POSSIBILITIES OF ADDITIVE MANUFACTURING TECHNIQUES IN INNOVATIVE PRODUCT DESIGN PROCESS

Lappeenranta–Lahti University of Technology LUT

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Else Lagerstam

Examiners: Professor Harri Eskelinen

Katriina Mielonen, D.Sc. (Tech.)

ABSTRACT

Lappeenranta–Lahti University of Technology LUT
LUT School of Energy Systems
Mechanical Engineering

Else Lagerstam

Possibilities of Additive Manufacturing Techniques in Innovative Product Design Process

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77 pages, 24 figures, 5 tables and 2 appendices

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Keywords: AM, 3D, additive manufacturing, innovative product design process, product design, creative, design process model, Design Thinking

This research studies the possibilities of additive manufacturing (AM) in innovative product design process. The goal of this research is to find out on what basis the researched AM techniques could be utilized in innovative product design process. Furthermore, the aim is to study whether the ways of utilizing the researched AM techniques in innovative product design process are generalizable to other AM techniques. For researching this subject, a methodological triangulation of scientific literature review, commercial references review, and expert interviews is utilized. The review of scientific references is conducted and evaluated in traditional manner. In the review of commercial references, the data is boarded to customer stories of such companies that provide AM devices, AM services, and AM expertise services for other companies. Expert interviews are made remotely for five different kinds of experts. The experts are interviewed by utilizing semi-structured interview method.

The results of this research point out that product design process model should enable for example, flexibility, design freedom, and countless iteration rounds for being suitable to be utilized in innovative AM product design. AM techniques enable doing parallel the different phases of iteration rounds. Thus, they make design processes faster. As a result of the evaluation of the conducted data, a comparison of four different product design models, VDI 2221, reverse engineering process model, concurrent engineering (CE) process model, and Design Thinking process model, is made from innovative AM product design process viewpoint. Moreover, a process model combination of Design Thinking, CE, and reverse engineering (DTfIAM) is proposed for innovative AM product design process. This novel approach may be utilized by AM designers and industrial design engineers. In addition, this research addresses that innovative AM product design process utilizing these design process models is equally possible with plastics and metals AM techniques. However, plastics AM is more suitable for innovative product design for it allows plethora of iteration rounds due to its cost-efficiency comparing to metals AM. In the future the compared product design models and the proposed combination model ought to be tested in practise. Further, additional design process models could be studied and compared from similar viewpoint.

TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT
LUT Energiajärjestelmät
Konetekniikka

Else Lagerstam

Lisäävän valmistuksen mahdollisuudet innovatiivisessa tuotesuunnitteluprosessissa

Konetekniikan diplomityö

2022

77 sivua, 24 kuvaa, 5 taulukkoa ja 2 liitettä

Tarkastajat: Professori Harri Eskelinen ja Katriina Mielonen, TkT

Avainsanat: AM, 3D, lisäävä valmistus, innovatiivinen suunnittelu, luova suunnittelu, tuotesuunnittelu, luova, suunnittelumalli, Design Thinking

Tämä tutkimus käsittelee lisäävien valmistusmenetelmien (LV) mahdollisuuksia innovatiivisessa tuotesuunnittelussa. Tutkimuksen tavoite on selvittää, millä perusteella tutkitut LV-tekniikat ovat hyödynnettävissä innovatiivisessa tuotesuunnittelussa. Lisäksi tarkoitus on saada selville, ovatko tutkittujen LV-tekniikoiden hyödyntämismahdollisuudet innovatiivisessa tuotesuunnitteluprosessissa yleistettävissä muihin LV-tekniikoihin. Tämän aiheen tutkimiseksi käytetään menetelmä-triangulaatiota, joka koostuu tieteellisestä kirjallisuuskartoituksesta, kaupallisten lähteiden kartoituksesta ja asiantuntijahaastatteluista. Tieteellinen kirjallisuuskartoitus on luonteeltaan traditionaalinen. Kaupallisten lähteiden kartoitus rajautuu LV-laitteita, LV-palveluita sekä LV-asiantuntijapalveluita toisille yrityksille tarjoavien yritysten verkkosivuihin. Asiantuntijahaastattelut ovat puolistrukturoituja teemahaastatteluja.

Tämän tutkimuksen tulokset osoittavat, että mahdollistaakseen innovatiivisen LV-tuotesuunnittelun, suunnittelumallin tulisi sallia esimerkiksi joustavuus, suunnittelun vapaus sekä rajaton iterointi. LV-tekniikat tekevät mahdolliseksi suunnitteluprosessin iteraatiokierrosten eri vaiheiden läpikäymisen limittäin tai yhtaikaa. Näin ollen LV-tekniikat nopeuttavat suunnitteluprosessia. Kerätyn aineiston läpikäynnin ja yhteenvedon tuloksena tehdään neljän suunnittelumallin vertailu. Vertaillut kohteena ovat VDI 2221, käänteisen suunnittelun, rinnakkaisen suunnittelun sekä muotoiluajattelun mallit. Niitä vertaillaan innovatiivisen LV-tuotesuunnittelun näkökulmasta. Lisäksi ehdotetaan muotoiluajattelua, rinnakkaissuunnittelua ja käänteissuunnittelua yhdistävä malli (DTfIAM) innovatiivista LV-tuotesuunnittelua varten. Uutta lähestymistapaa voivat hyödyntää esimerkiksi LV-suunnittelijat ja teolliset muotoilijat. Tämä tutkimus osoittaa myös, että innovatiivinen LV-tuotesuunnittelu onnistuu sekä muovia käyttävillä että metallia käyttävillä LV-menetelmillä. Muovia käyttävät LV-menetelmät ovat kuitenkin edullisempia ja siksi käyttökelpoisempia lukuisia iteraatiokierroksia vaativassa innovatiivisessa tuotesuunnittelussa. Tulevaisuudessa sekä vertaillut tuotesuunnittelumallit että uusi malliehdotus tulisi testata käytännössä. Lisäksi muitakin suunnittelumalleja voitaisiin tutkia ja verrata samasta näkökulmasta.

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ABBREVIATIONS

3D	Three-dimensional
$ADAM^2$	Augmented Design with AM Methodology
AM	Additive Manufacturing
APM	agile product management
CAD	Computer-aided Design
CE	Concurrent Engineering
CM	Conventional Manufacturing
DfAM	Design for Additive Manufacturing
DI	Design Innovation
DIwAM	Design Innovation with Additive Manufacturing
DTfIAM	Design Thinking for Innovative Additive Manufacturing
IPD	integrated product development
LUT	Lappeenranta–Lahti University of Technology LUT
NPD	New Product Developments
SL	Stereo Lithography
VDI	Association of German Engineers

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Tiivistelmä

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Appendix 1. Expert interview questions in Finnish

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1 Introduction

Additive manufacturing (AM) techniques, also commonly known as 3D printing, are constantly becoming more popular as an alternative for conventional manufacturing (CM) techniques. AM techniques provide a vast range of possibilities for AM allow a variety of techniques and materials. In many cases, when mass production is not required, AM techniques enable material, production time, and cost savings comparing to CM techniques. (Divakaran et al. 2022; Savolainen & Collan 2020) Various AM techniques provide freedom of design and strategy for innovation. In addition, they provide waste minimization and possibility to fabricate complex structures with rapid prototyping. (Divakaran et al. 2022) Thus, AM techniques may be considered as state-of-the-art production methods which utilizing possibilities ought to be mapped. Many users use AM techniques for rapid prototyping, which is a part of product design process (Savolainen & Collan 2020; Schniederjans 2017). Hence, AM techniques are already widely used as a part of design processes. However, Taborda et al. (2021) concluded in their review that products developed with the AM techniques has a lack of innovation. This means that AM techniques allow merely limited amount of creativity. Nonetheless, possibilities for utilizing AM techniques in innovative design process are somewhat uncharted. Furthermore, scientific literature lacks a comprehensive outline about utilizing AM techniques in different kinds of product design processes. Also, a summative process model for guiding AM utilization in most innovative and creative way in a product design process is missing. This thesis describes a literature review emphasized research which aims to recognize the possibilities of utilizing AM techniques in four different design process models. In addition, the study aims to find out which kind of product design process model enables highest creativity and innovativeness in design utilizing AM techniques. The research also discusses what kind of added value AM techniques may bring to creative and innovative design process. Furthermore, as a result of the process model comparison a process model for utilizing AM techniques in innovative design process is suggested. This kind of approach and process model may benefit designers to select the most suitable design process model for creative and innovative AM utilizing design in the future. The approach and process model can be used as a support in generating novel and innovative product design ideas.

1.1 Research Problem

When considering utilizing AM techniques in an innovative product design process, the strictly phased proceeding of AM process may be a notable limitation from unlimited creativity and innovation point of view. Hence, on the one hand, it may be argued that AM techniques represent predesigned and controlled technique. Whereas, on the other hand, innovation stand for unlimited and creative process where the designer and his or her personal characters play a key role. Finding suitable ways to fit AM and innovative design in the same process in the way that innovation process is not confined may be challenging. In other words, finding a way for AM to benefit creative and innovative design process might not be straightforward.

In the Figure 1 is presented the research problem as a continuum. The light blue box on the left indicates a product which is designed from the manufacturing point of view. In this kind of case may be argued that the product lacks innovativeness at least to some extent for the product cannot be designed without definite manufacturing consideration. It can be argued that AM as a manufacturing technique has such limitations because in design for AM the product must be designed considering the AM process. The yellow ball on the continuum (Figure 1) indicates the boundary conditions that AM techniques have related to product design. The light blue box on the right (Figure 1) indicates the situation where the manufacturing consideration of the product design is minimized and, thus it does not set boundaries for product design and further, for innovation in product design. It can be argued that product friendly manufacturing supports innovative product design which is presented as a purple ball under the product design continuum (Figure 1). The vertical dot line in the middle of the continuum (Figure 1) describes the leeway that the balls can move towards to the opposite side of the continuum. However, the vertical dot line may also be moved.

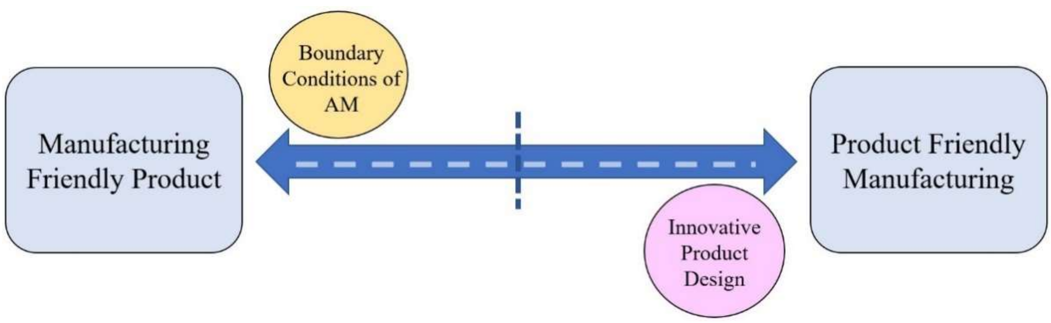


Figure 1. The research problem continuum.

The Figures 2 and 3 describes other possible positions of the balls comparing to Figure 1. All the Figures (1–3) are examples of how AM can benefit innovative design process and what kind of boundary conditions AM may have related to innovative product design process.

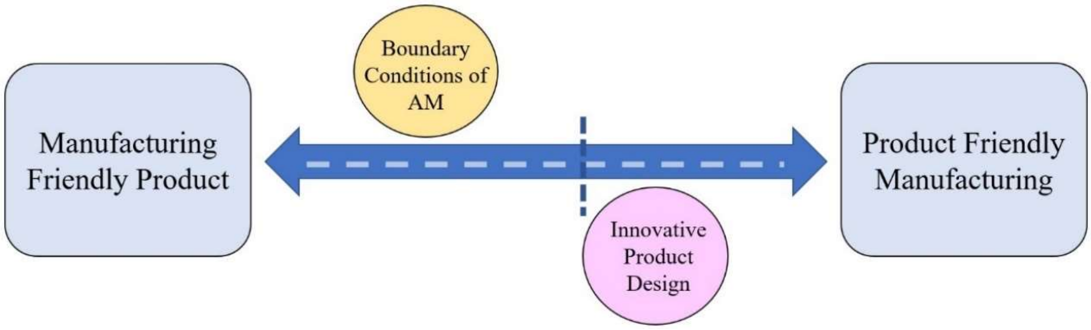


Figure 2. The research problem continuum where the yellow ball is located a bit closer to product friendly manufacturing. Correspondingly, the purple ball is closer to manufacturing friendly product. Also, the vertical dot line locates more on the right side of the continuum.

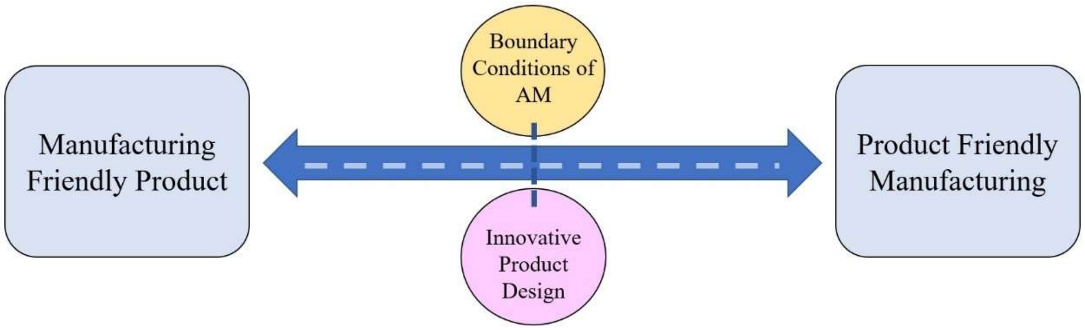


Figure 3. The research problem continuum where both balls are in the middle of the continuum.

These continuums (Figures 1–3) illustrates the research problem continuum by showing examples of how boundary conditions of AM and innovative product design may set between manufacturing friendly product and product friendly manufacturing.

1.2 Objective of the Research

The aim of this research is to gather an outline about utilizing AM techniques in innovative product design process. The outline is gathered via scientific literature, commercial references, and expert interviews. The outline aims to recognize pros and cons of AM techniques from creative and innovative product design process point of view. In addition, the goal is to create a process model for utilizing AM techniques in innovative product design process. Hence, the objective of this research is to find the best ways to use AM techniques to benefit creative and innovative product design process and bring added value to it. The objective is also to consider whether the results of the studied AM techniques may be generalized in all the AM techniques.

The Figure 4 describes a design process model continuum. On the most left (Figure 4) is VDI 2221 (VDI 2221:1993-05) process model which is an example of traditional controlled and straightforward phase by phase proceeding design process model. In traditional process model steps between phases are taken forward not backwards without iteration. (Jänsch & Birkhofer 2006) On the most right (Figure 4) is Design Thinking process model which is an example of free and highly iterative process model where the designer has freedom to step forward and back between the process phases freely. The Design Thinking process model underlines utilization of user-centred approach. (Brenner et al. 2016, pp. 6–7; Moran 2021) The purple balls under the continuum represents reverse engineering (for example Otto & Wood 1998) and concurrent engineering (CE) (Eppinger 1991) process models which are process model examples lying somewhere between VDI 2221 and Design Thinking. For one of the goals in this research is to create a process model for utilizing AM in innovative product design process the Figure 4 gives guidance for creating such model. As reverse engineering and CE process models the process model for utilizing AM in innovative product design process will be somewhere between VDI 2221 and Design Thinking on the model continuum (Figure 4).

