A design framework for additive manufacturing based on the integration of axiomatic design approach, inverse problem-solving and an additive manufacturing database

by

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A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Industrial Engineering

Program of Study Committee:
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The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University

Ames, Iowa

2018

TABLE OF CONTENTS

Page

LIST OF FIGURES iii

LIST OF TABLES vii

ACKNOWLEDGMENTS viii

ABSTRACT ix

CHAPTER 1. INTRODUCTION 10

CHAPTER 2. LITERATURE REVIEW 13
2.1 Design for Additive Manufacturing (DfAM) 13
2.2 Additive Manufacturing Capabilities 22

CHAPTER 3. METHODOLOGY 43
3.1 Axiomatic design approach 43
3.2 Inverse problem-solving approach based on TRIZ 46
3.3 Additive manufacturing database 49
3.4 Proposed design framework 52
3.4.1 Conceptual design phase 53
3.4.2 Embodiment design phase 55
3.4.3 Detailed design phase 56

CHAPTER 4. CASE STUDIES 57
4.1 Case study 1: Redesigning a housing cover 57
4.1.1 Conceptual design phase 58
4.1.2 Embodiment design phase 61
4.1.3 Detailed design phase 63
4.2 Case study 2: Redesigning a link-pin assembly 65
4.2.1 Conceptual design phase 65
4.2.2 Embodiment design phase 69
4.2.3 Detailed design phase 71

CHAPTER 5. DISCUSSION & CONCLUSIONS 74

REFERENCES 77

APPENDIX A. 87

APPENDIX B. 88

LIST OF FIGURES

Page

Figure 1 Powder-based additive manufacturing process. Adopted from Poprawe (2005). 10

Figure 2 Design methodology proposed by Rodrigue and Rivette (2010). 15

Figure 3 Redesigning a square bracket using parametric optimization. Adopted 15

Figure 4 Designing a salt shaker and ice cream scoop with and without using the DfAM database. Adopted from Bin Maidin et al. (2012). 17

Figure 5 A salt cellar and its 3D modular graphical representation. Adapted from Boyard et al. (2015). 18

Figure 6 Modified turbine blade with integrated ink cartridge designed by the forced association of a turbine blade (AM domain) and ball point ink pen (another domain). Adopted from Rias and Segonds (2016). 19

Figure 7 3D printed lamp designed by Bathsheba Grossman (Materialise, 2008) (a) and a 3D printed removable partial framework model (Stratasys, 2017a). 23

Figure 8 A lattice cell made using a laser fusion process (Petrovic et al., 2011) (a), acetabular cup with porous lattice structure (Sing et al., 2016) (b) and a tibial stem made using Electron Beam Melting process (Murr et al., 2012) (c). 24

Figure 9 Topology optimization process of a metal bracket. Adopted from Komi (2014). 26

Figure 10 Example of part consolidation. An aircraft duct with 16 components (a) consolidated into a single component (b) (Gibson and Rosen, 2015). 27

Figure 11 A pulley driven snake like robot made using stereolithography (a) (Gibson and Rosen, 2015), gear trains made of aluminum alloys with 0.8 mm clearance (b) (Calignano et al., 2014), a 13 piece articulating section made using laser sintering (c) (Zelinski, 2012) and a universal joint fabricated with Vero-white material (d) (Chen and Zhezheng, 2011) 28

Figure 12 Injection mold insert with cooling channel (Gibbons and Hansell, 2005) (a), hydraulic valve block (b) (Komi, 2014), and robot arm with internal air ducts (EOS GmbH, 2014) (c)(d) 29

Figure 13 Printed parts of a chair and the assembled chair (a) (Luo et al., 2016). Printed cantilever snap-fit (b) (Low, 2018) 31

Figure 14 Mold with conformal cooling channels (Campbell et al., 2013) 32

Figure 15 Wind turbine with 3D printed modular parts (Kostakis et al., 2013), dielectric pillars directly fabricated over a silicon chip (Rahman et al., 2015) (b), printed object with hair like structures (Ou et al., 2016) (c), hearing aid cap with 200μm diameter holes (Bertsch et al., 2000)(d) 33

Figure 16 Ice cream cup with surface texture (a) (Van Rompay et al., 2018), 3D printed motorcycle hand-grip (b)(Moto3designs, 2017), jewelry model built on a Solidscape 3D printer (c) (Rhinojewel, 2018), 3D printed text (d) (Sculpteo, 2018). 34

Figure 17 Example of materials suitable for 3D printing along with their properties. Copyright (Senvol LLC, 2018) 35

