LAPIN AMK
Lapland University of Applied Sciences

Additive Manufacturing Design Methods in Construction Industry

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Lapland University of Applied Sciences
Mechanical Engineering
Bachelor of Science

2022

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Abstract of Thesis

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Commissioned by	Ari Pikkarainen, D.Sc. (tech)		
Title of Thesis	Additive Manufacturing Design Methods in Construction Industry		
Number of pages			

In this work a literature review was conducted to determine the design methods utilized in three-dimensional concrete printing (3DCP). 3DCP is an additive manufacturing (AM) technique used in the construction industry. In this technique concrete is extruded through a nozzle to subsequently build a structure layer by layer.

Several benefits are introduced to engineering through AM of which many are associated to structural variety. In conventional manufacturing techniques structural variety is often not feasible due to the limitations of the manufacturing process. In concrete construction as well building slender shapes is enabled through AM due to the ceasing of formworks.

Design for additive manufacturing (DfAM) is a collection of tools and procedures to support addressing the characteristics of AM during the product design process. The review indicates that these methods are rarely used in construction industry in contrast to the product design field. By purposefully utilizing DfAM methods architects and construction engineers can advance in exploiting structural variety to add values such as thermal performance to concrete components

Key words: AM, construction industry, 3DCP, design process, DfAM, structural variety

CONTENTS

FOREWORD

About a year ago I decided to take on the challenge and to travel into an unknown place to not only finish my studies in renewable energy technologies but additionally in mechanical engineering. Although it was demanding to adapt to new living circumstances such as a foreign culture and substantial differences in climate and new social circles, eventually I managed to conceive these challenges as enjoyable adventures. I am proud of the outstanding experiences I made in this year as well as to successfully finish my studies. However, this would not have been possible without noteworthy support.

First and foremost, I want to highlight my teacher, supervisor, and guide Ari Pikkarainen for supporting my ideas as well as demonstrating ways to realize them. I highly appreciate the time and energy he invested in meetings with me to discuss every topic related to my studies and thesis, no matter if in an engineering context or regarding a working mindset. I feel greatly blessed to be taught by a such a wise, intelligent, and kind man. Furthermore, I am grateful to University of Applied Sciences Technikum Wien and Lapland University of Applied Sciences for organizing a double degree program and offering me the opportunity to expand my engineering knowledge and experience in not less than two subject areas.

I also want to express my thankfulness to Sanna Moisanen, who welcomed me in Finland in the most cordial way one can imagine. During my stay, I could always knock on her door with questions regarding paperwork, leisure time options in the Lapland region, needed tableware or to just have a friendly talk.

Finally, I want to thank my family and friends in Kemi. Especially my parents and siblings helped to encourage me in dark times during this year. Ofosu Jones-Quartey practised concentration and relaxation with me every day. And also of major importance, I share hilarious, impressive and amazing memories with my flatmates and international tutors from smaller and bigger travel trips and movie, party, or game-nights.

SYMBOLS AND ABBREVIATIONS

AM	Additive Manufaturing
3D CAD	three-dimensional computer aided design
3DCP	three-dimensional concrete printing
DfAM	Design for Additive Manufacturing
τ_c	Yield stress
γ_c	critical shear strain
G	elastic shear modulus
A_{thix}	rate of thixotropic build up

1 INTRODUCTION

Over the recent decades the technology of additive manufacturing (AM) found its value in many different fields of engineering and for a few years now also its importance in construction industry grew significantly. At first only single parts were manufactured by using 3D-printing technologies, but nowadays technology reached the certain milestone, that the first few buildings were completed by printing concrete layer by layer. (Alzarrad & Elhouar 2019.)

The introduction of a new manufacturing technology also opens up new possibilities of exploiting its benefits by targeting them already in the design process. Traditional AM, is mainly used as a well proven way of rapid and cheap prototyping. But also, compared to subtractive manufacturing methods it enables a wider range of geometrical variety and customization of each part at no extra cost. Transferring especially the benefit of structural variety to construction industry can have a significant impact. It can firstly help reducing build material for achieving the same static properties, which leads to reduced costs and a more sustainable handling of raw material. In addition, the geometrical variety promotes multifunctional usage of components, for example in thermal activity by varying the structure of the infill targeting the reduction of thermal bridges (Gosselin et al. 2016). This process is enabled only by extruding build material layer by layer compared to traditional formwork casting of concrete.

To meet this demand, this thesis discusses, how AM is applied in construction industry. Furthermore, it aims to point out, how the benefits of AM can be exploited by imbedding them already in the design process.

Overall, the main objective of the thesis is to discuss, how the advantages of AM can be exploited to create new design solutions.

1.1 Scope and Questioning

Generally spoken the manufacturing of buildings has always been additive, considering its main distinction from subtractive manufacturing. This is namely the adding instead of removing of building material to achieve the desired structure. However, in an engineering environment the term AM describes technologies mainly developed for rapid prototyping, in which a model generated by a three-dimensional computer aided design (3D CAD) system is manufactured by adding material in layers (Gibson, Rosen & Stucker 2015, 2). This process can be performed using various methods, of which fused deposition modelling (FDM) is the most popular in Nordic and Baltic states, according to a survey of the PLM Group (Kristiansson 2021). Moreover worldwide, FDM was 2021 the most used technique under 3D-printing designers (Statista, Inc. 2021).

In construction industry various methods are used including methods for mold-making and those using a particle bed approach. Also, over half of the processes under development employ extrusion of a high cement content mortar through a nozzle often mounted on a robotic arm (Buswell, da Silva, Jones & Dirrenberger 2018). Considering the similarities in the basic idea of positioning an extruded filament on the before printed layer and the setup of the equipment this method can be described as a mimicking of the FDM technology. It is referred to as three-dimensional concrete printing (3DCP), since this is the most commonly used term in the technical literature and regarding the two aspects of technological readiness and economic viability 3DCP is considered a frontrunner among other groups of AM approaches (Mechtcherine, et al. 2020). Therefore, this thesis focuses on discussing the extrusion-based method, mimicking FDM technology, 3DCP.

Based on the mentioned arguments the main research question reads as following:

“How can the structural variety enabled by AM be exploited in extrusion-based 3DCP to create new design solutions”

1.2 Methodology and limitations

One of the key areas of the study program of mechanical engineering at Lapland UAS is gathering knowledge and experience in the field of AM. The student learns the strengths and weaknesses of several different techniques through theoretical and practical work. Although the degree programme focuses on the techniques mainly used in small-scale desktop printing, some of the basic principles can also be transferred to other applications of AM such as in construction industry. The other part of the student’s double degree program, the studies of renewable energy technologies at Technikum Wien UAS, have one of its core areas in building physics and building technologies. Although the aim in this field of studies is to apply the knowledge in calculating, interpreting and optimising the energy qualities of buildings, the student also learns about structures of load bearing walls, ceilings and roofs. In this thesis the student expands his knowledge based on the combination of the basics of both of his studies.

However, since the examined technologies are rather upcoming than already well established, the equipment needed to perform any kind of 3DCP is hardly accessible. So, practical experiments in this field of studies require a big number of financial resources. But also, there is a strong call for interdisciplinary collaboration in technical literature. Multidisciplinary enables the freedom of design by assessing every aspect of the problem of interest (Gosselin, Duballet, Roux, Gaudillière, Dirrenberger & Morel 2016). So, the chosen topic and defined research question characterizes both a remarkable difficulty to produce data through practical experiments and a variety of viewpoints. The base knowledge in both construction engineering and additive manufacturing offers the possibility to approach the topic from two different point of views. Nevertheless, the discussed question offers a wide range of possible further research. So, in this thesis this will be done using the scientific method of a literature review.

A literature review is organised in four main phases. Firstly, the problem of interest is formulated. In this phase the topic being examined is defined and it is clarified what its component issues are. A research question is defined, and appropriate approaches from different perspectives based on the objectives are chosen. After that literature is gathered. This is done by entering key words into search engines of academic libraries. Also, after overviewing the search results reputable authors and academic intuitions in the considered field of studies are detected and searched for further publications. In the next phase the gathered literature is filtered by considering its contribution to the before defined issues. It is evaluated how relevant each piece of literature is to the discussed research question and irrelevant ones are sorted out. In the last phase the statements of the chosen literature are discussed and interpreted. Also, new concepts based on the findings are presented and suggestions for further studies are integrated.

In the first part of the thesis the current state of technology of 3DCP is in the focus. By reviewing existing cases of concrete printed buildings and literature research on ongoing developments, knowledge is gathered on different techniques of 3DCP. Also, the needed equipment and the workflow of 3DCP is examined. Furthermore, the inherent design process is researched and changes, new design possibilities, advantages and disadvantages of 3DCP compared to traditional design processes are analysed. As a precondition for concrete as a printable build material its specific material properties need to be considered.

The second part of the thesis approaches 3DCP from the point of view of traditional AM. Therefore, it is first pointed out, which main benefits AM brings to manufacturing in general and examined, how crucial these effects are in 3DCP. Especially the enabled structural variety and its potential effects is discussed. The design for additive manufacturing (DfAM) principles are considered and it is discussed, if these principles are used in 3DCP, if they are applicable or if there is a need for an adaption of these principles to construction industry. Furthermore, it is discussed, how small-scale 3D-printing can help pre-planning the actual printing of a building.