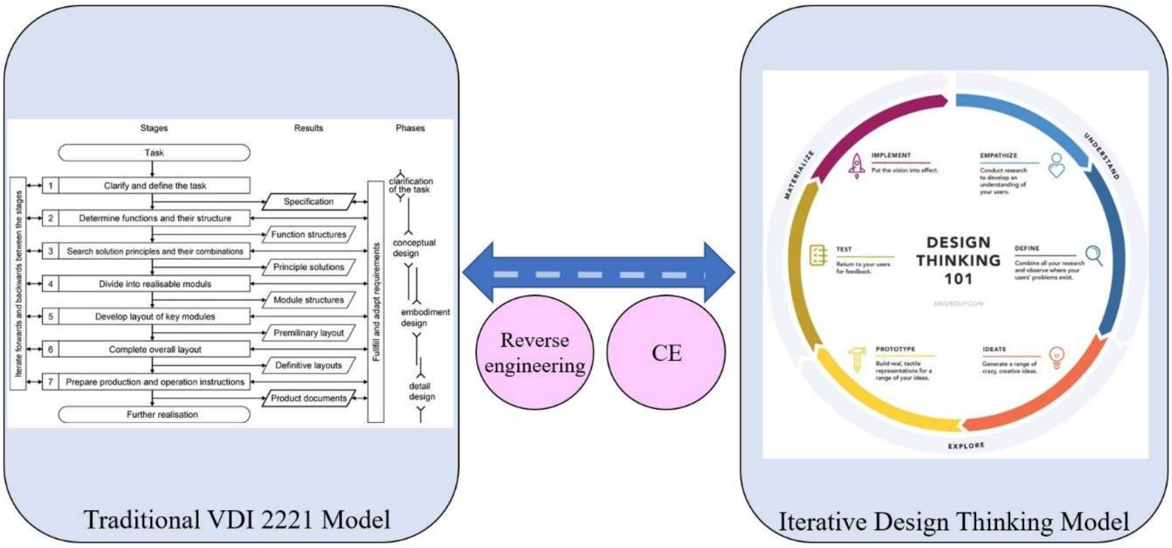


Figure 4. Innovative product design process including AM model continuum. (Model figure references: Bathelt et al. 2005; Moran 2021)

The innovative AM product design process continuum in Figure 4 illustrates the differences between traditional engineering product design model (for instance VDI 2221) and iterative product design model (for example Design Thinking).

1.3 Research Questions

The main research question is:

On what basis the researched AM techniques could be utilized in innovative product design process?

In Figure 5, the purpose of the main research question is presented with similar continuum than in chapter 1.1 (Figures 1–3). However, the continuum line between manufacturing friendly product and product friendly manufacturing is minimized. The Figure 5 presents the situation that follows answering the main research question. In other words, on what basis could be achieved a situation presented in Figure 5 where the concepts of manufacturing friendly product and product friendly manufacturing are, if not the one and same thing, at least very close to each other, and predefined AM process benefits uncontrolled innovative product design process.

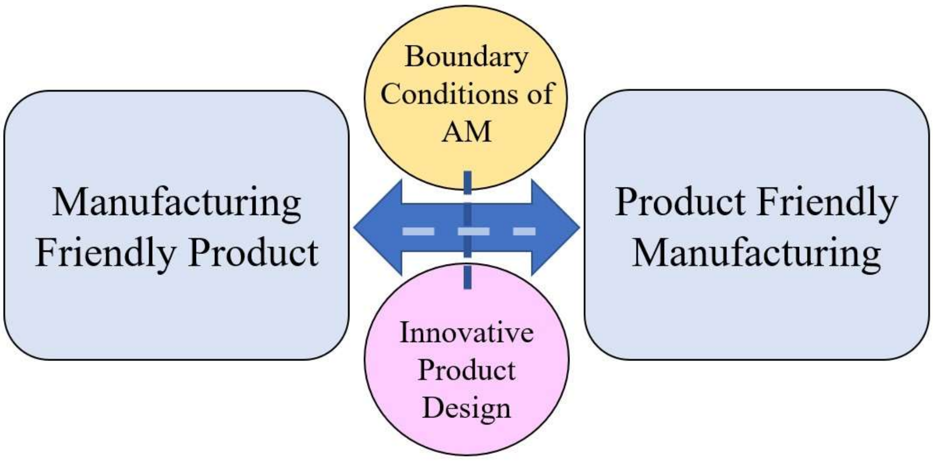


Figure 5. The research question continuum.

An additional research question is:

Are the ways of utilizing the researched AM techniques in innovative product design process generalizable to other AM techniques?

1.4 Research Methods

The research topic and the research question require a triangulation approach (Figure 6) which combines data from many sources. The topic is firstly researched by reviewing related scientific literature. Secondly, related commercial references are mapped and researched. Finally, expert interviews are made. In expert interviews different kinds of experts (Figure 6) are interviewed for gathering comprehensive number of varying viewpoints. Then, after gathering the research material via these three ways, the gathered data is evaluated and combined for answering the research question.

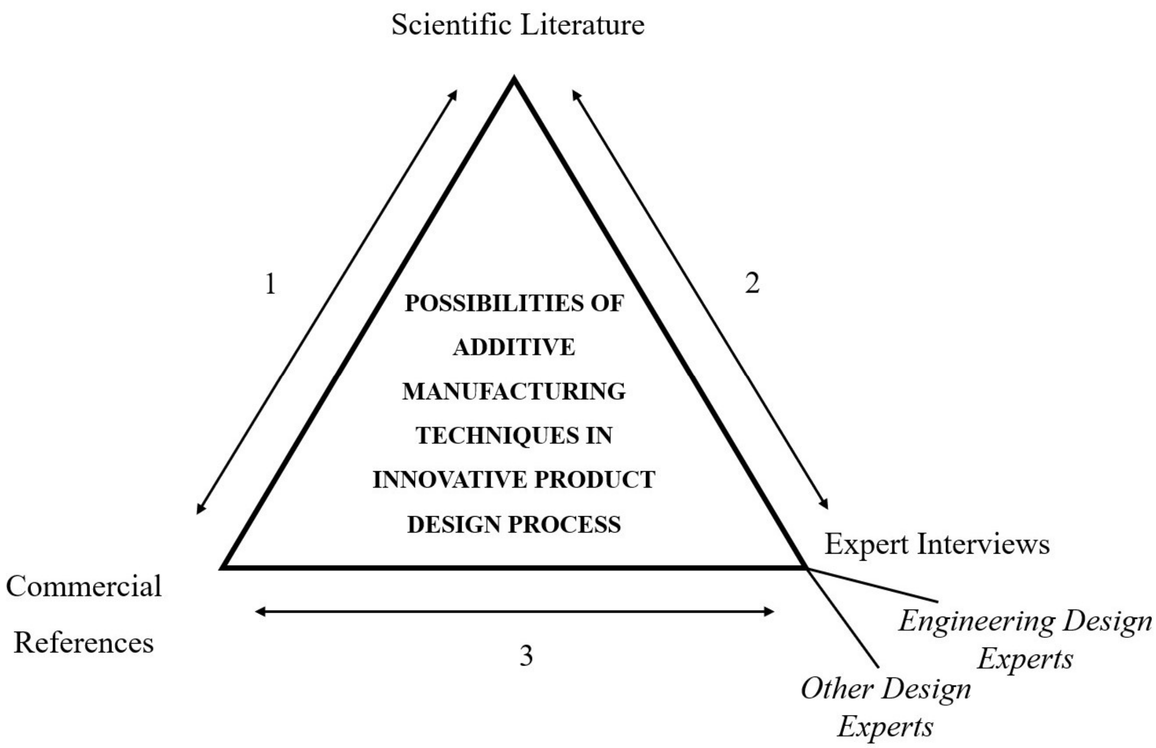


Figure 6. Utilized method triangulation.

As in the Figure 1 are illustrated, after research actions the aim is to compare gathered information to each other. Firstly, scientific literature information is compared to commercial references data (Figure 6, “1”). Secondly, expert interviews data is compared to both scientific literature information (Figure 6, “2”) and commercial references data (Figure 6, “3”) to find out whether experts insights related to the research topic support viewpoints which have come out from scientific literature information and commercial references data. Hence, experts’ interviews are utilized to provide further information for comparing if similar kinds of aspects can be found from all the three information sources.

1.5 Research Scope

For there are numerous different design process models to be utilized in product design processes, it is justifiable to border the researched models into four commonly used product design process models. Thus, this research comprises AM utilization for creative and innovative product design in traditional engineering process model VDI 2221, reverse engineering process model, concurrent engineering (CE) process model, and design thinking process model which is commonly used in innovation design processes.

The research considers all AM techniques and materials. In polymers utilizing AM techniques there are low-cost options which may provide lower threshold adaptation into innovative product design process and thus, wider freedom of usage in design process. In addition, a general rule of thumb is that a metal AM print design ought to be firstly tested with polymer material for metal material is more expensive. If the print fails with polymer, it will not succeed with metal either. Hence, polymers using AM techniques are perhaps the most obvious choice from innovative product design process viewpoint. However, though in this research the polymer utilizing AM techniques are emphasized that does not exclude covering for example metal AM techniques as well.

1.6 Structure of the Thesis

The thesis consists of six main chapters in the following order:

1. Introduction
2. Related Literature
3. Detailed Description of the Research Methods
4. Results
5. Discussion
6. Summary

2 Related Literature

According to the definition of additive manufacturing (AM) it is a process in which parts or components are built directly from a solid model utilizing a source of heat and filler material. AM process starts with creation of a 3D model via computer aided design (CAD) program. The data of the model is separated into layers by AM systems for final printing and production of the product layer by layer (Figure 7). (de Almeida et al. 2021; Badiru et al. 2017, pp. 4–5; Divakaran et al. 2022; Dutta et al. 2019, p. 2) This is different from "traditional" manufacturing where material is for instance, removed. Thus, "traditional" manufacturing is subtractive in nature. The three principal AM technologies are material extrusion, powder bed fusion, and vat photopolymerization. (Steenhuis & Pretorius 2017) One major advantage of AM is that it makes construction of complex geometries possible. The kinds of geometries may be for instance, honeycombs and lattices (Figure 8) which are impossible to create via conventional manufacturing (CM) methods. (Perez et al. 2019; Savolainen & Collan 2020) AM is capable to produce items from various materials such as polymers, gels, wax, fibres, ceramics, and metals (Perez et al. 2019). However, AM techniques cannot replace all the CM methods. For instance, forging, casting, and machining are the kind of CM processes that AM cannot substitute. Perhaps, the best way to consider AM utilization is as an additional tool for designers. AM is a tool that allows remarkable amount of design freedom. Furthermore, AM decreases the design-to-market time considerably and hence, helps innovation in the market. (de Almeida et al. 2021; Dutta et al. 2019, p. 7)

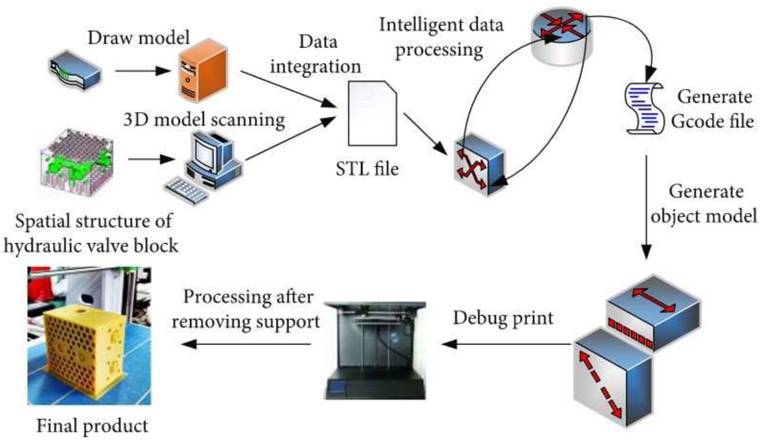


Figure 7. AM printing operation flow chart (Sun & Lv 2021).

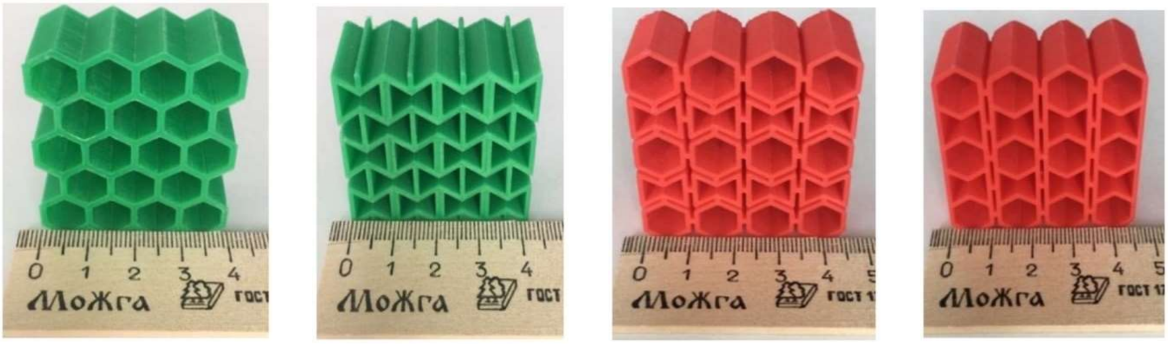
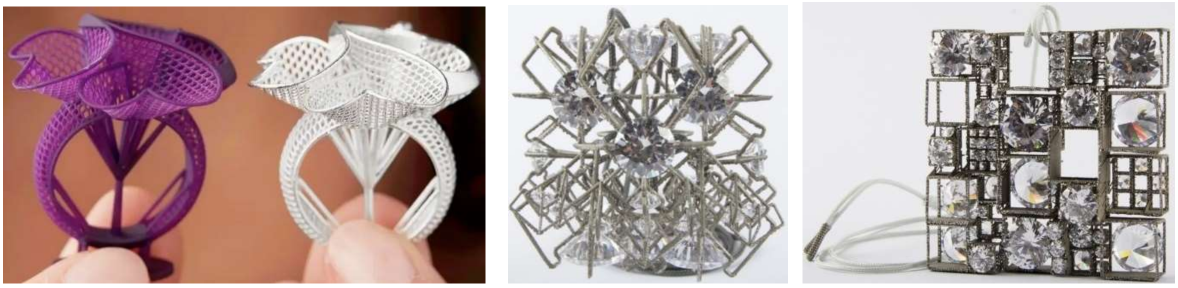


Figure 8. Examples of the kind of complex geometries AM enables (Hazrat Ali, Md et al. 2021).

The history of AM extends to at least to 1920. At that time Baker used an electric arc and metal electrode to produce walled structures and decorative articles. However, nowadays AM techniques create parts directly from CAD data integrating the layered manufacturing concepts. The first commercial versions of AM techniques were introduced Systems Corp. in 1987 when they introduced stereo lithography (SL) based system for 3D printing. (Dutta et al. 2019, pp. 3–6) From the beginning of the development of commercial AM techniques they have been introduced primarily to be suitable for rapid prototyping. (Killi 2017, p. 6; Savolainen & Collan 2020; Schuh et al. 2018) Nevertheless, nowadays AM is considered as a relevant option for CM when mass production is not needed. Smaller numbers of products with great production flexibility and customization can be produced economically via AM (for example Figure 9). Hence, AM enables for instance, economical spare part manufacturing and thus, better production sustainability with material savings. (Dutta et al. 2019, pp. 1–2) Furthermore, AM has enabled new business and service models. For instance, parts may be fabricated or customized to the end-user at the point of consumption. (Perez et al. 2019) For designers AM methods enable designing 3D objects and fabricating them swiftly and cheaply in offices. Thus, designers can fast and flexibly examine the physical form of their design. After evaluating their design and doing the needed modifications and achieve the ideal product. (Kantaros et al. 2022)



A B C

Figure 9. A) Conventional jewellery design produced with AM (Formlabs 2019). B) and C) AM aided jewellery art by Adam Grinovich (Grinovich 2022).