Figure 18 GPS device prototype printed using Poly-jet multicolor printing (a) (Stratasys, 2017b), globe printed using a dual-extruder printer (b) (Hergel and Lefebvre, 2014), and a carbon fiber reinforced part with nylon outer shell (Alex Crease, 2016) (c). 36

Figure 19 Infill percentages and infill patterns (3DPlatform, 2018) 37

Figure 20 Stair-case effect on a 3D printed frog (Francois, 2013). 39

Figure 21 Axiomatic design approach of mapping functional requirements, design parameters and process variables (Salonitis, 2016) 44

Figure 22 Hierarchical structure of functional requirements and design parameters (Shirwaiker and Okudan, 2008) 44

Figure 23 Defining the design problem in the axiomatic design structure in terms of FRs, DPs and AMCs 46

Figure 24 Inverse problem-solving approach. Adapted from Rodrigue and Rivette (2010). 48

Figure 25 Home screen of the database with "search" feature 50

Figure 26 Search results for "remove material" shown in Figure 25. 51

Figure 27 Flowchart of the proposed design framework 52

Figure 28 Searching the keyword in the additive manufacturing database (a), search results (b) and detailed description of the additive manufacturing capability (c). 54

Figure 29 A functional diagram of a wheel by Cascini et al. 2004. The components of wheel (rim, spoke and hub), their actions and their interactions. 54

Figure 30 Initial design (isometric view on the left and cross-sectional view on the right) of the housing cover 57

Figure 31 The initial design of the part and the functional analysis of its components (Housing cover, gasket and threaded socket) 57

Figure 32 Hierarchical structure of functional requirements, design parameter and process variables 60

Figure 33 Initial design of the housing cover (left). Consolidated design of the housing cover (right) 61

Figure 34 Consolidated design of the housing cover (left). Modified design of the housing cover with thin fins (right) 62

Figure 35 Modifying the internal structure of the part by adding a lattice structure (cross-sectional view of the housing cover). 63

Figure 36 Thermal analysis on the design without fins and with fins 63

Figure 37 CAD Design and polymer 3D printing example for a link-pin assembly in a hydraulic pump 66

Figure 38 Result summary of conceptual design phase 66

Figure 39 Derivation of an additive manufacturing capability for material removal 68

Figure 40 Initial design of the assembly (a) and consolidated design of the assembly (b) 70

Figure 41 Consolidated design of the assembly (a), finite element analysis on the consolidated design (b), topologically optimized shape of the part and the design after material removal (d) 71

Figure 42 Final part design derived in detailed design phase 72

Figure 43 Table in MS Access with additive manufacturing capabilities. 87

Figure 44 Additive manufacturing capability with detailed information. 88

LIST OF TABLES

Page

Table 1 DfAM approaches in literature 14

Table 2 Summary of additive manufacturing capabilities reviewed 40

Table 3 Inverse problems solving method 49

Table 4 Deriving solutions using inverse problem-solving approach 60

Table 5 Comparison between original and redesigned parts 64

Table 6 Deriving solutions using inverse problem-solving approach 69

Table 7 Comparison between original and redesigned parts 73

ACKNOWLEDGMENTS

First, I would like to thank my research advisor Dr. Gül Kremer, for her guidance, motivation, expertise and encouragement throughout my graduate career. I am grateful to have her as my advisor and she has been a tremendous source of inspiration. I have been fortunate to take some wonderful classes during my graduate studies at Iowa State University, especially with Dr. Michael Helwig, and Dr. Mark Mba-Wright and I would like to extend my sincere gratitude to them for being my committee members and for their guidance and support throughout the course of this research.

I would also like to express my special gratitude to Dr. Kijung Park for his guidance on my research. Without his valuable comments, suggestions and advice, this research would not have been possible. I am also grateful to Dr. Elif Elcin Günay for her support during the course of this research.

I would also like to thank IISE and ISERC 2018 for providing me an opportunity to present and discuss the preliminary work of this thesis.

In addition, I would also like to thank my friends, colleagues, the department faculty and staff for making my time at Iowa State University a wonderful experience. I would also like to thank my parents for facilitating all my needs and for their continuous love and support throughout my life.

This work was partially funded by the National Science Foundation under award number DUE-1723736. Any opinions, findings, conclusions and/or recommendations expressed in this paper are those of the author's and do not necessarily reflect the NSF's views.

