Assessment of additively manufactured end-use components

Current state and incremental improvements in design, materials, and decision making

Niklas Kretzschmar
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A doctoral dissertation completed for the degree of Doctor of Science (Technology) to be defended, with the permission of the Aalto University School of Engineering, at a public examination held on 20 March 2020.

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Abstract

Increasingly integrated into various fields of industries as rapid prototyping, rapid tooling and rapid manufacturing applications, since first commercialized in 1987, are layer-wise additive manufacturing (AM) techniques. Among those, end-use AM applications are particularly challenged, however, by economic and technological obstacles including slow production speeds, high material cost, insufficient part quality repeatability and (bio)material unavailability. This thesis aims at both exploring the economic and technological current state of AM end-use components, and providing incremental development steps in design, material, and decision-making.

To assess the current state of end-use AM, a computer-driven decision support system (DSS) for rapid economic assessments of uploaded components supported by a case study is developed and an industry-related survey is conducted to match the demands for AM with the existing capabilities of AM. The current situation can be further improved by introducing new incremental developments concerning experimental material development, AM process configurations, (re)design, and component classification based on case studies. These enhancements aim at developing new biocomposite materials for AM, implementing the axiomatic design methodology to design for AM (DfAM), and classifying end-use AM components according to the level of DfAM. The final version of the DSS provides rapid online quotations of uploaded digitized components to obtain insights into costs and production times for varying machine, material, and distribution scenarios (conventional manufacturing versus AM, make-or-buy decisions). In this context, the tool was used to demonstrate the trade-off between feature resolution and production speed on cost, which constitutes the importance of production speeds as a cost-driver in AM part production. However, further increases alone have no significant cost-saving potential for the already existing high-end metal powder bed fusion machines considering high production throughput scenarios. Thus, expenses on materials need lowering to increase cost efficiency. The underlying technological state of end-use AM components involved comparing size-, material-, and surface roughness demands with best-in-class and locally installed AM system capabilities.

The incremental developments imply that traditional design methodologies are applicable for AM and can potentially assist designers in DfAM. Components designed for the use of AM techniques can be logically classified according to their level of DfAM exploitation. Furthermore, the newly developed biocomposite material and its inherent process variations lead to new opportunities in environmental sustainability and design freedom, opening up new possibilities for AM part production.

Keywords Additive manufacturing, digital workflow, part assessment, material testing

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I would like to thank my colleagues, family, and friends for their valuable support over the last years, making it possible for me to gather numerous great experiences when working in the additive manufacturing group at Aalto University.

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Helsinki, 5 December 2019
Niklas Kretzschmar
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<th>Full Form</th>
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<tbody>
<tr>
<td>AM</td>
<td>additive manufacturing</td>
</tr>
<tr>
<td>BJ</td>
<td>binder jetting</td>
</tr>
<tr>
<td>CAD</td>
<td>computer-aided design</td>
</tr>
<tr>
<td>CFD</td>
<td>computational fluid dynamics</td>
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<tr>
<td>CM</td>
<td>conventional manufacturing</td>
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<tr>
<td>DfAM</td>
<td>design for additive manufacturing</td>
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<tr>
<td>DLP</td>
<td>digital light processing</td>
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<tr>
<td>DSS</td>
<td>decision support system</td>
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<td>ME</td>
<td>material extrusion</td>
</tr>
<tr>
<td>FDM</td>
<td>fused deposition modeling</td>
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<tr>
<td>GUI</td>
<td>graphical user interface</td>
</tr>
<tr>
<td>KPI</td>
<td>key performance indicator</td>
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<tr>
<td>MJ</td>
<td>material jetting</td>
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<tr>
<td>MTRL</td>
<td>manufacturing technology readiness level</td>
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<tr>
<td>OEM</td>
<td>original equipment manufacturer</td>
</tr>
<tr>
<td>PBF</td>
<td>powder bed fusion</td>
</tr>
<tr>
<td>SL</td>
<td>stereolithography</td>
</tr>
<tr>
<td>SLM</td>
<td>selective laser melting</td>
</tr>
<tr>
<td>SLS</td>
<td>selective laser sintering</td>
</tr>
<tr>
<td>SME</td>
<td>small and medium-sized enterprises</td>
</tr>
<tr>
<td>STL</td>
<td>standard tessellation language</td>
</tr>
<tr>
<td>VP</td>
<td>vat photopolymerization</td>
</tr>
</tbody>
</table>
List of Publications

This doctoral dissertation comprises a summary and the following publications, which are referred to in the text by their numerals.


3. Kretzschmar, Niklas; Lipponen, Sami; Klar, Ville; Pearce, Joshua; Ranger, Tom; Seppälä, Jukka; Partanen, Jouni. 2019. Mechanical properties of ultraviolet-assisted paste extrusion and postextrusion ultraviolet-curing of three-dimensional printed biocomposites. 3D Printing and Additive Manufacturing. Liebertpub. 6(3), 127-137. DOI: 10.1089/3dp.2018.0148. Julkaisufoorumi level 1 (ID 82215).


Author’s Contribution

Publication 1: “A decision support system for the validation of metal powder bed-based additive manufacturing applications”

The first author (Kretzschmar) designed the underlying cost structure, coded the decision support system including the graphical user interface, conducted the experiments and was the principal writer. The second author (Flores Ituarte) designed the experiments and participated in preparing the manuscript. The third author (Partanen) supervised this study.

Publication 2: “Evaluating the readiness level of additively manufactured digital spare parts: an industrial perspective”

The first author (Kretzschmar) designed the survey study, collected results, defined suitable analysis tools and was the principal writer of the manuscript. The analysis was performed in co-operation with the second author (Chekurov), who also participated in preparing the manuscript. The third (Salmi) and fourth (Tuomi) authors reviewed and supervised this study.

Publication 3: “Mechanical properties of ultraviolet-assisted paste extrusion and postextrusion ultraviolet-curing of three-dimensional printed biocomposites”

Idea creation, 3D printing of specimens, mechanical testing and writing of the majority of paragraphs constitute the contribution of the first author (Kretzschmar). The second author (Lipponen) developed the 3D printing materials, conducted the chemical analysis and wrote the related paragraphs. The third author (Klar) provided the 3D printing platform and wrote the section about the applied system. The fourth (Pearce) author supervised and reviewed the work of this study. The fifth author (Ranger) assisted in preparing the testing equipment, the sixth (Seppälä) and seventh (Partanen) authors supervised the study.
**Publication 4:** “Classification of end-use industrial applications of additive manufacturing”

The first author (Chekurov) initiated this study, defined the design workflow and wrote the majority of the related chapters. The second author (Kretzschmar) wrote the chapter 2.1 “Components designed for additive manufacturing” and was involved in discussions about the study’s scope and context.

**Publication 5:** Axiomatic design to foster additive manufacturing-specific design knowledge

The first author (Chekurov) designed the experiment and was the principal writer. The second author (Kretzschmar) contributed to the methodological decomposition process, conducted the result analysis, printed the water turbines, and wrote related paragraphs. The third author (Rossoni) conducted the computational fluid dynamics analysis. The fourth author (Redaelli) designed one water turbine. The fifth author (Colombo) supervised this study.
1. Introduction

The introduction of this thesis lists the standard terminology for additive manufacturing (AM) technologies and an AM application-based classification. Following this introduction is a brief history, some common industrial applications, leading to recent technological enhancements. This chapter also presents current challenges for end-use additively manufactured components, to create a basis for deriving the research problems and aims.

1.1 Background

The term AM comprises a set of manufacturing techniques that are capable of generating physical components layer-by-layer, which is substantially different to subtractive and formative techniques. As per the ASTM International standard 52900:2016 (standard terminology for AM technologies) [1], these AM techniques are classified into seven process groups based on a technological principle grouping: powder bed fusion (PBF), material extrusion (ME), sheet lamination, binder jetting (BJ), material jetting (MJ), vat photopolymerization (VP) and directed energy deposition. All AM process groups and underlying processes can be differentiated from one another when investigating their process characteristics. Their solidification and fusion principles vary significantly, resulting in different process speeds, part accuracy levels and their mechanical and environmental sustainability properties.

The growing number of components produced with AM necessitated the implementation of an application-based classification for AM [1], [2] to serve as a differentiation mechanism. Thus, for prototyping applications, the term rapid prototyping (RP) is defined as an “application of additive manufacturing intended for reducing the time needed for producing prototypes”. On the contrary, rapid tooling (RT), defines an “application of additive manufacturing intended for the production of tools and tooling components with reduced lead times”. Thus, the ASTM standard considers prototyping and tooling applications but omits directly manufactured end-use AM applications as defined by Hopkinson et al. [3], [4]. However, the existing term rapid manufacturing (RM) describes “the use of a computer aided design (CAD)-based automated additive manufacturing process to construct parts that are used directly as finished products or components”.

Introduction

1.1.1 A brief history of AM

In 1987, the current largest 3D printing company by revenue “3D Systems Corp.” historically commercialized the AM process stereolithography (SL). This process was initially used for visual and simple functional prototypes, applying it to end-use components at a later stage. The process mechanism is described by repetitive curing of UV-light sensitive resin, of which predefined patterns of the components’ cross-sectional areas are solidified by a laser. A subsequent major development step in AM technologies was the commercialization of the fused deposition modeling (FDM) process, defined as ME according to the standard terminology for AM technologies. The company Stratasys Ltd. introduced its first system in 1991, extruding molten plastics following a specific print path to create parts layer-wise [5]. The first commercial PBF systems were sold in 1992 by DTM Corporation, and consequently by EOS GmbH in 1994. Both systems were equipped with a 50 W CO₂ laser for polymer sintering and quickly expanded to (direct) metal sintering applications using higher laser powers [6]. The principle of PBF, however, dates back to Housholder’s invention in 1977. Housholder was the first to describe both a manufacturing process using a powder bed recoating system and a laser directed by mirrors to allow powder solidification. On the basis of these technological developments, a wide range of industrial applications for RP, RT, and RM are manufactured today.

1.1.2 Industrial applications in AM

Typical AM industries and applications exist in the medical, automotive and aerospace fields [7]. Example components comprise 3D printed hearing aids and dental guides [8] as fabricated personalized designs, thermostat covers for trucks (legacy part) [9] and turbine blades for jet engines (shape complexity) [10]. Figure 1 presents four example AM industrial components of Aalto University’s AM research group; the components involve demonstrators manufactured for the marine (a), medical (b), manufacturing (c), and automotive fields (d).

Figure 1. Overview of directly manufactured end-use components applying AM processes showing (a) a bushing (metal PBF), (b) dental splint (SL), (c) hydraulic pipe (metal PBF) and a (d) vending machine component in public buses (plastic PBF).
The increasing number of industrial applications significantly affects commercial growth in AM. According to [11], worldwide revenue of the AM industry amounted to $7.336 billion in 2017, increasing by 21% compared to the previous year. An estimated $0.918 billion was spent on end-use components, resulting in an annual incline of 32.4%; this incline demonstrates AM’s emerging relevance.

1.1.3 Recent technological enhancements

Recently gaining traction are several technological enhancements that are especially valuable in the manufacture of AM end-use components. These enhancements boost AM’s competitiveness compared to traditional manufacturing techniques and open up new opportunities for companies when adopting AM. The subsequent developments are expected to result in a growing number of end-use applications and revenues.