The detailed design of AM produced components and products is called design for additive manufacturing (DfAM). Usually, the term relates to design principles and tools which aid to considerate the optimal functional performance, reliability, manufacturability, and costs of AM products. DfAM aims to take the full advances of AM technologies and processes. Methods or tools like topology optimization, mass customization, and multi-material design are the most typical DfAM examples. (Hu et al. 2006; Perez et al. 2019; Pradel et al. 2018) For instance, topology optimization means producing optimized geometries with optimized strength to weight ratios. This is needed for example in automotive and aeronautic industries where the lightness of the parts is important. Hence, DfAM is essential in AM product design. (Primo et al. 2017) The level of applicability and specificity of the DfAM design principles vary. Some of the principles may be applied to all AM technologies while other of the principles are specific to certain AM technologies. An example of these low-level technology specific design principles is shown in the Figure 10. (Hu et al. 2006; Perez et al. 2019; Pradel et al. 2018)

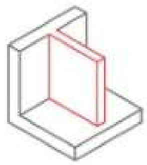
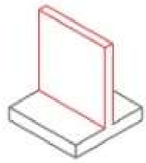
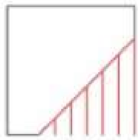
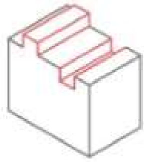
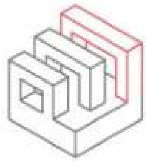
	Supported Walls	Unsupported Walls	Support	Embossed & Engraved Details	Horizontal Bridges
					
Fused Filament Fabrication	0.8 mm	0.8 mm	45°	0.6 mm wide & 2 mm high	10 mm
Stereo-lithography and Direct Light Processing	0.5 mm	1.0 mm	support always required	0.4 mm wide & high	×
Selective Laser Sintering	0.7 mm	×	×	1.0 mm wide & high	×
Material Jetting	1.0 mm	1.0 mm	support always required	0.5 mm wide & high	×
Binder Jetting	2.0 mm	3.0 mm	×	0.5 mm wide & high	×

Figure 10. An example of low-level technology specific DfAM principles (Redwood et al. 2017, p. 268).

According to the research of Zhu et al. (2017) the DfAM guidelines have traditionally considered detailed design stage. Therefore, they have proposed a holistic framework (Figure 11) which considers the whole AM design process and hence, provides guidance for all the design process stages. The aim is to enable designers design freedom with maximum benefit of AM possibilities. (Zhu et al. 2017)

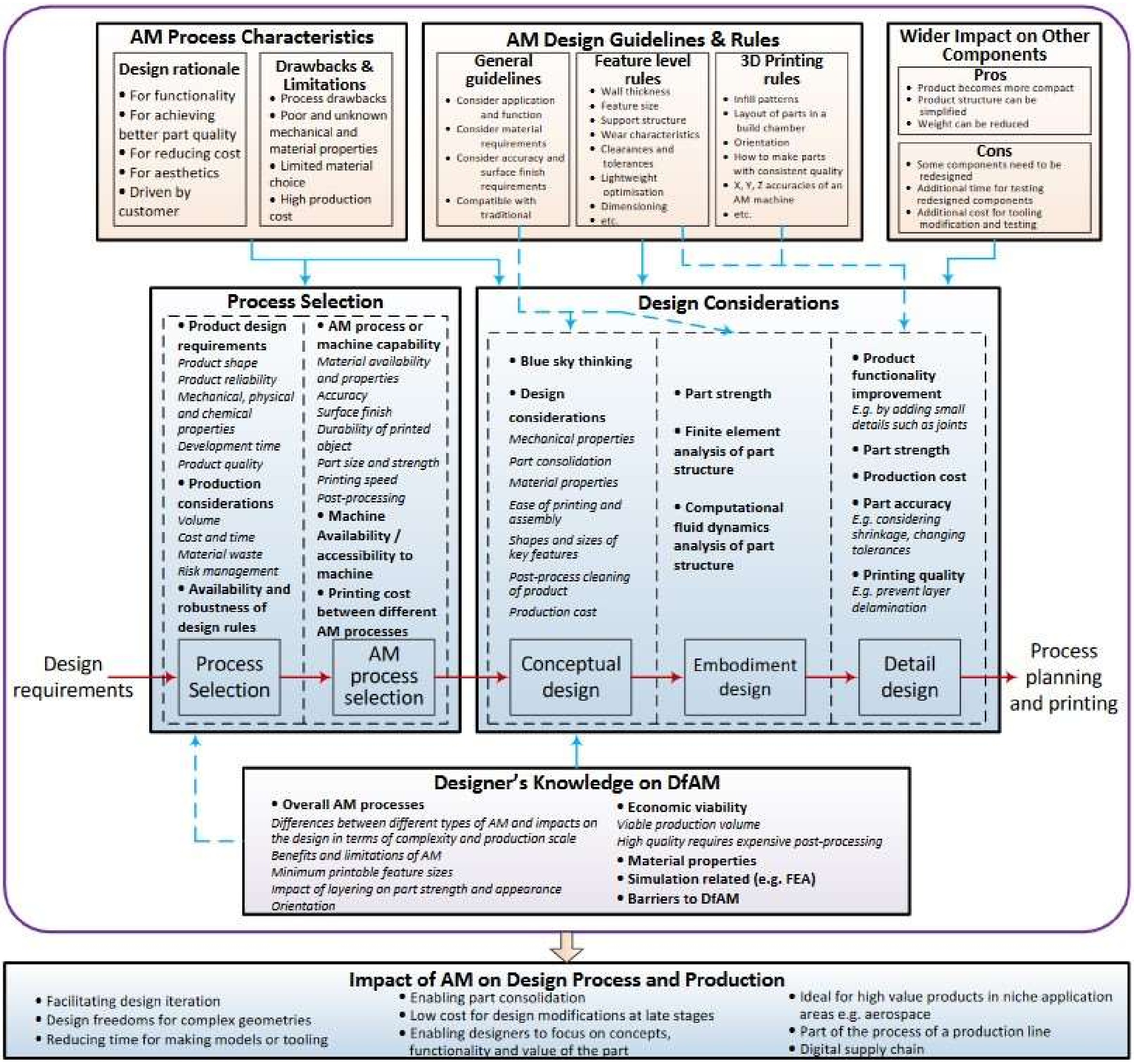


Figure 11. The framework for designing end use components / products for AM by Zhu et al. (2017).

According to Perez et al. (2019) the advancement of AM technology and design tools as well as the standardization of AM industry and technology terminology have enabled for instance the use of new materials and processing of multiple materials. Also, the processing time has decreased, and the quality of AM products improved. These improvements have made innovative AM outputs increasingly probable. Hence, AM technology makes new kinds of innovation in engineering product development possible. (Perez et al. 2019)

This paragraph has briefly backgrounded relevant AM related literature. In the further paragraphs the innovative product design is firstly backgrounded and then literature related to innovative product design and AM is presented. Finally, the four different product design process models compared in this research are itemised.

2.1 Innovative Product Design

Innovation and creativity are often described with three words: novelty, usefulness, and surprise (Han et al. 2019). This means that for being innovative and creative a product must be new in some perspective, suitable and usable for its purpose, and surprising in some way. Corpley (2015, p. 218) describes the creativity as generation of effective novelty. Thus, novelty and effectivity are the fundamental demands for creative product. He continues that innovation, then, means a certain focus on the utilization of the effective novelty. (Corpley 2015, p. 218) Corpley (2015, pp. 71–73) also presents the hierarchy of creativity criteria (Figure 12) which determines the parts of creative product to be effectiveness, novelty, elegance, and genesis.

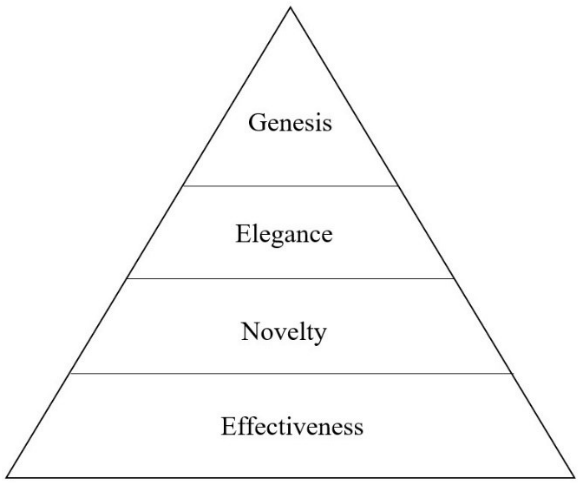


Figure 12. The hierarchy of creativity criteria by Corpley (2015, p. 72).

Innovation is considered as consisting of three phases: ideation, development, and launch (Candi & Beltagui 2019). Creativity is an essential character and source of innovative product design. However, it is still somewhat mysterious element of human thinking. Creativity can be described as a combination of new ideas and concepts which restructure and re-associate existing ideas. (Hsiao & Chou 2004) Howard et al. (2008) underline that in engineering design process creativity is an essential and integral part. They continue that innovation is not possible without creativity in design. Hence, innovation may be considered as an implementation of the results of creativity. (Howard et al. 2008; Hsiao & Chou 2004) Howard et al. (2008) describe the innovation process as a kind of black box processing a lot of design related information instead of producing many kinds of design outputs, some of which may be considered as 'creative'. (Howard et al. 2008)

For being a fundamental part of human thinking creativity and components of creativity has been studied a lot and for decades from different viewpoints (Ferrari et al. 2009, pp. 5–14; Han et al. 2019; Tomiyama et al. 2009). For instance, Taylor (1988, pp. 99–121) have presented the end-product approach of creativity which suggests that creativity is a process that results in a product or work or output. Finke et al. (1992) and Cropley (2015, p. 10) have underlined creativity as a process which has different phases. Figure 13 describes phase model of creative problem solving or innovation by Cropley (2015, pp. 51–50). However, the creative process is non-linear and includes free iteration (Finke et al. 1992).

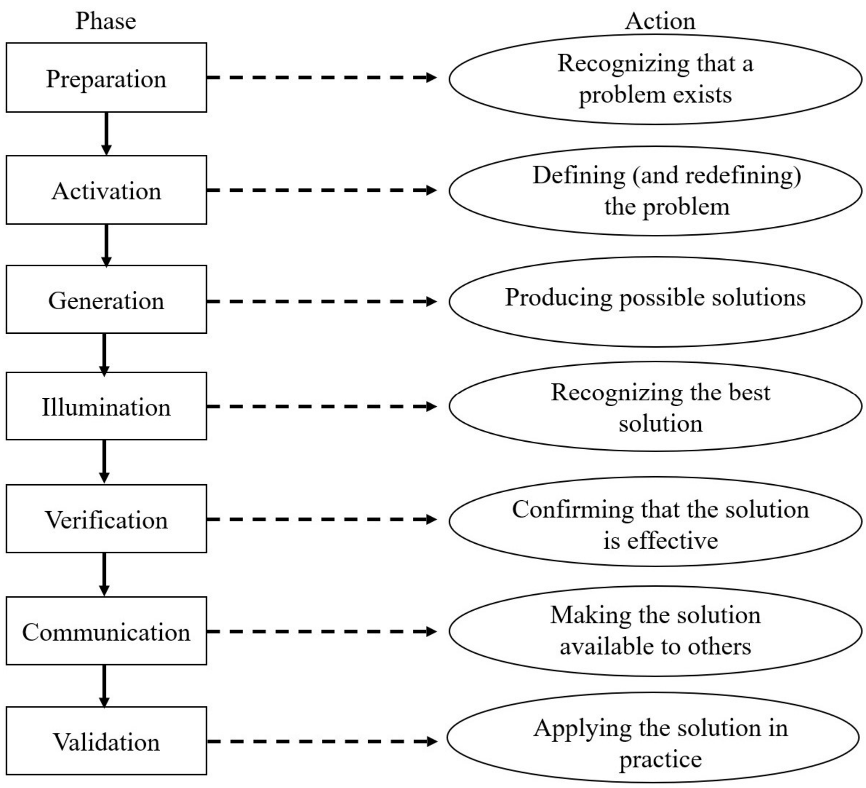


Figure 13. Phase model of creativity according to Cropley (2015, p. 50).

According to Amabile (1998) the three components of creativity are motivation, expertise, and ability for creative thinking (Figure 14). This approach is somewhat commonly used when describing creativity and characters which leads to creative results. (Ferrari et al. 2009) When considering creativity from engineering point of view expertise in for instance, some manufacturing method provides essential knowledge for creative product design process.

Without this expertise knowledge possibility for creative solution is rather limited. Hence, engineering creativity research is one example of different approaches in creativity studies.

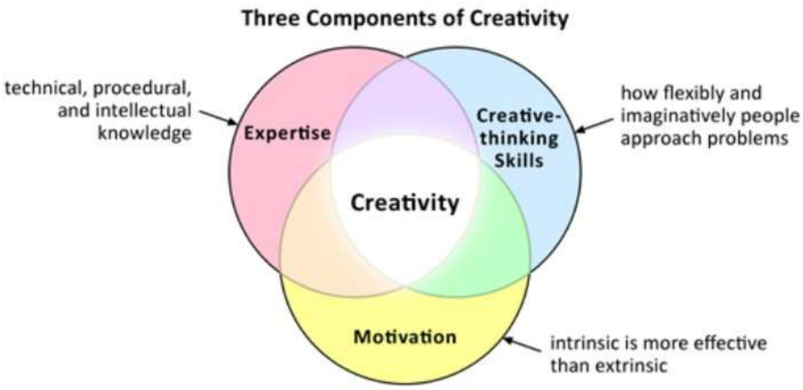


Figure 14. The three components of creativity (Amabile 1998; Thoughts on innovation, education, and design 2022)

Many times, achieving proper level of expertise in creative design process requires teamwork. Cropley (2015, pp. 207–209) points out that teamwork has many advantages such as giving and receiving feedback and possessing more knowledge. However, he continues that depending on the team members and how well they can work together the teamwork may fail as well especially when the aim is creativity and innovation. Consequently, teamwork may decrease design creativity and innovation for unsupportive feedback by team members. Therefore, it is essential to understand the role of interaction in design teams. Walton (2016, pp. 85–99) underlines that though teamwork has its' challenges, when the aim is innovation teamwork is always needed at some point. He proposes that the early phases of an innovative product design process would benefit individual working however, the further phases ought to be carried out in teams of different kinds of experts. (Walton 2016, pp. 85–99)

Engineering creativity research began to flourish in the 1950s (Charyton 2014, p. 1). According to Guilford (1950) creative behaviour includes activities like planning, contriving, designing, composing, and inventing. He continues that creative people have novel ideas (Guilford 1950). Creativity and innovation have been fundamental characters for engineering. However, as a separation to creativity of fine arts engineering creativity has often a demand of functionality and usability. According to Cropley (2015, p. 8) creative product is something novel and useful. He also points out that creativity is often considered as impulsive behaviour with free expression and thus, a "soft" and "not real engineering" factor which is a false association. Creativity is an essential character of engineering which aims to answer customer needs and solve practical problems. Cropley (2015, p. 6) Nowadays engineers need to be increasingly creative and innovative to be globally competitive and to be able to solve global problems such as problems concerning climate changing. The creativity need in engineering has led to the development of various creative design process aiding tools for engineering. The examples of these tools are different kinds of product creativity and innovativeness measuring tools. The essential part of creativity in engineering is problem finding and problem solving. Thus, engineering creativity demands adaptiveness, problem solving, and originality. These kinds of aspects are usually measured via these measuring tools. (Ahmed et al. 2021; Blockley 2020, pp. 6–8 and 15–18; Charyton 2014, pp. 1–7; Cropley 2015, pp. 74–84; Cropley 2016, pp. 155–173)

Product design has been studied a lot and the related literature have found product design as a critical part of company success. Further, the literature underlines that innovativeness in product design improves product success among customers and thus, in the market. (Moon et al. 2015) According to Kahn & Mohan (2021, p. 215) innovation ought to be considered as both a novel outcome and a novel process. The outcome may be a new idea, method, or device. The process can be described as an introduction of something new. (Kahn & Mohan 2021, p. 215) Many proposals for supporting innovative product design in theoretical level have been made. A list of these kinds of proposals has gathered for example Cropley (2015, p. 51) and he mentions Design Thinking as such innovative product design supporting approach. For instance, Camburn et al. (2017) have presented a systematic innovation framework (Figure 15) which aims to combine relevant design thinking, systems engineering, design engineering, and business design practises.