ABSTRACT

Additive manufacturing has emerged as an integral part of modern manufacturing because of its unique capabilities and has already found its applications in various domains such as aerospace, automotive, medicine, and architecture. In order to take the full advantage of this breakthrough manufacturing technology, it is imperative that practical design frameworks or methodologies are developed. Consequently, Design for Additive Manufacturing (DfAM) has risen to provide a set of guidelines during the product design process. The existing DfAM methods have certain limitations in that the capabilities of an additive manufacturing process are not effectively considered in the early design stage, and most of them rely on the direct application of existing methods for conventional manufacturing. Furthermore, existing DfAM methods lack suitability for additive manufacturing novices. To tackle these issues, this study develops a design framework for additive manufacturing through the integration of axiomatic design approach and theory of inventive problem-solving (TRIZ) with the consideration of additive manufacturing environment. This integrated approach is effective because an axiomatic design approach can be used to systematically define and analyze a design problem, while the inverse problem-solving approach of TRIZ combined with an additive manufacturing database can be used as an idea generation tool that can generate innovative solutions for the design problem. Two case studies are presented to apply and validate the proposed design framework.

CHAPTER 1. INTRODUCTION

Additive manufacturing refers to a group of technologies that can build three-dimensional solid objects from their digital models by selectively accumulating material layer-by-layer (SME, 2018). The process of additive manufacturing takes information from the computer aided design (CAD) model of an object and converts it into thin 'slices' that contain information of each layer to be printed. The CAD model is then built by an additive manufacturing machine one slice at a time with each subsequent slice built on the previous one (see Figure 1) (Wong and Hernandez, 2012; Diegel et al., 2010). Additive manufacturing has emerged as an integral part of modern manufacturing because of its ability to fabricate complex shapes (i.e., design freedom), to consolidate separated parts into one integral part, and to create sustainable products by reducing their environmental impact (Rosen, 2014; Salonitis, 2016). These unique capabilities of additive manufacturing have found their applications in various domains such as aerospace, automotive, healthcare, and architecture (Wong and Hernandez, 2012).

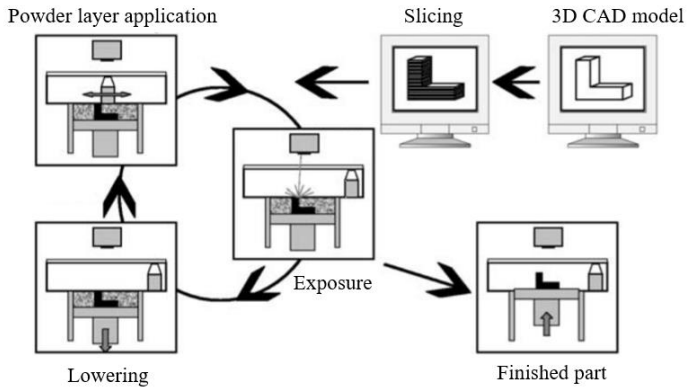


Figure 1 Powder-based additive manufacturing process. Adopted from Poprawe (2005).

With the capabilities of additive manufacturing, it is necessary to have practical design frameworks or methodologies that enable designers or engineers to generate

effective product designs for additive manufacturing (Diegel et al., 2010). In this regard, the concept of Design for Additive Manufacturing (DfAM) has risen to provide a set of guidelines and tools that facilitate the consideration and evaluation of constraints and capabilities in additive manufacturing during a product design process (Diegel et al., 2010; Laverne et al., 2014). However, DfAM approaches in literature tend to rely on the direct application of existing methods for conventional manufacturing without their appropriate transition for additive manufacturing (Salonitis, 2016). Also, the existing DfAM frameworks do not sufficiently reflect the process capabilities and constraints of additive manufacturing in the early design phase (Laverne et al., 2015); in fact, few DfAM methodologies make use of design problem analysis tools in order to systematically approach the design problem (Kumke et al., 2016). Furthermore, there is a lack of methods that enable additive manufacturing novices to generate creative design solutions (Booth et al., 2017; Rias and Segonds, 2016).

To tackle the above issues in DfAM, this study aims to develop a design framework for additive manufacturing through the integration of axiomatic design and inverse problem-solving in the theory of inventive problem-solving (TRIZ), that is facilitated through a database system for additive manufacturing capabilities. The main objective of the framework is to help users to systematically analyze design problems and thereby to develop innovative design solutions by identifying the suitable additive manufacturing capabilities. In the proposed framework, an axiomatic design approach is used to systematically define a design problem in terms of functional requirements, design parameters, and corresponding additive manufacturing capabilities. Under a defined design problem structure, an inverse problem-solving approach based on TRIZ is used to derive design parameters that can satisfy

initially defined functional requirements. Then, a database system searches appropriate additive manufacturing capabilities corresponding to the design parameters, so that users can easily identify effective additive manufacturing solutions to realize the product design. The proposed methodology, by considering additive manufacturing capabilities in the early design phase, allows designers who are not familiar with additive manufacturing to leverage the potentials of additive manufacturing. This design framework can be used to redesign existing products that are designed for conventional manufacturing as well as to design new products to be manufactured using additive manufacturing technologies.

