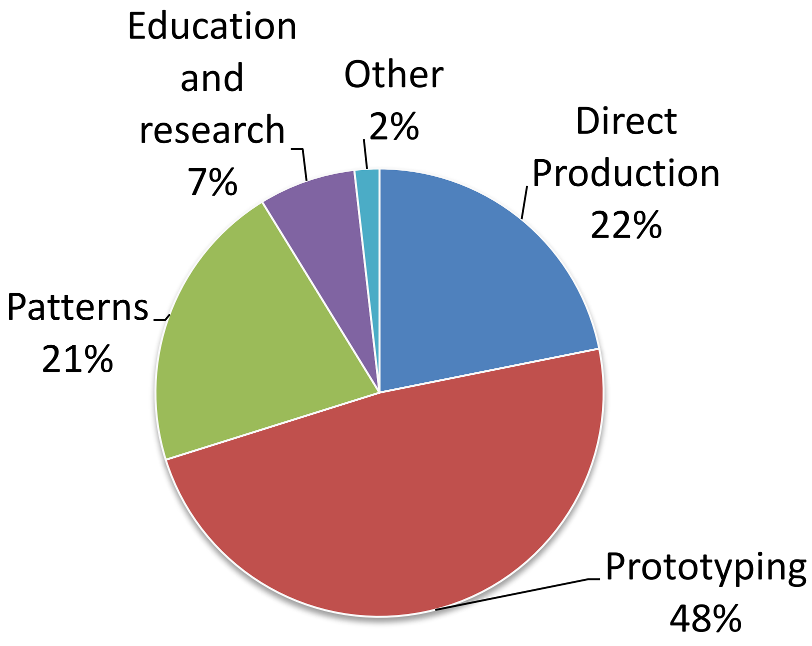

***Figure 3.20**. Applications additive manufacturing-produced parts are used for. (Compiled from Wohlers, 2012).*

We see that roughly half of all additive manufacturing part usage is for prototyping of some form or another (this category includes presentation models, for example).(Wohlers 2012)

3.4.1 Industrial applications

Industrially, additive manufacturing can be used to fabricate parts or products (i.e. direct part production), as part of the design process (i.e. prototyping) or to make molds or patterns for other manufacturing processes (patterns or tooling).

Direct part production using additive manufacturing has increased in recent years due to developments in technology. Several business areas are using additive manufacturing, including aerospace, automotive and industrial machinery, according to Wohlers (2012). For parts with a low volume and for parts which are wasteful to manufacture using conventional machining, additive manufacturing can be a cost-effective option. Also, custom parts for e.g. racing cars have been produced.

Wohlers (2012) states that tooling produced by additive manufacturing can be divided into two categories: the indirect approach and the direct approach. The indirect approach means that patterns for a mold or die are manufactured by additive manufacturing and some other technology like metal casting is used to fabricate the mold. In the direct approach, the actual mold is produced using additive manufacturing technology. Several technologies exist for indirect mold production, including: silicon rubber tooling, epoxy-based composite tooling, rubber plaster mold, spray metal tooling, Ford Sprayform, et cetera. For direct tooling production, many additive manufacturing technologies can be used, for example extrusion (fused deposition modelling), powder bed fusion and sheet lamination (Fabrisonic ultrasonic additive manufacturing). Benefits of producing molds with additive manufacturing include the possibility of implementing features which are impossible when using conventional machining, however, there can be a significantly higher cost as shown in Boivie (2011).

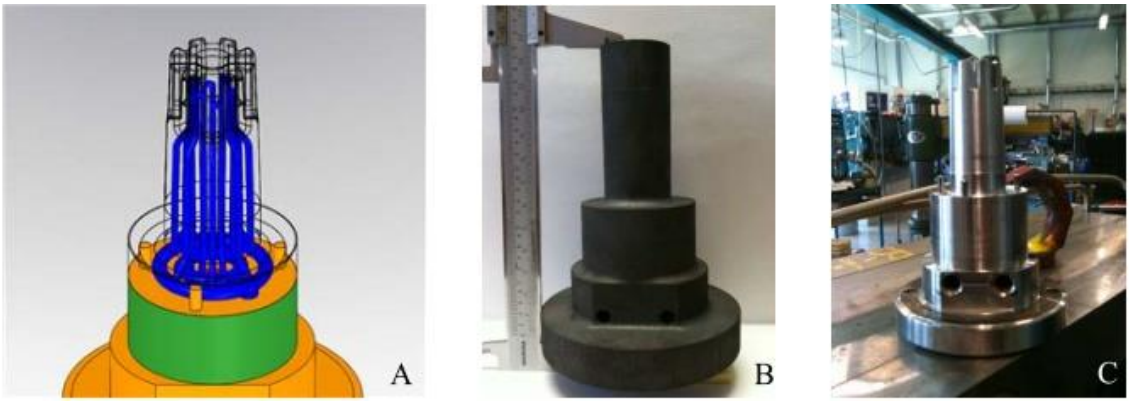

***Figure 3.21**. Injection mold with conformal cooling channel, produced with Concept Laser powder bed fusion technology and finished with conventional machining (Boivie et al. (2011).*

Prototyping (in the physical sense) is used during product development processes to validate the function, fit and form of the product. It is one of the earliest uses of additive manufacturing and is still the most common use today, as shown by figure 3.20.

3.4.2 Medical applications

Wohlers (2012) states that medical applications (and research) in the additive manufacturing field are driven by the need for custom-made products, stemming from patients' unique shape, functionality and cost requirements.