The third part of the thesis deals with the challenges of 3DCP from a constructional point of view. Concrete also in its hardened state has to fulfil several rheologic properties. A main challenge is the need of reinforcement because lone concrete does not have the capacity to withstand high amounts of tensile loading. However, in a printing environment reinforcement cannot be implemented before spreading concrete as known from traditional formwork casting (Wangler et al. 2016). So, it needs to be researched how these arguments affect further design guidelines.

To conclude based on the gathered information new design ideas are brought up. There is an already ongoing discussion about, how 3DCP can promote the multifunctional usage of elements. For example, de Schutter et al. state:

“Implementing structural optimization as well as functional hybridization as design strategies allows the use of material only where is structurally or functionally needed. This design optimization increases shape complexity, but also reduces material use in DFC [digitally fabricated concrete]” (De Schutter et al. 2018). Another usage of the geometrical complexity enabled by 3DCP is to optimize the thermal and acoustic properties of building elements (Gosselin et al. 2016). Furthermore, the surface structure resulting from 3DCP could also promote greening of facades.

2 STATE OF TECHNOLOGY

In this chapter an overview of current 3DCP is given. The aim is to provide a clear picture to the reader of what the challenges are that technology faces nowadays but also what can already be done.

Therefore, in Section 2.1 several examples for outstanding achievements in the recent years will be given. The reader will learn about frontrunning companies and projects worth mentioning, which are remarkable in certain aspects, such as printing time or location.

Proximately in Section 2.2 prerequisites to perform 3DCP will be discussed. Since concrete is printed in its fluid state, it has to fulfil certain viscous and thixotropic properties, to not clog the printing equipment, but also carry the weight of the subsequent layers. Also, to enable the perpetual connection of the layers and to avoid so called cold joints, it has to be respected, that the concrete is not already hardened, when the subsequent layer is placed. This is connected to the composition of the build material as well as the speed of printing. (Wangler et al. 2016.)

Furthermore, in Section 2.3 the necessary equipment is discussed. The existing four different kinds of technological systems for 3DCP including their field of application, advantages and disadvantages are pointed out. Thereby the reader gets a clear picture of the technological extent of a 3DCP process.

2.1 Examples for 3DCP

In this section several examples for the usage of AM in construction industry will be given. The aim is to provide a picture of the relevance of these manufacturing techniques to the reader. Although the thesis focuses mainly on FDM-mimicking techniques, in this section a broad spectre of techniques will be respected. This is because the reader should also get an idea of the variety of techniques currently under development. Nevertheless, the most investigated technique in the research community is 3DCP (Labonnote, Rønnquist, Manum & Rüther 2016).

2.1.1 Military housing in India

To meet the fast-growing demand of housing in the Indian military the Military Engineering Service (MES) recently cooperated with the private company Tvasta Construction. By using 3DCP the housings shown in Figure 1 were deployed within 35 days. But the technique is not only confined to housing in the Indian military, but also the construction of bunkers and facilities for military vehicles are asked. Especially in hostile areas the conditions can be challenging for traditional construction. Harsh weather conditions and short supply of labor due to threat from hostile neighbors can be the reason therefore. But by using 3DCP a solution to these challenges was found. A design characterized with a lot of curves was used to avoid sand deposits. Also, a new composite with anti-ultra-violet properties was developed, so the material does not corrode. (Ahaskar 2022.)

Figure 1. Housing in the Indian Army (Hindustan Times 2022)

2.1.2 A Spherical home in Japan

In 2020 the Japanese company Serendix filled the first patents for the design concept of a spherical 3D-printed home. The main objective of this project was to provide an emergency housing, which is transportable, quick to build up and capable of resisting earthquakes and typhoons. Lately, the company completed the construction of this model (Figure 2) in a total time of 23 hours and 12 minutes, of which 3 hours were attributed to assembling it on-site. (Fornari 2022.)

Figure 2. Spherical home printed in Japan (Fornari 2022)

2.1.3 Extraterrestrial shelters

In 2019 the National Aeronautics and Space Administration (NASA) completed the “3D-Printed Habitat Challenge”. In this Centennial Challenges program, the participants were mandated to design a 3D-printed habitat for deep space exploration. The aim for this program is to advance in settlement plans on the Moon, Mars or beyond. One of the objectives in the competition was to implement a design using on-site available resources, since the supply of building material represents a significant difficulty for these plans. Another challenge is the shortage of workforce in not yet colonized terrain. Therefore, 3DCP and other automated technologies offer a valuable solution. However, 3DCP can not only be used to establish housing, but also shelters to protect exploration equipment from present environmental conditions such as cosmic radiation.

2.2 Prerequisites

Concrete has its main properties in common with visco-plastic Bingham materials. This means that, when submitted to a stress higher than a critical threshold value called yield stress (τ_c) the material begins to flow. As long as the submitted stress is under this value the material is at rest and shows rather elasto-plastic properties. (Roussel 2018.)

However, to perform reasonable 3DCP a material is required, which fulfils certain properties:

- pumpability
- extrudability
- buildability (Asprone, Auricchio, Menna, & Mercuri 2018a.)

Pumpability describes the capability of the build material to be pumped towards the printing head. Extrudability describes the capability of flowing continuously through the printing head. Buildability describes the capability of the already printed material to sustain the weight of subsequent layers and thereby form an upright structure (Asprone et al. 2018a.)

Thus, a divergence between the requirement of diminished τ_c, to enable the material to be pumped and extruded, and elevated τ_c to maintain the shape results.

Consequently, the thixotropy of the material to be worked with is a key characteristic. The thixotropy of a material describes, how the rheological parameters, including not only τ_c but also the critical shear strain (γ_c) and the elastic shear modulus (G), change over certain environmental conditions, such as the time at rest. For cementitious materials, such as concrete, with time at rest $\tau_c(t)$ and $G(t)$ are increasing and, $\gamma_c(t)$ is decreasing. Therefore, with time at rest the material becomes harder, due to higher τ_c, as well as more rigid, due to higher G. The exact behaviour of these functions is depending on the rate of thixotropic build up (A_{thix}). (Roussel 2018.)

Furthermore, a material specific aspect, which is also connected to A_{thix}, is the maximum time for a layer to be produced. If the critical resting time is exceeded when placing the subsequent layer, it can limit intermixing of the material of the two layers. (Wangler et al. 2016). This is called a cold joint and can lead to weak interfaces. (Roussel 2018.)

Based on this Wangler et al. defined an operation window, shown in (1) and (2) between the minimum rest time for a high enough yield stress to allow buildability and a maximum rest time to avoid cold joints. (Wangler et al. 2016.)

$$t_{h,min} = \rho g h / (\sqrt{3} * A_{thix}) \tag{1}$$

where

$t_{h,min}$	…	minimum rest time to allow sufficient buildability
ρ	…	density
g	…	gravity constant
h	…	layer height
A_{thix}	…	rate at which yield stress increases

$$t_{h,max} = \frac{\sqrt{\frac{(\rho g h)^2}{12} + \left(\frac{2\mu_p V}{h}\right)^2}}{A_{thix}} \tag{2}$$

where

$t_{h,max}$		Maximum rest time to avoid cold joints
ρ	…	density
g	…	gravity constant
h	…	layer height
V		horizontal velocity
μ_p	…	plastic viscosity

Zhang et al. presented an example how the rheological properties of concrete can be manipulated by utilizing additive materials. A novel 3D printing concrete was introduced, in which the addition of nano clay (NC) and silica fume (SF) lead to the structural rebuilding of the cement paste. Thereby, the buildability of this concrete with a small quantity of NC or SF was increased by 150% and 117%, while still showing good flowing properties. (Zhang et al. 2018)

2.3 Equipment

The equipment used for 3DCP can be classified into four primary kinds of systems, that are gantry systems, fixed robotic systems, mobile robotic systems and crane systems. All systems will be described more detailed and can be seen below. In all four systems a control unit processes the digital information of Cartesian coordinates, extrusion rates, automation speed, and particular printer parameters, the build material is supplied through a tube originating from mixing and pumping devices and a nozzle is utilized through which the build material is extruded. However, the four systems vary in the technology used to place the nozzle in its intended location. (Kruger 2019.)

In the gantry system for 3DCP, for example depicted in Figure 3, rails are utilized to allow movement in three dimensions to a lift carrying the nozzle. In addition, an axe to enable the rotation of a possibly non-circular shaped nozzle can be embedded. This system exists in various scales up to industrial-grade size (40 x 10 x 6 m). However, since in this system the designated printing area is enclosed by rails, the scale of the printing system consequently determines the maximum scale of the print. (Kruger 2019.)