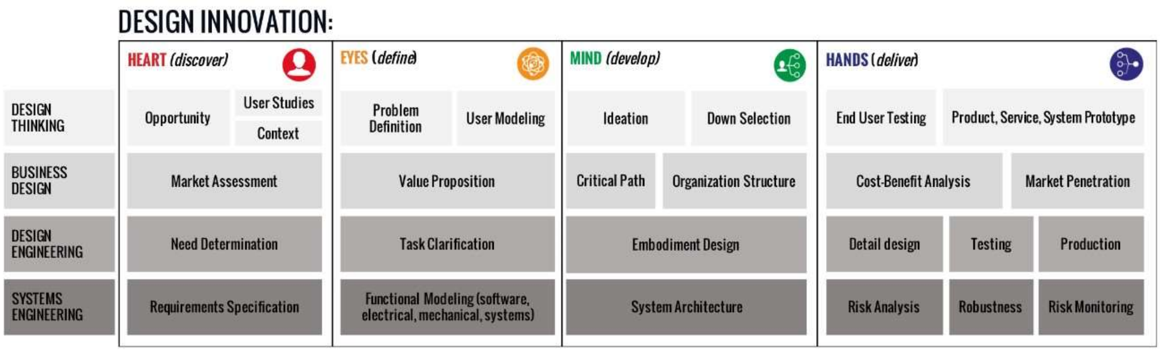


Figure 15. Design Innovation process model by Camburn et al. (2017)

The next paragraph handles AM as a part of innovative product design by presenting some examples from related scientific literature.

2.2 AM as a Part of Innovative Product Design

There are many approaches when considering AM as a part of innovation or innovative product design processes. According to Perez et al. (2019) there are four general areas of opportunities that ought to consider when utilizing AM in innovative product design. These areas are the creations of novel products and new business models with AM, the product design processes improvement with AM, and the identification of new AM technology classes. These four general areas are presented in Figure 16. (Perez et al. 2019)

Figure 16. Four general areas of AM opportunities by Perez et al. (2019).

Sun & Lv (2021) adduce that in AM the interactive relationship between the design and printing process restricts and promote each other simultaneously. However, they continue that AM enables free design of mechanical parts and innovative design. AM printing is used to realize innovative design result parts. Thus, the structure of freely designed and innovative machine parts is possible with AM. (Sun & Lv 2021) Candi & Beltagui (2019) summarizes that in innovative product design process AM ought to use in all the three phases, ideation, development, and launch, of innovation. Thus, merely a simple distinction between prototyping and manufacturing is not justifiable when utilizing AM in innovative product design process. AM helps in communicating and developing product ideas in ideation phase for it enables creating physical representations. They can be more usable and effective in ideation than CAD models or sketches. (Candi & Beltagui 2019) Nonetheless, though AM has many benefits Jacobs (2016, p. 133) reminds that sketching by hands is essential in design process for it enables the kind of free ideation which for instance CAD modelling and hence, AM does not allow. In the development phase of innovation process AM enables better form and function testing. And in the launch phase of innovation process AM aids to provide users an accurate physical representation which helps, for instance to determine whether the product is too small or big. Further, AM models may be used to involve users in designing in the launch phase. (Candi & Beltagui 2019) According to de Jong & de Bruijn (2013) as an example open collaborative innovation is possible via open-source AM. The idea in open collaborative innovation is to share the design work and efforts freely for anyone to use (de Jong & de Bruijn 2013).

Lang et al. (2021) have presented a designer aiding method for capturing the design potential of AM. The Augmented Design with AM Methodology (ADAM^2) is a method which helps in designing creative solutions at the early phases of product design process. ADAM^2 trusts on the potential of AM which is determined in 14 possibilities and a set of 14 inspirational objects. Every object represents a possibility. The methodology enables forcing of the association among the design potential of AM and knowledge of a company's sector. (Lang et al. 2021) According to de Almeida et al. (2021) New Product Developments (NPD) including innovation, flexibility, and speed is required from industries for the global competition. It is strongly connected with new manufacturing technologies for obtaining continuous growth and success. As an emerging part of Industry 4.0 techniques AM may be a solution to such challenges. Therefore, de Almeida et al. (2021) propose an innovative framework to manage NPD integrating AM and agile product management (APM) (Figure 14). The framework presents an innovative structure, and it aims to guide researchers and managers to develop novel products via AM and agile approaches. As a study result de Almeida et al. (2021) present a process model suggestion (Figure 17) which may be used as a reference model for adopting AM and APM combination in companies. (de Almeida et al. 2021)

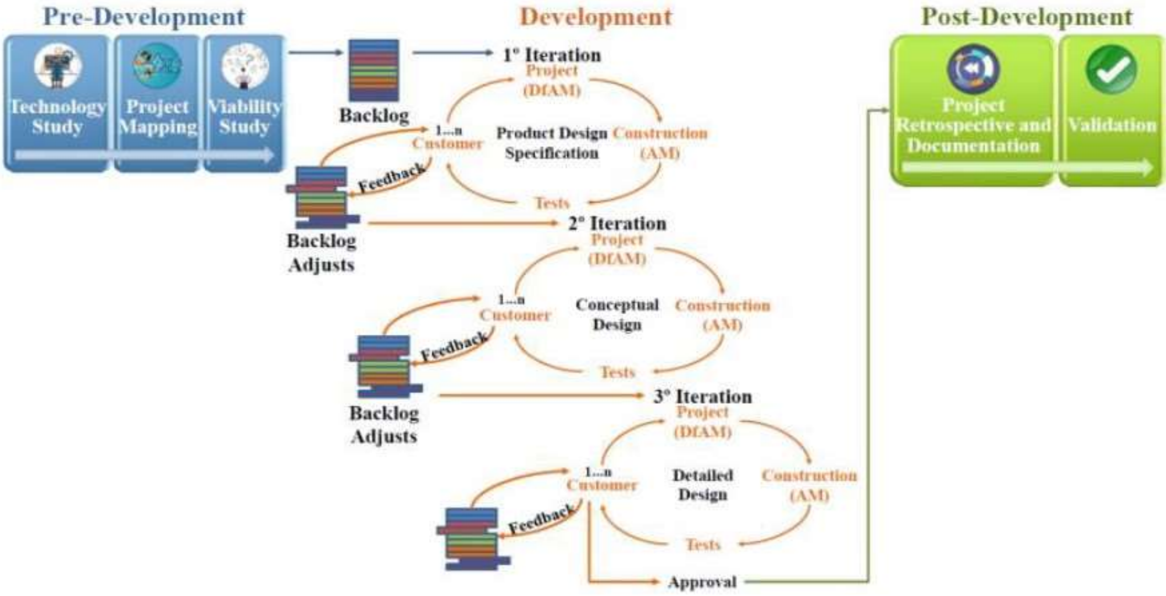


Figure 17. A process model suggestion for AM and APM combination adoption (de Almeida et al. 2021).

In their study Perez et al. (2019) developed the Design Innovation with Additive Manufacturing (DIwAM) methodology (Figure 18). It is based on the SUTD-MIT International Design Centre's Design Innovation (DI) framework (Figure 15) (Camburn et al. 2017). The aim of DIwAM is to help organizations to find effectively and in a guided manner all the opportunities of AM. Further, the aim is to aid identifying and realizing new innovations which AM enables. DIwAM include a set of design methods that are essential and usable for the design innovation process. Some of the methods are particularly usable from AM viewpoint. Perez et al. (2019) conclude that DIwAM points out that AM is a powerful tool which is useful in all the design process phases.

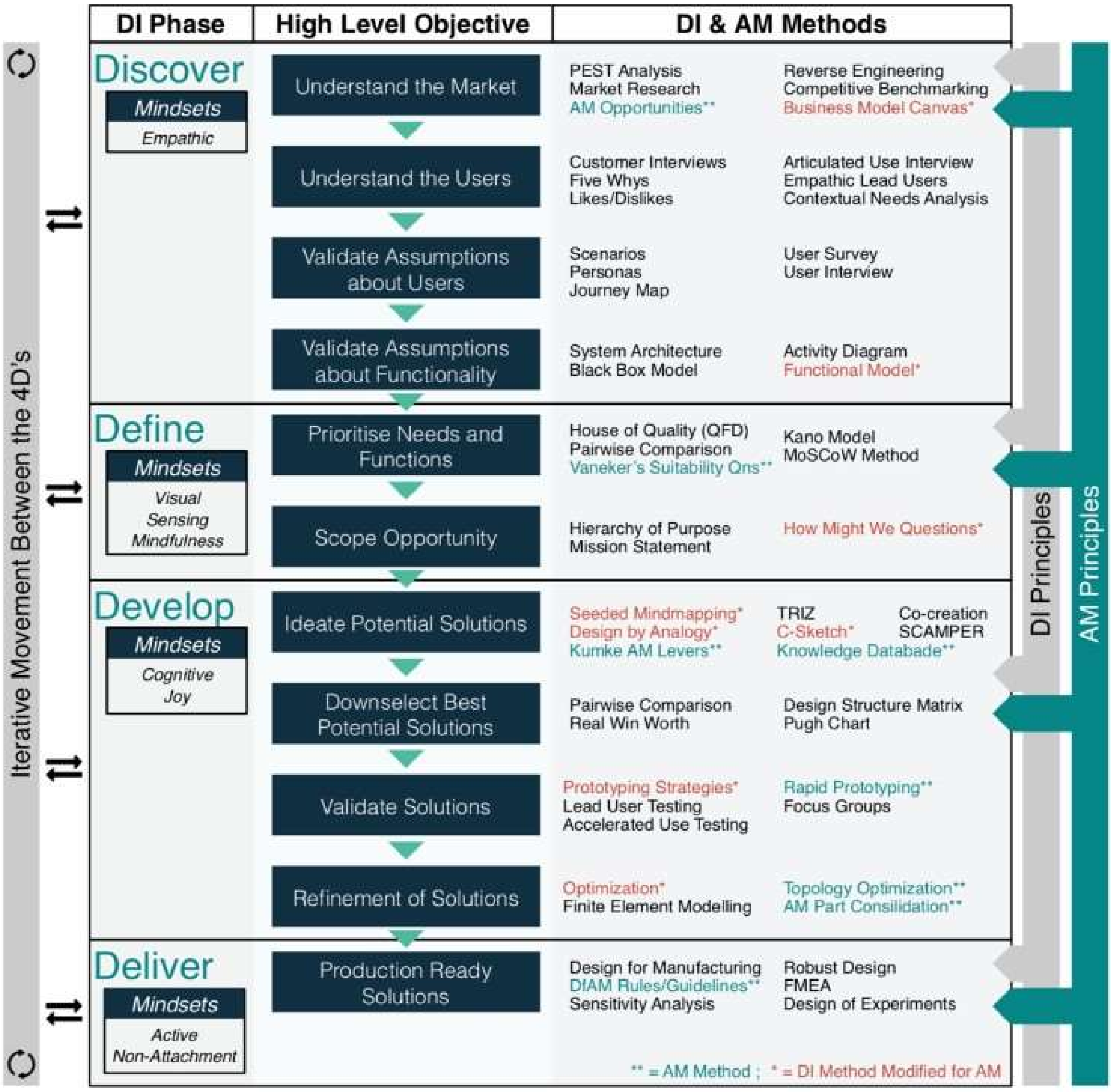


Figure 18. The Design Innovation with Additive Manufacturing (DIwAM) methodology created by Perez et al. (2019).

This paragraph has presented examples of product design process models for design innovation utilizing AM techniques. Consequently, in the next paragraph are presented the industrial design engineering product design process models which are in this research further compared from innovative product design and AM utilization point of view.

2.3 Compared Industrial Design Engineering Process Models

There are many product design process models to be applied in industrial design engineering (Howard et al. 2007; Howard et al. 2008; Otto & Wood 1998). These design process models or design methodologies may be considered as structured guidelines for engineering design. (Kumke et al. 2017, pp. 187–195) Engineers build suitable models based on expert knowledge and science to help in decision making which is needed for their purpose filling (Blockley 2020, p. 20; Tomiyama et al. 2009). That purpose is to meet the human needs. However, the used models are always approximate and contextual. A model is a representation of something for instance, a product design process. Hence, there are always some attributes that are not included to the model. Some of the design process models are specific and others generic (Howard et al. 2007). Nevertheless, for being a representative and thus, not exact, process models may be applied in different kinds of processes. For example, design process models are created for a specific purpose. The essential thig is the nature of the purpose and the quality of the model to accomplish the purpose. The model and the result will be poor if some relevant attributes are missing. (Blockley 2020, p. 20) Hence, it is necessary that for example design process models are discussed, compared, and updated whenever needed. Nonetheless, some product design process models allow more design freedom and thus, more room for creativity and innovativeness than the others. This chapter presents the four different industrial design engineering product design process models studied in this research.

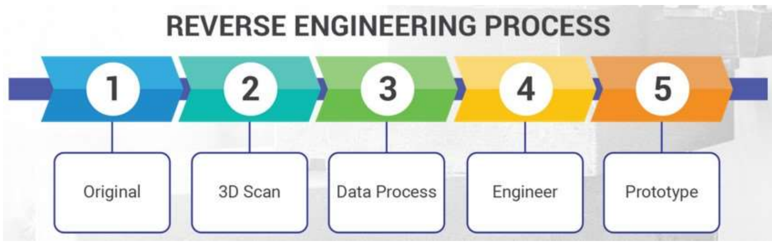
2.3.1 VDI 2221

One of the most well-known traditional phases by phase proceeding design process model is VDI 2221 (VDI 2221:1993-05) (Figure 4). According to Jänsch & Birkhofer (2006) this guideline was developed in 1970s and it was based of several professors' scientific considerations and practical experiences. The aim of VDI 2221 is to provide valid design model from precision mechanics to electrical engineering. VDI (Association of German Engineers) recommendations 2221 includes guidelines for product development process. In addition, the aim is to give a more scientific basis for design processes. VDI 2221 includes the four main design phases: task clarification, conceptual design, embodiment design and detail design. The phases of VDI 2221 proceed straightforward phase by phase from start to the end (Jänsch & Birkhofer 2006; Tomiyama et al. 2009) Howard et al. (2007) considers VDI 2221 as conventional engineering process model.

2.3.2 Reverse Engineering

Reverse engineering process (Figure 19) starts with the redesign process. In a reverse engineering process a product is observed and disassembled and then, analysed. This includes testing, ‘experiencing’, and documenting the product from functionality, physical principles, form, assemblability, and manufacturability viewpoints. The purpose of the reverse engineering process is to completely understand and represent the current product for evolving the product or a product component further. (Otto & Wood 1998)

A



B

Figure 19. A) A classic reverse engineering process model (Mechanical Design Tutorial 2016) and B) A reverse engineering process model utilizing CAD modelling (ATW Engineering 2022).