For instance, industrial AM machines with the underlying process selective laser melting (SLM) have been equipped with four or more lasers. Each laser operates in a specific section, dividing the build platform into equally large areas to significantly accelerate component production to enable shortening AM production times for metals [12], [13]. Additionally, the introduction of dual laser systems to polymer-based selective laser sintering (SLS) systems [14] has increased plastic-part production. In the introduction of the multi jet fusion (MJF) technique, another main development must be acknowledged. This technology is harnessing heat-absorbing binders to selectively fuse components’ cross-sectional areas in a PBF approach using a print head compared to a laser. This process is applicable to polymers and metals (post-sintering required) and must be understood as an emerging competitor to SLS as it can further increase build rates and does not rely on expensive fiber lasers. Simultaneously achieved are comparable material-dependent yield strengths (e.g. for PA12) [15], [16] are achieved. In addition to powder bed-based process developments, continuous liquid interface production (CLIP) represents a prominent technological improvement as a sub-process of digital light processing (DLP). The advantage of CLIP concerns its ability to continuously cure UV-light sensitive resins by relying on an oxygen-permeable membrane to guarantee a constant supply of material without lifting the build platform to the resin surface [17]. Furthermore, developed within the metal AM production domain were commercially available metal filaments, with metal particle shares of up to 80% that are applicable to low-cost filament-based ME systems. These metal filaments thus represent a promising direct manufacturing technology alternative for a cost-effective production of end-use components in small-scale production volume scenarios. This approach can be used as a process upgrade or as an alternative to metal injection molding processes, which already require furnace equipment for thermal debinding and sintering [18].

Despite the above-mentioned recent technological enhancements, which open up new opportunities in the field of AM, several challenges need consideration when fabricating end-use components with AM techniques.
1.2 Challenges and opportunities for AM end-use components

The obstacles in adopting AM for end-use part production are both technological and economic. The achieved technological readiness level and cost-effectiveness for visual and functional prototypes have been perfected to significantly accelerate the design process [19] and to enable the manufacture of customized complex parts [20]. However, major enhancements are demanded of the production of end-use AM component types. This group of components has been discussed since the early 2000s. The discussion concludes that economic barriers, such as exorbitant machine and material costs and technological barriers constituted by material properties and part quality levels, represent the main challenges to adoption [4]; these challenges still exist.

As per Huang et al., establishing a base for viable current AM part production requires addressing several technological elements including (i) “material development and evaluation”, (ii) “design methodologies and standards”, (iii) “modeling, monitoring, control, and processes” and (iv) “characterization and certification”. These elements are required to harness successful system integration in cyber-physical production systems. Challenges include limited numbers of AM materials, part accuracy-related issues and residual stresses, along with quality repeatability and qualification. The authors recommend investigating new materials including biomaterials, tools to assess the impact of AM part production, design methodologies for AM, and process innovations to increase the overall manufacturing technology readiness level (MTRL) [21].

1.2.1 Technological aspects

The main difference between end-use applications and prototyping applications concerns the fulfillment of numerous performance targets (e.g. sufficient tensile and compression strength, long-term cycle behavior, ultraviolet light-, corrosion- and heat resistance) along with part quality requirements (e.g. surface roughness, porosity levels, color). These demands are often insufficiently met, for instance, if the complex thermal history of PBF processes is not properly controlled [22], [23].

As a process-related readiness example from 2015 [24], some researchers indicate that the MTRL of SLM does not exceed an evaluation of 3 (out of 10), which means that the “manufacturing principle is tested (in laboratory)” and the “impact on product design” is defined. The main reason for such a low MTRL level is insufficient part quality properties. Part quality repeatability particularly poses a major challenge to guaranteeing viable AM part production if not assessed carefully [25]. However, these sources might contradict already existing small-series AM production lines in high-quality demanding industrial sectors [26] and existing AM end-use components used for production [8], [9]. Thus, certain industries seem to have developed enhanced production control mechanisms to guarantee repeatable part quality.

Alongside quality requirements and issues of processed materials, AM material availability remains challenging. A wide range of available materials for AM
is needed to allow performing specific material-property requirements as defined by the original material. An alternative solution is to switch to an adequate substitute material. However, the literature indicates that the adoption of AM still suffers from the unavailability of required materials [27] along with other limiting factors such as machine sizes for the fabrication of large-scale components and the amount of necessary post-processing [28]. Materials for AM with decreased environmental footprints represent an already existing need to slow down climate change and to decrease the environmental pollution of fossil-fuel based non-biodegradable plastics. Today, bio-based materials such as polylactic acid and polyamide 11 are applied to the AM processes filament-based ME and SLS, respectively. However, a wider range or bio-based AM materials must be developed and commercially offered to further substitute non-renewable material sources that cause high CO2-emissions.

A general overview of the existing technological readiness level, matching demands from the industry with underlying AM capabilities, would help to shape the current situation for end-use components. Furthermore, the development of new AM materials, particularly biomaterials, and process-modifications could provide solutions to the outlined challenges in AM.

1.2.2 Economic aspects

In addition to the above-mentioned technological obstacles, the cost of AM remains the main challenge when selecting the most economically viable manufacturing method (AM versus conventional manufacturing (CM)) [29].

The main cost drivers of AM result from slow build rates, expensive materials, high purchasing prices for high-end production machines and extensive post-processing operations that increase labor costs. High machine prices concern all AM processes. For instance, as reported by the Wohlers Report [11], the system price for a Fortus 450mc (filament-based ME process) costs $145,000, an EOS M400 costs €1,250,000 (metal PBF process) and a Prodways L5000 costs €200,000 (DLP process), arising from significant development costs combined with low numbers of sold units. For processed special AM materials, machine customers need to additionally spend up to hundreds of euros per kilogram or liter and pay for expensive software licenses to allow preparing and operating part production. These materials can often be processed with only several mm³/s and require time-consuming post-processing.

Furthermore, in-depth knowledge is required to run AM production runs as cost-effectively and successfully as possible. Educated personnel are needed to optimally select processes and post-processes, in conjunction with AM capabilities, to master the transition to AM production and to manufacture using the most plausible manufacturing alternatives.

Despite the presented cost drivers, components produced with AM can be cheaper. Typically, cases of low production volumes that involve the elimination of tooling to lower up-front costs [30], which require a high sequence of production steps in CM result from advanced degrees of design complexity [31].

In this context, equipoise between CM and AM typically occurs for production-volume comparisons [32], [33], [27]. Once the tool for a CM process (e.g.
injection molding) is produced and the process parameters are optimized, high manufacturing throughput continuously lowers unit costs, often making it impossible for AM to compete in high-volume production scenarios. This situation causes prototyping and tooling applications to establish higher footings in industries, since their production volume can be as low as one and part complexity does not constitute an impactful cost driver when manufacturing with AM.

Simultaneously, demand-dependent aspects can favor AM part production. The viability of low volume production series is enabled by slow-moving, costly spare parts, which would ideally be created additively on-demand in a distributed manner, located close to the customer to omit expenses for storage and to keep transportation costs to a minimum [34]–[36]. This situation correlates with the finding that the bulk of AM part cost is linked to direct manufacturing costs and not to logistics costs, as is the case in supply chains for CM [37]. Switching to AM can have cost advantages [38] resulting from both production and supply chain management criteria, for example, high lead times, large minimum order quantities, low numbers of specific component- and product suppliers, and long service lifetimes of traditionally manufactured components. In this coherency, spare parts are highly interesting since AM allows, for instance, replacing costly legacy and non-frequently used spares, by printing them more cost-effectively on demand.

Open-access tools [39]–[41] both allow practitioners assess the economics behind AM to help identify AM business use-cases (e.g. for spare parts), and provide a platform to systematically test influencing factors on economic measures such as cost and production time. This development would be particularly useful in metal PBF processes, which have been gaining traction in the end-use fabrication of metal parts. Finally, the developed tool could be integrated into an enterprise resource planning system to serve as a plug-in for AM and CM as well as make-or-buy [42] decision-making.

### 1.2.3 Design aspects

In addition to advantages in mastering design complexity of original designs, (re)design opportunities enabled by AM positively impact costs [43]. Firstly, AM enables redesigning components by significantly lowering the amount of material used. Redesigning is possible by allowing higher degrees of design complexity, and by enabling mass customization compared to CM. Secondly, design modifications aimed at reaching functional enhancements of the component potentially lead to improved inherent performance values of the components. Thirdly, approaches such as part consolidation attempt to rethink products by combining several parts into one, omitting the assembly stage for merged parts [44]–[46]; even the redesign and manufacture of several assemblies as one seem plausible.

Similar to any CM technique, designers must respect numerous design rules and guidelines when designing under both the restrictions and freedom in design of the selected manufacturing technique. Design for additive manufacturing (DFAM), which is based on the mindset of conventional “Design for Manufacturing”, aims at implementing manufacturing knowledge in the early design
stages to optimize the AM design process. DfAM defines an engineering design process following design requirements, rules and guidelines regarding the underlying process and material-dependent restrictions and opportunities in AM; this allows taking full advantage of inherent capabilities and ensuring manufacturability [46]. This design process results in new designs, typically designs with higher degrees of shape complexity, aiming to be either functionally advantageous, economically more feasible, or both [44]. Common examples of applied (re)design processes are described by both topology optimization of existing components to create enhanced lightweight designs and part-consolidation approaches to combine single parts into one by maintaining their functionality; these (re)design processes save both manufacturing and assembly costs [47], [48]. In this regard, when designing a component for AM, material is only placed into regions where it is necessarily required, affecting the overall geometry of a part and its inner structure. This can result in more delicately- and organically shaped components, containing inner lattice structures with varying cross-sectional profile thicknesses of the struts (different regional density gradients), which are redirected to master specific loading conditions.

Moreover, the material properties within one component can vary to design functionally-graded materials. For some AM processes, voxel-based material modifications are possible to optimally tune components for yielded stress-strain regional behaviors. These functional material gradients can be implemented as one-, two-, or three-dimensional types [49]. To implement advanced functional material gradients, AM techniques must be most commonly understood as the only viable production methods available today [50].

Currently being developed are tools to support practitioners during the design process using AM techniques [51]; however, convincing commercial software solutions are still lacking to eventually combine several DfAM approaches and incorporate underlying AM process- and material limitations including minimum feature sizes, clearances, and anisotropy. Thus, preventing its full exploitation, and not ensuring to respect its technological limits [52].

Despite the enormous design advantages AM provides [53], [54], many designers are restricted by their thinking that is based on traditional design processes. Thus, the way of design thinking towards AM defines a challenge that should be addressed when designing for AM [28].

Design guidelines for designers in AM provide a starting point to respect underlying process-varying constraints. As Table 1 demonstrates, support structures are not required for polymer-based SLS. Thus, all overhang angles are free of support structures and undefined maximum unsupported horizontal bridges are producible, as opposed to all other presented AM processes.

MJ requires support structures for all overhang angles and does not allow designs with unsupported horizontal bridges (similar to SL). These guideline values represent typical values applicable to generalized manufacturing environments; however, each feature depends on the machine, the material and the process parameters being used. Process subclasses are, for instance, described by micro SL [55], which enables printing much finer features (minimum feature
sizes of several microns limited to applied laser beam diameter and layer thickness). This AM process is not widely applied, particularly not for large end-use AM parts, due to its slow manufacturing build rates, but it demonstrates the difficulty in providing absolute numbers. Table 1 presents a set of crucial design features and their critical threshold values when designing for AM, specifically used to present absolute rough numbers and their process principle underlying differences.

Table 1. Example DfAM design feature guidelines for five AM processes [56], [57].

<table>
<thead>
<tr>
<th>Design feature</th>
<th>AM process</th>
<th>SLM</th>
<th>SLS</th>
<th>ME</th>
<th>SL</th>
<th>MJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. supported wall thickness [mm]</td>
<td></td>
<td>0.4 - 0.5</td>
<td>0.3 - 1</td>
<td>0.8 - 1</td>
<td>0.5 - 1</td>
<td>1</td>
</tr>
<tr>
<td>Min. overhang support angle [°]</td>
<td></td>
<td>35 - 45</td>
<td>none</td>
<td>45</td>
<td>30 - 45</td>
<td>all</td>
</tr>
<tr>
<td>Min. feature size [mm]</td>
<td></td>
<td>0.5 - 0.6</td>
<td>0.3 - 0.8</td>
<td>2 – 2.5</td>
<td>0.2 – 0.5</td>
<td>0.5 – 0.8</td>
</tr>
<tr>
<td>Min. hole diameter [mm]</td>
<td></td>
<td>1.5 - 2</td>
<td>1 - 1.5</td>
<td>1 - 2</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Max. length unsupported horizontal bridges [mm]</td>
<td></td>
<td>2</td>
<td>all</td>
<td>10</td>
<td>none</td>
<td>none</td>
</tr>
</tbody>
</table>

Applying methodological approaches [58], [59] in AM design processes supports designers, especially those who are rather unfamiliar with DfAM, to gain from process-related advantages in designing components. Since there are numerous varying (re)design processes existent with AM, a classification scheme analyzing components would support depicting the differences in DfAM.