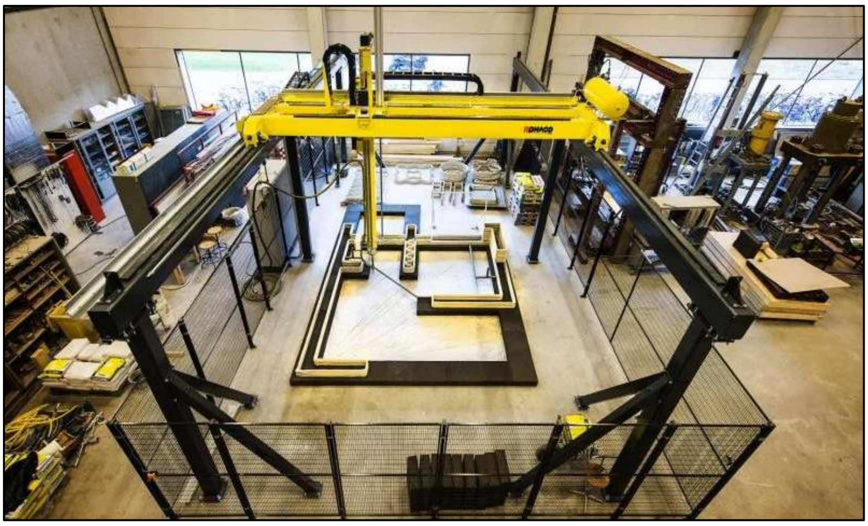

Figure 3. Gantry system for 3DCP at TU Eindhoven (3dprintr.com 2022)

A frontrunning company to implement both fixed and mobile robotic systems for 3DCP, depicted in Figure 4 and Figure 5, is CyBe Construction based in the Netherlands. In both systems 6-axis robotic arms are utilized to move and rotate the nozzle, which allows increased degrees of freedom. Thus, printing of complex geometries, yet retaining high precision becomes feasible. In fixed robotic systems the robotic arm is mounted onto a platform. In mobile robotic systems the robotic arm is mounted on caterpillar tracks. Thereby the advantage of covering a larger building area is added. (Kruger 2019.)

Figure 4. fixed robotic system for 3DCP (CyBe Construction 2022)

Figure 5. moveable robotic system for 3DCP (CyBe Construction 2022)

Similar to a fixed robotic system is a crane system, for example the model by Apis-Cor depicted in Figure 6. However, instead of a joint to a rail is used to move the nozzle back and forth on the plane parallel to the build platform. A crane system can be applied, if a need to print a building from within is perceived. This can be useful to construct multi-story buildings, where the crane is disassembled after finishing one story and reassembled in the following. (Kruger 2019.)

Figure 6. crane system for 3DCP by Apis Cor (Aniwaa Pte. Ltd. 2022)

3 AM APPROACH

In this section first an overview of AM is given and afterwards the crucial required steps are described more detailed. AM is an automated method to manufacture physical objects using a formerly created digital model of the object. The model is created using a 3D CAD software and then exported as an STL-file. Importing the STL-file into a suitable slicing software, depending on which printer is planned to be used, enables to describe the model as subsequent layers, with a defined height. Also, the file can then be saved in the suitable format required for different printers. This file is read and processed by the printer as an instruction, where material needs to be placed. By processing this information, the printer builds up the object layer by layer. There are several techniques, how this can be done, including extruding, sintering, curing or jetting material. After building the physical object, it can be removed and if necessary post-processed. This can include removing support material, abrasive finishing, like polishing and sandpapering, or application of coatings. (Gibson, Rosen & Stucker 2015, 44-50.)

The name STL is derived from stereolithography, which was the first commercial AM-technique. STL is a standardized file format used to show solely the geometry of a digital model. This is done by removing any construction data and modeling history and describing its surfaces through a series of triangular facets. The triangular size is calculated by the minimum distance between the created triangle and the actual surface of the model. In a common CAD software STL files can be exported, and the triangular size can be manipulated affecting the resolution of the model and digital file size. (Gibson, Rosen & Stucker 2015, 45, 46.)

A layer is an approximation to a two-dimensional cross section of a digital model of the physical object to be manufactured. By subsequently and with a defined distance slicing a digital model saved as STL - file horizontal to the build platform layers numbered from first to last result. The distance between two slices is called layer height. The layer height can be downsized in order to increase the resolution of the later on resulting print. Or the layer height can be upsized in order to decrease the number of layers resulting in a shorter processing time of the later on print. (Cain 2022.)

3DCP can be described as a mimicking of an extrusion-based technology of traditional AM, which is called FDM. This is an AM technique patented in 1992 by founder of Stratasys, USA Scott Crump. In this technique a nozzle follows a formerly programmed printing path. The built material in form of a filament is pushed into a heating chamber attached to the nozzle where it melts and is then extruded through the nozzle and deposited on the build platform or the previously printed layer. After finishing the path of one layer the distance between the nozzle and build platform is adjusted according to the defined layer height. This can be done either by lowering the build platform or raising the nozzle. Afterwards the subsequent layer is printed on top of the previous. Common materials for FDM are polymers that are amorphous in nature rather than the highly crystalline such as ABS and PLA. (Gibson, Rosen & Stucker 2015, 160 – 161, 163.) For 3DCP cement-based mortar substances are used (Perrot, Rangeard & Pierre 2016).

3.1 Possibilities through AM and applicability in 3DCP

In this section the reasons for the rise of AM are pointed out. Several benefits, for product designers and manufacturers can be perceived when utilizing AM. Also, from an entrepreneurial perspective the automation of manufacturing processes in general brings economic benefits such as a lower demand for craftsman-personal and a reduction in workers accidents. Besides economic benefits, there are several other benefits related to the product development process, which promote the growth of AM. Firstly, AM is characterized by rapidity not only in the actual building phase of a part but also in the whole product development. The transfer from 3D-CAD to AM is relatively seamless and therefore the principle ”What You See Is What You Get” characterizing 3D-CAD is easily transferred to ”What You See Is What You Build” in AM. In addition, this seamlessness also affects the number of process steps. Regardless of the complexity of the part production steps are generally reduced to only one single step when using AM. When using conventional manufacturing methods, a simple change in the design may result in a significant increase in the number of production stages. AM can therefore help to more effectively predict the amount of time required in this formative stage of the product development. Furthermore, the number of processes and resources required can be significantly reduced using AM instead of conventional manufacturing methods. Manufacturing a part conventionally may not only require a variety of construction steps, such as hand carving, molding and forming, or CNC machining but also the necessary tools to perform those. In conclusion AM generally helps to predict, simplify and speed up the development and building of a part. (Gibson, Rosen & Stucker 2015, 9-10.)

3.1.1 Freeform shapes

The creation of freeform shapes is eased through utilizing layer-based AM. This enables the designer to develop products of almost any shape or topology. Compared to conventional manufacturing methods, through which only finite spectrum forms are buildable, AM eliminates the constraints by providing design freedom. Especially for custom-designed geometries the need for retooling each time when creating a new shape is eliminated. (Perkins & Skitmore 2015.) Therefore, the possibilities provided by AM on product parts with complex shapes have not only found application in automotive, medicine, and euro space industries but also in designing concrete structures. This is because such geometric varieties enable functional benefits also in the construction industry, which will be discussed in Chapter 4.

3.1.2 Lattice structure and porous objects

The integration of lattice structures plays an essential role in product development because the constructions offer excellent energy absorption, such as thermal and acoustic insulation, and a high strength-to-stiffness ratio. In addition, the structures, such as shown in Figure 7, have a large surface area, allowing efficient heat transfer to the environment. Another motivation to use these structures is to lighten an object's weight. These characteristics are very similar to foams, but lattice structures can be about three times stronger per unit weight than foams. (Gibson, Rosen & Stucker 2015.) AM enables a design flexibility that helps deploying the architectural characteristics and superior properties in many areas and also enhancing multifunctionality of single parts (Tao & Leu 2016).