Melchels et al. (2010) divide the potential medical applications of stereolithography into the following groups: patient-specific models and functional parts, implantable devices, tissue engineering and cell-containing hydrogels. Patient-specific models are parts which physically represent a part of the patient's body. These can then be used in diagnosis, pre-operative planning, guides for e.g. drilling and implant molds. Functional parts are parts which can be used in the patient's body, for example a customized heart valve or hearing aid. Implantable devices are implants customized to the patients' body. Tissue engineering refers to the practice of using bioresorbable scaffolds and biologically active compounds to induce tissue generation. This can happen *in vitro* (i.e.

in a laboratory environment) or *in vivo* (i.e. inside the patient). Cell-containing hydrogels are an attempt to achieve higher cell densities by encapsulating cells in fabricated structures (as opposed to building scaffolds and seeding them with cells).

Table 3.3*. Medical applications of additive manufacturing. Compiled by the author from (Wohlers, 2012., Melchels et al. 2010., Gibson et al. 2010).*

Patient-specific models	Functional parts	Implantable devices	Tissue engineering
• Specialized surgical tools e.g. drill guides • Molds or patterns for implant preparation • Visual models	• Customised heart valves • Shaped implants (scaffolds)	• Parts for artificial joints • Prosthetics Hearing aids	• Organ printing

The table above illustrates some medical applications of additive manufacturing from various sources. It demonstrates how varied the potential applications of additive manufacturing for medical purposes are. For example, visual models are primarily representations of medical data while, on the other hand, tissue engineering facilitates the printing of functional biotissues. Obviously the materials, processing speed, processing methods, cost and other parameters will also vary widely within the field.
The materials used for medical additive manufacturing applications are of course determined by the purpose of the part being printed.

An example of small-sized medical additive manufacturing equipment is the 3D-Bioplotter from Envisiontec GmbH, shown in figure 3.22. The Bioplotter is designed to fabricate scaffolds for tissue engineering from a wide variety of materials, including (but not limited to) titanium, PCL, PLGA, PLLA, chitosan, polyurethane and silicon. The machine has a resolution of 0.001mm and a build volume of 150 x 150 x 140mm. The overall size of the machine is 976 x 623 x 773 mm and it weighs 80 kg. (Envisiontec, 2011).

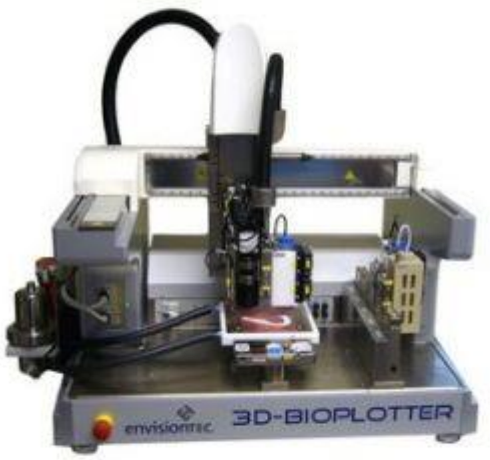

Figure 3.22. *The Envisiontec bioplotter. From (Envisiontec, 2011).*

Gibson et al. (2010) report some current limitations of additive manufacturing use in medical applications. These include the process speed, overall cost, part accuracy, the limited range of materials and the usability of the machines. It is stated that medical professionals often lack an engineering background and thus the manipulation of e.g CAD data is not as straightforward as in the traditional production process. (Gibson et al. 2010)

3.4.3 Consumer applications

This section lists some commercial products marketed at consumers, as well as some applications developed by hobbyists. The examples here can be categorized as direct part production, often for consumers by consumers.

Wohlers (2012) lists some examples of additive manufacturing-produced consumer products. These include figurines, musical instruments, art, jewelry, gifts, trophies, memorials, three-dimensional maps, props, museum displays, clothing and so forth. Obviously, the possibilities are near endless. An example of a musical instrument is the guitar shown below, printed using Selective Laser Sintering (SLS) (a form of powder bed fusion). The guitar is made out of Duraform PA, a polyamide (nylon) material. The guitar is being sold worldwide with a price of roughly $3300.

***Figure 3.23**. The “Spider LP” 3D-printed guitar. Note the spiders inside the body. ODD Guitars (2012).*

The possibilities of what consumers will produce using a 3D printer are virtually limitless. An application which has garnered considerable interest at the time of writing has been three-dimensionally printing a record based on a sound file. This record can then be used to reproduce the sound using a conventional record player (not very well). The printer used in the project was the Objet Connex 500 (a UV-curing photopolymerization printer) with a resolution of 600 dpi (X and Y axis) and 16 microns for the Z axis. Regrettably, this is not enough to accurately reproduce a vinyl record. This partially successful attempt demonstrates a) the ingenuity of the hobbyist 3D printer operator and b) the relatively low accuracy of the technology compared to 1950’s manufacturing. (Ghassaei, 2012).

3.5 Advantages and disadvantages of using additive manufacturing

Chua et al. (2010) categorize the benefits of using additive manufacturing into direct and indirect categories. The direct benefits include cost savings in production, the ability to increase the complexity of the part without increased cost or lead time, reduction of part count and fewer constraints in part design, to name but a few. Stated benefits from multiple sources have been combined in table 3.4:

***Table 3.4**. Benefits of additive manufacturing. Compiled from (Chua et al. 2010, Fox & Stucker, 2009 and Wohlers, 2012).*

Business area	Cost Saving	Increase in functionality
Design	Machining costs eliminated as a design consideration	Fewer constraints in part design Wider variety of possible product shapes
Prototyping	Reduces the likelihood of flawed products	
Manufacturing	Reduction in: • material waste • set-up time • machines needed • Work-in-progress	Possibility of on-the-spot manufacturing
Marketing	Rapid change in production capacity	Reduction in time-to-market Diversity of product offerings increased
Consumer	Lower prices	More customized products to suit individual needs
Logistics	Simplified supply chain	

Additive manufacturing is a relatively new technology and there are some drawbacks to using it in some situations. A main concern is the build speed which is not comparable with traditional machining. Also the build quality may not be suitable for certain applications and often parts require postprocessing. Another factor is that the technology is relatively new and there is a distinct lack of practical knowledge (compared to traditional methods) on the “factory floor”.