1.3 Research problem and aim

The evolving technological and economic readiness level of AM techniques raises the question for companies when, to what extent, and for which components this set of production techniques should be adopted to allow end-use fabrication of industrial parts, a situation that is greatly linked to the above-mentioned obstacles and the already existing capabilities of AM. The current state of AM still implies numerous downsides, which need to be addressed to enable a more viable future AM part production.

This study aims at exploring the current technological and economic state of AM end-use components. Additionally provided are incremental development steps to improve the current situation by material-, process-, design- and concept-related enhancements. The study’s specific aims derive from the following challenges AM is facing:
- Development of a rapid analysis tool regarding the economic viability (CM versus AM and make-or-buy decisions) for the most-relevant AM processes to assist in identifying promising AM component- and product use-cases, and to establish a platform for practitioners of AM
- Assessment of the overall percentage of matching commercial AM materials to evaluate if AM material unavailability still poses a major technological restriction for frequently used materials in production environments
- Investigation of additional limiting factors preventing the use of AM such as maximum part sizes and achievable surface roughness levels
- Development and testing of novel AM materials with higher functionality, bio-based composition, or both, to lower fossil-fuel consumption in the manufacture of end-use products
- Application of existing design methodologies to aid the systematic generation of digital models according to DfAM guidelines and thus gain from newly designed AM components and to simultaneously guarantee manufacturability
- Definition of an approach classifying existing components and products designed for AM to analyze their level of DfAM exploitation

The above-mentioned research aims are addressed by the following main research questions (RQ):

**RQ1:** How can current end-use AM components be evaluated from an economic and technological viewpoint to support decision making?

**RQ2:** How can the current situation be improved considering (re)design, AM processes, and materials?

RQ1 is addressed in publications 1 and 2, which cover the current state of AM in evaluating end-use AM components economically and technologically. Publications 3–5 are connected to RQ2, providing approaches and perspectives on improving the underlying situation regarding design methodologies and classifications, modifications of AM processes and novel materials for AM.

### 1.4 Scope and outline of this thesis

The scope of this thesis is twofold: firstly, involving an analysis of the current state (publications 1 and 2) and research on incremental improvements of the current situation (publication 3-5). Publication 1 comprises a decision support system (DSS) for a (semi)automated analysis of end-use components; publication 2 presents a survey on spare parts from an industrial perspective. Secondly, presenting ideas and concepts on improving the underlying technological state, additionally focusing on process- and material capabilities (publication 3), and (re)design (publications 4 and 5) using AM technologies.
As presented in Figure 2, all publications (1–5) are linked to one another through a physical component, a material, or a simulation. Publication 1 describes how a DSS was developed for the well-known AM process metal-based PBF; publication 2 presents a more general approach on the readiness level of AM, by conducting an industry-related survey on industrial spare parts. The link between these publications relates to the possibility of automatically analyzing components by applying the DSS to draw conclusions from economic assessments and technological constraints of metal AM parts (i.e. size of the parts and materials being applied).

![Figure 2. Scope and links between the publications to both evaluate the current state and provide incremental improvements for end-use AM components.](image)

All required materials cannot currently be manufactured additively; therefore, positively affecting the total technological readiness level of AM requires the adoption of new materials and necessary AM process configurations. This aspect is addressed by publication 3, describing an incremental improvement in materials and processes, in which an AM paste extrusion system is equipped with UV lights to process new biocomposites to both prevent collapse during the print and enable enhanced print overhang angles. The above-mentioned process modification and the development of a new biocomposite allow 3D printing a slightly larger share of current components, resulting in new production alternatives by applying biocomposite materials instead of fossil fuel-based materials. This process modification additionally led to advantages in design freedom. The connection between publications 3 and 4 are revealed by a design iteration of an auger screw-based extruder equipped with UV lights, which was initially developed for extruding low-viscous pastes.

This approach was not applicable for viscosity levels of the developed biocomposite, therefore, the component was modified in a final design iteration to perform as the UV-light holder. Nevertheless, the initial design of the extruder was feasible for publication 4, a classification of end-use components, in which the extruder is categorized as a “component designed for AM”. This means that the
part is designed exclusively according to design opportunities and restrictions arising from AM, excluding CM techniques. Existing design opportunities enabled integrating the screw directly into the part, omitting the assembly stage, thus allowing it to be manufactured as a single component. Furthermore, publication 5 presents an approach to apply axiomatic design guided by DfAM rules.

To this end, several water turbine models are designed according to the axiomatic design methodology, aiming at guaranteeing their manufacturability, functional performance, and cost-effectiveness. These designs are also classified as “components designed for AM”, which links them to publication 4. Additionally, the obtained designs are tested and economically quantified with the DSS of publication 1 to validate dimensional feasibility, lead times and costs for metal PBF.
Introduction
2. Methods and materials

This chapter presents the applied research methods of this study and describes which AM processes were utilized in each publication.

2.1 Research methods

Applied research methods used in this thesis involve a combination of engineering-, information technology-, and statistical methods. The most commonly used methods are described by the case studies used in several publications (i.e. analyzed timing pulley in publication 1, design example cases in publication 4, designed and analyzed water turbines in publication 5), while all other methods are used singularly, as presented in Table 2.

Table 2. Applied methods in the considered publications.

<table>
<thead>
<tr>
<th>Method</th>
<th>Publication 1</th>
<th>Publication 2</th>
<th>Publication 3</th>
<th>Publication 4</th>
<th>Publication 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Survey</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Mann-Whitney U-test</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiment</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Case study</td>
<td>x</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concept definition</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Axiomatic design</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
</tbody>
</table>

Except for publication 3, all publications contain combinations of research methods, such as the combined quantitative survey study and Mann-Whitney U-test used to analyze the influence of respondents’ entrepreneurial attributes quantitatively.

2.1.1 Case studies

Case study research is widely applied in research fields including business, education, medicine, and engineering. The main challenge in case study research relates to their result transferability, since specific cases appear as isolated results and theories developed from a case study do not allow for generalizations, leading to subjective conclusions [60]. However, case studies are suitable for demonstrating certain capabilities. In this context, the timing pulley of publica-
tion 1 demonstrates the feasibility of the simulation tool. Scaling the timing pulley into ten different height levels addresses the issue of transferability, since this approach reflects a multi-case analysis. The main factor influencing results concerns the component volume, which is varied by different heights. Thus, this circumstance allows a result transfer to other components, with geometry representing a secondary influencing factor, to draw general conclusions.

The simulation in publication 1 is based on “Matlab” (version R2016b, Mathworks Natick, Massachusetts), which is generated to automatically analyze digital representations of components based on a developed classification scheme for AM. The major steps in establishing a logical DSS for metal PBF are described in a literature review on the existing systems and holistic incorporation of the main process steps, their characteristics, and relationships.

Publication 4 is methodologically constructed on a concept definition, extending the AM subclass element RM (see Figure 17) by “components designed for AM”, “components redesigned for AM” and “components not designed for AM”. This construction allows the classification user to group industrial end-use components accordingly; each classification stage is supported by one case study demonstrator.

The last publication, publication 5, represents a case study in which two water turbine demonstrators are designed for AM, applying the engineering-design based axiomatic design methodology [61]. For this reason, models were designed with the CAD programs SolidWorks, and PTC Creo. The Computational fluid dynamics (CFD) analysis is performed by using Ansys Fluent CFD software to estimate pressure drops in the water turbines; cost and support volume estimations were retrieved using the developed DSS tool of publication 1.

2.1.2 Survey study

Publication 2 involved conducting an industry-focused survey to gather insights into the possible integration of AM processes in spare-part production workflows. Survey studies constitute a widely applied statistical research method, particularly preferred in the field of operations management. Respondents show at least one homogenous characteristic such as the same applied technology; alternatively, larger respondent numbers are required to enable drawing objective conclusions [62]. Previously conducted were example surveys regarding the adoption of AM technologies; these surveys did not, however, investigate in detail AM process-specific obstacles of AM [63].

This survey was prepared and carried out in the context of an academic research project (Diva: “Digitaaliset varaosat”), exploring the applicability of digital spare parts for AM. The list of participants, 50 in total, comprises employees of numerous SMEs, large companies, and research institutions specializing in 3D printing. These companies and research institutions acted as stakeholders in the above-mentioned project, representing a specific sample group with knowledge on AM combined with spare parts. Participation was extended to selected external European companies. An assumed confidence level of 95% and a response distribution of 50% resulted in an estimated margin of error of 14%.

Table 3 presents the demographics of survey participants.
Table 3. Demographics of survey participants.

<table>
<thead>
<tr>
<th>Demographic</th>
<th>N (-)</th>
<th>Share (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Number of employees in the organization</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Less than 10 employees (micro)</td>
<td>16</td>
<td>32.0</td>
</tr>
<tr>
<td>10–50 employees (small)</td>
<td>7</td>
<td>14.0</td>
</tr>
<tr>
<td>51–250 employees (medium)</td>
<td>7</td>
<td>14.0</td>
</tr>
<tr>
<td>251–1000 employees (large)</td>
<td>8</td>
<td>16.0</td>
</tr>
<tr>
<td>More than 1000 employees (very large)</td>
<td>12</td>
<td>24.0</td>
</tr>
<tr>
<td><strong>European region</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Finland</td>
<td>35</td>
<td>70.0</td>
</tr>
<tr>
<td>Germany</td>
<td>10</td>
<td>20.0</td>
</tr>
<tr>
<td>Other European countries</td>
<td>5</td>
<td>10.0</td>
</tr>
<tr>
<td><strong>Industry</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Industrial manufacture and machine assembly</td>
<td>9</td>
<td>18.0</td>
</tr>
<tr>
<td>Research institutions, university or education</td>
<td>8</td>
<td>16.0</td>
</tr>
<tr>
<td>AM service and small series production bureaus</td>
<td>8</td>
<td>16.0</td>
</tr>
<tr>
<td>Consultancy</td>
<td>5</td>
<td>10.0</td>
</tr>
<tr>
<td>Consumer products and goods</td>
<td>3</td>
<td>6.0</td>
</tr>
<tr>
<td>Automotive and transportation industry</td>
<td>3</td>
<td>6.0</td>
</tr>
<tr>
<td>Aerospace</td>
<td>3</td>
<td>6.0</td>
</tr>
<tr>
<td>Medical industry, pharmaceutical and healthcare</td>
<td>1</td>
<td>2.0</td>
</tr>
<tr>
<td>Architecture, art and design</td>
<td>1</td>
<td>2.0</td>
</tr>
<tr>
<td>Others</td>
<td>9</td>
<td>18.0</td>
</tr>
<tr>
<td><strong>3D printing use within supply chains</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No use</td>
<td>30</td>
<td>60.0</td>
</tr>
<tr>
<td>Internal use</td>
<td>10</td>
<td>20.0</td>
</tr>
<tr>
<td>External distribution through international Additive Manufacturing (AM) service providers</td>
<td>6</td>
<td>12.0</td>
</tr>
<tr>
<td>External distribution through national AM service providers</td>
<td>4</td>
<td>8.0</td>
</tr>
<tr>
<td><strong>Affinity of company towards sending 3D models to external AM providers</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acceptance</td>
<td>30</td>
<td>60.0</td>
</tr>
<tr>
<td>No acceptance due to knowledge transfer</td>
<td>6</td>
<td>12.0</td>
</tr>
<tr>
<td>No acceptance due to IT security issues</td>
<td>9</td>
<td>18.0</td>
</tr>
<tr>
<td>No acceptance due to an interruption in value chain</td>
<td>3</td>
<td>6.0</td>
</tr>
<tr>
<td>No acceptance due to other reasons</td>
<td>2</td>
<td>4.0</td>
</tr>
</tbody>
</table>

The Mann-Whitney U-test is applied to analyze results on participating focus group comparisons. This test supports the evaluation of three survey questions (Questions 4–6 in Table 4) containing 5-point Likert scales [64] that investigate the opportunities, technological barriers and economic hindrances of additively manufactured spare parts. This statistical test is required to analyze the influence on results of entrepreneurial factors including company size (i.e. number of employees in the organization) and the already existing “3D printing use within supply chains”:

\[
U = n_1n_2 + \frac{n_2(n_2 + 1)}{2} - \sum_{i=n_1+1}^{n_2} R_i
\]

Where \( n_1 \) represents the first sample size, \( n_2 \) the second sample size and \( R_i \) the sample size rank.
Table 4 presents the most relevant survey questions to both apply the Mann-Whitney U-test and investigate the technological barriers to AM adoption.