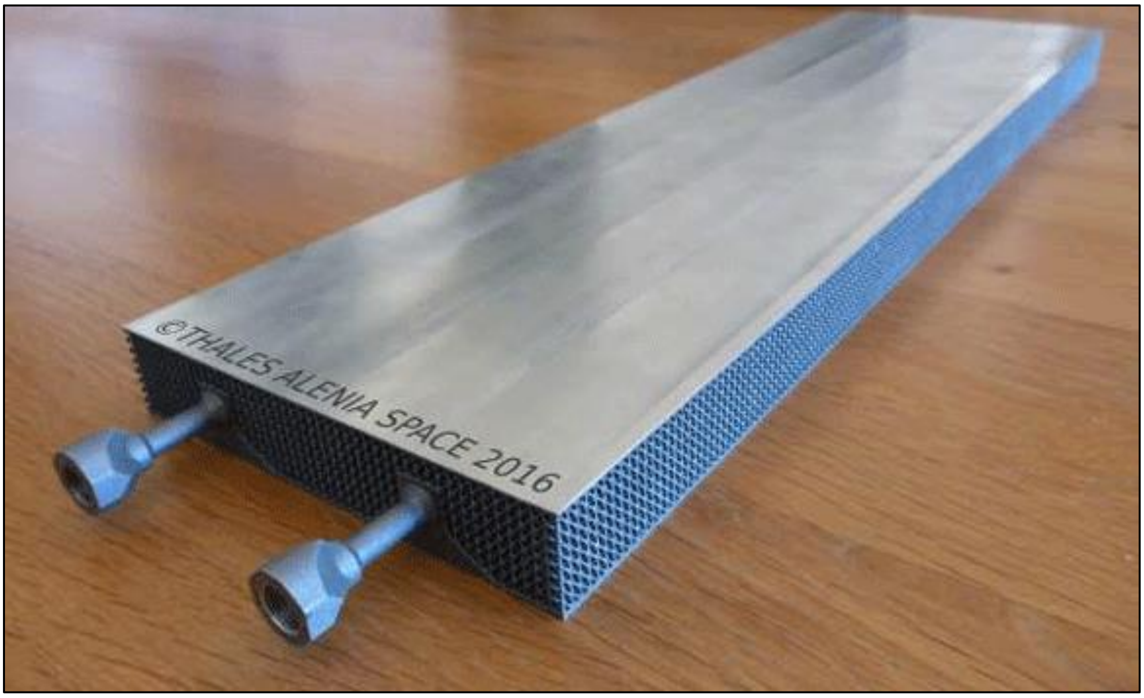

Figure 7. Lattice structure used in a part for satellite manufacturing (Inovar Communications Ltd 2022)

3.1.3 Topology optimization

Topology optimization is a Finite Element Analysis (FEA)-based approach for optimizing the past geometry to reduce weight while retaining strength. The FEA program divides the component into parts and optimizes each element's density. The program optimizes forms as part of the created parts, removing material from all unstressed places. The form is sophisticated and cannot be produced using traditional methods. Topology optimization paired with AM can be utilized to construct durable, lightweight components since AM can be used to generate intricate shapes. (Zegard & Paulino 2016.)

3.1.4 Part consolidation

Component consolidation lowers the part count in an assembly by combining several pieces in an assembly into one integrated part. AM allows assemblies printing as one integral part, which had been made possible by the broadening due to the evolution of the technology. Consolidation is a significant benefit since it reduces the number of different components, making assembly easier.

Furthermore, removing joints from parts reduces the possibility of leakage. To better understand the process of redesigning a multi-consistent assembly and redesigning a part, a mixing device was optimized, resulting in reduced number of parts, less assembly effort and advanced functionality (Figure 8). Therefore, part consolidation yields a profit proportionate to the total number of components and the design's complexity. (Becker, Grzesiak & Henning 2005.)

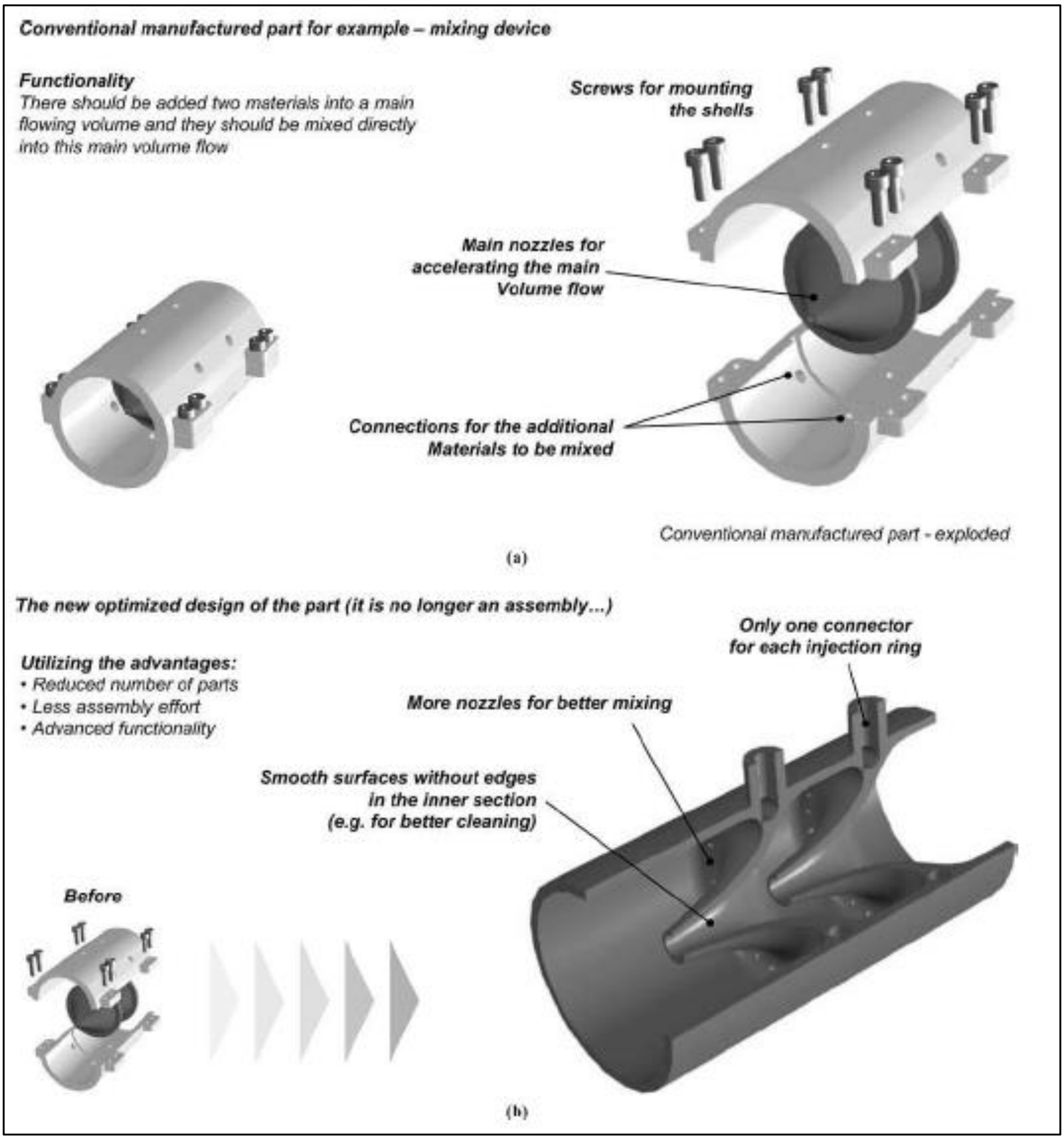

Figure 8. Example for redesigning an assembly to take advantage of the opportunities of the rapid manufacturing processes (Becker, Grzesiak & Henning 2005)

3.1.5 Material choice

The AM technology can process various materials such as metal, concrete, alloys, ceramic material, sand, and paper. Here, the users choose to select the material that best suits them depending on the properties that most suit their application. Some AM technologies can also produce parts in colours that usually achieve colour adding process of raw materials, thus blending multiple-coloured filaments. The technology also allows for the printing of multiple materials simultaneously as an essential possibility. AM machines such as Ultimaker S5 enable the user to print multiple materials simultaneously using multiple extruders. Thus, the ability to print using multiple materials enables the creation of high-quality prototypes for end-users due to the ability to embed multifunctionality for example both fine details and smooth surfaces. (Bandyopadhyay & Heer 2018.)

3.1.6 Non assembly mechanism

Advances in AM have greatly increased the degree of freedom in design and provided promising opportunities for the development of non-assembled manufacturing. Still, AM is a few steps away from replacing today's traditional manufacturing and assembly lines. Assemblies manufactured by AM in a single step have various drawbacks, depending on the process used. In general, the key defects found in current non-assembled mechanisms manufactured by AM are backlash, poor surface quality or poor mechanical properties. Of all the limitations of manufacturing with AM, the main drawbacks are the need for overhanging structures, limited choice of building materials, and inadequate manufacturing accuracy, which makes assembly in a single step very complex. However, AM has some unique characteristics that could move the current manufacturing process to a non-assembled paradigm. Given that AM processes can be used to create shapes that cannot be created by other manufacturing techniques, a new design approach can be used to obtain parts that deliver performance equal to or better than traditional assembly mechanisms. An alternative design of a monolithic compliant mechanism that can replace a traditional rigid hinge is just one example. New AM technologies such as metamaterial design can also be introduced to facilitate the unconstructable manufacturing of highly complex parts and need to be further implemented to maximize their potential regarding non-assembly mechanisms. (Cuellar, Smit, Plettenburg & Zadpoor 2018.)

3.2 Design for Additive Manufacturing (DfAM)

While AM is a manufacturing breakthrough, it has yet to be followed by a design process breakthrough (Thompson et al. 2016). To solve this challenge, several guidelines have been developed within the research and product design community. DfAM is a collection of various tools and procedures used by designers during the product design process to assist them in addressing the characteristics of AM. By utilizing the capabilities of AM, the techniques aid designers in delivering value to manufacturers and users. Nevertheless, no clear definition of DfAM was found in the literature since the term is used for several varying contributions. However, numerous of the most crucial contributions are presented in this section.

The various methods were found to have different impacts on product definitions and were proposed to be classified by Rias, Bouchard, Segonds & Abed into three levels of change, which are:

- formal newness
- functional reconfiguration
- AM form & function implementation (Rias et al. 2016.)