Some areas have been highlighted for future research (and thus improvement) by academia and industry practitioners. These can be seen in table 3.5.

***Table 3.5.** Additive manufacturing research recommendations.*
From Fox & Stucker (2009), Bourell et al. (2009) and Gibson et al. (2010)

Design	Process control	Materials and Machines	Education and community
• Conceptual design methods (e.g. Design for AM) • Easy-to-use CAD for non-professionals • CAD systems which can handle: - multiple materials - variability - - complex geometries	• Predictive modelling methods • Closed-loop, adaptive control systems • New sensors	• Better understanding of underlying physics • Open-architecture controllers, machine modules • Fast line or area processing methods to increase throughput • Sustainable materials: - Recyclable - Reusable - Biodegradable	• University courses, education materials, curricula for all education levels • Training programs for industry practitioners • International standards

The above table demonstrates the need for improvements throughout the additive manufacturing process, from education to materials to process control to better hardware. A key part will be improved software to control the production process and maintain the product data.

4 MOTIVATIONS

In this chapter, the motivations to implement additive manufacturing technologies in the microfactory scale are further explored and justified. An important topic of the thesis was finding real justification for combining additive manufacturing with microfactories. This chapter can be characterized as the “why” of the thesis, with chapters 5 and 6 forming the “how” and the “what” respectively. Furthermore, section 4.1 examines the production paradigms of the future, section 4.2 deals with the industrial context of AM/MF integration based on industry needs, and section 4.3 discusses the role of the customer in future manufacturing.

4.1 Production paradigms

Returning to the production paradigms introduced in subsection 1.1.(Jovane et al., 2003), we can see that after the advent of mass production, the emphasis of the consumer in product design has been emphasised. Mass production, famously, eliminated the individual customer’s wishes. This is illustrated by Henry Ford’s famous remark, “"Any customer can have a car painted any colour that he wants so long as it is black." (Ford & Crowther, 1922). This product standardization, in which complexities and custom work were avoided and eliminated, resulted in lower costs. However, with every successive paradigm, the customer has more and more impact on the product and thus the production process itself.

Table 4.1*. Production paradigms (Jovane et al., 2003).*

Production paradigm	Started
Craft production	~1850
Mass production	1913
Flexible production	~1980
Mass customization	2000
Sustainable production	2020?

Table 4.1 presents the production paradigms as listed by Jovane et al. (2003). A case can be made for adding the digiproneurship paradigm (also presented in chapter 1) to the list. To summarize, digiproneurship uses digital technology to enable (geographically distributed) product development. Product information is then distributed in a digital form and production happens close to the customer. (Fox and Stucker 2009).

An important thing to consider while discussing production paradigms is that they are not mutually exclusive, but tightly integrated with specific products, industries, geographic regions, etc. This means that future manufacturing will not consist of one overarching holistic paradigm, but many different ones coexisting and overlapping. I propose three main paradigms of future manufacturing: mass customization, sustainable production and digiproneurship. The mass customization paradigm represents the needs of consumers to have individually tailored products, while sustainable production is a necessity driven by ecological, economic, societal and political factors. Finally, digiproneurship (or ubiquitous production) takes into account the increasing digitization of manufacturing data and the tendency of modern consumers to be active remixers and curators of content.

After briefly analyzing each future paradigm, some essential requirements have been found. These requirements have been collected in the table below, along with some implementations which respond to the requirements.

Table 4.2. *How paradigm requirements can be answered.*

Production paradigm	Requires	Implemented by
Mass customization	Flexibility	Modular production systems Rapid reconfigurability
	Customer intentions	
Sustainable production	Energy saving	Miniaturization
	Recycling	Traceability
Digiproneurship	Distributed production systems	Small-scale production equipment
	Distributed product development	Product development software

Collectively, the manufacturing requirements are solved by modularity, reconfigurability and miniaturized production equipment. It is evident that microfactories possess these characteristics and thus are eminently suitable for future production paradigms. Customer requirements are solved by software development, which allows the customer to communicate, refine and monitor their product wants and needs.

This chapter has attempted to identify the future paradigms and to determine how they can be implemented successfully. The implementation requirements are twofold: miniaturized production systems and increased reconfigurability (i.e. flexibility). An important caveat is the parallelism of paradigms presented in chapter 1, which means that paradigms can and will coexist: in practice, this means that the future production paradigms are not applicable to the low-cost, low value added, mass produced products of today.

4.2 Industrial context

What drives the evolution of a new technology in a production process? Certainly, new technologies often have significant benefits (cost saving, increasing functionality) but also overcoming the inherent drawbacks is an important driver for research and development. Thus it is wise to analyse both the benefits and shortcomings of a particular technology to find potential research areas.

Nurmi (2012) states that there are three potential business areas for miniaturization of production equipment (i.e. microfactories): the traditional supply chain, relocating production further downstream and on-the-spot manufacturing. The traditional supply chain is further subdivided into five distinct categories in the product lifecycle, from raw material production to finishing and inspection. Production relocation is comprised of on-the-fly (on-the-way) manufacturing, storage and wholesale, and retailing. Finally, on-the-spot manufacturing consists of production at the point of ordering and entirely new applications (in this thesis, on-the-spot manufacturing is included in the consumer context).

Nurmi also illustrates some motivations for adopting microfactory technology in these business areas. For the traditional supply chain, the main drivers are reducing costs (by lowering energy consumption, facility costs, etc.) and enabling new product characteristics. Cost reduction is also a driver in the production relocation business area, along with add-on sales (enabled by customization and fast delivery) and enabling new product characteristics (for fragile or perishable products). For on-the-spot manufacturing, microfactory technology might be critical in enabling the entire business.