Zjang & Yu (2016) present a study of utilizing AM technology in innovative design of reverse engineering products (Figure 20). In their study AM technology is used in the integrated process of rapid prototyping, detection and analysis of the product, reconstruction, and manufacturing of the product. They conclude that AM technology can make the product development cycle shorter and contribute to the product analysis and manufacturing. (Zhang & Yu 2016)

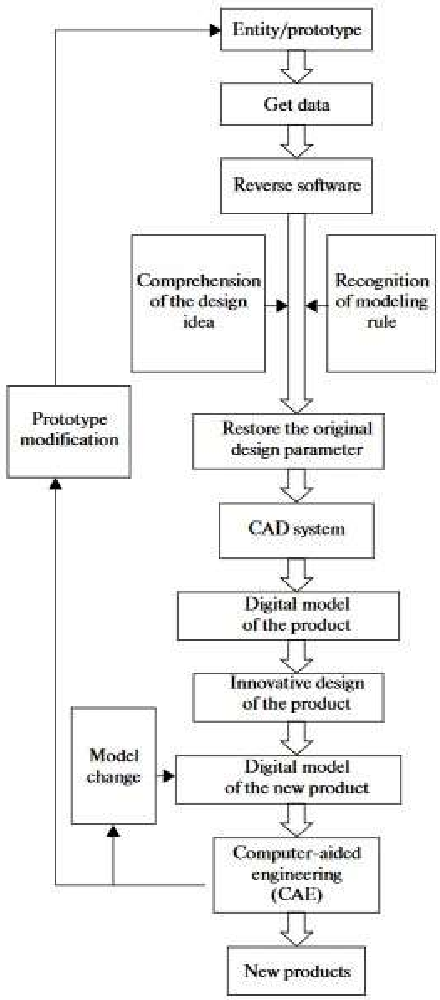


Figure 20. Reverse engineering process utilizing AM technology (Zhang & Yu 2016).

Among utilizing in AM processes, reverse engineering is used in several other application areas as well. Often it may be necessary to make a copy of a part and there are available neither original documentation nor drawings. Thus, by reverse engineering an existing part is scanned to a CAD model. Sometimes an existing part ought to be re-designed and hence, by utilizing reverse engineering an analysis and modifications are done. In addition, reverse engineering is usable when such ready parts as for instance, helmets needed to be custom fits. Consequently, a part customizing is done by using reverse engineering process. (Várady et al. 1997)

2.3.3 Concurrent Engineering

When considering iterative design process models, concurrent engineering (CE) design process model (Figure 21) takes into account feedback which causes iteration during the process (Eppinger 1991). Thus, CE design process is not phase by phase proceeding. In a CE process the product and its downstream production, and the support processes are designed simultaneously from the very beginning of the design process (Sawhney 2018, p. 27). The fundamental idea in CE is that different experts work with the different model phases simultaneously and hence, product design time and costs are aimed to diminish.

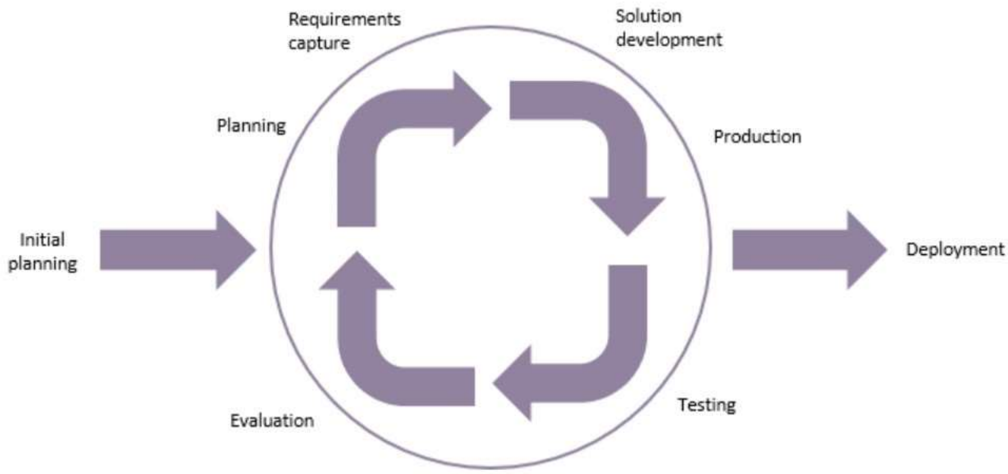


Figure 21. Concurrent engineering (CE) design process model. (Praxis)

CE considers product life cycle processes, product planning, design, phases from production to delivery, service, and end-of-life. All these aspects are integrated in order to decrease product development lead time and improving the quality of the product. Hence, CE is also called as integrated product development (IPD) or simultaneous engineering. (Tomiyama et al. 2009) According to Eppinger (1991), inordinate feedback consideration may cause inefficiency to the CE design process and hence, the feedback consideration ought to be controlled. Therefore, CE design processes are often based on the utilization of computer-aided CE design tools which can assist the process efficiency (Sawhney 2018, p. 27).

2.3.4 Design Thinking

Design Thinking design process model (Figure 22) allows freely iteration among the five (or six in some process model versions (Figure 4)) different phases without control which is a difference comparing to CE. These phases are empathise, define, ideate, prototype, and test (and implement in some model versions). In the empathise phase (Figure 22) the users' needs are researched and gathered. In the define (Figure 22) phase the original design problem is reframed based on the analysed user data gathered in the empathise phase. The ideate phase (Figure 22) is for creative and innovative "think outside the box" ideation where the material of the previous phases is utilized. In the prototype phase (Figure 22) best possible solutions for identified design problems are tried to find in an experimental way by preparing a prototype (or several prototypes). The test phase (Figure 22) is for testing the prototype. Iteration rounds (Figure 22) may be done whenever needed. In Design Thinking process iteration is considered as a benefit and further, as a basis for innovation. For instance, Cropley (2015, p. 51) and Howard et al. (2007) account Design Thinking as creative problem-solving model which follows the creativity phase model in Figure 13. Design Thinking approach emphasizes the importance of user feedback and hence, it may be considered as particularly user-centred approach. (Brenner et al. 2016, pp. 10–13; Interaction Design Foundation; Moran 2021) The phrase design thinking was originally created in 1960s when a unique, traditional scientific way of thinking differing approach was suggested by Simon Herbert. The alternative mindset was further developed by L. Bruce Archer. Later for instance, 1991 founded IDEO, started to utilize and develop Design Thinking method. (Brenner et al. 2016, pp. 6–7; Clarke 2020)

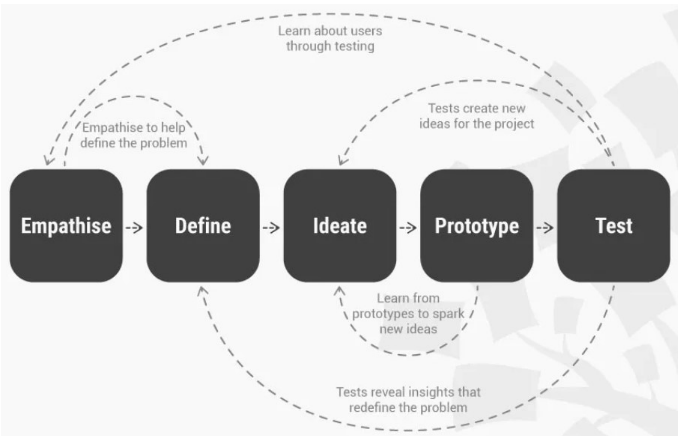


Figure 22. Design Thinking process model. (Interaction Design Foundation)

This chapter has presented 54 relevant related literature sources considering the study subject of this research. 17 of the sources backgrounded AM and DfAM in general level. 23 of the sources concerned innovation and AM in innovative product design. Finally, 14 of the sources presented the four industrial design engineering applicable product design process models which are compared from the innovation and AM viewpoint further in this research. The literature review points out that AM is considered as a suitable method to be utilized in innovative product design process and furthermore, some frameworks for AM utilizing innovative product design have been developed.

3 Detailed Description of the Research Methods

This research utilizes a methodological triangulation which consists of scientific literature, commercial references, and expert interviews (1.4 and Figure 6). This chapter provides a detailed description of the utilized study methods.

3.1 Scientific Literature Review

There are various kinds of literature review approaches. Traditional or narrative literature review analyses and summarizes a body of literature, highlight new research streams, recognize inconsistencies, and identify gaps in knowledge. It may also describe as qualitative literature review. The aim of traditional literature is to present a comprehensive background of the literature under the studied topic. Traditional literature review is used to develop theoretical and conceptual frameworks. (Jesson et al. 2011, pp. 73–76; O'Gorman & MacIntosh 2015, pp. 37–39; Snyder 2019) This research uses mainly traditional literature review approach.

This research starts with a literature review. The scientific literature of this research is mainly searched from Scopus (Elsevier) which is a comprehensive scientific literature database and can be used via LUT Primo university library service. In addition, Google Scholar is used for searching relevant literature. The scientific literature is searched by using suitable keywords and keyword combinations like “product AND design AND AM”, “innovation AND model AND AM”, and “innovative AND product AND design AND model”. The search results are boarded whenever needed for finding relevant sources.

3.2 Commercial References Review

The commercial references are searched mainly from the Internet via web-searches. The commercial references are limited in a way that only AM companies providing AM devices, AM services, and AM expertise services for other companies are included. Thus, for example companies selling only AM machines and accessories are not included. The aim of this limitation is to find for instance customer stories about AM services from early phase to final product and hence, find out which kind of product design processes are used in AM according to commercial references. This is justifiable considering the topic of this research and the aim to make product design process model comparison from innovative design and AM utilization viewpoint. Moreover, according to van den Hende & Schoormans (2012) customer stories are not only a part of company advertisement, but they provide understanding of the value and benefits of new technologies. Examples of the commercial references are the webpages of 3ERP, Pro Tech, Huld, GE Additive, and 3D Form Tech. In addition, some companies providing holistic product design services utilizing AM may be included to commercial reference review.

3.3 Expert Interviews

An interview is a pre-planned interactional discussion session. The idea is to conduct qualitative data for research via linguistic interaction. The benefits of interview method are that it is flexible, and it enables interaction with people. (Vuorela 2005) Interviews may be conducted in a structured, semi-structured, or unstructured way. In a semi-structured (theme) interview only few questions are prepared beforehand. Otherwise, room for open discussion and freely formed questions is provided. (Courage & Baxter 2005, pp. 247–292; Stickdorn et al. 2018, pp. 34–35; Tietoarkisto) In this research the interviews are theme interviews and gathered via semi-structured manner.

According to Stickdorn et al. (2018, pp. 34–35) interviews can be conducted by remotely and online. In this research the interviews are conducted via Microsoft Teams video call, telephone, or email whatever the participant prefers. The interview includes some similar questions to all participants however, the structure of the interview can be modified during the interview if needed. The interview structure is presented in the next chapter.

3.3.1 Interview Structure of the Expert Interviews

The interview contains six main questions in Finnish (Appendix 1) or in English (below this chapter) depending on the interviewee native language. These questions are sent beforehand for the interviewees via email after the interview time is set.

The interview questions and the interview structure of this research are:

1. What kinds of possibilities additive manufacturing (AM) methods provide to product design?

2. What kinds of limitations using AM methods brings to product design?

3. If considering the limitations of AM methods and the freedom of innovative / creative product design process, how (well) these two aspects can be combined?

    - Can AM methods which has certain limitations be combined with innovative / creative product design? Or do the limitations of AM methods limit innovativeness / creativity?

4. If AM methods according to your consideration can be utilized in innovative / creative product design process, how will it happen?

    - How using AM methods can support innovative / creative product design in different phases of the design process?

    - How using AM methods affects to innovative / creative product design process proceeding and how it affects to the design process phases?

    - If considering Design for Additive Manufacturing (DfAM) approach, how does it effect on innovative / creative product design according to your opinion? Does DfAM and innovative / creative product design fit (well) together?

5. In which kind of product design process models (for example, Concurrent Engineering (CE), Reverse Engineering, Design Thinking, VDI 2221) utilizing AM techniques suits well or best?

    - Why?

    - In which product design phases using AM techniques is possible?

6. Do AM methods provide such added value to innovative / creative product design process what conventional manufacturing methods cannot provide?

The purpose of the interview questions is to gather answers and material for answering the research questions. In addition, some novel viewpoints to the researched topic are aimed to find.

3.3.1 The Interviewed Experts

The contacted experts were selected following the methodological triangulation presented in chapter 1.4 and Figure 6. Thus, both engineering design experts and one other design expert were interviewed. In addition, the contacted engineering design experts were selected from both scientific and commercial company positions. The interviewed experts of this research are presented in the table of Appendix 2 in the order they were interviewed.

The preliminary plan was to gather six expert interviews. However, after conducting the first interviews, it could be estimated that five interviews would be adequate from the data amount and research validity point of view.

3.3.2 The Practical Arrangements of the Interview Sessions

The experts were contacted via email and not all the experts answered to the inquiry. Thus, receiving enough experts' answers to the email inquiry took time. Nonetheless, altogether five expert interviews were finally made which is an adequate number for this research.

All the interview sessions were kept between 6th of April and 6th of May 2022. The duration of the interviews varied between 20 and 40 minutes. The preliminary planned interview structure (chapter 3.3.1) was followed however, in a flexible manner. All, the interview sessions were recorded for supporting note taking and later, transcribed for results reporting and analysis. Permission for interview session recording and for using the name of the interviewee in the thesis were asked from the interviewee at the beginning of the interview session.

This chapter has described detailed the utilized research methods. The next chapter will present the results of the material gathered via these methods.

4 Results

The results of this research are presented in the following sub-chapters. The result descriptions are divided according to the utilized research methods. Hence, at first the results based on the literature review are presented. Then, the results of commercial references search are described. Finally, the results of the expert interviews are summarized and presented.

4.1 Results Based on Scientific Literature Review

The results of the scientific literature review are presented in this chapter. At first comparison of different product design process models is made from innovative design point of view. Then, the possibilities of utilizing AM techniques in innovative product design process is considered.

4.1.1 Comparison of Different Product Design Process Models from Innovative Design Viewpoint

The scientific literature points out that there is plethora of design process models which are appliable in product design process. These models are highly useful for instance, when planning a design process for they are based on scientific research and often practical experience and thus, represent the process proceeding somewhat well. The product design models studied in this research were aimed to select in a way that they would be on the one hand used rather commonly in engineering design field and on the other hand different to each other in a way that comparison would be reasonable. The product design models handled in this research are VDI 2221 (2.3.1 and Figure 4), reverse engineering process model (2.3.2 and Figure 19), concurrent engineering (CE) process model (2.3.3 and Figure 21), and design thinking process model (2.3.4 and Figure 22).

When considering these product design models from innovative product design point of view it means that it should be discussed how well the researched models support innovation.

However, innovation is somewhat board concept and hence, it ought to be determinate based on scientific literature and, discuss what makes product design process innovative and what kind of things a product design process model should allow and support for enabling innovative product design.

The scientific literature points out that innovative product design is not possible without creativity. There are various approaches in creativity research nevertheless, in most of the references creative product design is determined to be something novel, useful, and surprising. Furthermore, creative product design demands motivation, expertise, and creative thinking skills (Figure 14) from product designer. In AM the required expertise includes for instance, knowledge of DfAM and CAD modelling skills. For enabling creative product design, a product design process model should allow design freedom and unlimited iteration between different process phases. Creativity is often described as ability to think "outside the box". From product design process viewpoint this could mean for example, proceeding freely between the process phases and not too detailed and limited phase definitions and hence, enabling design freedom. However, many scientific references argue, that creative design is a process and thus product design process models are needed and utilizing them is justifiable in innovative product design processes.