Methods of the first class, formal newness are orientated to remodel existing products to make the product appropriate for AM. The characteristics of AM are then exploited by taking into account the shape and function as input data. (Rias et al. 2016.)

Methods in the second class, functional reconfiguration, are dedicated to re-designing existing products that represent assemblies. Here the capability of manufacturing multiple components in a one-step-process using AM is addressed by defining relationships between multiple components. The purpose of the method is to reduce the number of components in an assembly of an existing complete product. These approaches facilitate the reconstruction of the relationships between the components of an assembly, using as input data existing features that are not AM-specific or customer-requested. (Rias et al. 2016.)

In the third class, desirable product characteristics with respect to AM specificity are evaluated using questionnaires. This involves firstly assessing whether AM is recommended in relation to the most important details (production volume, desired surface finish, mechanical properties, and accuracy). In the next step, the most important characteristics needed for the product are determined. Consequently the "concept profile" is determined based on the answers. (Rias et al. 2016.)

In addition, a five-step design technique that includes discovering features, exploring ideas, evaluating ideas, generating concepts, and evaluating concepts was proposed. The ideas are proven by creating a modified turbine blade with a built-in cartridge. The workflow of this method is shown in Figure 9. (Rias et al. 2016.)

In the first phase examples of AM products as well as examples of other domains are collected. Examples can be represented by illustrations, text, or physical objects. The purpose of this phase is to get an overview of what has been done and what can still be done. Consequently, the features of the examples are labelled and according to the keywords 3D models of these features are created in a simplified and editable way. The second phase a random and systematic match of one wheel of examples with the other wheel of examples is performed. In other words, associations of AM examples with other domain examples are forcibly established to generate ideas. For each combination one idea at minimum should be elaborated. Ideas are expressed by adjusting the formerly prepared simple 3D model. The outcome of this phase is a pallet of diverse ideas that represent possible collaborative product development. In the third phase the gathered ideas are evaluated, considering the feasibility in current or possibly improved AM processes.

Some combinations might be assessed as unrealizable due to significant technical constraints or technical risks and thus eliminated. To verify the feasibility the idea is realized using actual AM. The output of this stage is a lessened pallet of ideas represented by physical objects. In the fourth phase the prototypical objects are refined into concepts representing application scenarios. As an output of this phase, numerous concept sheets that clarify the possible creation of products for the industrial sector are provided. In the fifth and last phase the originality, usefulness and realizability of the concepts is evaluated by experts of AM such as innovation managers, senior designers and trade engineers. The aim is the identification of the concepts reasonable to further scale and elaborate. (Rias et al. 2016.)

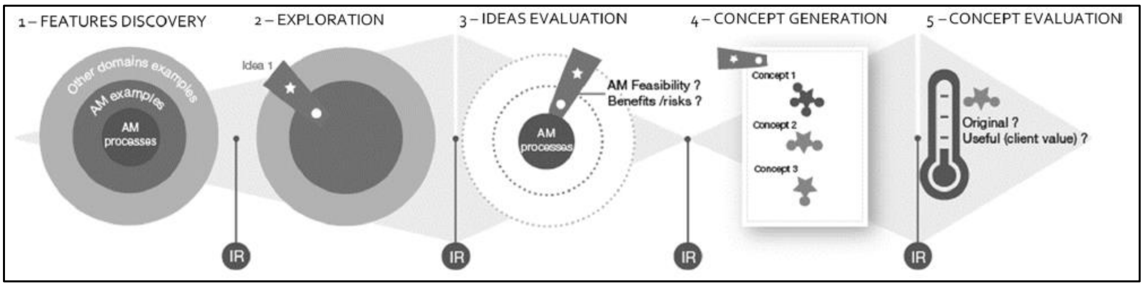

Figure 9. Framework of the proposed Creative-DFAM method (Rias et al. 2016)

Another classification was conducted by Laverne, Segonds, Anwer & Le Coq in 2015 and is shown in Figure 10. DfAM was primarily categorized into the two groups of design making and design assessment. Methods within the group of design making provide guidelines throughout the design process to create intermediate response (IR) and methods within the group of design assessment help to evaluate IR by deploying various measures such as cost and time manufacturability. It is pointed out that late changes lead to higher costs and thus IR creation and IR evaluating should be conducted in the early design stages. (Laverne et al. 2015.)

Moreover, the group of design making was divided into two main subcategories:

- Opportunistic DfAM
- Restrictive DfAM (Laverne et al. 2015.)

The primary goal of opportunistic DfAM is to use the geometric and material complexity of accessible AM to implement new shapes such as lattice and cellular structures or bionic approaches. Opportunistic DfAM methods follow the premise, that by using AM no limitations are set on the feasibility of shapes and on material distribution. Restrictive DfAM, methods, on the other hand, rather focus on the constraints of AM processes, such as the manufacturability of certain features and the quality of compatible materials depending on the considered AM technique. The aim of restrictive DfAM methods is to assist users in designing around them. Furthermore, if both opportunistic and restrictive techniques are applied it is called dual DfAM, which is proposed to be utilized for product development. (Laverne et al. 2015.)

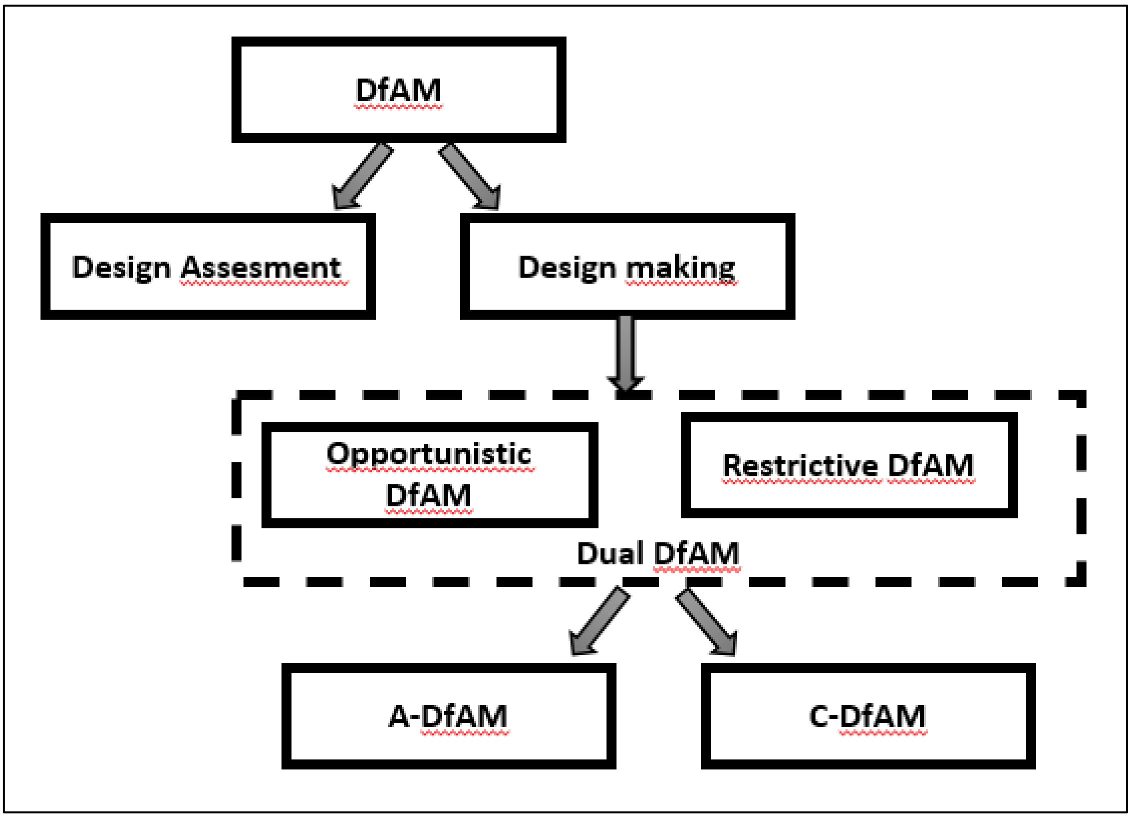

Figure 10. Schematic categorization of DfAM methods (adapted from Laverne et al. 2015)

Two types of principles within opportunistic and restrictive DfAM, ergo dual DfAM were identified. C-DfAM focuses on the optimization of components for AM, whereas A-DfAM is devoted to assemblies by using either the costumers needs or an existing assembly with the aim of part consolidation as input data. (Laverne et al. 2015.)

Kumke, Watschke & Vietor chose a similar approach to classify DfAM methods, which is shown in Figure 11, as Laverne et al.. What is called opportunistic, restrictive and dual DfAM within the group of design making by Laverne et al., is described as utilization of AM design potentials, AM design rules and the combination of both approaches within the framework of DfAM in a strict sense by Kumke et al.. Additionally, DfAM in a broad sense by Kumke et al. does not only include manufacturability analysis, which roughly equals design assessment, but also the selection of parts and applications (Kumke, Watschke & Vietor 2016.)