Additive manufacturing benefits by various authors were listed in table 3.4. To reiterate, benefits were envisioned throughout the production process from design to logistics.

These benefits were further categorized into cost saving and increasing functionality by the author. Below, in table 4.3, these benefits are combined and sorted by business area.

Table 4.3. *Drivers of both microfactory and additive manufacturing technologies (Nurmi, 2012, with additions by the author).*

Business area	Microfactory benefits	Additive manufacturing benefits
Traditional supply chain	Cost reduction Enabling additional product characteristics Production enhancement	Decreased time-to-market Enabling additional product characteristics Cost reduction: - Material savings - Simplified supply chain
On-the-way production	Cost reduction Enabling additional product characteristics	Unknown
On-the-spot production	Enabling business opportunities	Enabling production

Looking at table 4.3, the main interest in microfactories is threefold: energy saving (and sustainability in general), cost reduction (which overlaps with sustainability) and enabling additional production opportunities or business models.

Table 4.4*. Challenges of both microfactory and additive manufacturing technologies (Nurmi, 2012, with additions by the author).*

Business area	MF challenges	Additive manufacturing challenges
Traditional supply chain	Size only a secondary sales argument for most industrial customers Lack of commercial components Lack of examples Attitude of production engineers Cleanroom standards do not support local cleanrooms	Material properties Finishing Sustainability Processing speed
On-the-way production	Small systems are more sensitive to external issues, thus practical issues decrease accuracy	Unknown
On-the-spot production	1) Difficulty of use 2) Business case	1) Difficulty of use 2) Process parameters 3) Speed 4) Cost

Table 4.4 shows that one of the main challenges for microfactories is the lack of examples of industrial systems. In effect, this means the low market penetration of microfactories is a direct barrier for further adoption. This is a vicious cycle: the lack of adoption in industry leads to a lack of suitable components which leads to a lack of systems. An important question thus arises: how can the adoption rate be increased? One solution is to increase the capabilities of microfactories by implementing new functionality in microfactory-sized modules. Another is to raise awareness among production engineers, students and the general populace. However, in the end, the most effective strategy is that of the bottom line: maximizing ROI and productivity in industrial settings.

4.3 Consumer context

Consumers can function in two different ways in today's economy: a) as "traditional" end-users of products and b) as producers, remixers and curators of content. While not novel (end-users of the 1800's were surely also equipped to make personalized products), the internet has amplified this effect. This has been evident in various business areas, most importantly software. One could argue that the rise of the "app store" model is a business strategy designed to harness the creative power of modern consumers. In addition, the rise of crowdfunding (e.g. Kickstarter and similar services), peer production and digital model sharing services (e.g. Thingiverse) demonstrate how modern consumers are acting in a more interactive manner.

Fox and Stucker (2009) state that developments in advanced manufacturing and materials (additive manufacturing is listed as a "great aid" to aMM) make it possible to radically reduce the consumption of non-value adding resources when creating products. Also an important factor is the radical reduction in the size of production facilities, which enables on-the-spot production (detailed in chapter 4). The authors present three categories of business opportunities (individual person, business-to-business and business-to-consumer) with corresponding future opportunities in Design, Production of physical products and production of integrated physical components. For example, the business-to-consumer physical product opportunity is a customized toothbrush printed at the dentist's while the customer's teeth are being cleaned (Fox & Stucker, 2009).

5 TECHNICAL ANALYSIS

This chapter outlines some possible technical solutions to give a general idea of how these ideas might be realized in the future. If there are existing solutions available, these are presented to provide context and validation. This chapter is divided into four subchapters, each dealing with a different technology. Some of the themes of this chapter are also further elaborated on in Chapter 6.

To be able to accurate judge the feasibility of implementing various technologies and functionalities in the microfactory concept, some definitions of that concept are required. Since the literature on the subject differs widely, I have used my own definitions of a modular microfactory (based on the TUT microfactory concept). These restrictions are presented in table 5.1 below.

Table 5.1. *Microfactory attributes.*

Attribute	Requirement
Module weight	Less than 25kg
Module dimensions	Smaller than 500x500x500mm
Accuracy (manipulation)	Better than 1mm
Feature size	Better than 1mm
Power consumption	Less than 1 kW
Product size	Smaller than 250x250x250mm

Obviously these values are closer to guidelines than firm restrictions. Even if only the actual production cell is microfactory sized and the additional equipment such as control cabinets. occupies 4-5 times the volume elsewhere (under the table), many of the benefits of a microfactory can be realized. For example, the physical layout of the system can often be changed without moving the additional equipment. However, it is best to primarily design systems with as small a physical footprint as possible.

Many advantages of miniaturizing production equipment were listed in chapter 2.3. However, when processes are miniaturized there are also some challenges to overcome. The author has listed some of these in table 5.2.

Table 5.2 *Challenges of miniaturization*

Domain	Challenges
Spatial	• Difficult to fit cabling, pneumatic systems in small space • Accessory equipment (compressor, chiller) is often not miniature or miniature equipment has reduced performance
Process	• Difficult to disperse heat • Material handling with small equipment can be problematic • Implementation and automation of post-processing may be challenging
Construction	• Difficulty of finding suitable parts (e.g. motors with high torque and low revolutions, as in chapter 2.3) • Cost of miniature parts may be prohibitive • Balancing between lightweight frame and heavy frame: light frame benefits transportation, reconfiguration and construction costs while heavy frame benefits process control (lessens vibration) • Small process area size reduces the size of the part
Human factors	• Parts may be difficult to manipulate manually • Process monitoring may strain eyesight
Economic	• Less ROI from smaller machines than larger ones • Benefits of miniaturization might not outweigh the costs in all cases

In the additive microfactory case, the most critical of these from a business standpoint is the small process area, which reduces the size of the parts which the machine can produce. If the same process equipment (laser / Cartesian axis system) is used in a larger and a smaller machine, it is possible that the smaller machine will be more expensive and produce smaller parts with no benefit to accuracy or finish. This means that the benefit must be in the small form factor, which increases portability and makes securing the process area easier.