VDI 2221 product design model may be considered as traditional and straightforward from beginning to end proceeding. The process steps are determinate somewhat detailed though the model allows iteration. VDI 2221 is a conventional product design model which is commonly utilized in engineering design. It is also a basis for several commonly used traditional product design process models such as the model of Ulrich and Eppinger. When considering the product design process models compared in this research, VDI 2221 is perhaps the one that allows less innovative product design enabling design freedom. Though it would allow creative thinking and design freedom it does not encourage innovative product design. For being such detailed process model VDI 2221 does not give room for creative thinking very well. As an example, if creative product design process outcome is determined to be something novel, useful, and surprising VDI 2221 model does not provide flexibility and space for surprises. Furthermore, when considering creative product designs' demands for motivation, expertise, and creative thinking skills strictly guided VDI 2221 design process may decrease motivation though the designer would have the expertise and ability to think creative. VDI 2221 does neither exclude nor emphasize teamwork and human-centred design methods however, innovative product design needs usually considering the design from several viewpoints. This kind of considering is not possible without teamwork with different kinds of experts. In addition, user data often gives novel aspects to any kinds of design processes and thus, supports thinking “outside the box”.

Reverse engineering product design process model is often called as backwards engineering model for the basic idea in reverse engineering is to start the design process from an existing product. This is opposite to for instance VDI 2221 which is a forward engineering process. Reverse product design process is often used for updating and improving an existing product or designing spare or additional parts for an existing design. Thus, reverse product design process is used partly in different purposes than for example VDI 2221. Regardless, reverse product design process may be used in product design which aims to a novel product. When considering innovative product design, reverse product design process sets boarders for design freedom in the very beginning of the design process. Namely, the existing design from which the reverse design process starts limits creativity at least on some amount. However, in an optimal situation the existing product may nourish creativity as an inspiration. Nevertheless, though reverse design process has not as detailed determinate phases as in VDI 2221 it lacks support of teamwork and user data utilizing in the beginning of the process which may decrease the possibility for innovative product design. In addition, reverse engineering does not support free iteration among the different process phases and hence, it does not support very well free and unconventional “outside the box” ideation. Some references argue however, that reverse engineering process model is capable to support innovative product design and further, may aid traditional forward engineering product design methodologies to produce innovative product design (Table 1).

CE product design model is based on iterative process in which, however, the number of iterations is aimed to be kept limited. In addition, iteration is somewhat limited for it is not allowed freely among different process phases. The basic idea is that different experts work with the different model phases simultaneously and thus, product design time and costs may be decreased. Also, CE aims to optimize product manufacturability. CE intends to consider and involve all the stakeholders in the product design process. However, it does not emphasize the importance of the user viewpoint. Nevertheless, CE product design process consider different kinds of aspect more versatile than VDI 2221 and reverse engineering design process. Furthermore, CE utilizes teamwork and the viewpoints of different experts in the design process which supports innovative product design process. When considering the three different elements of creativity expertise, motivation, and ability for creative thinking, CE supports all of them mostly. Nevertheless, the freedom of design which is needed to support creative thinking is somewhat limited in CE. Also, the aim for cost efficiency often bounds innovative product design and creative thinking. Hence, CE product design process model has perhaps better ability to support innovative product design process than VDI 2221 design process model, but it lacks the kind of design freedom which is an essential part of creative and innovative product design.

Though Design Thinking model is commonly used in service design processes, it is applicable in product design processes too. The benefit of Design Thinking approach is that it enables and encourages free iteration among the model phases. Hence, it also supports creativity and innovative design. Design Thinking approach underlines the importance of iteration and human-centred design. Users and customers are involved to Design Thinking process already in the early stages of the design process. In addition, the benefit of the teamwork of various kinds of experts is underlined as well as the importance of brainstorming. Therefore, from the innovative product design point of view, Design Thinking product design model is perhaps the most useful. Design Thinking process enables novel, useful, and surprising design. It also gives room and thus, motivates for expertise and creative thinking. The phases of the Design Thinking approach are not strictly determinate, and they allow a great variation of different kinds of study methods. In the scientific literature Design Thinking approach is commonly described as creative and innovative design enabling and motivating approach (Table 1). Consequently, Design Thinking product design process model differs significantly from VDI 2221, reverse engineering, and CE product design process models. Furthermore, Design Thinking model may be considered to be the best model from innovative product design process viewpoint of this research.

Table 1. Examples of aspects considering design process model and methodology suitability for innovative product design

Process Model Suitability for Innovative Product Design	**Reference**
VDI 2221 as a basis for several conventional product design process models and CE are very good for systematic design but not for innovative design.	Tomiyama et al. (2009)
“Based on reverse engineering, forward engineering contributes positively to the innovation output”	Zhang & Zhou (2016)
“Design Thinking is an innovation method”	Brenner et al. (2016, p. 19)

This chapter has considered and compared VDI 2221 (2.3.1 and Figure 4), reverse engineering (2.3.2 and Figure 19), concurrent engineering (CE) (2.3.3 and Figure 21), and Design Thinking (2.3.4 and Figure 22) process models from creative and innovative product design point of view. This consideration has been based on scientific literature review. The next chapter will address the possibilities of AM techniques in these product design process models.

4.1.2 Possibilities of AM Techniques in Considered Product Design Processes

The basic AM process has three phases namely, CAD modelling, digital slicing of the CAD model, and 3D printing. In addition, many AM techniques require post processing of the printed part. The AM process is more precisely presented in Figure 7. Consequently, AM process is an ongoing process which can not be stopped ones it has been started. This means for instance, that the CAD model design can not be changed and thus, the printed part can not be modified after the process has been started. Hence, if the printed item under the process is noticed to need design changes, the whole process must be start again from CAD modelling. However, the process may be stopped without finalizing the part under printing process, but the basic rule of thumb is that the design can not be changed in the middle of the AM process.

When considering AM process in compared VDI 2221 (2.3.1 and Figure 4), reverse engineering (2.3.2 and Figure 17), concurrent engineering (CE) (2.3.3 and Figure 19), and Design Thinking (2.3.4 and Figure 20) processes VDI 2221 guides straightforward from beginning to the end proceeding. After ending the process, it starts again from the very beginning. Hence, VDI 2221 process model suits somewhat well to be used with AM however, the structure of VDI 2221 bounds design freedom and creativity. Starting the design process many times from the beginning may degrease motivation which is one of the three elements of creativity. Though AM process has certain phase order, the needed changes may be done to the CAD document after the previous printing process is finalized and the part is tested. Thus, VDI 2221 may be considered as too rigid and strict for innovative AM product design. In addition, VDI 2221 lacks the prototype testing and evaluation phase which is essential in any innovative product design process, and which AM enables very well.

Reverse engineering process starts from an existing item. Hence, reverse engineering suits to be utilized in AM product design somewhat well. In reverse engineering the AM design may start from a part which is not originally designed to be manufactured via AM or it may start from a previously printed AM part. Thus, reverse engineering process for AM starts the process from a prototype. Figure 20 presented reverse engineering design process utilizing AM. It also presented how reverse engineering enables innovativeness in AM design. Thus, it may be argued that reverse engineering design process model is suitable to be used in AM utilizing innovative product design process. Furthermore, reverse engineering for AM considers for example, the benefits of prototyping. Consequently, it is justifiable to state that reverse engineering enables innovative AM product design better than VDI 2221.

Concurrent engineering (CE) is based on overlapping phases which can be processed simultaneously. Thus, for instance, improving CAD model may be started already before the printing of the previous part has been finalized. Therefore, CE provides more design freedom and space for creativity from innovative AM product design point of view than VDI 2221. However, the efficiency demand of CE approach may be harmful from both AM and innovative product design viewpoint. AM tends to need certain amount of time and it has the basic proceeding of process phases. In addition, innovative product design benefits from free and unlimited iteration which CE does not support very well. Thus, CE is perhaps more suitable for innovative AM product design than VDI 2221. Nonetheless, it may be argued that both reverse engineering and Design Thinking are more useful in innovative AM product design than CE.

Design Thinking may be considered to suit innovative AM product design very well. Figure 18 shows one example of suggested approach for innovative AM product design in Design Thinking based model. In Design Thinking approach the fundamental character is free iteration among different process phases. Often, the actual AM process is utilized in the prototype phase of Design Thinking model. However, that does not exclude in any way utilizing Design Thinking in innovative AM product design, on the contrary. Design Thinking provides the kind of design freedom and flexibility that innovative AM product design needs. For instance, after testing previously printed AM part it is possible to return in ideate phase or in prototype phase, whatever is needed and considered useful. In addition, Design Thinking supports teamwork which benefits innovative AM product design by offering the variety of viewpoints. However, for having the optimal basis for innovative AM product design, expertise as an element of creativity ought to emphasize. Namely, AM and DfAM need the kind of expertise which should have for enabling innovative AM product design. Nevertheless, it may be concluded that Design Thinking product design model provides the best precept for innovative AM product design when comparing to VDI 2221, reverse engineering, and CE.

In this chapter VDI 2221 (2.3.1 and Figure 4), reverse engineering (2.3.2 and Figure 19), concurrent engineering (CE) (2.3.3 and Figure 21), and Design Thinking (2.3.4 and Figure 22) process models have been considered and compared from innovative AM product design viewpoint. The basis for this consideration has been scientific literature review of this research. The next chapter will present the results and consideration based on the review of studied commercial references.

4.2 Results of Commercial References Review

The commercial references give a very positive view of AM. According to them AM provides unlimited possibilities for product design. AM is primely presented as a prototyping tool and secondary as a product manufacturing tool. All the researched commercial references emphasize flexibility and cost efficiency of the product design process. Some commercial references underline the importance of teamwork and working with several prototypes simultaneously and hence, cost and time savings. In addition, AM enables better answering to customer needs. In the commercial references AM product design provides highly iterative and fast product development process which means not only cost savings but ability for innovative product design as well. Many customer stories tell about utilizing AM mostly in prototyping but in manufacturing of some product parts too. In addition, customer companies consider that AM aids in improving product sustainability. AM seems to locate somewhere between the product continuum where on the one side is a piece of fine art and on the far opposite side is mass produced product. AM is considered as a tool which enables product custom product design and manufacturing. The following quotes (Table 2) from commercial references describe the possibilities of AM from innovative product design viewpoint.

Table 2. Quotes from commercial references and conclusions

Quote from Commercial Reference	Conclusion
”AM gives a lot of freedom to part design and it works with small scale, but surprisingly large scale too.” (3D Form Tech, 2021) (1)	The company sees design freedom as an essential benefit.
“In an optimal situation a lot of time and money is saved.” (3D Form Tech, 2021) (1)	Product design and in best case innovative product design is possible in an effective way.
“Especially, from the viewpoint of novel products 3D printing provides enormous possibilities because prototypes may be tested easily and fast. The first version of a product is rarely the last one. When you see the physical parts and the prototype assembled, you can get a lot more of new ideas comparing to just seeing the CAD model.” (3D Form Tech, 2021) (2)	Possibility for physical prototypes with a lot of fast iteration rounds aids innovative product design.
“AM has enabled bringing innovations in to manufacturing phase more flexible. Conventional manufacturing limits quite a lot of part geometry.” (3D Form Tech, 2021) (3)	Innovative AM product design benefits from process flexibility.

Table 2 continues. Quotes from commercial references and conclusions

Quote from Commercial Reference	**Conclusion**
"When we design something new, we receive feedback quickly from AM expert." (3D Form Tech, 2021) (3) *"We have always found the proper ways to get printed the parts that we have designed."* (3D Form Tech, 2021) (3)	Expertise and teamwork with different kinds of experts is essential in innovative AM product design process.
"Without 3D printing we would be less flexible, and we couldn't offer as versatile options to our customers." (3D Form Tech, 2021) (4)	The process flexibility is underlined.
"Product development process is an iterative and effective process, and the efficiency is admired over organizations." (Huld) (1)	Innovative AM product design process is highly iterative and fast.
"After ideation we gave an industrial designer a pencil and A3 papers and asked for making the sketches. After view hours we were able to give the AM designer clear parameters for AM product design." (Huld) (1)	In innovative AM product design CAD modelling is not able to substitute the initial design and sketching by hands. Further, teamwork among different kinds of experts is needed.
"Several new tools were designed during the project. In addition, many components were designed from the beginning or based on an old part." (Huld) (2)	Innovative AM process may proceed either forwards or backwards.
"If our employee has an idea our design department can realise it. Only the sky is the limit. AM has improved the product development of the company. Major advantages of AM are fastness, efficiency, and flexibility." (Pro Tech)	AM improves innovative product design process in many ways.

This chapter has presented the results based on commercial references review. The next chapter will present the results of the expert interviews.

4.3 Results of Expert Interviews

The results of the expert interviews are based on the interviews of five experts. These experts are presented in Appendix 2. The data of the expert interviews points out that basic AM product design process may be realized utilizing any of the four models compared in this research. However, for innovative AM product design process all the models are not equally suitable. When considering AM possibilities in innovative product design all the experts agree that AM provides a lot of opportunities for product innovation. The following quotes support that aspect well:

"AM provides incredible possibilities for product design. What was not possible in manufacturing (before) is becoming possible. A quick example in mechanical point of view, if we do topology optimization, the result could be a little bit complicated, sophisticated shapes and so on, you better forget it with regular manufacturing, but you can do it with AM, you can reach incredible efficiency." Professor at LUT University

"In the early phases of the design process many geometrical and formal limitations can be forgotten with the aid of AM." Laboratory engineer at LUT University

"AM is of course enabler when it comes to creativity. For instance, when it comes to topology or shape optimization, there are things that you cannot do in another way. It is of course a great message to designers." Professor at LUT University

"I think the fact that AM process has certain proceeding order is a limitation for creativity. When you do things with your hands you can react instantly in everything that feels good and whatever you want to do. However, if you can form the AM part after printing somehow you could add things to it or remove something and hence, use your creativity" Jewellery Artist

"AM supports innovative product design in a way that as a designer you are not bounded to certain forms. In an AM part it is possible to get more functionality in one and the same part. In addition, forms can be considered more freely." 3D printing specialist

"There are a lot of simulation applications which are quite precise nowadays. Thus, you can simulate and test creative ideas quite easily. When the easy prototyping is added to these

simulation possibilities it brings very much added value to innovative product design." 3D printing specialist

"I think the biggest pro in AM product design is the possibility to make prototypes. For instance, totally novel kinds of functional parts are possible with AM but very difficult, even impossible to manufacture with conventional methods. Examples of these kinds of parts are different kinds of mesh structures and individually designed parts." Technical product specialist (Planmeca Oy)

"For instance, in the ideation and design phase AM methods bring a huge number of possibilities. You can for example, make prototypes freely." Technical product specialist (Planmeca Oy)

"From the innovative AM product design point of view, I consider that AM methods are much better than other manufacturing methods." Laboratory engineer at LUT University

The previous quotes address that AM is considered as an opportunity for innovative product design. According to the interviewed experts AM enables such geometries and functionality that conventional manufacturing does not. AM is considered as a good addition to conventional manufacturing methods. Thus, AM promotes innovative product design very well. However, the following quotes point out that for enabling innovative product design expertise is required:

"Absolutely AM methods increase utilizing innovative and creative product design. If a designer understands AM deeply enough, this expertise guides the design right from the beginning of the process without limiting innovative and creative design." Laboratory engineer at LUT University

"My feeling is that they can support innovation, if you are aware the technology of AM, then you can design much more beautiful things, because you know what is possible." Professor at LUT University

"You must know AM processes and DfAM deeply enough for being creative." 3D printing specialist

"DfAM brings a lot of opportunities, but you must be aware of them. When you are aware of the limitations then you can utilize all the pros of AM." 3D printing specialist

"AM demands a lot of expertise from the designer. You must also understand that all the AM techniques are not suitable for every AM design. You must be able to choose the most appropriate technique." Technical product specialist (Planmeca Oy)

"It is true that the limitations of AM techniques may bound somewhat innovative product design. On the other hand, if you are an expert of AM techniques it brings freedom to design process." Technical product specialist (Planmeca Oy)

"There are limitations, because there are certain geometrical limitations for instance, you cannot print similar things with every AM technique." Professor at LUT University

"Summa summarum, DfAM and innovative product design fit together well if you have the expertise of AM." Technical product specialist (Planmeca Oy)

All the experts agreed that AM expertise is needed for innovative AM product design. Without expertise in AM the designer does not know what is possible and what is not. Nonetheless, if a designer has AM knowledge deep enough it gives a lot of design freedom and further, supports creativity. Hence, AM expertise is an essential element of innovative AM product design. The following quotes point out that when a designer is an AM expert or works with AM experts it brings flexibility, cost efficiency, and time saving to the product design process:

" If you have chosen to utilize AM methods then the design process in general is easier and provides possibilities and thus, supports innovative design." Laboratory engineer at LUT University

"AM methods make the design process a lot faster. You can for instance, print product covers in a way that the product looks right though it is not functional. Then, you can test it. In addition, it often happens that a product misses a part which is needed for instance for electricity safety. With AM you can just print it and continue the product design. AM is flexible as a method, and you can print temporary parts easily and then, wait the real parts from the subcontractor." Technical product specialist (Planmeca Oy)

“AM makes product design processes faster. Making prototypes is faster.” Technical product specialist (Planmeca Oy)

“AM makes it easy, cost efficient, and flexible to design and test genuinely novel innovations. AM makes the whole design process faster.” Technical product specialist (Planmeca Oy)

Experts consider that the flexibility that AM provides into product design process aids innovation. In addition, the following quotes address that AM enables fast and short iteration rounds which nourishes innovative product design.