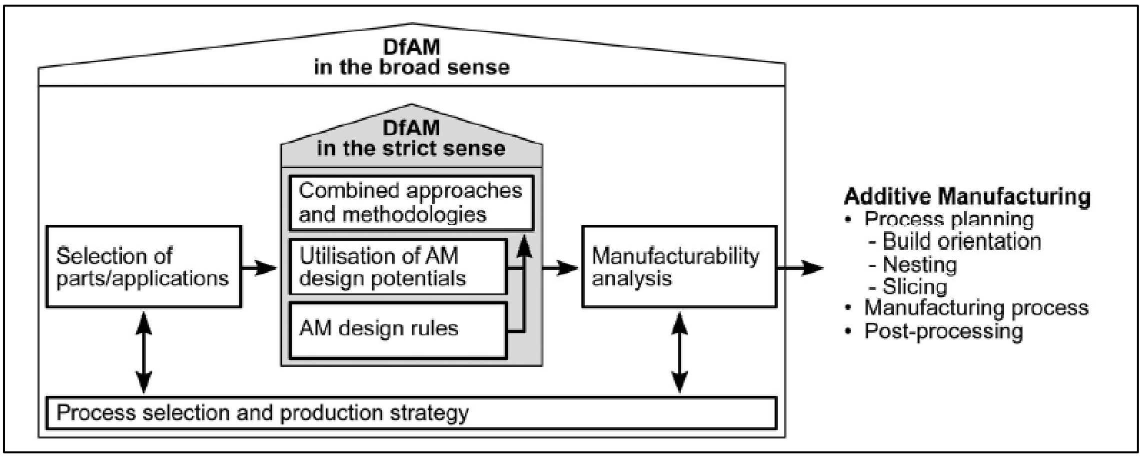

Figure 11. Classification of DfAM methods according to (Kumke et al. 2016)

Furthermore (Klahn, Leutenecker & Mirko 2015) describe, that when starting to design a product utilizing AM technology one of two strategies for the design process must be chosen:

- Manufacturing driven
- Function driven (Klahn et al. 2015)

Manufacturing driven solutions should be used when there is a financial benefit to employing AM instead of traditional techniques. This is the case for small lot sizes or individualized products such as dental implants. This strategy requires designers to follow traditional manufacturing design rules. A function driven approach is applied when AM capabilities are used to improve the performance of a product. The advantage of this design strategy is that it can significantly improve product performance in terms of weight, efficiency, and number of assembly steps connected to the number of parts. The designer disregards conventional design guidelines, resulting in a design that can be created through AM. (Klahn et al. 2015)

Based on a systematic design standard created by the Association of German Engineers a new wide-ranging framework for DfAM was developed by Kumke et al.. A depiction of this concept is shown in the Appendix. The process consists of ten modules within four phases, which are determined to be iterated forwards as well as backwards after various evaluations. Due to the modularity of the framework, it offers easy integration of individual approaches and tools into the general structure and is also able to be easily updated with newly developed methods. (Kumke et al. 2016.)

3.3 Tangential continuity Method (TCM)

The traditional approach to AM technologies is to define the printing path for each layer by slicing an STL file into layers of constant height. This means each layer printed represents an approximation to the two-dimensional cross section parallel to the build platform at its specific height. By stacking all layers on top of each other they merge to a three-dimensional object. If this object is then cut along the plane normal to the printed path and the build platform, the layers appear as circles intersecting each other subsequently. But to compensate for deformation through gravity and allow for the layers to joint, the layer height is defined normally smaller than the radius of one circle resulting through cutting perpendicular to the print platform. So, the circles do not intersect each other in only one point but in two points forming a line with a given distance. This distance is constant as long as the subsequent layer is placed exactly vertical on the previous. But if for example an overhang needs to be printed, this distance would diminish depending on the angle of the overhang. A very steep overhang would cause a very small intersection leading to lower stability and possibly unfeasibility. This effect is caused by the so-called cantilever method commonly found in commercial 2D-slicing software and can be seen in Figure 12 to the left. (Gosselin et al. 2016.)

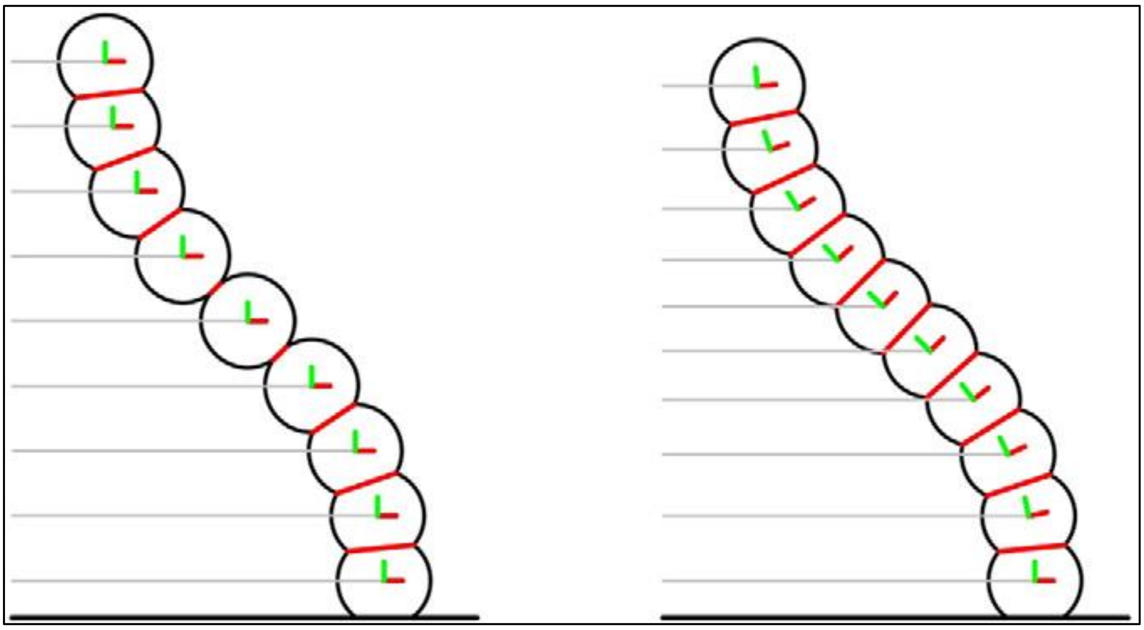

Figure 12. Schematic cut perpendicular to layers 3D printed using the cantilever method commonly found in commercial 2D slicing software (left) and the tangential continuity method (right) (Gosselin et al. 2016).

The constraints caused by this issue were targeted by Gosselin et al. in 2016. The authors presented a concept called TCM. In this concept the layer height is varied in order to keep the contact surface between two layers constant and is shown in Figure 12 to the right. Realizing this avoids geometrical gaps and leads to more robustness of complex geometries. Though considering that the layer height must therefore be varied along the printing path also within one specific layer, this concept would lead to a more complex computational process of the slicing software. The resulting layers would then be not flat like they were thus far, but uneven depending on the horizontal offset to the previous layer. Also, the TCM would require a more elaborate printing system hence in the authors' attempt the printhead was mounted on a 6-axis robotic arm controlled by an Arduino Mega 2560 micro-controller. (Gosselin et al. 2016.)

However, applying the TCM could enable the feasibility of printing more slender designs. Without the need of additional support materials, the steepness of overhangs can be increased. Also, by maximizing the contact surface between the layers the need for possibly expensive admixtures to the concrete build material responsible for enabling bonding might diminish or disappear. This leads to diminishing costs of raw material. (Gosselin et al. 2016.)

4 CONSTRUCTIONAL APPROACH

Over the ages cement-based materials have been used in construction industry and are still the most common material in modern structures (Statista Research Department 2022). Cement is both cheap and plentiful. Because of its workability at room temperature, its convenience of usage, and the ability to manufacture artificial rocks quickly, cement has had a lot of success in the construction industry. From simple houses, offices, and highways to more intricate buildings or nuclear power plants, cement remains the most extensively used building material. Due to the importance of cementitious composites and the urgent demand for acceleration and mechanization in the construction industry, 3D printing technology has been widely endorsed in the building and construction sector, reducing waste materials and related expenditures. (Asprone et al. 2018a). However, there are several aspects about the development of this new technique, representing challenges as well as opportunities (Bos, Wolfs, Ahmed, & Salet 2016). The most crucial and most frequently addressed in the literature are presented in this chapter.

4.1 Reinforcement

It is common knowledge that concrete structures show a need for reinforcement to overcome the lack of tensile capacity and ductility (Asprone, Menna, Bos, Salet, Mata-Falcón & Walter Kaufmann 2018b). This means that though concrete is capable of sustaining an adequate amount of compressive stress, it can be labelled as brittle when facing a force that tenses or bends the material. Therefore, the utilization of concrete is commonly known in combination with metal bars, which are enclosed by concrete in conventional casting techniques. For 3DCP though, this issue of mechanics is a key challenge. (Asprone et al. 2018b). In the research and development community several approaches have been presented, how to incorporate reinforcement integration in the manufacturing process (Mechtcherine et al. 2020). The highest promising solutions according to Mechtcherine et al. are presented in this section.