5.1 Extrusion

Implementing extrusion-based additive manufacturing in almost any microfactory concept should not be very challenging, as there are several consumer- and industrial machines which are already microfactory-sized. Thus, the main challenge from a development standpoint would be integrating the additive manufacturing process (i.e the additive manufacturing cell) with the various other cells in the microfactory (if we are considering a modular microfactory). Another worthwhile area of research would be process monitoring, i.e. how control systems can monitor and automatically correct the build quality without human intervention.

***Figure 5.1**. The 3D Systems CUBE personal printer. (3D Systems Inc., 2012a).*

An example (along with the already presented RepRap and Ultimaker) of a microfactory-sized extrusion machine is the Cube, made by industry leader 3D Systems Inc. The Cube has a maximum build area of 140 x 140 x 140 mm and it weighs only 4.3 kg. The printing material is supplied in cartridges sold by 3D Systems. The cost of the device is around 1300 USD. An important part of the offering is the Cubify web store, detailed in subsection 5.4. (3D Systems Inc., 2012a).

A practical implementation of extrusion-based additive manufacturing in a microfactory would almost certainly use a XY Cartesian structure to move the extruder and a leadscrew to move the build platform in the Z-direction. Part handling could be implemented by using the TUT H-SCARA robot (section 2.2) in an adjacent cell. The robot has a large work area in the Y-dimension allowing it to handle parts in other cells. A concept based on this is modelled in chapter 6.

5.2 Photopolymerization

Implementing photopolymerization in the microfactory-scale is an attractive proposition due to the high resolution and relatively low cost of the technology. The author has observed that in effect, most of the research and development “cost” have been in developing a suitable material for photopolymerization, while the machine is relatively simple (1 moving axis, a laser source and a laser scanner). Validating the sensibility of the implementation concept, at least two microfactory-size photopolymerization devices have been introduced within the last two years (one of them commercial).

In 2009, researcher Klaus Stadlmann of TU Wien decided to implement the “world’s smallest 3D printer”, shown in figure 5.2. The build volume of the printer is 20 x 30 x 50 mm and it weighs 1.2 kilograms. The researchers have suggested a price of around 1200 euros for the device. Currently, no models are for sale. (TU Wien 2011, Stadlmann 2011.)

Figure 5.2. *The “World’s smallest 3D printer” developed at TU Wien. (TU Wien, 2011).*

On a more commercial note, the American company Formlabs Inc. have announced their first product, the Form1 in September 2012 (shown in figure 5.3). The Form1 is a “prosumer” printer with a build volume of 125 x 125 x 165 mm using photopolymerization. The Form1 uses a proprietary gray-colored resin and the company intends to develop and sell more materials in a variety of colors and flexibility. The company is pre-selling the device at c.a. 1800€ via Kickstarter. Both Formlabs and Kickstarter have subsequently been sued by 3D Systems in November 2012 for alleged patent violations related to the simultaneous curing of multiple layers (BBC News, 2012).

Figure 5.3. *The Formlabs Form1. (Formlabs, 2012).*

Considering the examples above, it seems that photopolymerization is suitable for microfactory-sized applications. Integration into an (automated) microfactory, however, would require research and development, as none of the presented machines provide means for automated control or material flow. The author concludes that profitable commercialization opportunities as well as viable research avenues exist, although these may be limited by patents.

5.3 Beam deposition

Beam deposition offers many interesting applications for microfactory-sized products. The main drawbacks of slow processing speeds mitigated by the small part size. Also, in a modular microfactory, the possibility of postprocessing the parts within the microfactory is not unrealistic. This could even be done with some degree of automation.

A distinct possibility would be to use a coaxial laser (e.g. the CAVIPRO laser presented in section 3.3.6.) in conjuction with the TUT microfactory module. The weight of the laser is only 2 kg, which is not too heavy for microfactory applications. However, as microfactories such as the TUT microfactory concept rarely have that degree of manipulation capability, the laser would have to be fixed and the workpiece consequently mobile. A conceptual model of this idea is presented in chapter 6.

5.4 Powder bed fusion

Implementing a full-featured PBF process within the constraints of a microfactory cell seems to be problematic. The nature of the process, with its roller and vertically moving bed, makes it difficult to fit into the small size of a microfactory. However, ReaLizer GmbH from Germany is selling the SLM 50, which is a tabletop-sized powder bed fusion machine. The machine weighs 80 kg and has outer dimensions of 800 x 600 x 500 mm. The build volume is 70mm in diameter with a maximum height of 40mm. The machine is aimed at dental and jewelry applications and is priced at 120000€. (Realizer, 2012, Wohlers, 2012).

An idea which arose out of discussions with researchers at TUT is a movable powder bed concept. Here the powder bed (including roller, reservoir and control systems) is a distinct component and can be paired with any laser to obtain the necessary process parameters. The powder bed could control the process (including the laser) via any of several communication options. The ideal size for the movable device would be in the range of 500 x 300 x 300 mm (L x W x H).