The thesis is structured as follows: Chapter 2 comprehensively reviews the existing literature on Design for Additive Manufacturing (DfAM) and the additive manufacturing capabilities in subsections 2.1 and 2.2, respectively. Chapter 3 discusses the proposed methodology in detail through four subsections. Section 3. 1 discusses the axiomatic design approach used to systemically structure a design problem, Section 3.2 discusses the inverse problem-solving method based on TRIZ used to derive design parameters that can satisfy initially defined functional requirements, Section 3.3 discusses the additive manufacturing database system used to identify additive manufacturing capabilities corresponding to the design parameters, and Section 3.4 proposes a design framework that integrates the axiomatic design approach, the inverse problems solving method, and the additive manufacturing database. Chapter 4 applies the proposed DfAM framework to two case studies to demonstrate the application of the framework. Finally, Chapter 5 discusses results from the two case studies and provides conclusions with limitations and future work.

CHAPTER 2. LITERATURE REVIEW

2.1 Design for Additive Manufacturing (DfAM)

Laverne et al. (2014) defined Design for Additive Manufacturing (DfAM) as a set of methodology and tools that helps designers to take the specificity of additive manufacturing into consideration during a product design stage. These methods enable designers to exploit the unique capabilities of additive manufacturing, so that they can create an additional value for manufacturers and users (Klahn et al., 2015). Kumke et al. (2016) classified the DfAM approaches in literature into two categories: DfAM for design decisions and DfAM for manufacturing decisions. Design approaches for additive manufacturing that comprise of guidelines, rules, and methodologies to support designers to utilize the design potentials of additive manufacturing fall in the former category. The latter category includes upstream, downstream, and other generic DfAM related activities carried out in a new product development processes such as activities concerning the manufacturing process itself (e.g., process selection, selection of part candidates) that are performed by manufacturing specialists instead of design engineers.

This study focuses on the DfAM approaches in literature that belong to DfAM for design decisions. Recent DfAM approaches in this category are summarized in Table 1. A general design methodology comprises of three main phases; 1) conceptual design phase, where the basic solution principles for a design problem are identified to derive initial design concepts, 2) embodiment design phase, where most of the design engineering work is done by incorporating the solution principles, and 3) detailed design phase, where the design is refined to satisfy the design parameters and requirements such as tolerance, loading conditions, and process specifications (Laverne et al., 2015).

Table 1 DfAM approaches in literature

Authors	Design problem analysis tool	Idea generation tool	Design phase considered			AMCs considered in conceptual phase?
			C	E	D	
Rodrigue et al., 2010	□	TRIZ	◘	■	□	◘
Maidin et al., 2012	□	Design feature database	■	□	□	■
Vayre et al., 2012	Parametric optimization	□	◘	■	■	◘
Boyard et al., 2013	3D modular graph	□	■	◘	□	□
Klahn et al., 2015	□	□	◘	◘	◘	□
Laverne et al., 2015	□	Brainstorming	■	□	□	□
Salonitis et al., 2015	Specification analysis	□	◘	■	■	◘
Kumke et al., 2016	DfAM based on VDI2221	Catalogues, feature database	◘	◘	◘	◘
Rias et al., 2016	□	Forced association	■	□	□	□
Salonitis et al., 2016	Axiomatic design	□	■	□	□	◘
Kamps et al., 2017	TRIZ	Biomimicry database	■	□	□	◘

*C = conceptual phase, E = embodiment phase, D = detailed phase, □= not covered, ◘ = partially covered, ■ = covered in detail, AMC = additive manufacturing capability

Different design frameworks in the literature focus on one or multiple general design phases by incorporating the existing design problem analysis tools and idea generation tools into their design frameworks. Rodrigue and Rivette (2010) proposed a design methodology for additive manufacturing that combines the benefits of Design for Assembly (DFA) and Design for Manufacturing (DFM) (see Figure 2). The process begins by determining the parts of an assembly that can be consolidated, and a product is then redesigned by consolidating those parts. Next, the functions and characteristics of the parts for user requirement satisfaction and design failure prevention are identified using TRIZ and are optimized using a

Finite Element Analysis (FEA) software. This step follows the selection of materials based on the functions and characteristics identified in the previous step. The primary focus of this approach is the embodiment design phase, and it does not elaborate on how the appropriate additive manufacturing capabilities are identified for each feature to be optimized.