**Table 4.** Most relevant survey questions for result analysis.

<table>
<thead>
<tr>
<th>Question #</th>
<th>Question</th>
</tr>
</thead>
<tbody>
<tr>
<td>Question 4</td>
<td>Which opportunities of Digital Spare Parts would you rate most significant (5 = highest score)?</td>
</tr>
<tr>
<td>Question 5</td>
<td>Which technical barriers of 3D-printed Digital Spare Parts are the greatest challenge (5 = highest score)</td>
</tr>
<tr>
<td>Question 6</td>
<td>Which economical barriers of 3D-printed Digital Spare Parts are the greatest challenge (5 = highest score)</td>
</tr>
<tr>
<td>Question 12</td>
<td>Name the TOP 5 materials you are currently using for spare part production in your company (e.g., “Aluminum Alloy AlSi10Mg”, “Polyamide PA6”, “Stainless Steel SS316L”) in descending order.</td>
</tr>
<tr>
<td>Question 13</td>
<td>What are the minimum roughness values Ra [μm] for the selected materials?</td>
</tr>
<tr>
<td>Question 14</td>
<td>Which percentage of spare parts would lie below certain build chamber volumes?</td>
</tr>
</tbody>
</table>

The remaining survey questions are presented in Publication 2 in Appendix A.

### 2.1.3 Experimental study

Publication 3 is fully experimental, involving material development, machine setup, and testing of novel biocomposite materials for a modified paste extrusion process based on UV-light polymerization. To create a material that is potentially fully bio-based, cost-effective, wood-like, robust, scalable, and without notable shrinkage after the printing process for enhanced dimensional conformity, several material combinations were tested. The material consequently proposed were varying compositions of acrylic acid (AA), cellulose acetate (CA), α-cellulose (Cel) and fumed silica (Si). Table 5 presents the varying resin composites including their constituents.

**Table 5.** Tested resin composites in vol-% (weight-% in parenthesis). 0.5 WT-% TPO-L photoinitiator is used in all resins.

<table>
<thead>
<tr>
<th>Resin</th>
<th>AA</th>
<th>CA</th>
<th>Si</th>
<th>Cel</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>83 (80)</td>
<td>17 (20)</td>
<td>0 (0)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>B</td>
<td>67 (60)</td>
<td>13.7 (15)</td>
<td>0 (0)</td>
<td>19.3 (25)</td>
</tr>
<tr>
<td>C</td>
<td>67 (58.4)</td>
<td>13.7 (14.6)</td>
<td>5.1 (9)</td>
<td>14.2 (18)</td>
</tr>
</tbody>
</table>

All specimens were fabricated on a purpose-built modular extrusion platform, which can be equipped with standard 10 mL luer lock syringes. The intensity of UV in the applied UV LEDs is based on the total power consumption of 12 W with a wavelength of 395 nm. Tensile testing was conducted in accordance with ASTM standard D638-14 Type 4, while compression testing complied with ASTM D695-15; both used an Instron 4204 Universal Tensile Tester. Analysis of the dimensional conformity of printed samples used an Atos core 3D scanner. Thermogravimetric analysis and Fourier-transform infrared spectroscopy were
performed to analyze the UV-curing behavior using a TGA Q500 (TA Instruments) and a FTIR Unicam Mattson 3000 (PIKE GladiATR), respectively. Scanning electron microscopy (Σigma VP, Zeiss) and high-vacuum coating (EM ACE600, Leica) were applied to analyze cross-sectional areas of fabricated samples.

2.2 Applied additive manufacturing processes

In addition to the applied methods, several AM processes were used to visualize, support, conceptualize, and test components. Table 6 outlines these AM processes within process groups such as PBF, BJ, and MJ.

<table>
<thead>
<tr>
<th>Publication #</th>
<th>PBF</th>
<th>BJ</th>
<th>MJ</th>
<th>VP</th>
<th>ME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Publication 1</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Publication 2</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Publication 3</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Publication 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Publication 5</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In Publication 1, the underlying AM process in the DSS was SLM, which belongs to the AM process group PBF. All cost and production time values are simulated for this process after undergoing the technological feasibility analysis.

Publication 2 theoretically encompasses all the above-mentioned AM process groups. Particularly regarding the estimation of the share of printable components [%] derived from requested part dimensions, metal and plastic PBF, metal and plastic BJ, MJ, VP (SL) and ME (filament-based) are considered AM processes requiring investigation.

Publication 3 involved the manufacture of functional specimens for tensile, compression and overhang testing, along with lattice structures that serve as visual demonstrators, due to their production with UV light-assisted paste extrusion of biocomposites. This approach involved applying an in-house developed piston-based extrusion system with a syringe capacity of 10 ml using a 0.84 mm nozzle diameter. The printer set-up required modification; thus, the final version of the UV-light syringe attachment was printed using a Stratasys “uPrint SE” filament-based ME system and “ABSplus” material for functional prototyping, providing sufficient material properties and accessible support-removal possibilities.

Publication 4 involved manufacturing an extruder head with an integrated auger screw and UV light attachments by applying the SL process, which belongs to the VP process group. Inner support structures were avoided by reorientation of the component concerning maximum overhang angles and part stability during fabrication. The manufacture of this component used a “Formlabs Form 2” 3D printer, with a so-called tough resin selected for functional and visual prototyping.
The last publication, publication 5, involved two turbine models, which were designed by taking the axiomatic design approach as a baseline following DfAM guidelines for SLM (belongs to the AM process group of PBF). These models were manufactured with a “3D Systems Z250” printer using gypsum powders for real-sized visual prototyping without needing support structures.
3. Results and discussion

This chapter is divided into results and discussion of approaches to evaluate the current economic and technological state of end-use components. Following this section is the presentation of incremental enhancement steps to further improve the underlying situation, as presented in Figure 2.

3.1 Evaluating the current state of end-use components

The current state of industrial AM end-use components is assessed by the development and implementation of a DSS for metal PBF. Additionally, a survey study on the overall readiness level of additively manufactured spare parts is performed to clearly establish part-requirement demands from the industry compared to existing capabilities arising from AM.

3.1.1 Economic assessment

The DSS resulted in a cost structure model adapted from [32], [65], modified and expanded according to metal PBF process characteristics such as powder reuse possibilities, part positioning, manufacturing input-dependent build rate variations, employees’ monitoring time, set up and removal times (Figure 3). This cost structure accounts for material, labor and machine costs, eventually resulting in unit costs ($c_{op}$). High machine utilization rates of 70% are assumed to simulate manufacturing conditions of high-end AM service providers with considerable manufacturing throughput. Around this cost structure, the DSS tool was established and expanded by initial technical feasibility analysis, production time estimates, and a graphical user interface (GUI). Components for analysis are uploaded as binary standard tessellation language (STL) files, which are consequently (re)oriented by rotation according to their x, y, z-axis. (Re)orientation allows identifying the optimal position to minimize the necessary support volume. The next step involves placing the (re)oriented components onto the build platform by considering suitable gaps between the parts and the platform edges.
Figure 4 presents the GUI that is generated to facilitate the use of the DSS, which requires the following input parameters: AM machine, AM material, accuracy mode, support structure mode selections and production volume (i.e. AM batch size in the GUI).

The cost structure can be manually adjusted using the following parameters: machine prices, build chamber volumes, densities and build rates to enable the analysis for excluded machine and material types or deviating price levels.

When all input parameters are set, the user must click on the “STL-Input and START” button to run the script. If the selection of input parameters is not complete, the uploaded file type is not supported by the tool or the component is too large for the selected machine and a failure code can pop up. In this case, the input needs corresponding modification to proceed with the analysis.

To demonstrate the feasibility and performance of the tool, a model of a timing pulley (Figure 5) is used as a case study component, scaled from 7.5mm to 135mm according to its z-axis.
Finally, the scaled components are analyzed with the DSS tool to calculate cost projections, including several additional key performance (KPI) indicators such as information on support structures. The obtained cost values were consequently compared to price quotes from a 3D printing service provider [66] to prove that the modeled DSS provides realistic estimates.

Therefore, cost results should fulfill at least the following conditions: estimated cost values must be below price quotes to reflect profit margin requirements of the related 3D printing service provider. Simultaneously, obtained values from the DSS must show similar behaviors when modifying input settings compared to the 3D printing service provider, for instance, when changing the manufacturing material and the size of the part. Accordingly, for the majority of test runs, results indicate that both aspects are sufficiently ensured, as Table 7 illustrates (extract of Table 3 in publication 1).

Table 7. Calculation results of a scaled timing pulley for the materials AlSi10Mg (aluminum alloy), MS 1.2709 (maraging steel) and SS316L (stainless steel), evaluated in the "normal accuracy" (NA; machine-dependent standard build rate) mode, "high accuracy" (HA; reduced build rate) mode, finally compared to official price quotes.

<table>
<thead>
<tr>
<th>Part no.</th>
<th>Part height z (mm)</th>
<th>Batch size (-)</th>
<th>Support value (%)</th>
<th>AlSi10Mg</th>
<th>MS 1.2709</th>
<th>SS316L</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cost NA (€)</td>
<td>Cost HA (€)</td>
<td>Price quote (€)</td>
<td>Cost NA (€)</td>
</tr>
<tr>
<td>1</td>
<td>7.5</td>
<td>288</td>
<td>9.39</td>
<td>1.23</td>
<td>1.30</td>
<td>n.d.</td>
</tr>
<tr>
<td>2</td>
<td>15</td>
<td>157</td>
<td>9.38</td>
<td>2.42</td>
<td>2.93</td>
<td>24.9</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>68</td>
<td>9.29</td>
<td>14.02</td>
<td>18.13</td>
<td>74.52</td>
</tr>
<tr>
<td>4</td>
<td>45</td>
<td>37</td>
<td>9.29</td>
<td>46.61</td>
<td>60.47</td>
<td>185.67</td>
</tr>
<tr>
<td>5</td>
<td>60</td>
<td>24</td>
<td>9.38</td>
<td>117.59</td>
<td>150.43</td>
<td>384.58</td>
</tr>
<tr>
<td>6</td>
<td>75</td>
<td>16</td>
<td>8.07</td>
<td>244.43</td>
<td>308.57</td>
<td>696.76</td>
</tr>
<tr>
<td>7</td>
<td>90</td>
<td>12</td>
<td>11.64</td>
<td>549.61</td>
<td>660.43</td>
<td>1151.6</td>
</tr>
<tr>
<td>8</td>
<td>105</td>
<td>9</td>
<td>11.57</td>
<td>1011.9</td>
<td>1187.9</td>
<td>1775.9</td>
</tr>
<tr>
<td>9</td>
<td>120</td>
<td>7</td>
<td>9.38</td>
<td>1542.2</td>
<td>1804.9</td>
<td>2589.5</td>
</tr>
<tr>
<td>10</td>
<td>135</td>
<td>5</td>
<td>12.66</td>
<td>3343.1</td>
<td>3717.2</td>
<td>3626.6</td>
</tr>
</tbody>
</table>

An important aspect of cost estimates concerns simulated support structures. Demonstration of their viability involved performing a comparison between support generation in the DSS and commercial software for 3D print-preparations (i.e. “Magics” Materialise). Results show that the principle of mandatory support structures for overhangs of less than 45° in relation to the horizontal build platform is fulfilled in both cases, orienting the part diagonally (see Figure
The main differences to the commercial system relate to the larger gaps between the build platform and the part to guarantee simplified support removal; however, this distance can be manually adjusted in the back-end of the DSS tool. Additionally, features included in the commercial software comprise commonly used block-support structures in metal PBF and optimized reorientation processes; the features account for additional aspects, apart from minimizing support structures (e.g., center of gravity, heat dissipation). These differences must be understood as limiting factors of the DSS tool, aspects that should be addressed in the succeeding version that is currently under preparation. Nonetheless, it must be stated that crucial similarities (e.g., occupied platform area per part) are already implemented to allow an automated-rough estimate with plausible orientations, support structure volumes, and production batch numbers.