There are several approaches to utilize steel bars to reinforce concrete in 3DCP. One of them is to place automatically or manually bent steel bars horizontally ergo parallel to the printing plane (Mechtcherine et al. 2020). Though it was proved that conventionally cast concrete can bond to the reinforcement more perpetually, respecting pull out forces, than printed concrete, it was pointed out that methods such as applying vibrations can increase the bond strength (Baz et al. 2020). Another possibility is to not only additively manufacture the concrete but also the reinforcement itself by employing Wire and Arc Additive Manufacturing (WAAM). The principle of this technique is to build up steel bars drop by drop during the printing process. It was shown that this technique can result in bars with reasonable load bearing as well as a ductile failure behaviour comparable to conventional reinforcement bars (Müller et al. 2019.). In addition, this technique promotes the geometric flexibility of the structure. However, a complication of the process times of extruding the concrete and simultaneously weld reinforcement bars was identified. (Mechtcherine et al. 2020.)

The conventional method to integrate reinforcement in concrete walls is to cast the concrete into a formwork including a prebuilt steel mesh grid or mat. These mats can also be used for 3DCP in various ways. One method includes placing short steel bars horizontally protruding the width of the wall between the layers while printing. After the printing process the mat can be attached to the ends of the protruding bars onto the walls surface and covered by a protective layer of concrete. (Mechtcherine et al. 2020.). Another approach is to utilize a split nozzle which is able to enclose the mat with concrete from both sides (Scott 2022). But also, to promote geometrical flexibility the mesh can be not prebuilt but formed on-site. This technique has the advantage that the nozzle does not need to overcome such great heights as it needs to when utilizing prebuilt mats. Furthermore, there are examples showing that the construction of the mesh grid can be automized. (Hack et al. 2020.)

Similar to the techniques utilizing steel mesh grids, a carbon grid can be used. The carbon grid is bendable which facilitates single-curvature structures. It can be applied to already hardened concrete structures by using a laminating technique. (Mechtcherine et al. 2020.) In addition, carbon grids can be previously placed, and concrete is extruded from one side as shown in Figure 13 (Ayres, da Silva, Nicholas, Andersen & Greisen 2019). Furthermore, other objects such as cables, yarns and textiles are discussed to be utilized as reinforcement in a similar way (Mechtcherine et al. 2020).

Figure 13. Extruding concrete onto a previously placed carbon mesh grid (Mechtcherine et al. 2020)

Another approach to reinforce concrete is to disperse fibres of various materials, including steel, stainless steel, glass, carbon and polymers in the build material. The fibres align rather in the direction of the horizontal printing path than randomly, depending on the build material properties, the fibres properties and the printing facility. However, in general the fibres do not cross filament interfaces and therefore only provide reinforcement in the print plane. (Mechtcherine et al. 2020.). It has been shown that intermixing steel fibres of 6 mm length increases flexural strength and eliminates the strength difference that exists between cast and printed concrete without fibres (Bos, Bosco & Salet 2019).

4.2 Thermal activity

A key aspect of construction industry is the thermal performance especially of exterior walls, since it affects the overall energy efficiency to a large extent (Verbeke & Audenaert 2018). The thermal performance of a constructive element is described by the heat flux due to a temperature gradient and expressed as the thermal transmittance (U). The thermal conductivity is the material’s specific ability to conduct heat (Pessoa, Guimaraes, Lucas & N. Simoes 2021). For air the thermal conductivity is lower than for solid materials. Therefore, materials with enclosed voids have in general, disregarding other thermal effects, a lower thermal transmittance. On the other hand, materials with higher density allow less air of different temperature to travel through, which is called convection. Since in AM infill structures can be varied, a topology optimization was conducted, using PLA as build material to optimize printable structures not only regarding their stiffness but also their thermal properties. (Vantyghem, De Corte, Steeman & Boel 2019.).

Another aspect of increasing the thermal performance lies in the reduction of thermal bridges, which is closely connected to optimizing the geometry. A wall element was introduced, with an infill designed to support heat insulation. The wall element can be seen in Figure 14.

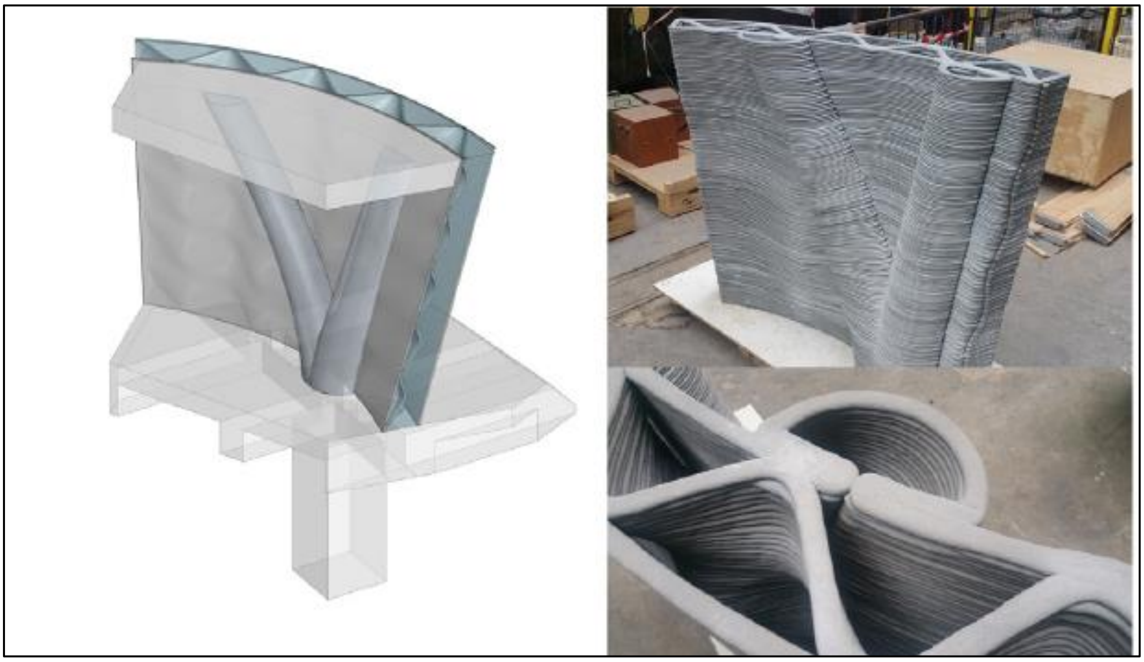

Figure 14. Wall element with infill designed to enhance thermal insulation (Gosselin et al. 2016)

The infill of the wall element was designed to specifically reduce the area of contact between two sides of a wall. It was pointed out that thereby a gain in thermal insulation performance of 56 % can be possible. (Gosselin et al. 2016)

5 FINDINGS AND ARGUMENTATION

The research has shown that AM in construction industry is rather lately upcoming than already sufficiently established, to be labelled a common technique. However, starting in the early years of the twenty-first century, but especially since 2015 there have been remarkable efforts to encourage the necessary technological development.

Multiple projects have already been realized to add various aspects through AM to construction industry, such as seismic resistance of buildings and extra-terrestrial construction. With these aspects value in construction is associated as building in formerly inaccessible territory is facilitated. Emergency homes in earthquake areas rapidly provide shelters for affected citizens. Realizing automated construction in extra-terrestrial locations on the other hand, can advance exploration, because it offers a possibility to install stationary research equipment, that possibly needs protection from environmental influences such as space radiation. In addition, for the military housing of the Indian army the feasibility to construct curved shapes, which is characteristic for AM, was exploited to avoid corroding of the concrete due to sand deposits. Therefore, research and development in AM in construction industry should be further promoted because it results in a variety of new possibilities.

5.1 Technology and material

A vast majority of research is accomplished in the field of materials science and already proves to deliver relevant results. In general, build material which fulfils the key prerequisites of pumpability, extrudability and buildability is already available. Moreover, a considerable progress has been made in gathering knowledge of how certain compositions and admixtures contribute to these prerequisites and how to determine the parameters of the build material. Depending on the length of the horizontal printing path, the thixotropic properties of the build material and the printing speed can be manipulated. However, to exploit the full potential of AM in more complex situations further interdisciplinary research is necessary.

5.2 Recognized and unrecognized potentials

In literature originating from a constructional engineering environment a substantial call for interdisciplinary collaboration was recognized. In many sources the areas of statics, materials science and mechanical engineering are mentioned for this instance, aiming to improve the rheologic qualities of the build material. However, in this research no literature was found, stating that DfAM-methods stemming from product design are used for 3DCP.

In product design though the study showed that the possibilities through AM are widely recognized and exploited. Some of the mentioned possibilities are connected to the fact that AM provides more geometric flexibility than conventional manufacturing techniques. Freeform shapes, lattice structures and topology optimization are facilitated largely due to the ceasing of molds, which are equivalent to formworks is concrete construction. However, not all of the presented possibilities in product design are directly transferable to concrete construction. Since in concrete construction dynamic assemblies rarely exist, part consolidation and non-assembly mechanisms are not relevant in this field. Nonetheless, besides manipulating the material to show desired thixotropic properties, the structural variety enabled through AM can add noteworthy value, as it does in the field of product design.