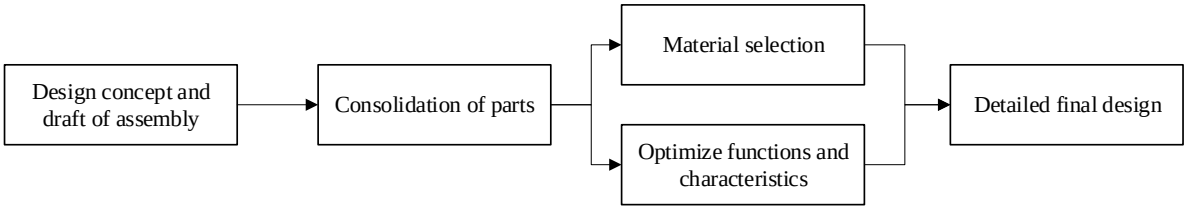


Figure 2 Design methodology proposed by Rodrigue and Rivette (2010).

Vayre et al. (2012) claim that additive manufacturing is a breakthrough in manufacturing, but it is yet to be followed by a breakthrough in the designing process. They proposed a general design methodology for additive manufacturing, involving analysis of part specifications, generation of initial shapes, analysis of these shapes based on geometrical parameters, and optimizing the shape by tuning up the parameters (Figure 3).

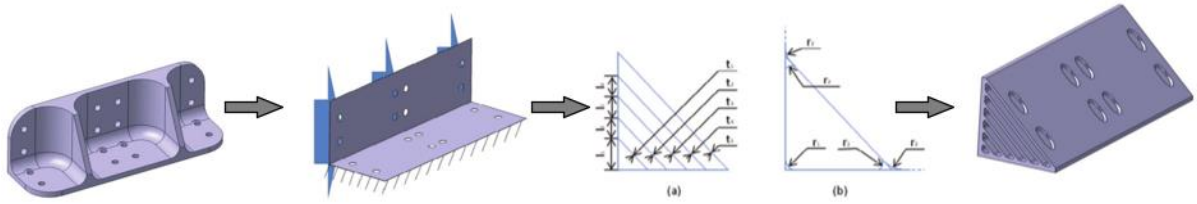


Figure 3 Redesigning a square bracket using parametric optimization. Adopted from Vayre et al. (2012).

Salonitis and Zarban (2015) proposed a methodology to redesign existing components for additive manufacturing, which begins with the evaluation of additive manufacturing process specifications and functional requirements of the part. This is followed by topological optimization to remove unstressed material from a part to derive initial concepts and a multi-criteria decision analysis to evaluate design alternatives. Focusing on the

embodiment and detailed design phases, these studies do not explicitly describe how the capabilities of additive manufacturing can be effectively determined to optimize design parameters.

Salonitis (2016) proposed a design framework for additive manufacturing using axiomatic design theory where the functional requirements are mapped to design parameters and process variables through a zig zag decomposition method. Design solutions were evaluated using the independence axiom and information axiom of axiomatic design theory. This design framework focuses on the conceptual design phase, and it does not discuss how to systematically map functional requirements into design parameters and process variables. Kamps et al. (2017) proposed a creative design methodology that incorporates biomimicry and TRIZ for part optimization. The steps in the design framework include part analysis, functional analysis of the main and subfunctions of the components using TRIZ, abstract biomimetic design (database augmented analogy search for each function), and final part design. The methodology was demonstrated by redesigning a gear wheel. Six functions (torque transmission, mass reduction, friction reduction, mechanical stability, heat transfer and damping) were identified through the functional analysis. A biomimetic analogy search for each of these functions was conducted. The design solutions were identified by selecting a biomimetic-analogy for each of the functions. This framework demonstrates the benefit of using an existing design problem analysis tool in the conceptual design stage to systematically define and understand the design problem.

Bin Maidin et al. (2012) developed an additive manufacturing design feature database to support new product development and to inspire designers during the conceptual design phase. The authors identified a total of 113 additive manufacturing enabled design features

from case studies in literature and organized these into a taxonomy with four top-level categories; user fit requirement, improve functionality requirement, consolidation requirement, and aesthetics requirement. The effectiveness of the database was determined through user trials and feedback from respondents who indicated that the database tool enabled them to access more information (i.e., additive manufacturing enabled features) during the design process. Figure 4 shows two products that were designed during the user trials. The trials showed that the tools provided various ideas and features for the product designs. This study demonstrates that the use of an idea generation tool in the conceptual design phase could be effective to incorporate additive manufacturing capabilities into product design.