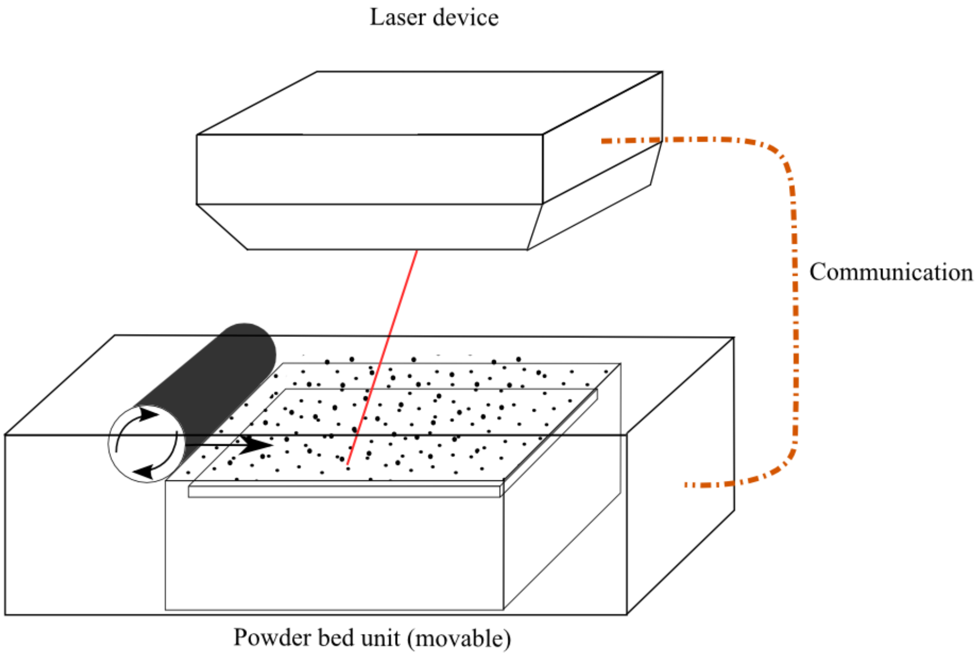

Figure 5.4. *Standalone powder bed concept illustration.*

The concept is aimed at reducing the setup times of laser processes while simultaneously offering a mobile setup to ensure optimal laser parameters can be obtained while producing parts. For example, with an easily movable setup, several lasers in geographically diverse locations can be tested.

6 PROPOSALS

To respond to the needs of future production and reap the benefits of AM/MF technology, some steps must be taken. This section lists some promising ideas which occurred to the author during the thesis process. Some concepts have been modelled and are shown in their respective sections. The models are provided for demonstration purposes only and have not been realized, validated or verified in any way. Commercial solutions provided some insights for the concepting process. Some issues which couldn't be modelled or demonstrated within the scope of the thesis include the control software, usability aspects and internal (within the microfactory) or external (to other devices) integration. These are interesting topics and well worthy of research and development in the future.

6.1 Production equipment

As exemplified by many cases in literature, additive manufacturing can be a valuable tool to enhance the product development process. However, to reiterate, the speed and accuracy of processes can prove problematic. Thus, a system combining both traditional machining and additive capabilities is desirable, such as the Mebotics Microfactory.

***Figure 6.1**. Mebotics Microfactory (Mebotics, 2013).*

The Mebotics microfactory, shown above in figure 6.1, consists of a enclosure containing the build platform, print heads, milling tool and control computer. The print heads and milling tool have a Cartesian work envelope. The milling tool can be used for both milling and etching and the standard spindle has 300 W of power. The machine can print in two materials or four colors at the same time (Mebotics, 2013).

While it is surely more than adequate for consumer (i.e. hobbyist) use, the Mebotics microfactory could be improved for industrial purposes. Revisiting the microfactory concepts introduced in chapter 2, we see that assembly capabilities and modularity have been heavily researched and demonstrated. In the author's opinion, these two attributes are critical for any industrial microfactory concept incorporating additive manufacturing. In this context, assembly capabilities mean that the system can manipulate individual parts in an automated manner and perform the desired joining operations, among other automated tasks. This has been successfully demonstrated by a variety of modular microfactories, as can be seen in Chapter 2.

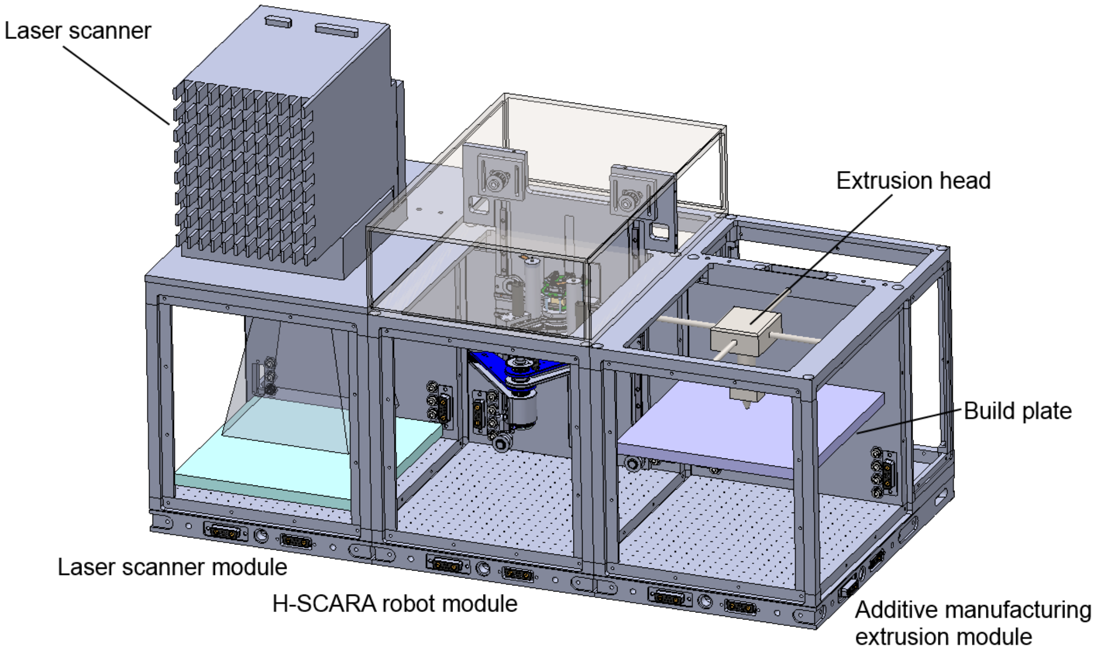

***Figure 6.2**. Modular microfactory concept consisting of a laser scanner module, H-SCARA robot module and AM extrusion module. Some parts are not shown.*