The next step presents cost and production time results, extended by several KPIs. Figure 6 shows an analysis of the uploaded timing pulley, in this case with a height of 60 mm. Hence, 24 parts can be placed onto the platform considering the orientation shown, leading to a cost value of €117.59 in the “normal-accuracy” and €150.43 in the “high-accuracy” mode. On the contrary, the same part from the same material is offered for a price of €384.58 by a 3D printing service provider. Thus, cost and price comparisons on the basis of production runs with the same AM system would result in a profit margin of 227% and 156%, respectively, excluding rental and extensive post-processing costs in the DSS.

Further calculated is a processing time of 106.98 min per part for the selected material “AlSi10Mg”. The generated support structure leads to a support percentage value of 9.38% when divided by the overall part volume. The support volume is calculated by adding up incremental volumes of all vertical struts for areas with overhang angles of less than 45° in relation to the build platform.

**Figure 6.** Results for the analyzed timing pulley (from top left): cost per part over production volume, cost structure per part, visualization of part orientation and support structures, production time over production volume and KPIs including cost per part, part process time, batch size and support percentage.
The cost function shows that cost decreases for the first 24 parts are significant, lowered from approximately €270 to €120 per part; the lowering mainly arising from initial print preparation efforts. Cost decreases subsequently flatten until reaching a minimum cost of €117.59 per part. This cost per part approximation can be divided into three main cost types: material, machine and employee. In this case, material and machine costs encompass the largest share, whereas employee costs are almost negligible. The total time function, showing the production time over the production volume, is described as a linear function, incorporating minor vertical steps resulting from machine set-up, pre-heating and cooling down. In these durations, the system is not manufacturing parts.

When analyzing the incline of production speeds on the overall cost structures, it could be demonstrated that the cost-saving potential of high-volume metal PBF machines (EOSINT M 400, 300 parts) is significant for all evaluated materials (i.e. AlSi10Mg, TiAl64V, Maraging steel DIN 1.2709) until reaching a build rate of approximately 20 mm³/s.

Exceeding this value results in rather marginal cost savings; the percentage of material and employee costs on the total cost is maximized, while the percentage of machine costs reaches its minimum. The analyzed variation in part sizes of the related component did not impact the degree of cost-savings.

Nevertheless, the overall cost-saving potential amounts to 90% when comparing build rates of 1 mm³/s and 100 mm³/s, which demonstrates the trade-off between feature resolution and production speeds.
This paradigm is explained by the correlation of tiny features, which require production with smaller laser beam diameters and result in slower production rates, thus leading to increased costs.

Future cost savings could mostly arise from reduced material costs, resulting from the influence of decreased machine prices being lower for series AM production (considering high machine utilization rates of 70%) than for material price decreases. Ideally, an overall cost decrease of 55% would occur until 2025, if the material and machine prices are each lowered by 60%, assuming a constant build rate of 12 mm³/s for maraging steel DIN 1.2709.

To show the applicability of the DSS for components of higher design complexity, an additional example part is used for technical and economic evaluations.

In this context, assessment concerns a water turbine model (Figure 8) that is linked to publication 5 (axiomatic design). Features of this component design include: being easily transportable (max. dimensions of 100mm x 100mm x 200mm (l*w*h)), consisting of a single part (non-assembly), being manufacturable for SLM without functionality-impairing inner supports, and respecting both clearances and wall thickness minimums (i.e. above 1 mm).

On the left of Figure 8, the designed turbine model is visualized in CATIA. The center model illustrates a scheme of the turbine, which comprises the inlet/outlet, the hull, the shaft, the pre-chamber, and the turbine blades. The model on the right shows a printed prototype of this turbine using gypsum-based BJ. This water turbine uses an integrated pre-chamber to control the water supply, ensuring uniform water supply to the blades and guaranteeing higher pressure levels in the pre-chamber than in the following blade section. Furthermore, the blade sizes are maximized regarding the build volume and the walls of the structure are hollowed to save material. This water turbine model is currently not considered in the second axiom of the axiomatic design process; however, it will be included in a future publication that focuses on comparing the axiomatic design to other design methodologies for DfAM.

![Figure 8. Render, scheme and physical 3D print (SL process) of the designed water turbine.](image)

The DSS tool in publication 1 was created with Matlab and therefore represents an offline tool, which was only accessible by installing it as a desktop application. To provide the DSS for company representatives, scientists and other
practitioners in the field of AM, the GUI was redesigned and deployed as a .ctf-file.

The presented online application (https://amdsp.org.aalto.fi) in Figure 9 is based on the algorithms of publication 1, allowing the user to upload binary STL files to rapidly analyze components from both a technical (e.g. dimensional verification of the uploaded part) and economic viewpoint (cost and production times) for metal-based PBF.

Expanding the offline DSS, underlying cost values for CM can be implemented and compared to estimates for AM, along with the possibility of including operational costs (i.e. costs for logistics and storage) to provide a holistic comparison of manufacturing alternatives.

When all mandatory selections are made and required input is provided, pressing the button “show results” stores the inputs and transfers them, together with the STL-file, to the back-end of the Matlab tool. Consequently, running the algorithm returns six figures and three KPIs, which are represented by the support percentage, production number per bmanusatch and cost per part. Currently, the platform encompasses nine different machines, three material types, three accuracy levels and varying frequencies of support structures. Similarly to the offline tool, several variables can be modified in the manual settings module, for example, machine price, build chamber volume, and material price.
As Figure 10 illustrates, the output figures (calculation results) show, from left, a comparison of conventionally (yellow line) and additively (blue line) manufactured cost graphs (cost per part over the production volume). The following diagram shows cost-per-part based cost structures for several manufacturing processes (filament-based ME, SLS, SLM, SL, and CM); cost estimates of additional AM processes such as filament-based ME are calculated on the basis of one predefined industrial machine and material combination. Based on a renowned business consultancy [67], presented next are: future cost projections for CM and AM, a total time estimation for the overall number of parts, and a build time per part comparison. These figures are based on implemented future material and machine price estimates, with declines of 25–45% in the coming years for each aspect.

Figure 10 includes a frontal and side preview of the uploaded component, which in this context involves the water turbine model obtained from the axiomatic design approach. The vertical support structures highlighted in red reflect the orientation, containing the minimum possible support structure volumes that are needed to fulfill overhang requirements. However, to avoid inner support structures, for the rotating shaft and turbine blades, this component should be vertically in line with its original position. The reorientation can be performed on the backend side of the tool, a feature that is currently not present in the online DSS.

In this example, the break-even point between SLM and CM amounts to 10 parts; thus, for economic feasibility, the AM must be used below this threshold number. Assuming a production volume of 100 parts, which is higher than with CM techniques for the same material “AlSi10Mg”, returns a cost quote of €768 per part. Lower cost values are commonly present for polymer-based component comparisons for additional AM processes such as SLS and, therefore, varying materials such as polymer. Cost estimates of additional AM processes are
based on simplified cost algorithms to allow for automated benchmarking of pre-selected machine- and material combinations without the need to implement additional input from the user. To account for a similar production environment as compared to metal PBF, a machine utilization rate of 70% and a machine depreciation period of 8 years are assumed. Furthermore, a fixed standard build rate for each system and an overhead of 25% on total costs is considered. Pre-selected machine- and material combinations include a Stratasys “Fortus 450mc” applying “ABS-M30” material (filament-based ME), an EOS “P396” system using “PA 2200” material (SLS), and a 3D Systems “ProX 950” AM machine applying “Accura Phoenix” material (SL). According to the future cost projections before 2025, SLM will not undergo the cost of CM for the same machine-material combination. The next two graphs focus on production durations, in which the build time per part is estimated at 2200 min (described by a linear total time function), clearly above those of polymer-based processes. The required support volume is minimal when the turbine model is reoriented diagonally upside-down, leading to a support structure amount of 21.9% regarding the part volume.

The online version of the developed DSS does not only allow economic assessments of uploaded components but also preliminary technical analysis by automated verifications of maximum build envelope dimensions (Table 8 shows example parameters).

### 3.1.2 Technological assessment

In addition to the simulation tool for rapid economic evaluations, publication 2 particularly focuses on investigating technological aspects of additively manufactured spare parts. A survey was consequently conducted, gathering insights on demands, requirements, opportunities, and threats for industrial spare part production scenarios.

As Figure 11 demonstrates, supply chain networks are modified drastically when replacing traditionally manufactured (e.g. sand and die casting, injection molding) parts by 3D printed spare parts. In the presented scenario, the end-user (tier 3) is theoretically no longer forced to buy spares from service locations, which are supplied by distributors and original equipment manufacturers (OEM). If AM production is adopted, spare parts can instead be ordered from tier 2 on the supply side. Thus, related component suppliers could act as distributed manufacturers close to the end-customers. This scenario results in a distribution-bypass of several tiers, including the OEM, assuming that the end-customer or AM component supplier has access to the 3D model, and does not violate any intellectual property rights. Notably, this scenario is not only limited to AM distribution scenarios, but also expandable to conventional machining shops, and third-party component manufacturers, which may act similarly. A case study example for end-users ordering components directly from an AM service provider is represented by the governmental railway company of Germany [68]. This company is replacing damaged headrests of their high-speed train fleet by procuring components through external services. In this scenario, the end-user (i.e. railway company) does not have to procure the parts from the
OEM, but pays for the external manufacture and related shipments of additively manufactured spare parts. Thus, the OEM is bypassed, which may lead to the situation that the end-user can select amongst the most cost-effective and most flexible AM service provider.

Conversely, from the perspectives of OEMs, several distribution scenarios are feasible when adopting AM. Firstly, the OEM purchases and operates AM machines in-house to directly replace internal spares and to offer spare parts to end-customers, potentially even competing with component suppliers. Case study examples of OEMs producing end-use components internally for end-users or for internal use (e.g. maintenance) involve large manufacturing companies such as GE [10], producing jet engine parts, and Siemens [69], manufacturing gas turbine components additively. This business model is suitable for companies with a high degree of knowledge in AM and underlying large production volume demands enabling high utilization rates of AM machines.

Secondly, component suppliers switch to AM, ideally offering AM end-use components next to their existing conventional production machines to cover a wide range of components and post-processing capabilities, from which the OEM purchases parts for internal use or to ultimately forward them to end-use customers. An example for this supply chain option is given by [70]. MAN, a truck OEM, has been qualifying and ordering guide vane segments for a gas turbine from an AM service provider called Rosswag. Finally, the OEM is selling the assembled end-product including the externally distributed AM parts to end-users. For low quantities of requested spare parts, this distribution approach can be a feasible business model for both the end-user and the AM service provider, keeping the investment costs for the OEM at a minimum.