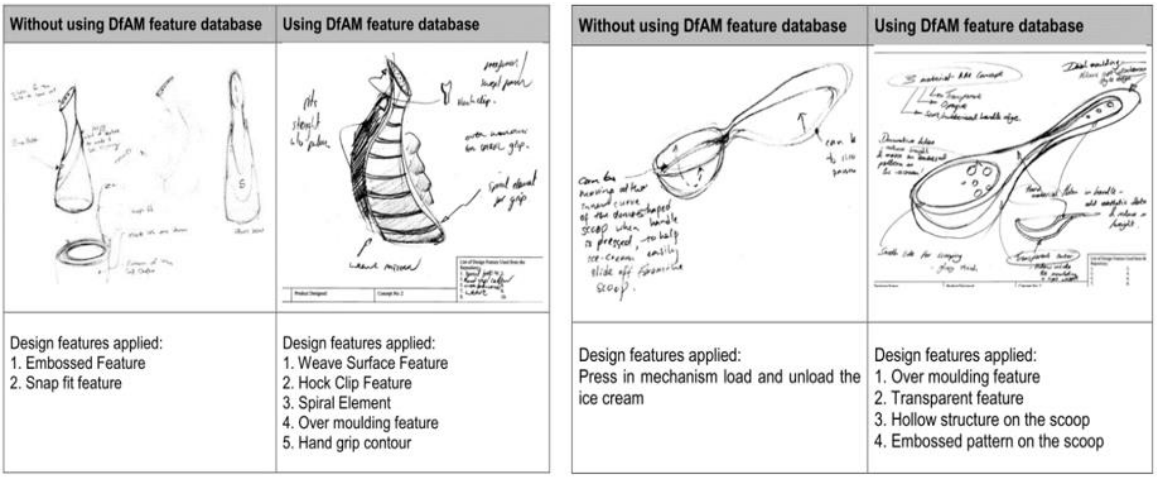


Figure 4 Designing a salt shaker and ice cream scoop with and without using the DfAM database. Adopted from Bin Maidin et al. (2012).

Boyard et al. (2015) proposed a five-step design methodology including identification of functional specifications, conceptual design, architectural design, detailed design, and implementation. The authors performed loops of Design for Manufacturing (DFM) and Design for Assembly (DFA) in parallel during the architectural design and detailed design stages of a design process. They used a 3D modular graph to represent a product (See Figure

5). Each function (of the product) is represented as a sphere and the functions are grouped into sets. The segments indicate the direct connections between the functions and the 3D modular graph represents the spatial organization of the functions with each other. According to the authors, this modular representation allows reconfiguration of the design, if necessary, during discussion of conceptual design with the stakeholders.

Figure 5 A salt cellar and its 3D modular graphical representation. Adapted from Boyard et al. (2015).

Rias and Segonds (2016) categorized existing DfAM methods into three categories; 1) DfAM methods focused on modifying the inner and outer form of a part, 2) DfAM methods focused on redesigning products that embody assemblies, and 3) DfAM methods focused on incorporating AM capabilities into the product design. The authors assert that very few methods focused on generating creative concepts in an early design stage. They proposed a five-step design methodology including features discovery (gathering examples of features that have been already realized using additive manufacturing and examples from other domains), idea exploration (forced association of additive manufacturing example with other domain example), ideas evaluation, concept generation and concept evaluation. The methodology was illustrated by the generation of a modified turbine blade (i.e., cartridge blade) with an integrated ink cartridge an as shown in Figure 6. The forced association

between an additive manufacturing domain and other domain examples could be effective to find new products that can be manufactured using additive manufacturing. However, this study does not describe how the additive manufacturing capabilities could be incorporated into the product design effectively.