To illustrate some of the potential benefits, a theoretical concept has been modelled above in figure 6.2. This system incorporates three TUT microfactory modules: a laser scanner module for marking parts, an H-SCARA robot module (presented in subsection 2.2) to manipulate parts and finally an additive manufacturing extrusion module for printing plastic parts. The robot could transfer completed parts from the extrusion module to the laser scanner module for marking. For example, a barcode or a QR-code could be inscribed on the part directly after manufacturing for a variety of purposes.

While lasers have been used often in the context of industrial additive manufacturing machines, they are still rare in consumer devices (and hence in microfactory-sized modules). Some exceptions were introduced in the previous chapter. This subsection introduces some concepts for future laser additive manufacturing in microfactories.

There are many benefits for implementing laser AM in a modular microfactory. A key factor is safety considerations: the area which needs to be secured using laser-resistant materials is very small. This also lessens the expenditure of any gas used in the manufacturing process. If the process requires a cleanroom the small volume also reduces costs. Obviously the other benefits of modularity and small-sized production equipment (listed in chapter 2) are also fully applicable in this context.

Some drawbacks are the small build volume which of course means that part sizes will be quite small. Another is managing the excess heat from the process which could have an adverse effect on the part and the production system in such a small area. Additionally the laser chiller and power source can be quite large depending on the laser used in the process. While these can be situated nearby, e.g. underneath work surfaces, they might still hinder the portability and reconfigurability of the system.

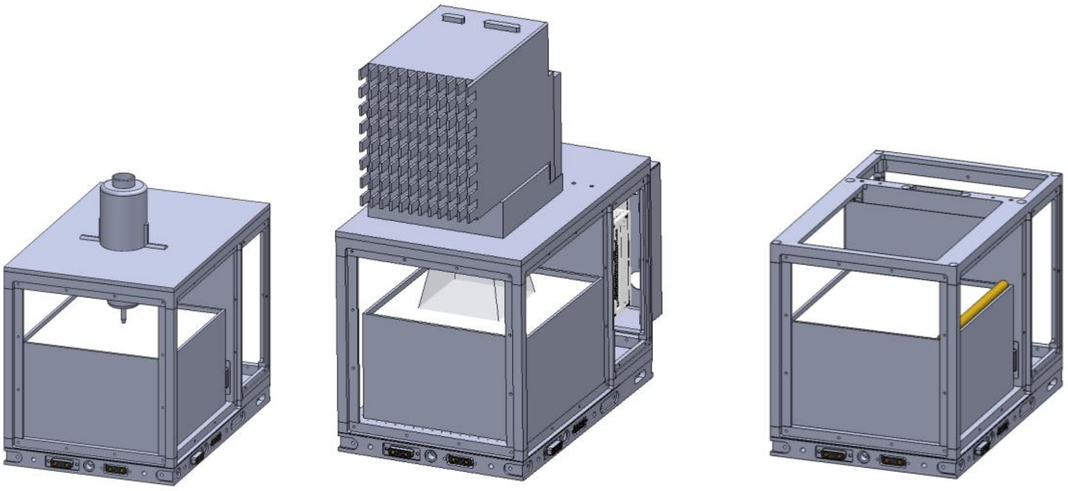

***Figure 6.3**. Some conceptual models for TUT microfactory modules.*
Left: Coaxial laser module for beam deposition.
Center: Laser scanner module for photopolymerization.
Right: Powder bed fusion module. Some parts omitted for clarity.

Figure 6.3 above shows three conceptual models of potential applications for the TUT microfactory: a coaxial laser module for beam deposition, a laser scanner module for photopolymerization, and a powder bed fusion module (shown here without a laser source). The modules are presented without material feeding or chilling equipment.

The coaxial laser module could be used to fabricate new parts but also coat or repair existing parts. Here the laser device itself is fixed which limits the part size (as the build plate would have to move in the X,Y and Z directions within the confines of the module). Moving the laser in the X and Y dimensions would make the build volume much larger but would then necessitate the need for a system to move the laser, which would be challenging to implement in the small size of a microfactory (due to the mass of the laser and the precision required). The coaxial laser uses powder or wire feeding.

The photopolymerization module shown in the center of figure 6.3 uses a laser scanner to harden the top layer of the liquid resin in the vat. Since the scanner can project a laser beam to any XY coordinates in its work envelope, the laser apparatus is stationary. Only the build plate moves in the Z-direction. This module is similar to many commercial products on the market today and could be used for prototyping and lightweight part construction.

The powder bed fusion module (figure 6.3, right) could be used to fabricate small-scale metal parts. No laser source has been shown as the required laser power is highly dependent on the material used. In some eventualities the module could even be used in a similar manner to the powder bed fusion concept illustrated in figure 5.4, i.e. it would be physically moved next to a laser device with the required power. If developed further, this module could be used in conjunction with other microfactory modules to produce jewelry or similar products even in the store.

6.2 Production concepts

Different production paradigms were presented and analyzed in chapters 1 and 4. However, new production equipment and workflows often result in new paradigms and products. Possible concepts and products relating to the AM/MF technical convergence are presented in this chapter and the next chapter.