These options reflect the paradigms of centralized and decentralized distribution models, each of which having their own advantages and disadvantages for tiers and OEMs in terms of: market power, liability risks, supply chain network agility and robustness. One of this study’s main focuses concerns the identification of applied materials in production to evaluate if they are replaceable by 3D printing materials, which would imply comparable material properties. Hence,
survey participants were asked to list their five most frequently processed materials. Collected materials were consequently grouped into material categories, their ranks inverted and normalized to determine weighting factors. Calculation of the final percentages involved summing up rank-values of corresponding material names.

Figure 12 presents the resulting grouped spare part materials, demonstrating that applied materials can be divided almost evenly into metallic and non-metallic materials (48.51% versus 51.49%). In the furthest decomposed stage of exact material types, SS316L (16%) is followed by PA6 (13.46%), PAxx (7.95%) and AlSi10Mg (6.12%). Matching requested materials with commercially available 3D printing materials results in 70% of frequently used materials currently being available, not considering possible substituting and researched AM materials. This matching indicates that the majority of 3D printing materials is currently already commercially available; however, evidence exists of variations in their mechanical performance, visual appearance, repetitive part quality, surface roughness properties and the synthetic character in the vast majority of investigated AM materials.

Figure 12. Subdivision of applied spare part materials of participating companies.

Survey participants were subsequently asked to specify underlying sizes of spare parts in their facilities. This information was collected by presenting specific build chamber volumes including their single dimensions; thus, participants provided answers on the percentage of spare parts fitting into certain volumes (i.e. 0.001 m³, 0.027 m³, 0.125 m³, 0.343 m³, 0.729 m³, 3.275 m³). This resulted in more than 20% of single components fitting into a volume of fewer than 0.001 m³ (0.1 m for a single dimension) and more than 85% into a 0.729 m³ (0.9 m for a single dimension) volume. Accordingly, this information was compared to the best-in-class (available on market) and local (installed in Finland [71]) machines existent for industrial end-use AM processes. Table 8 out-
lines process-related AM machines for best-in-class and local distribution scenarios, additionally providing data on build envelopes and relevant AM process types.

**Table 8.** Maximum AM machine build envelopes (best-in-class versus local) for industrial AM processes.

<table>
<thead>
<tr>
<th>AM Process</th>
<th>Best-in-Class vs. Local</th>
<th>AM Machine</th>
<th>Build Envelope Dimensions (mm × mm × mm)</th>
<th>Build Envelope Volume (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal-based PBF</td>
<td>Best-in-class Local</td>
<td>Concept Laser X line 2000 R</td>
<td>800 × 400 × 500</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>Local</td>
<td>SLM solutions SLM 280HL</td>
<td>280 × 280 × 365</td>
<td>0.029</td>
</tr>
<tr>
<td>Plastic-based PBF</td>
<td>Best-in-class Local</td>
<td>Wuhan Binho XRS-VII</td>
<td>1400 × 1400 × 500</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>Local</td>
<td>EOSINT P95</td>
<td>340 × 340 × 620</td>
<td>0.072</td>
</tr>
<tr>
<td>Metal-based binder jetting</td>
<td>Best-in-class Local</td>
<td>ExOne M-Print</td>
<td>800 × 500 × 400</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>Local</td>
<td>Not existent</td>
<td>0 × 0 × 0</td>
<td>0</td>
</tr>
<tr>
<td>Plastic-based binder jetting</td>
<td>Best-in-class Local</td>
<td>Voxeljet VX 1000</td>
<td>1000 × 600 × 500</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>Local</td>
<td>Voxeljet VX 1000</td>
<td>1000 × 600 × 500</td>
<td>0.3</td>
</tr>
<tr>
<td>Material jetting</td>
<td>Best-in-class Local</td>
<td>Stratasys Object 1000</td>
<td>1000 × 800 × 500</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>Local</td>
<td>Stratasys Object Connex 350</td>
<td>540 × 340 × 200</td>
<td>0.023</td>
</tr>
<tr>
<td>Vat photopolymerization</td>
<td>Best-in-class Local</td>
<td>3D Systems ProX 950</td>
<td>1500 × 750 × 550</td>
<td>0.62</td>
</tr>
<tr>
<td></td>
<td>Local</td>
<td>3D Systems SLA-500</td>
<td>508 × 508 × 610</td>
<td>0.157</td>
</tr>
<tr>
<td>Filament-based extrusion</td>
<td>Best-in-class Local</td>
<td>Stratasys Fortus 900nc</td>
<td>914 × 610 × 914</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>Local</td>
<td>Stratasys Fortus 400nc</td>
<td>406 × 355 × 406</td>
<td>0.0585</td>
</tr>
</tbody>
</table>

As Figure 13 shows, based on this investigation, locally produced components have a size-related manufacturability share from 0% (i.e. metal BJ) to 72% (i.e. plastic BJ) compared to a range from 63% (i.e. metal PBF) to 93% (i.e. plastic BJ) for best-in-class systems.

![Figure 13. Size-related printability for best-in-class and locally installed AM processes.](image)

The Mann-Whitney U-test result demonstrated that companies already applying 3D printing in their supply chains consider the digital storage of spare parts as the main opportunity and advantage, simultaneously demanding 3D printing specialists to master related challenges. Larger (i.e. 251–1000, more than 1000 employees) and medium-sized companies (51–250 employees) consider limited build chamber volumes more challenging than micro-companies (less than 10 employees). Additionally, compared to large companies, very large corporations (more than 1000 employees) do not consider problematic the IT capabilities required to set up a digital spare part environment.

These observations could be explained by the higher production volumes and larger part varieties of large and medium-sized companies that rely on larger and more productive AM machines. Moreover, very large companies seem capable of acquiring sufficient resources to invest in modern IT systems, allowing the establishment of digital part libraries and workflows.
When analyzing the requested surface roughness levels, post-processing is required for several steels (stainless steel (SS316L), tool steel (H13)), non-ferrous metallic materials (aluminum-alloy (AlSi10Mg), nickel-alloy (In718), gold (Au)), and investigated plastic materials except for polylactic acid (PLA). Indeed, the surface roughness requirement of 25 μm for PLA represents the lowest requested quality demand and was therefore easily fulfilled.

In general, the main technological barriers concern both limited build chamber volumes, especially regarding local AM part procurement, and insufficient part accuracy and quality levels, including tolerances and repeatable mechanical properties. Regarding economic barriers for companies, costs considered significant concern AM part production and investments for necessary IT infrastructure. However, opportunities of additively manufactured spare parts are mainly identified in the on-demand and rapid part production possibility of gaining in flexibility and shortening lead times-to-market. Thus, the digital spare part concept requires extensive developments to enable its consideration as a realistic mature part distribution alternative to CM.

A developed DSS for AM, along with a survey study regarding additively manufactured spare part components for industries, assessed the economic and technological state of end-use AM components. Further improvement in the reported situation requires incremental enhancements to exploit the capabilities of AM and to tackle existing challenges, such as limitations in the material selection, especially for bio(composite) materials.

### 3.2 Incremental improvements

As referred to in Figure 2, this chapter comprises three main topics related to AM end-use components: a newly developed biocomposite material, a classification scheme for DfAM, and the applicability of a traditional design methodology for AM.

#### 3.2.1 New biocomposite material development

As Figure 14 (a) shows, the combination of AA/CA alone has not fulfilled viscosity requirements to maintain its shape after extrusion (loss modulus exceeds storage modulus), whereas by adding Cel, the rheology of the generated pastes behaved favorably for paste extrusion. The addition of a small share of Si reduced the risk of nozzle clogging without affecting the rheology negatively, hence, resin “C” is finally selected for experimentation. Figure 14 (b) shows the extruder and its printing mechanism; Figure 14 (c) describes the investigated process alternatives (including or excluding UV light assistance during the print; successful attempts by implementing UV cross-linking in ME exist [72]–[75]); Figure 14 (d) demonstrates the applicability of this approach to complex lattice part production.
Results and discussion

Figure 14. (a) Rheological data, (b) extruder and printing scheme, (c) printing process alternatives, (d) example print demonstration of a lattice structure.

The resulting selection of materials makes the paste (potentially) bio-based, wood-like and scalable, since a considerable amount of cellulose can be added (Cel and partially from CA). All material constituents can be provided as bio-based [76] and paste extrusion is applicable for large components with high build rates when attached to a robotic arm or large frame extrusion systems [77]. To simultaneously meet relevant material requirements (i.e. shrinkage prevention, robustness), the material is modified with both a UV initiator (Ethyl (2,4,6-trimethylbenzoyl)-phenyl phosphonate (Omnirad TPO-L; IGM)) and several UV lights with an overall power consumption of 12 W. This method allows avoiding freeze-drying approaches to maintain structural integrity [78], which results in poor mechanical properties [79]. Since different approaches to applying UV light during the process chain exist, comparisons were made between parts printed with UV light assistance during the print and components manufactured using UV light only after the print in a post-curing step.

Accordingly, as per Figure 15, tensile testing bars were printed both when applying UV light (Figure 15 (a)) and without applying UV light (Figure 15 (b)); related final specimen are presented in Figure 15(e) and (f). Results indicate that tensile stress, load and elongation levels at break are slightly higher when UV light is applied during the print. As Figure 15(d) demonstrates, 3D scans of the
tensile testing bars reveal that no notable shrinkage is present, facilitating dimensional conformity of printed parts.

![Mechanical tensile testing](image)

**Figure 15.** Mechanical tensile testing for (a) paste extrusion with UV light during the print, (b) paste extrusion without UV light and (c) view through a video recording system, (d) 3D scan of tensile testing samples, (e) printed tensile testing bar when UV-curing after the print, (f) printed tensile testing bar when UV-curing during the print, (g) condensed tensile testing stress-strain curves.

This study demonstrates that the prepared biocomposite material is applicable for paste extrusion when stabilized by UV light, reaching tensile stresses of almost 20 MPa. This result establishes a competitive value to commercially available filament-based ME cellulose-filled composites reaching 28 MPa [80]. As Figure 16 (a-e) presents, samples for overhang testing show that applying UV light during the print is more advantageous than exclusively post-curing samples by enhancing the possible overhang angles, resulting in 60° overhangs compared to 35°.

This enhancement enables manufacturing components with higher shape-complexity, as executed for a face-centered lattice structure consisting of 45°-overhanging structures (Figure 16 (f-i)). This 3D printed design could not be manufactured for the underlying process and material without UV light assistance, due to overhang and stability issues that can lead to a collapse of 3D printed structures. However, common obstacles when UV curing during print concern print-nozzle clogging, cracks between layers leading to weak layer adhesion and 3 mm maximum UV light penetration depth from each side.
Applications of this biocomposite include catalysts, insulations, and absorbers; allowing the manufacture of, for instance, honeycomb lightweight or face-centered lattice structures [81].

This material expands the selection of available materials for AM and, combined with the modified paste extrusion process by UV curing, the current state of material selection and design-freedom for end-use AM components is incrementally increased.

The design of the attached UV light module is based on the extruder head presented in publication 4, inheriting a mandatory design iteration. In the related concept definition, the initial design of the extruder head is used as a case study example to explain the sub-classification of RM “Components designed for AM” (Figure 17). The process modification simultaneously affects the design workflow in Figure 18, increasing the opportunistic design potential because of increased overhang angles and thus, enhanced freedom in design.
3.2.2 Design-specific classification

In 2003, Pham and Dimov [2] classified AM applications into RP and RT, which can be further divided into subcategories such as direct and indirect tooling. This classification could be developed further by an extension with RM for directly manufactured end-use applications and subdivided into “components designed for AM”, “components redesigned for AM” and “components not designed for AM” to address the rising demand for AM end-use components. The selection of a design-centric classification for end-use components is justified by its increased relevance and demand, describing different degrees of DfAM exploitation. To fully harness the potential of DfAM, designers should consider designing new components and assemblies from scratch by initially defining functional requirements and interfaces, simultaneously applying part consolidation concepts when possible (Figure 21). This approach potentially results in components showing higher functional performance indicators and enhanced mass reduction levels.