”AM methods are good for making prototypes and for that purpose they have been originally utilized. Making these prototypes certainly aids innovation in product design. Actually, all the AM parts are prototypes in the beginning of the product design process.” Laboratory engineer at LUT University

” With AM product design is possible to test with very short cycles which is important.” 3D printing specialist

The unlimited iteration between prototyping and testing is considered as a support for innovative product design. This is considered something that is not possible with conventional manufacturing methods. Moreover, the following quote address that AM and CAD modelling enable teamwork between different kinds of experts:

“Nowadays, when the design is in digital format it is easy to consider the design among different experts and thus, aid innovation.” Laboratory engineer at LUT University

This kind of teamwork supports innovative product design. However, sometimes innovative product design needs something surprising to happen:

” Innovative and creative product design would be possible with AM process if the printing process would be interrupted or disturbed somehow, or if the printing process would interrupt accidentally. Then you would see what happens with the incomplete part. You could use that for nourishing creativity and innovation.” Jewellery Artist

Hence, in innovative AM product design process the AM process does not always need to be flawless or straightforward. Creative and innovative design needs incompleteness and design mistakes which AMs' capability for easy and free iteration can repair. Consequently, it may be argued that the Design Thinking product design model is the most suitable process model for innovative AM product design as the following quotes point out:

"Design Thinking product design model suits well with AM when considering the large number of iteration rounds needed in AM design process. Design Thinking is probably the most suitable of these models for innovative AM product design process." 3D printing specialist

"In Design Thinking process AM makes the prototyping and testing easy and inspiring for innovative ideation. With AM making of prototypes is fast and precise. AM is best in ideation and prototype phases." Technical product specialist (Planmeca Oy)

In addition, reverse engineering and CE are considered as suitable to be utilized in innovative AM product design process as can be inferred from the following quotes:

"Another thing is reproduction of things. Let's assume that we are in a submarine, or we are flying to Mars, and we need to rebuild some elements, if you have metal AM devices you can rebuilt parts." Professor at LUT University

"Reverse engineering suits well too when the design process starts from a ready product and then you can start to add parts to it." 3D printing specialist

"Perhaps CE is suitable as well for different AM process phases can be processed simultaneously." 3D printing specialist

"Reverse engineering suits well for innovative AM product design. With reverse engineering for instance, the parts of some product may be designed lighter and more efficient." Technical product specialist (Planmeca Oy)

Finally, VDI 2221 is perhaps not very usable for innovative product design process:

"So I think that in conceptual design, what it comes to creativity, we are not trying to limit ourselves, you just release your creativity and consider that production would be great with this or that machine, but in detailed design, when you have to actually design parameters, there will be geometric limitations, then of course, you have to think the manufacturing method and use some common sense that is it reasonable, can you for example produce in required speed, because AM typically takes time." Professor at LUT University

This chapter has presented the results of the expert interviews made for this research. The next chapter will present the summary of the research data triangulation gathered via literature review, commercial references review, and expert interviews.

4.4 Summary of the Research Results of the Three Methods

The results of this research are gathered by using methodological triangulation of literature review, commercial references review, and expert interviews. The results of the research address that there are several different viewpoints which ought to consider when evaluating the possibilities of AM techniques in innovative product design process. The elements of creative product design have been considered firstly from the characters of innovative product point of view. These characters are novelty, functionality, and surprise. Secondly, the elements of creative product design have been considered from the elements of creativity aspect. The elements of creativity are expertise, motivation, and ability to creative thinking. These kinds of aspects ought to enable for accomplishing creative and innovative product in design process. In the Table 3 are gathered aspects concerning innovative AM product design process based on the research data.

Table 3. Aspects about innovative AM product design

Character of the Process	**Source**
Considering customer / User needs, and product ergonomics are a part of innovative product design	Scientific literature Commercial sources
Cost and time savings and efficiency are possible	Scientific literature Commercial sources Expert interviews
Parallel design with CAD modelling and prototypes is possible	Scientific literature Commercial sources Expert interviews
High number of iteration rounds is possible with AM and required for innovative design	Scientific literature Commercial sources Expert interviews
Essentiality of prototyping and testing	Scientific literature Commercial sources Expert interviews

Table 3 continues. Aspects about innovative AM product design

Character of the Process	Source
Expertise and knowledge of DfAM is required and hence, teamwork is usually needed for innovative design	Scientific literature Commercial sources Expert interviews
AM enables design flexibility and design freedom which are required in innovative design	Scientific literature Commercial sources Expert interviews
AM benefits innovative product design	Scientific literature Commercial sources Expert interviews
Innovative AM product design process is possible utilizing reverse engineering approach	Scientific literature Commercial sources Expert interviews

This chapter briefly summarized the results of this research. The next chapter will summarize the research results concerning the compared product design models. In addition, a process model proposal for innovative AM product design is made.

4.5 Process Model Proposition for Innovative AM Product Design

The results of this research address that innovative AM product design needs for example, design freedom and possibility for unlimited iteration. In addition, it requires expertise from the designer and benefits from teamwork of different kinds of experts. Therefore, the product design approach and model should enable and support these kinds of aspects. This research considers and makes comparison among four different product design models from innovative AM product design viewpoint. The compared product design models are VDI 2221, reverse engineering, CE, and Design Thinking. The suitability for innovative AM product design of these four models is compared based on the research data. The Table 4 presents a list of innovative AM product design characters and the models that enable that certain character.

Table 4. A list of innovative AM product design characters and the models that enable that certain character

Character of the Process	Suitable Design Model
Considering customer / User needs, and product ergonomics are a part of innovative product design	Design Thinking
Cost and time savings and efficiency are possible	Reverse engineering CE Design Thinking
Parallel design with CAD modelling and prototypes is possible	CE Design Thinking
High number of iteration rounds is possible with AM and required for innovative design	Design Thinking
Essentiality of prototyping and testing	Reverse engineering CE Design Thinking
Expertise and knowledge of DfAM is required and hence, teamwork is usually needed for innovative design	CE Design Thinking
AM enables design flexibility and design freedom which are required in innovative design	Design Thinking
AM benefits innovative product design	VDI 2221 Reverse engineering CE Design Thinking
Innovative AM product design process is possible utilizing reverse engineering approach	Reverse engineering Design Thinking

The Table 4 shows that Design Thinking seems to be the most suitable approach for innovative AM product design process. In addition, the results of literature review and expert interviews support this kind of conclusion. However, the Table 4 also points out that reverse engineering and CE may also be appropriate approaches for innovative AM product design process. This conclusion can be done based on the data of all the utilized research methods. However, the scientific literature does not quite support the view that CE would be usable for innovative product design though it is usable for AM product design. Finally, the Table 4 shows that traditional engineering process model VDI 2221 seems to be the most inappropriate process model to be utilized in innovative AM product design process. This conclusion can also be done from the data of all the research methods. Hence, Table 5 makes a conclusion and a proposition of process models for innovative AM product design. Similarly, Table 5 presents the possibilities of AM techniques in innovative product design.

Table 5. Product design model comparison from innovative AM product design point of view

Design Process Model	**Creativity**	**AM Plastics**	**AM Metals**	**Conclusions**	**Evaluation Points**
VDI 2221		x	x	Is suitable for AM product design but does not support creativity	●○○
Reverse engineering	x	x	x	Is suitable for innovative AM product design	●●○
Concurrent engineering (CE)	x	x	x	Is suitable for innovative AM product design	●●○
Design Thinking	x	x	x	Is very well suitable for innovative AM product design	●●●
Combination of Design Thinking, Reverse engineering, and CE (Figure 22)	x	x	x	Is excellently suitable for innovative AM product design	●●●

The Table 5 shows that VDI 2221 product design model is suitable for plastics and metals AM product design but does not support creativity. Reverse engineering and CE are both suitable for innovative plastics and metals AM product design. Design Thinking suits very well for innovative plastics and metals AM product design (Figure 23).

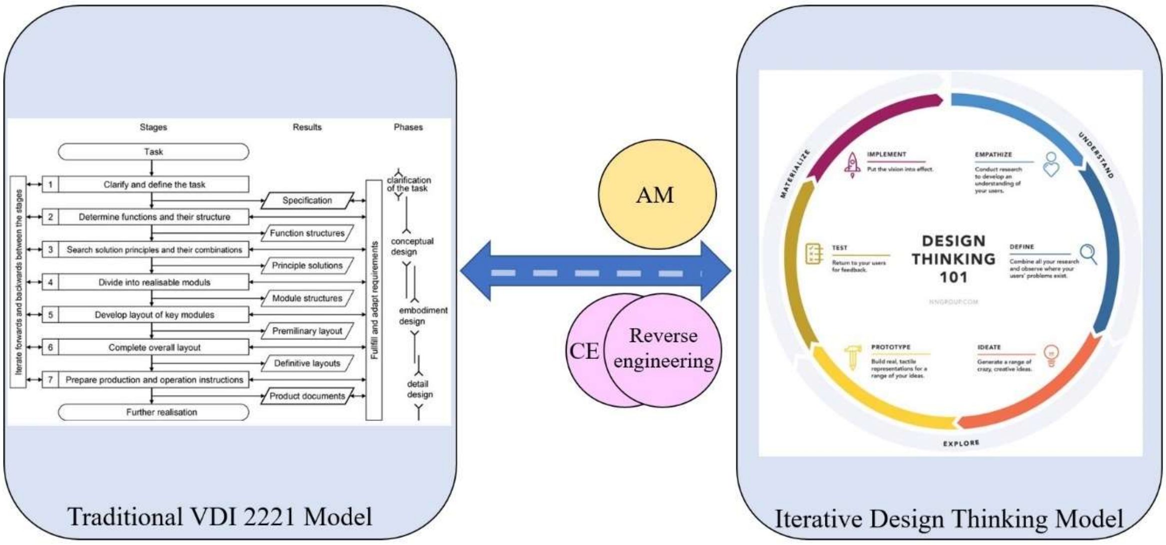


Figure 23. AM product design model continuum based on the results of the research.

However, the most suitable product design process model for innovative AM product design would be a combination of Design Thinking, reverse engineering, and CE (Figure 24). This combination model is called Design Thinking for innovative AM (DTfIAM). This combination model is a basic Design Thinking model with free iteration however, in the phases ideate, prototype, and test iteration can be done parallel and simultaneously with all these three phases like in CE. If needed the iteration may be done backwards like in reverse engineering.

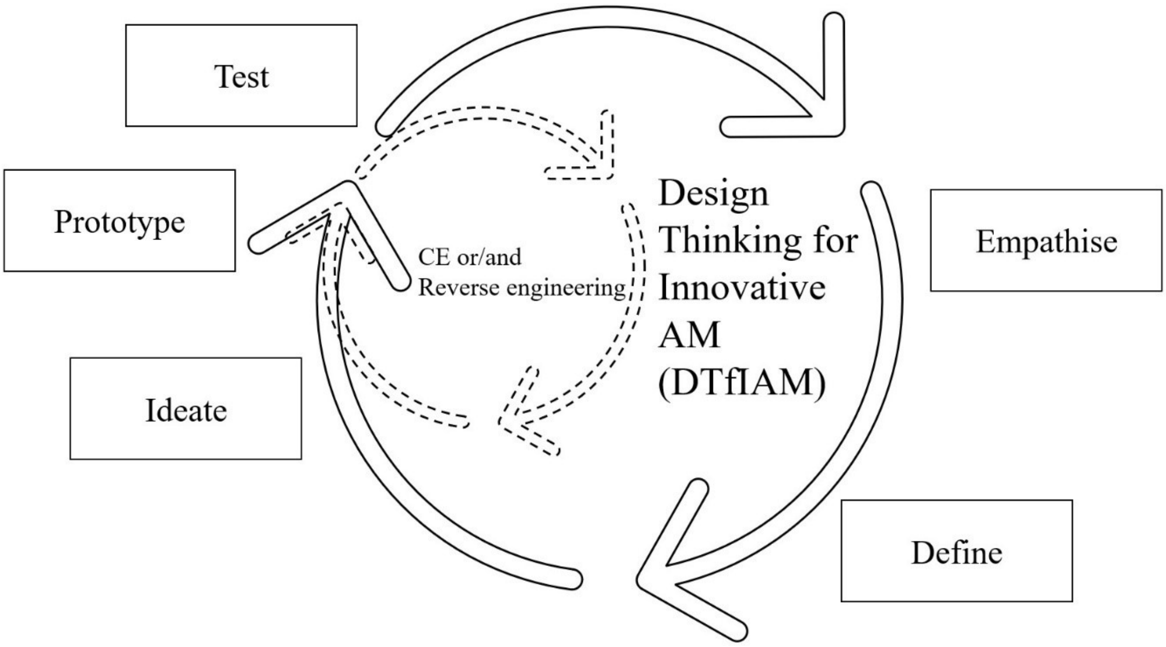


Figure 24. Proposed combination model DTfIAM for innovative AM product design.

When considering the suitability of plastics and metals AM techniques for innovative AM product design for instance, the results of the expert interviews point out that metals AM materials and devices are more expensive than in plastics AM. Thus, the design for metals AM products is less iterative and the product design is aided by simulation applications for avoiding waste of materials. Thus, when thinking about the iterative nature of innovative AM product design, plastics AM enables it better than metals AM. Therefore, plastics and metals AM are not equally suitable for innovative AM product design process though they would be equally suitable for AM product design in general.

This chapter has evaluated and compared the product design process models from innovative AM product design viewpoint based on the research results. As a generalized result a proposal for product design model combination for innovative AM product design (DTfIAM) was presented. The next chapter will present the discussion of the results of this research.

5 Discussion

This chapter discusses about the research methods and results. The following chapters discusses about the research connection with previous research, objectivity, reliability and validity, and key findings of this research. In addition, novelty value and generalization and utilization of the research results are considered. Finally, future work of this research is proposed, and conclusions are made.