A recent trend in production has been the significant growth of DIY or hobbyist production, as illustrated in chapter 3.4.3. A strong continuation of this trend may well lead to an increase in materials, machinery and product data suitable for home production. The additive microfactory is an ideal concept for this paradigm as it allows easy automation of production processes and allows for scaling the production quickly. In addition, all forms of metal manufacturing are presently underrepresented.

Moving from the domicile-level to the municipal level, AM microfactories might provide a boost to all forms of bespoke manufacturing. For example, when a customer purchases a car, some of the customization might be done in the dealership based on the customer’s measurements. This is an easy way to add value: customer engagement is increased and the customer gets a better product. This can be applied to any reasonably modular product, such as golf clubs, mobile phones, televisions, etc. As the knowhow required to manipulate product data and production equipment decreases, the barriers to this type of business will become significantly lower.

The next few decades will also mean changes in all types of production systems. An exciting concept is an automatically reconfigurable production system, which can generate fixtures and tooling automatically based on the desired product. On a whole different level, automatically generated process plans and physical configurations can be envisioned. An ideal automatic reconfigurable production system will probably be modular, with module size and interconnectivity being critical issues. Also, additive manufacturing is one of the easiest ways to construct custom fixtures, grippers and parts even today, so it is very likely that it will play a critical role in these types of systems.

6.3 Products

In the future, the way we view products will change. Mass production will have to adapt to the demands of customers who are used to an entirely different level of personalization in their purchases. Customization and personalization are trends which will become dominant in consumer goods over time and this means modularity and flexibility in production processes, workflows, product data and product architecture.

The rise of the “Internet of things” also leads one to imagine a future of smart products, which can access the internet autonomously in order to perform tasks for the end-user and the producer. Something similar to this already exists in jet engines and certain cars, and the paradigm will probably extend further in the years to come. This might lead to more refurbishing and local production of products.

When production methods and systems become automated enough, designing new products becomes more a matter of aesthetics than of engineering. Obviously people will design (and manufacture) their own, unique products in the future, but there is also a possibility to have procedurally generated products. This means that the product specifications and data are generated automatically and the actual product is manufactured by request. We are already seeing hints of this in online clothes retailing today.

In conclusion, production systems as we know them are facing massive changes as we head towards 2020 and beyond. Only time can tell which paradigms and concepts will emerge as dominant ideas on the world manufacturing stage, but it seems certain that additive manufacturing and microfactory-sized production will play a large if not critical part in future production on a local, national and international level. This is an area of research with many possibilities especially concerning the process, automation and production data areas of the technologies involved and hopefully in the future we will see some progress made in these areas.

7 CONCLUSIONS

In the introductory chapter, three research questions were defined that this thesis attempted to answer. This final chapter summarizes the answers to the questions one-by-one and ends on some general remarks by the author.

RQ1: What is the current state of both microfactory and additive manufacturing technology?

This question was answered in chapters 2 and 3. It is evident that both technologies are maturing rapidly and have potential for future success. While additive manufacturing is the more known of the two, it is merely a production process while microfactories are essentially a radical disruption of the traditional mass production concept.

RQ2: What are the motivations and benefits of integrating additive manufacturing into microfactories?

To justify the direction and motivations for the research, existing and future manufacturing paradigms were analyzed in Chapter 4. Mass customization and sustainable production were proposed by Jovane et al. (2003) and to account for the emergent trend of peer production, the new digiproneurship paradigm proposed by Fox & Stucker (2009) was included in the analysis. The principles of the paradigms were examined to obtain the requirements, resulting in the table below.

***Table 7.1**. How paradigm requirements can be answered (Chapter 4.)*

Production paradigm	Requires	Implemented by
Mass customization	Flexibility	Modular production systems Rapid reconfigurability
	Customer intentions	
Sustainable production	Energy saving	Miniaturization
	Recycling	Traceability
Digiproneurship	Distributed production systems	Small-scale production equipment
	Distributed product development	Product development software

To respond to the requirements, some technical solutions are required. Based on the above table, we see that microfactories are a valid solution for these challenges. However, as chapter 4 clearly stated, there are some barriers(technological and business) to microfactory adoption for large-scale production operations. Incorporating additive manufacturing could prove valuable in increasing the attractiveness of the technology to potential investors.

RQ3: Which additive manufacturing technologies are suitable for implementation in a microfactory?

Based on the technology analysis done in chapters 2 and 3, four additive manufacturing processes were selected as promising candidates for implementation in microfactories. They were: extrusion, vat photopolymerization, beam deposition, and powder bed fusion. The excluded technologies (printing, sheet lamination) are, in the author's opinion, not sufficiently developed for integration at the present. All of the selected technologies had already been implemented at near microfactory-size in some form or another. However, powder bed fusion was considered to be challenging to implement in microfactory-size, as demonstrated by the high cost of the ReaLizer SL50 (chapter 5.4).

Chapter 6 illustrated the four selected additive manufacturing processes as TUT microfactory modules. While the module implementation was not verified, the commercial applications in the same size (as seen in chapter 5) are a good indicator of the technical viability of the modules. The modules could be connected to a wider production system also consisting of modules, however a degree of work would be required to examine the hardware and software needs of any sort of automation. Once these requirements are solved, the system would be quite flexible and have a wide variety of capabilities, from traditional machining to assembly operations to additive manufacturing and beyond.

During the thesis process, the idea of implementing additive manufacturing in microfactories was validated by both the author's own research and a commercial implementation (see chapter 6.1). However, a true industrial and/or modular concept (as demonstrated in chapter 6.1 by the author) has yet to be realized. While the idea remains attractive, significant research and development is required before a real-life prototype could be realized. Production and research trends are driven by megatrends more than most research and development and it remains to be seen if the drive for sustainability, customization and distributed production will lead to a widespread adoption of microfactories capable of additive manufacturing.

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