![Figure 17. Sub-classification of AM according to its DfAM (re)design level.]

Omitting extensive (re)design processes is possible by taking components designed for traditional production processes and 3D printing them in their existing state. Accordingly, components must be verified as consistent with AM-design restrictions and constraints to ensure printability (restrictive design phase) both before the file is exported and the manufacture of the component is started [82]. Thus, to conform with the process, material, and machine-dependent manufacturing restrictions, only minor design changes are necessary. Alternatively, already existing components can be redesigned for AM, making use of the inherent design opportunities AM provides (opportunistic design), for instance, applying topology optimization.

![Figure 18. Generic design workflow of end-use components according to their degree of (re)design.]

Detailed explanations of each category involved designing three case examples. The first case study, an example of the category “components not designed for AM”, is presented in Figure 19. This electronics case enclosure acts as a demonstrator for an obsolete spare part, which is not available in stock and for which required tools are nonexistent. If such spare parts are needed, expensive tools must be produced and extensive set-up times must be accounted for when using CM. Consequently, AM can be an economically viable alternative to produce legacy parts on-demand, omitting tooling and lengthy set-up times. However, the switch to fundamentally different production methods often requires minor design modifications. Ensuring manufacturability of this part required increases in both wall thickness and slide width, following the underlying restrictions of the AM process filament-based ME. Nevertheless, the mentioned design modification had no negative effect on the performance or functionality of this part and was therefore acceptable.

Figure 19. Electronics enclosure showing the original model designed for injection molding (left) and the slightly modified component for AM (right).

Figure 20 represents a case study for the second category, “components redesigned for AM”. In this category, existing components are significantly redesigned but kept their interfaces and functional requirements as defined in the original part design. A typical method of this category is described by topology optimization. Topology optimization involves defining a design space, applied loads and additional boundary conditions such as temperature levels, to compute a shape-optimized part with decreased mass, increased functional performance, or both. The hydraulic block example encompasses the following process steps: (a) CAD file upload, (b) interface and performance analysis, (c) opportunistic flow channel design, (d) topology optimization and (e) resulting optimized shape.

Figure 20. Redesign process via topology optimization of a hydraulic block designed for subtractive manufacturing processes.

The third category, “components designed for AM”, implies the highest degree of design-specific technological exploitation of AM. In this case, designers do
not start the design process with an existing design, but by newly defining functional requirements and interfaces of the desired product, solely considering AM being constrained as the sole manufacturing technique. This process is supposed to result in new functionalities and enhanced performances of created products, benefiting from AM design opportunities including part consolidation approaches. Hence, this procedure can result in completely new designs, which in turn, often can only be manufactured by relying on AM processes.

Figure 21 shows a case study example for this category, involving an extruder equipped with UV-LEDs simultaneously containing a rotating screw on the inside of the component to extrude and UV-cure photosensitive pastes. Figure 21 (A) presents a scheme of this component, consisting of a syringe pump that transports the material to the auger extruder, a motor to rotate the auger screw and four UV-LEDs to cure manufactured components. Publication 3 presents a similar concept, although modified by using a piston instead of a syringe pump. This modification was necessary since the rotating screw for starting and stopping the extrusion process and occurring material supply issues often lead to nozzle clogging. Figure 21 (B) shows the printed extruder head, which was successfully tested on a delta printer for low-viscous resins. As a single component, this component is not manufacturable with CM methods due to the imprinted screw and design features of high-detail resolution. The print orientation required careful consideration to avoid the need for inner support structures. To resolve this issue, the nozzle of the component visualized the highest point in the z-direction when printing. Interfaces were determined by a rigid connection to the motor shaft, the inlet diameter, the nozzle outlet, and attachments to the printer.

![Figure 21. 3D-printed auger extruder equipped with UV-LEDs to UV cure photosensitive pastes; an imprinted screw allows start/stop-extrusion. Printing scheme (left) and printed extruder (right).](image-url)

Publication 5 describes additional components, classified as “designed for AM”, that are represented by the designed water turbine models. These models are newly designed AM components that consider AM from the beginning of the design process.
3.2.3 Applying design methodologies

This study tests for applicability in AM the well-established engineering axiomatic design methodology [83], which is useful for a wide range of application areas [84]. The study aims to demonstrate the methodology’s usefulness as a supportive tool in the design process of complex AM end-use components, such as non-assembly water turbines.

The presented fictional case study has the objective of designing a non-assembly turbine for remote locations; these remote locations were only accessible by foot, which required the component to be easily transportable and installable. Further required was granting reproducibility as an on-demand spare part. According to Figure 22, the decomposition process of axiomatic design begins with customer need and is followed by a continuous zigzagging process between functional (functional requirements), physical (design parameters) and process domains (process variables).

![Figure 22. Decomposition process and zigzagging between the functional, physical and process domains according to the first axiom of axiomatic design.](image)

In total, the decomposition process resulted in five main and four sub-functional requirements, involving the need to be able to: generate energy from movement (FR1); pass water through (FR2); operate in prolonged use (FR3); use as a turnkey solution (FR4); and present a realistic possibility of being manufactured (FR5), as shown in Figure 23.
The requirement of creating uncoupled designs led to a switch between two functional requirements: FR42 (fit in a defined space) and FR41 (portable by the user). The remaining sub-functional requirements are described as: FR51 (conforms to AM process requirements) and FR52 (guarantees functionality of mechanism). These requirements are interlinked with main (e.g. DP1 mechanical powder) and sub-design parameters (e.g. DP41 weight of assembly), which are subsequently cross-linked to the main variables (e.g. PV1 shape and dimensions of the impeller) and subprocess variables (e.g. PV42 overall dimensions of assembly). Figure 2 of publication 5 presents details of the decomposition process.

Figure 24 illustrates the design renders of two water turbines, which were designed according to all considered functional requirements, design parameters, and process variables. The following constraints were defined: (i) maximum bounding box of 200 mm in height, 100 mm in depth and 100 mm in width (EOS M 290 or SLM 280 machine as a reference) to facilitate the transportability of produced components, (ii) material selection prior to the beginning of the design process, (iii) inner support structures avoidance due to limited accessibility for removal, (iv) overhang angles according to the build direction should not exceed related process and material related recommendations, (v) respect underlying minimum clearances and (vi) wall thicknesses must exceed 1 mm.
Results and discussion

Figure 24. Resulting design renders and drawings of the frontal and cross-sectional views obtained from the first axiom for two designs (D1 and D2).

Further analysis of these two competing designs involved applying five decision-supporting criteria (i.e. part volume, support volume, support %, cost, and pressure drop) to compare the turbines according to the second axiom in axiomatic design (Table 9). The water-turbine analysis is supported by the DSS tool and CFD analysis; consequently, the main analysis parameters significantly differ in volume, support percentage, and costs. Obtained values directly affect the second axiom, in which the design with the lowest information content is considered advantageous (i.e. D2 with 1.91 compared to D1 with 8.53). Information contents are calculated by summarizing the probabilities and their process variations of the five parameters, thus fulfilling the design requirements (design variation). Table 4 of publication 5 presents the details.

Table 9. Competing water turbine analysis parameters used for the second axiom.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>D1</th>
<th>D2</th>
<th>Design variation</th>
<th>Process variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume</td>
<td>258e03 mm³</td>
<td>127e03 mm³</td>
<td>0-400e03 mm³</td>
<td>10%</td>
</tr>
<tr>
<td>Supports</td>
<td>111e03 mm³</td>
<td>98e03 mm³</td>
<td>0-100e03 mm³</td>
<td>10%</td>
</tr>
<tr>
<td>Support %</td>
<td>43%</td>
<td>8%</td>
<td>0-30%</td>
<td>10%</td>
</tr>
<tr>
<td>Cost</td>
<td>1836 €</td>
<td>884 €</td>
<td>0-2000 €</td>
<td>20%</td>
</tr>
<tr>
<td>Pressure Drop</td>
<td>0.4 MPa</td>
<td>0.51 MPa</td>
<td>0-0.5 MPa</td>
<td>0.1 MPa</td>
</tr>
</tbody>
</table>

Figure 25 shows how the water turbine models were printed to improve visualization and demonstrate theoretical functionality. Therefore, designs D1 and D2 were manufactured with BJ of gypsum powders and surface-finished with super glue to maintain their structure.
Figure 25. Visual prototypes D1 and D2 of the designed water turbines in their original size (highlighted inner turbine wheels). Models printed with BJ of gypsum powders using a 3D Systems Zprinter 250.

Of the total four water turbine designs created, only two have yet been analyzed. Figure 5 introduces and shows Design D3 (the author’s design), linking it to publication 1, which analyzes this component with the developed DSS for preliminary technical and in-depth economic analysis.
4. Conclusions and perspectives

Compared to RP applications, the fabrication of end-use AM components still demands significant future development. Underlying challenges of AM end-use components were presented according to their technological-, economic-, and design domain, which highlighted several research areas requiring investigation for viable AM part production. These areas include new materials, further process innovations, understanding the current technological capabilities of AM, tools to assess the impact of AM, cost decreases, and design methodologies for AM.

Accordingly, the current state of AM end-use components is analyzed from an economic and technological side, introducing incremental development steps including material, process modification, and (re)design.

The DSS for AM enabled rapid economic analyses of end-use components for cost and production time evaluations, ultimately providing online-quotations. Manufacturing speed related innovations alone were established as not allowing further significant cost reductions; rather, essential is a focus on material price decreases, particularly for metal PBF. From a technological point of view, industrial demands were matched with underlying capabilities of the current AM ecosystem, concluding that several technological challenges need addressing before AM can be considered a realistic larger-scale alternative to CM.

Traditional design methodologies are applicable to AM and can assist designers in DfAM. Furthermore, components designed for the use of AM techniques can be classified according to their level of DfAM exploitation. Finally, the newly developed biocomposite material and its inherent process variations led to new opportunities in environmental sustainability and design freedom.

4.1 Answered research questions

RQ1: How can current end-use AM components be evaluated from an economic and technological viewpoint to support decision making?

A detailed economic evaluation of end-use AM components is presented by the use of the established DSS tool. Tested example components led to the conclusion that the calculated cost values in the DSS appear comparable to the price quotes from 3D printing service providers, when being tested for the same materials, batch sizes and part dimensions. In general, cost values of the DSS were
lower than price quotes of service providers, which is considered appropriate due to realized profit margins and secondary costs including rental and energy consumption expenses. The investigated correlation between feature resolution and build rates indicates that series AM production using metal PBF should exceed 20 mm³/s to avoid exorbitant production costs stemming from expenses for the AM machine. To further significantly lower production costs, particularly material costs must be decreased, assuming build rates above 20 mm³/s.

An online DSS was established to provide cost and production time comparisons for researchers and company representatives, enabling in-house and outsourcing scenario comparisons. In summary, this tool displays a rapid cost, time and dimensional-feasibility evaluation tool for AM end-use components. It contains in-depth metal PBF algorithms including nesting, part orientation, and support calculation to simulate specific production scenarios. The DSS is specifically applicable to small-series production scenarios of end-use components to simulate the manufacture of one specified component to meet repeatable high-quality manufacturing standards, applicable to make-or-buy decision-making as well as CM and AM comparisons.