5.1 Comparison and Connections with Previous Research

The scientific literature review of this research points out that different kinds of product design models have been developed a lot. Furthermore, in the field of creativity and innovative product design research have been presented plethora of studies from different angles. When considering this research for instance, Zjang & Yu (2016) have presented a study where they have created a model for innovative AM product design with reverse engineering process (Figure 20). In addition, Perez et al. (2019) have developed the Design Innovation with Additive Manufacturing (DIwAM) methodology (Figure 18). In this approach AM is utilized in the design innovation framework of Camburn et al. (2017) (Figure 15) which is Design Thinking -based approach for combining relevant design thinking, systems engineering, design engineering, and business design practises. DIwAM framework of Perez et al. (2019) utilizes AM as a design tool for innovation. In this framework AM is used to aid innovation with other design methods and AM is utilized in every phase of this framework. Hence, this research differs from these studies by providing a comparison of four different product design approaches. Moreover, this research proposes a combination of three product design models (DTfIAM) which is appointed to innovative AM product design process. Thus, DTfIAM is for AM process unlike DIwAM by Perez et al. (2019) which is for innovative design where AM is a design tool. Many previous studies like the study of result de Almeida et al. (2021) propose that utilizing AM makes the design process innovative and utilizing AM as such promotes innovative design (Figure 17). However, this research aims to study what are the possibilities of AM techniques in innovative product design and on what basis AM may be utilize in this kind of process.

Consequently, though this research has a strong basis in previously researched product design process models and in creativity and innovative design research it provides a novel angle to this subject.

5.2 Objectivity of the Research

The research methods of this study were scientific literature review, a review of commercial sources, and expert interviews. The utilized methods in this research were used in a qualitative manner. This means that the conclusions of this research are based on qualitative data. This may decrease the objectivity of this research and its' conclusions for gathering and evaluation of qualitative data is usually somewhat subjective, and the conclusions based on qualitative data are always made from some viewpoint. If one or two of the methods of the methodological triangulation of this research would have been quantitative, it would perhaps increase the objectivity of this research. In addition, this research was made by one person. If the research would have been teamwork and the results and conclusions would have been considered by more than one person, it would probably increase the objectivity of the research. In addition, for the data was gathered by one person it may be considered to be somewhat subjective from the bordering point of view. Moreover, though the scientific literature review has scientific basis and thus it has an aim for objectivity the commercial references are highly subjective for having commercial agenda. Thus, it may be concluded that though the aim of this research has been objectivity and utilizing methodological triangulation has supported that goal there is rather subjective angle in this research.

5.3 Reliability and Validity

The aim of this research was to research on what basis the researched AM techniques could be utilized in innovative product design. Furthermore, the goal was to develop an innovative AM product design model. The utilized research methods in this study were scientific literature review, a review of commercial sources, and expert interviews. All the utilized methods were used in a qualitative manner and expert interviews is a qualitative method. Thus, the results of this research are based on qualitative data. This may decrease the reliability and validity from firstly, the gathered data and secondly, the results and conclusions viewpoint. The scientific literature has a scientific basis. However, the bordering of the data collection is made by one person and thus, it may have a subjective bias. Also, the commercial references have somewhat strong subjective bias for their commercial agenda. Furthermore, for the expert interviews have been planned, interviewed, and analysed by one person it may have probably added subjectivity in the results of the expert interviews. This decreases the reliability and validity of this research and its' results.

The reliability and validity have been aimed to increase by using methodological triangulation. Using three methods supports the reliability and validity of the results and conclusions much better than using just one method. In addition, the proper number of interviewed experts was tried select in a way that it would increase the reliability and validity of the research. Hence, five different kinds of experts with different kinds of backgrounds were interviewed for receiving different kinds of viewpoints from the same topic. However, in a qualitative interview the number of interviewees should not be too high for analysing the gathered data may come too difficult for a one person as is in this research. Nonetheless, in this kind of interview approach the problem is that for the different kinds of viewpoints are aimed to gather there is no such reliability and validity what conducting similar kinds of aspects and thus, quantitative data would bring into research.

For this research was done by one person and the research data have not been checked with fresh eyes the possibility for mistakes and absence of some relevant data may increase. In addition, there is a possibility that the commercial references have not been evaluated critical enough. These aspects may affect to the reliability and validity of this research decreasingly. However, by utilizing the methodological triangulation and conducting a proper amount of data probably ensures that the reliability and validity of this research stay in sufficient level.

5.4 Key Findings

The utilized methodological triangulation of this research points out that AM techniques support innovative product design process. Especially plastics AM increases motivation for novel product design and makes the whole process easier and faster by providing fast iteration with relatively low costs. Thus, the utilized process model for innovative AM product design should support and give room for these kinds of activities and free design. The most suitable product design model for innovative AM product design seems to be Design Thinking or a combination of Design Thinking, CE, and reverse engineering. The aim of the combination model is to utilize the features of these product design models which are most useful from innovative AM product design viewpoint. For being an innovation model Design Thinking provides free iterations and room for ideation. AM process phases may be done parallel or simultaneously, and CE supports that kind of approach. Reverse engineering adds the possibility for backwards design which may be useful for innovative AM product design in many cases. However, both plastics AM, and metals AM are not equally suitable for innovative product design process for the plethora of iterations which is often required for innovative product design are much more expensive and thus inefficient with metals AM than plastics AM. Hence, these are the basis that the researched AM techniques could be utilized in innovative product design and the ways of utilizing the researched AM techniques are generalizable to other AM techniques merely partially.

When considering design freedom and flexibility containing innovative product design process it is often considered more inefficient than traditional and effective appearing engineering design process. Often, the efficiency of the product design process is emphasized and for instance, the duration of the design process may be the indicator of the process efficiency. Cropley (2015, pp. 54–56) presents the concepts of theoretical and available design spaces in innovative product design process. Theoretical design space describes the design freedom and flexibility that innovative product design should have to be successful. Available design space describes much constrained space for design freedom and flexibility comparing to the theoretical design space. These concepts concretise the basic problem of innovative design processes. For efficiency demands the available design space is limited in many ways and thus, the designer or a design team cannot utilize the theoretical maximum design space. Therefore, successful innovative product design is often very bounded or even impossible. (Cropley 2015, pp. 54–56) Hence, it is justifiable to argue that for being successful and thus, effective an innovative product design process must provide design freedom and flexibility for designers. Traditional and efficient appearing engineering design process produces innovative results inefficiently.

However, for instance, AM technologies such as CAD modelling may help to improve data sharing among design team members and thus, decrease time consuming. Fluent data sharing can improve efficiency of design processes and furthermore, release more time to innovative product design. Fluent data sharing enables utilizing parallel working with different design process phases of CE. It also improves the efficiency of free iteration of Design Thinking. Fluent data processing of product 3D scans enables efficient usage of river engineering as well. Thus, it may be argued that AM technologies and particularly CAD modelling increase innovative product design process efficiency. Furthermore, design freedom and flexibility of innovative product design and design process efficiency may be fitted in the same process for example, by utilizing AM technologies.

5.5 Novelty Value of the Results

This research provides a comparison of four somewhat commonly used product design models for researching what kind of design process model would be most useful in innovative AM product design. In addition, a proposal for a combination model DTfIAM for innovative AM product design is suggested. Thus, the research points out on what basis the researched AM techniques could be utilized in innovative product design. Though different kind of product design and innovation models have been studies a lot, this research provides slightly different and thus, novel angle to this research field. In addition, it encourages to use of untraditional product design model or model combination for enabling creativity and product innovation in industrial design engineering.

5.6 Generalization and Utilization of the Results

The results and conclusions of this research are generalizable and utilizable at least somewhat though there might be some uncertainty with objectivity, reliability, and validity aspects. Thus, the results and conclusions may help for instance, to support innovative AM product design process among researchers and designers. The results of this study can help for instance, product designers to choose the most appropriate product design model for innovative AM product design and other product design too. AM designers may find novel ways for innovative product design for example, by adding human-centred design approach of Design Thinking into their product design processes.

For generalization of such results of this research and DTfIAM product design model the research topic ought to be studied further and the proposed combination model ought to be tested in a practical manner.

5.7 Future Research

This research provides a somewhat strong basis for research of the same topic further in the future. The data collection could be enlarged with all the used research methods and perhaps one quantitative method like inquiry could be added. A bigger number of different kinds of product design process models could be perhaps compared. Thus, different kinds of engineering design models and creative process models could be research from innovative AM product design process viewpoint. As a basis for this kind of comparison could be used for example a study of Howard et al. (2007; 2008) where engineering process models and creative process models are compared based on process phases. For there are various engineering design methods after studying CE and reverse engineering in product design model continuum, for example modular design and sustainable design methods could be studied from innovative AM product design point of view and further, perhaps located on the AM product design process continuum (Figure 23).

When considering engineering design models that could be studied from innovative AM product design viewpoint Cropley (2015, pp. 56–60) presents for instance, Pugh's Total Design approach and the Vee Model approach of Forsberg, Mooz, and Cotterman as engineering design models which could be interesting to study further. As a creative problem-solving model Double Diamond model of Design Council (den Dekker 2020, p. 55) could be studied further from innovative AM product design point of view. By studying bigger number of different kinds of product design process models maybe more precise or versatile results about the most suitable process model or models for innovative AM product design could be accomplish.

However, the most interesting approach for this topic in the future could be testing of the compared models and the proposed combination model in practice from innovative AM product design point of view and thus, gather both qualitative and quantitative data for further results and conclusions. Testing the product design model in practice could increase objectivity, reliability, and validity of the research. In addition, an interesting approach to the topic of this research could be educational. This means integrating the findings of this research in industrial design engineering education and hence, perhaps testing the findings in practise. Simultaneously, creative approach in industrial design engineering could be maybe supported from a novel viewpoint.

5.8 Conclusions

The goal of this research has been studying the possibilities of AM techniques in innovative product design process. The topic has been researched by using methodological triangulation of scientific literature review, commercial references review, and expert interviews. Gathering and analysing this data aimed to find out that on what basis the researched AM techniques could be utilized in innovative product design and further, are the ways of utilizing the researched AM techniques generalizable to other AM techniques. As a result, a comparison of four different product design models were made from innovative AM product design viewpoint. The outcomes of this comparison show that innovative AM product design requires the kind of design freedom, flexibility, and unlimited iteration which Design Thinking product design model provides best comparing the other three design process models of the comparison. However, CE and reverse engineering have beneficial characters from innovative AM product design point of view as well. Thus, a novel product design process model (DTfIAM) combining Design thinking, CE, and reverse engineering were proposed. This comparison and the proposed novel product design model provide an answer to the main research question on what basis the researched AM techniques could be utilized in innovative product design. The further evaluation of the research data points out that though both plastics and metals AM are suitable for innovative AM product design as techniques, plastics AM techniques are far more cost-effective choice for myriad iteration rounds demanding product innovation. Hence, the ways of utilizing researched plastics AM techniques are generalizable to metals AM techniques only partly. These results answer the research questions and by this way the research has achieved its objectives.

This research however, studied merely limited number of design process models. Consequently, it would be beneficial to include more product design models and approaches to this kind of research. It would perhaps bring novel aspects and increase the validity of the research results. Nevertheless, this research provides guidelines for selecting suitable product design process model for innovative AM product design process and thus, the results of this research may help designers and engineers to achieve innovative AM products. The results of this research may also encourage designers and engineers to utilize creative process model in their product design processes. Though previous scientific literature points out that engineering design models and creative design models have been studied and compared previously, as a scientific contribution this study provides comparison of this kind of models from AM product design viewpoint.

6 Summary

The aim of this research was to study the possibilities of AM techniques in innovative product design process. Furthermore, the goal was to find out on what basis the researched AM techniques could be utilized in innovative product design. For researching this topic, a methodological triangulation of scientific literature review, commercial sources review, and expert interviews were conducted. In the literature review of scientific references literature was searched and evaluated in traditional manner. In the commercial references review the gathered data was limited to customer stories of such companies that provide AM devices, AM services, and AM expertise services for other companies. Expert interviews were made for five different kinds of experts via Microsoft Teams application in semi-structure manner. By utilizing this methodological triangulation, the objectivity, reliability, and validity of the research were aimed to increase.

The results of the research pointed out that to be suitable for innovative AM product design process a design model should enable for example, countless iteration rounds and design freedom. Nevertheless, AM enables doing different phases of iteration rounds simultaneously. As a result of evaluation of the gathered data a comparison of four different product design models, VDI 2221, reverse engineering process model, concurrent engineering (CE) process model, and Design Thinking process model, was made from innovative AM product design process viewpoint. Moreover, a process model combination of Design Thinking, CE, and reverse engineering (DTfIAM) was proposed to be utilized in innovative AM product design process. This novel approach could be utilized by AM designers and industrial design engineers. This research also addressed that innovative AM product design process utilizing these design process models is equally possible with plastics and metals AM techniques. Nonetheless, plastics AM is more suitable for innovative product design for it allows plethora of iteration rounds much more cost-effectively than metals AM. In the future, the compared product design models, and the proposed combination model however, ought to be tested in practise. Furthermore, additional design process models could be evaluated from innovative AM product design point of view.

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Appendix 1. Expert interview questions in Finnish

1. Minkälaisia mahdollisuuksia lisäävät valmistusmenetelmät (additive manufacturing (AM); esim. 3D-tulostus) tarjoavat tuotesuunnitteluun?

2. Minkälaisia rajoitteita lisäävien valmistusmenetelmien käyttö tuo tuotesuunnitteluun?

3. Jos ajatellaan lisäävien valmistusmenetelmien rajoitteita ja innovatiivisen / luovan tuotesuunnittelun vapautta, miten nämä kaksi ovat näkemyksesi mukaan yhdistettävissä?

    - Voidaanko lisääviä valmistusmenetelmiä, joilla on rajoitteita, ylipäätään yhdistää innovatiiviseen / luovaan tuotesuunnitteluun? Vai rajoittavatko lisäävien valmistusmenetelmien rajoitteet innovatiivisuutta / luovuutta?

4. Jos lisääviä valmistusmenetelmiä voidaan näkemyksesi mukaan hyödyntää innovatiivisessa / luovassa tuotesuunnitteluprosessissa, millä tavoin se tapahtuu?

    - Kuinka lisäävien valmistusmenetelmien käyttö voi tukea innovatiivista / luovaa tuotesuunnittelua suunnitteluprosessin eri vaiheissa?

    - Miten lisäävien valmistusmenetelmien käyttö vaikuttaa innovatiivisen / luovan tuotesuunnitteluprosessin etenemiseen / vaiheisiin?

    - Jos ajatellaan Design for Additive Manufacturing (DfAM) lähestymistapaa, miten se vaikuttaa mielestäsi innovatiiviseen / luovaan tuotesuunnitteluun? Sopivatko DfAM ja innovatiivinen / luova tuotesuunnittelu (hyvin) yhteen?

5. Minkälaisiin tuotesuunnittelun prosessimalleihin (esim. Concurrent Engineering (CE), Reverse Engineering, Design Thinking, VDI 2221) AM tekniikat soveltuvat hyvin tai parhaiten?

    - Miksi?
    - Missä eri tuotesuunnittelun vaiheissa AM tekniikat soveltuvat käytettäviksi?

6. Tarjoavatko lisäävät valmistusmenetelmät mielestäsi innovatiiviseen / luovaan tuotesuunnitteluun jotakin sellaista lisäarvoa, jota perinteiset valmistusmenetelmät eivät tarjoa?

Appendix 2. Table of the experts interviewed in this research

Interviewee	**Expertise**
Leonid Chechurin	Professor (at LUT University)
Ilkka Poutiainen	Laboratory engineer (at LUT University)
Helena Lehtinen	Jewellery artist
Eetu Holstein	3D printing specialist
Kalle Kohtanen	Technical product specialist (Planmeca Oy)