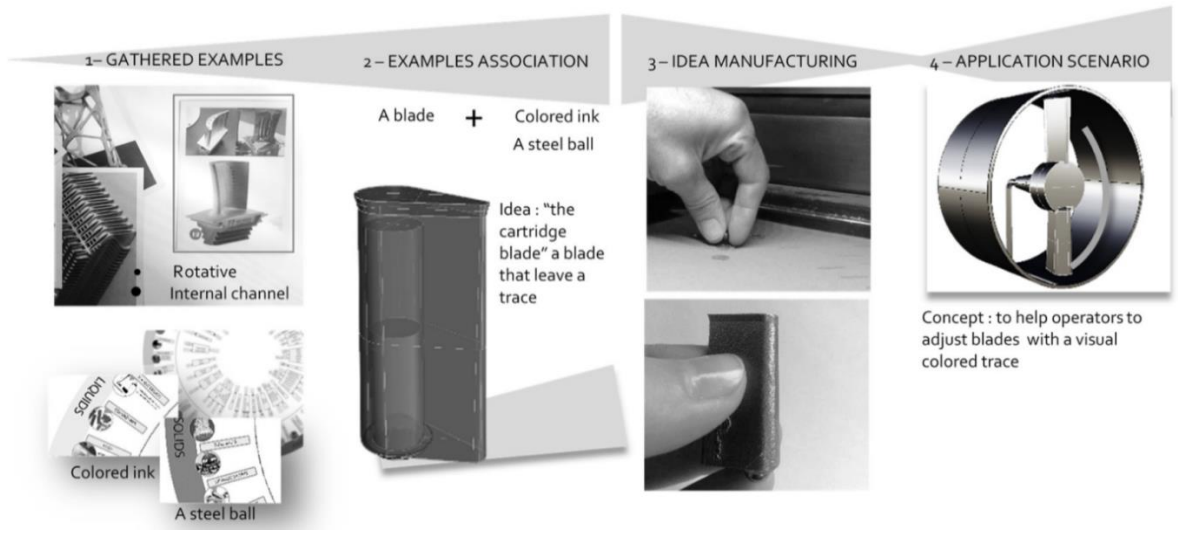


Figure 6 Modified turbine blade with integrated ink cartridge designed by the forced association of a turbine blade (AM domain) and ball point ink pen (another domain). Adopted from Rias and Segonds (2016).

Laverne et al. (2015) classified existing DFAM methods into three categories: opportunistic DfAM, restrictive DfAM, and dual DfAM. The aim of opportunistic DfAM is to fully take advantage of geometric and material complexity available in additive manufacturing. Restrictive DfAM focuses on the limitations of a specific additive manufacturing process such as the performance and specifications of an additive manufacturing machine, manufacturability and properties of usable materials, and guides the users to design around these limitations. A dual DfAM combines both the opportunistic and restrictive approaches. The authors state that such a combined approach is more conducive for product innovation. The authors proposed an assembly based DfAM method that uses

additive manufacturing knowledge during the idea generation stage of a product design process. The steps in this method include development of concepts, working principles, working structures, and synthesis and conversion of data into design features. The authors conducted an experiment where three groups of participants were asked to design a robot. Two groups had knowledge of AM (i.e., one group had AM experts among them and the other group was provided with technical memos that described advantages and drawbacks of AM). The results showed that the initial design concepts developed by the groups with AM knowledge had more functionalities that were in line with AM capabilities. This study demonstrates the effectiveness of using idea generation tools in the conceptual design phase in developing innovative solutions.

Klahn et al. (2015) presented two design strategies (i.e., manufacturing driven and function driven) to develop products using additive manufacturing for two case studies. The manufacturing driven strategy should be selected when there is a cost benefit associated with using additive manufacturing instead of conventional manufacturing, and the designer will have to stick to the design rules of conventional manufacturing. For instance, when mass customization is involved, like in the case of additively manufactured dental implants, a manufacturing driven strategy could be followed. A function driven strategy is selected when additive manufacturing capabilities are used to improve the functions (or performance) of the product. According to this strategy, an object is designed only according to the functions of the component (e.g. reduce weight, improve efficiency etc.) and the designer neglects the rules of conventional manufacturing. The resulting design can be only produced by additive manufacturing.

Kumke et al. (2016) proposed a new design framework for additive manufacturing based on an existing design methodology (i.e., VDI 2221, a systematic design development standard by The Association of German Engineers). The design development process is divided into ten modules (i.e., 1) defining product requirements, 2) determination of functions, 3) development of basic solution ideas, 4) dividing product into realizable modules, 5) technical feasibility analysis and process selection, 6) economic feasibility analysis, 7) optimization of product properties, 8) AM-conformal embodiment design, 9) design validation and manufacturability analysis, and 10) functional extension and parts consolidation. The framework can be advantageous since it provides structured guidelines to a designer to incorporate additive manufacturing potentials. The modularity of the framework allows the integration of existing DfAM tools and methods into the framework. The authors also emphasize the need of systematic utilization of AM potentials in the early design phase.