Contrasting the technological capabilities of AM in relation to needs from industrial sectors allows drawing general conclusions on AM end-use components, in particular regarding spare parts. To this end, a general demand and supply mapping, from companies and 3D manufacturing capabilities, was conducted. Companies consider the digital spare parts concept, that is, distribution of spare parts through AM, a realistic option in future manufacturing scenarios. However, interviewees perceive as critical several technological barriers. These are described as: a non-presence of 3D printing materials to fully replace traditional manufacturing materials; insufficient (surface) accuracy and tolerance levels; and limited-build chamber volumes to 3D print demanded dimensions of components. By further investigating these perceived barriers, we conclude that to address surface roughness requirements, post-processing (e.g. machining) is a mandatory process step in most cases (13 out of 14). Also necessary are larger build envelopes, requested by large companies, especially in local distribution scenarios (only 47% of part sizes are manufacturable as a single part compared to 76% for best-in-class machines). Conversely, a lack of available commercial 3D printing materials cannot be confirmed, since 70% of frequently requested materials are already additively manufacturable without accounting for substituting materials. This conclusion, however, is limited to issues of repeatable mechanical, surface roughness properties and material sustainability. Overall, the readiness level of additively manufacture end-use components as a serious large-scale component distribution scenario is not yet sufficiently mature; to become a serious competitor to traditional distribution scenarios, further developments on the technological side are necessary.
**RQ2:** How is the current situation improved considering (re)design, AM processes, and materials?

Focusing on the material-dependent situation for AM end-use components, a novel biocomposite material was iteratively modified and successfully tested for a UV-assisted paste extrusion process modification. The selected material contained a cellulose content of more than 25%, a tensile strength of approx. 18 MPa, an average compressive strength of approx. 20 MPa and a print overhang angle of 60° (30° as measured from the build platform), allowing higher freedom in design. All obtained parameters were more advantageous than exclusively UV curing after the print in a post-processing UV light chamber. Additionally, this approach opens up new possibilities in design when applying the proposed system for paste materials. These possibilities include: enhanced stability during the print, preventing part collapse; the fabrication of more complex designs; a (fully) bio-based approach to manufacture future eco-friendlier components; and the ability to scale up part sizes and production speeds by using larger nozzle diameters. These advantages are not exclusively restricted to this specific material but could be also applied to other extrusion materials.

Since environmental aspects will be of increased importance in the future, alternatives to fossil fuel-based plastics for AM end-use components are necessary. The developed material and process modification can be considered a starting point towards UV-assisted wood-composite pastes for rapid and distributed eco-friendly end-use manufacturing, expanding the existing set of AM materials.

From a component-design perspective, a classification scheme for end-use AM components facilitates their evaluation according to their degree of DfAM integration. The class “components not designed for AM” is exclusively accompanied by restrictive design modifications to guarantee manufacturability by only implementing necessary design changes to the original design; however, the class “components redesigned for AM” goes further. In this class, the design opportunities of AM are exploited by redesigning original designs through topology optimization. This process leads to increased cost-efficiency and is supported by numerous simulation tools available on the market. The difference between this class and the class with the highest DfAM integration degree, “components designed for AM”, is the need to newly define functional requirements and interfaces. Hence, components with new functionalities are imaginable, when considering AM technologies from the beginning of the design process as the sole manufacturing choice selectable. This concept is not only linked to single parts, but also to several parts of an assembly. These components can potentially be consolidated by maintaining their overarching functionalities.

By using this approach, end-use AM components can be classified logically according to their level of AM (re)design, from which the implementation degree of DfAM is derived, subsequently showing the exploitation level of mass and functionally optimized end-use components.

Regarding the design process, the two water turbines presented were designed according to the axiomatic design process, in conjunction with AM techniques.
for non-assembly mechanisms. This systematic approach has helped to identify existing AM manufacturing limitations and to harness its design opportunities. Additionally, functional requirements, design parameters, and process variables could be collected and derived from the decomposition process. The first axiom was fulfilled when the designs were composed and uncoupled by switching positions of functional requirements. Furthermore, the axiomatic design process enabled the comparison of obtained turbine designs by applying the second axiom according to predefined analysis criteria. Particularly for highly-complex functional parts newly designed for AM, this approach appears promising, tackling the psychological inertia of designers restricted to designing with traditional manufacturing techniques. The applicability of a traditional design process for end-use AM components designed for AM is explored, describing systematically how even rather complex new products are designed beneficially and evaluated according to several KPIs, for example, to minimize material being used to lower production costs.

4.2 Limitations and future work

The economic analysis of metal PBF components is limited in its support calculation and the analysis of only one component type at a time. Support calculation involves identifying the most suitable print orientation according to the minimum amount of required support. Likewise, support structures in metal PBF are also needed to hold the part in position during the manufacturing process and to enable heat dissipation mechanisms, preventing warping and distortions. Furthermore, inner supports are difficult to remove and might block rotating elements. These aspects are currently not considered when evaluating support structures automatically with the DSS. Additionally, different support types, especially commonly used block supports, are not yet available. To estimate costs for additional AM processes in more detail to provide accurate benchmarks, specific AM process-related support structures (not for SLS), batch size calculations (e.g. 3D-stacking for SLS), and specific pre-and post-processing steps, need to be considered.

Hence, the tool is currently expanded to enable enhanced support calculations and continuous screening of several components at a time, by accounting for related additional part information such as production volume, material, storage, and logistics costs. These modifications will allow companies’ part libraries adopt top-down screening approaches to screen for the most suitable components of AM, as demonstrated in principle by [85].

Limitations in the analysis of technological state-of-the-art additively manufactured components include its limited scope, as analysis typically focuses on spare parts in Finland and other European countries. However, insights from other industrial components, including the American and Asian markets, would widen the scope. Furthermore, Mann-Whitney analyses could benefit from the acquisition of more respondent-based personal information, such as age, hierarchy level in a company and professional background, to obtain additional insights and conclusions.
A remaining issue concerns the upscaling of developed biocomposite approaches. Currently, the UV-assisted extrusion process is restricted by its small machine platform and print volume. Fulfillment of large-scale production conditions, thus enabling the production of larger end-use components, requires: material upscaling, nozzle-diameter widening (further limited by a multi-directional UV-light curing depth of 6mm) and larger-build platform provision. Simultaneously, the material should be modified further to comply with bio-compatibility demands.

The viability of the classification scheme for end-use AM parts is limited to an example listing of case studies and was not tested on a larger number of components. A detailed technological and economic analysis of an array of varying components classified with this approach would address this limitation.

The axiomatic design process is currently demonstrated for only two water turbine designs. Additional designs would help to draw conclusions from the second axiom and potentially lead to improved designs. Furthermore, the resulting designs were neither additively manufactured with a metal PBF system nor further tested under realistic conditions to evaluate their underlying performance. Ultimately, both comparisons of designs inheriting the axiomatic design process and designs based on other design methodologies or even intuitive designing should be performed. These developments are needed to confirm the viability of axiomatic design, thus resulting in more functional and cheaper components. The axiomatic design methodology itself is limited to the considered aspects of a design, since not all aspects that influence the final design are typically incorporated. This circumstance may result in unfeasible solutions, requiring readjustments and reassessments of the decomposition process and/or the set constraints. Furthermore, the result quality strongly depends on the expertise and the critical mindset of the practitioner when applying the axiomatic design approach.

Therefore, this study will be expanded by two additional water turbine designs (D3 and D4) and a benchmark study, to enable comparing and analyzing all designs obtained with the axiomatic design methodology with four “traditional” designs. The suitability of this comparison is based on the potential to investigate the positive or negative effect of applying axiomatic design to AM.

Other main challenges mentioned, but not addressed, in this study concern issues preventing the adoption of AM, such as high component costs and knowledge gaps of (potential) AM practitioners; these challenges constitute limitations. Two studies under preparation aim at dealing with these challenges and providing appropriate answers. The development of a quantification model of potential cost and lead-time reductions in metal PBF is based on the integration of DfAM for lightweight designs. This model should bridge the gap between design and economic aspects.
4.2.1 Techno-economic effect of DfAM

Based on holistic comparisons for in-house (DSS) and outsourcing scenarios, this future study will investigate cost and lead time reductions. To this end, proof for manufacturability of critical lattice structures (as demonstrated by [86]) will be assessed, and their integration in part design will be demonstrated. Structures in Figure 26 are manufactured from stainless steel 1.4404 using a “ConceptLaser MLab Cusing R” metal printer (build envelope 90mm x 90mm x 80mm, 100 W fiber laser).

Figure 26. (a) Cubic-truss and octet-truss based lattice structures produced with SLM of stainless steel powders (50mm x 50mm x 50mm, including a volume fraction of 0.15), (b) Re-design of a mounting bracket. From left: original design, micro complexity by lattice structures with different volume fractions, and macro complexity by topology optimization.

Dimensions of the lattice structures are 50mm x 50mm x 50mm including elementary lattice cell sizes of 10mm x 10mm x 10mm and a volume fraction of 0.15 for both lattice types. Comparing the listed design guideline values according to Table 1 with the printed metal lattice cubes in Figure 26 shows how the minimal feature-size guideline is achieved (0.611mm for the cubic-truss based lattice and 0.62mm for the octet-truss based lattice), due to the recommended minimum feature-size of 0.5mm. However, the printed parts contain unsupported horizontal bridges of 7.5mm and 6mm, significantly exceeding the design threshold dimension of 2mm.
To quantify the economic impact of lightweight designs, result analysis will be performed using ANOVA tests to evaluate the features of different components including lattice types, volume fractions, material type, and production volumes. This process will involve using the DSS tool (in-house production) and 3D printing service providers (outsourcing scenario). Industry practitioners and researchers will eventually gain from a possible repetitive design/analysis optimization workflow to increase cost and time efficacy of industrial parts when using the DSS tool for optimization purposes.

The gathered knowledge arising from evaluations of the current technological AM states lead to another investigation of end-use components.

### 4.2.2 Development of a knowledge base

An ontology for AM consisting of knowledge graphs was designed to support the evaluation of industrial end-use components (Figure 27). This knowledge-base consists of numerous relevant AM industrial machines, processes, post-processing, materials, mechanical properties, layer thicknesses and build envelopes, reflecting the available capabilities of end-use AM. Thus, users can benefit from this information by answering a set of queries, which are currently automated, to receive information on AM print opportunities and alternatives regarding specific technical requests. The ontology was created by collecting 137 AM machines and several hundred material specifications from AM machine-and material vendors’ websites. When collecting this information, the focus was set on the manufacture of end-use industrial components, comprising common metal, plastic, and composite materials. In a next step, the data of different features/domains are logically interlinked to establish knowledge graphs, for example by defining which AM machine is capable of processing certain material categories. Thus, these knowledge graphs are operating in the back-end of the commercial system and are addressed by using queries to provide answers to specific requests rapidly and in a flexible manner. Commercial development of this tool involves the knowledge base being integrated with a CAD handling tool, in which STL files are uploaded, and according to the resulting AM process alternatives, users are forwarded to specific 3D service providers to additively manufacture the requested component.
Figure 27. AM ontology visualized in Protegé showing AM machines, AM process groups, AM processes and AM post-processing possibilities (top left). GUI of the commercial solution (top right). Manufactured metal component (bottom).

An example component, which was analysed by the knowledge graph-based software tool, is represented by a redesigned bracket component (containing an octagon lattice structure infill), shown at the bottom of Figure 27. The requirements for this component were defined by a minimum layer thickness of 50 μm, a bounding box of 156mm × 72mm × 30mm, an ultimate tensile strength of 1000 MPa, and the material category “steel”. As a feasible option, the component was selected to be manufactured at Aalto University’s premises using an EOS M290 system applying a layer thickness 20 μm and stainless steel powder “PH1”. As post-processing steps, the system suggested heat treatments, support removal, metal plating, polishing, and surface CNC milling.

Both the study about the techno-economic effect of DfAM and the development of an AM knowledge base reflect future approaches on the assessment of end-use AM components.
Conclusions and perspectives
References

References


Assessment of additively manufactured end-use components

Current state and incremental improvements in design, materials, and decision making

Niklas Kretzschmar