5.3 Structural potentials through AM

As pointed out, utilizing lattice structures can help to lighten an objects weight and provide thermal and acoustic insulation. These characteristics specifically possible through AM can not only be favourable in product design for automotive, spacecraft and aircraft industry, but are moreover key features in construction industry. In combination with conducted topology optimization to respect statics, implementing voids in a concrete wall could lead to a lower thermal transmittance and better acoustic properties than in a solid cast component. Furthermore, saving build material can contribute to economizing the building process.

Nevertheless, in this research only a few examples were found, in which this opportunity was purposefully exploited. A wall element with an infill structure explicitly designed to reduce thermal bridges was presented. The gain of thermal insulation performance of 56 % in this case represents an example of how the advantages of structural variety can be exploited. In the calculation of the thermal insulation performance of this component though, the heat flux was reduced to the thermal conductivity solely and convection through the pores of the material was disrespected. It can be assumed that the heat flux through convection increases with reducing density of the structure. Another example, although in this case the build material was PLA, presents a method to conduct topology optimization of a 3D-printed structure, considering both stiffness and thermal properties including conductivity as well as convection. In general, it is therefore suggested that architects and engineers in construction industry should be attentive of methods already utilized in the more advanced field of small-scale AM. Adapting methods such as the topology optimization to 3DCP can help to expand the knowledge and technology necessary for reasonable 3DCP.

5.4 Design methods

Furthermore, numerous strategies for DfAM applied in product design were presented. Especially function driven and opportunistic DfAM have been recognized as methods targeting especially the benefits of AM. As the example of the military housing in India shows, there are shapes and structures solely buildable through AM. Applying opportunistic DfAM-methods involves specifically looking for shapes and structures in other examples, which can also be bionic approaches, to integrate them in the design and capitalize from additional functions. Though in the reviewed literature no cases were found where a method developed particularly for AM was used to create architectural shapes enabled by AM. When adapting small-scale DfAM-methods to 3DCP, different material properties accompanying the replacement of the build material need to be considered. However, utilizing opportunistic DfAM-methods as a tool, provides a possibility to develop into a niche special field for architects.

Design assessment on the contrary is utilized in product design to determine the reasonability of the usage of AM techniques and the feasibility of the design. In general, design assessment is conducted at the end of a design step characterized by a given resolution of details. It can lead to either reconsidering the design or proceeding to the next step, which means adding further details and dimensions, or finishing the design process. To advance the feasibility of more complex designs it is crucial to further develop techniques such as the presented TCM. The TCM is a method for 3DCP targeting the construction of overhangs by conceiving the layer height as a variable in the course of printing a single layer, using a 6-axis print head. Thereby the reduction of the contact surface between two filaments when printing overhangs is avoided. Similar concepts, advancing the feasibility of complex structures resulting in benefits, such as better thermal and acoustic properties, need to be promoted in order to capitalize on.

5.5 Process strategies

In addition, the literature review showed that a broad variety of process strategies exists, and one crucial method used in product design was presented. The framework provides a ten-step workflow to create new product designs. Nonetheless in this study no literature was found which states that a process strategy especially created for AM was used for architectural designs. Consequently, on the strategical level too small-scale AM offers a pallet of solutions that should be actively considered to be implemented in 3DCP. Although in some cases minor adaptions need to be conducted, process strategies developed for AM can help adding value to architectural designs as well.

To conclude it was found, that in 3DCP several approaches already exist to add value to building components by exploiting the structural variety enabled by AM. However, DfAM-methods are rarely used in construction industry. Especially opportunistic DfAM methods and strategical frameworks should be adapted to and implemented in the design process of 3DCP to advance in creating new design solutions.

6 DISCUSSION AND OUTLOOK

In this work a literature review was conducted, to determine the design methods used in 3DCP. To build underlying knowledge, relevant examples were gathered, the necessary equipment was explored, and the prerequisites of the build material were researched. Furthermore, it was chosen to approach the topic from two points of view. Firstly, since AM is already considerably advanced in product engineering, the benefits accompanying AM and which methods are used to exploit them in this field were investigated. Secondly, it was researched specifically in the field of construction engineering how it is capitalized on the benefits of AM. Based on this knowledge, the two topics were connected, and new ideas have been evolved and discussed.

The study demonstrated that, numerous tools and frameworks especially developed to create designs targeting the strengths of AM, mostly labelled DfAM-methods, already exist in the product design and engineering community. Although designs capitalizing on the structural variety enabled by AM have been spotted, no evidence was found that similar concepts are applied in construction engineering.

The process structures and DfAM-methods in product engineering contribute largely to the success of AM in this field. Therefore, it is suggested to adapt especially opportunistic DfAM-methods to construction engineering. The most crucial difference would be the replacement of the build material and properties that are connected to it. The impacts of the thixotropic behaviour of concrete need to be considered regarding the feasibility of complex shapes.

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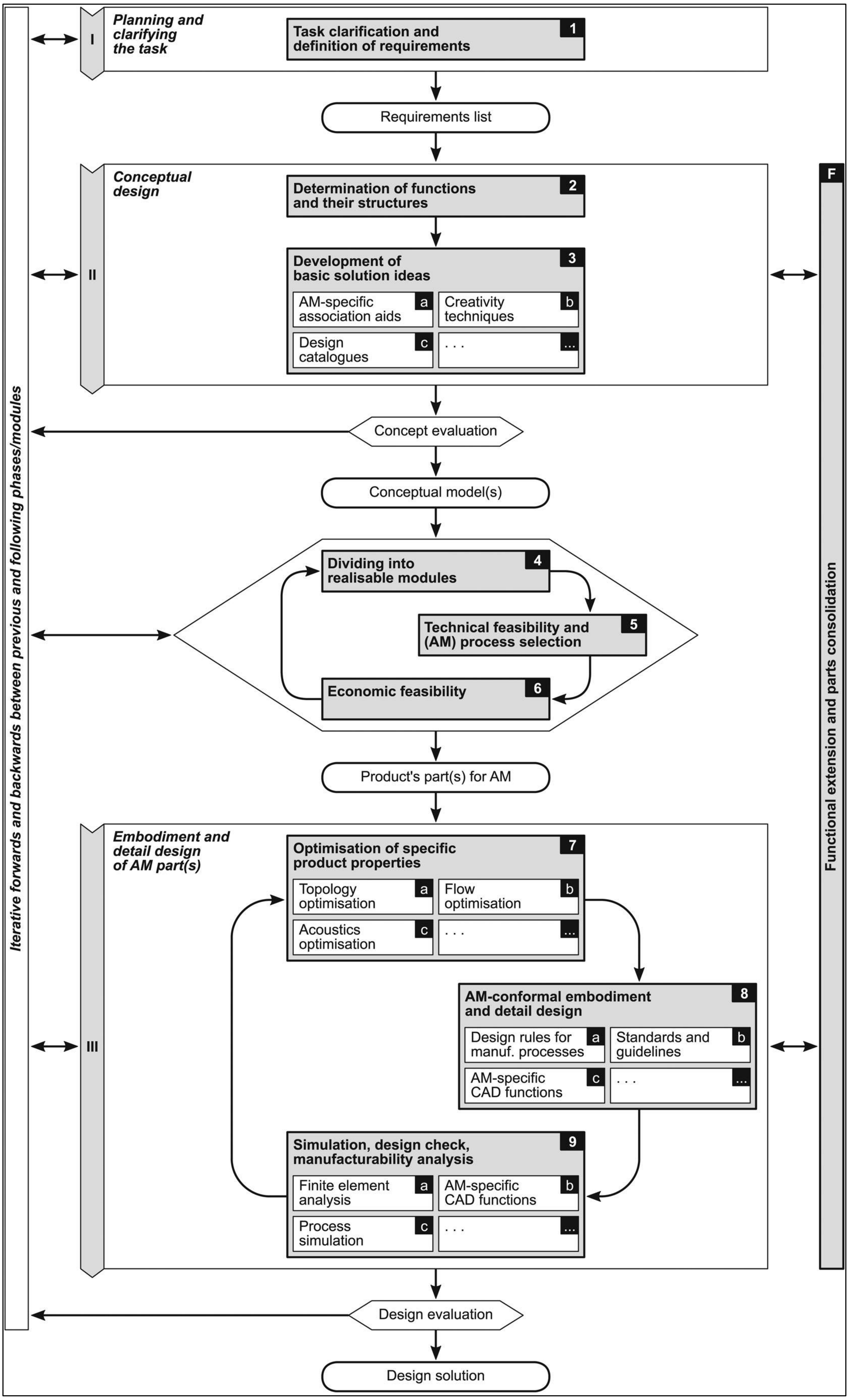
APPENDICES

- DfAM framework overview by Kumke et al. 2016



Annex 1. DfAM framework overview (Kumke et al. 2016)