Though the DfAM frameworks and methodologies that were reviewed have their merits, they have certain limitations as well. Enabling designers in identifying and incorporating the AM capabilities into the product design, is one of the main challenges in developing a DfAM framework. From Table 1, it can be seen that, few studies have considered AM capabilities in the conceptual design phase. Among those, only few have considered AM capabilities in detail in the conceptual design phase. It is evident that there is a lack of design frameworks that enable the user to consider the process capabilities of additive manufacturing in the early design stages. Another limitation of the existing frameworks is the complexity of the methodology. The usability of a design framework gets

restricted to experienced designers if the framework itself is over complicated. Among the existing DfAM methodologies, few make use of design problem analysis tools in order to systematically approach the design problem and generate creative solutions. A design framework, that supports designers with AM capabilities effectively during the conceptual design phase, is lacking in literature.

To tackle these issues, this study proposes a design framework combining the axiomatic design approach (AD), an inverse problem-solving method based on the theory of inventive problem-solving (TRIZ) and an additive manufacturing database. The axiomatic design approach is used to systematically define a design problem in terms of functional requirements, design parameters, and corresponding additive manufacturing capabilities. Under a defined design problem structure, an inverse problem-solving approach is used to derive design parameters that can satisfy initially defined functional requirements. Then, a database system searches appropriate additive manufacturing capabilities corresponding to the design parameters, so that users can easily identify effective additive manufacturing solutions to realize the product design. This systematic approach is expected to be beneficial for designers who are AM novices, in incorporating the AM capabilities effectively into the product design during the early design phase.

2.2 Additive Manufacturing Capabilities

A thorough literature review was conducted to understand capabilities of additive manufacturing technologies. The design parameters associated with these capabilities were identified during the review. This section summarizes main additive manufacturing capabilities that were identified from literature. These capabilities identified in this section are included in an additive manufacturing database system discussed in section 3.3.

1) Freeform shapes

Additive manufacturing involves a layer-by-layer fabrication process. This enables designers to fabricate almost any shape or topology (Seepersad et al., 2012). Additive manufacturing, which can eliminate the manufacturing constraints of conventional manufacturing processes (e.g., tooling clearances and undercuts), has significantly broadened design freedom through (Yang and Zhao, 2015). While traditional manufacturing methods can only make a finite spectrum of shapes, 3D printing eliminates the need of re-tooling and can fabricate a different shape each time, paving way for mass customization (Lipson and Kurman, 2017). This geometric freedom enabled by additive manufacturing provides aesthetic, functional, economical, and ergonomic benefits (Thompson et al., 2016). The capability of additive manufacturing to produce parts with complex shapes has found its applications in interior designing, medicine, automotive, and aerospace industries (see Figure 7).

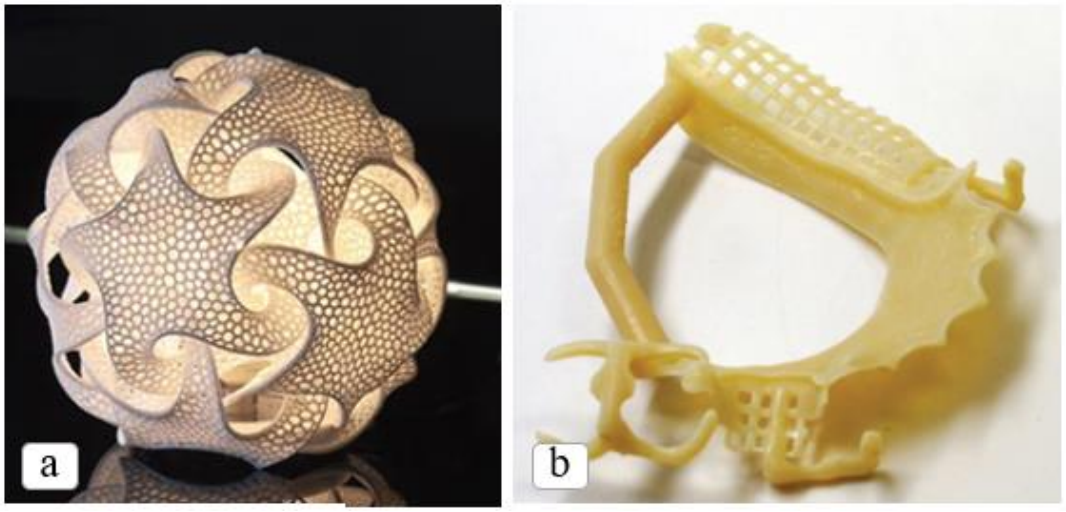


Figure 7 3D printed lamp designed by Bathsheba Grossman (Materialise, 2008) (a) and a 3D printed removable partial framework model (Stratasys, 2017a).

2) Lattice structures and porous objects

Lattice structures, also known as cellular structures, are a network of struts (Kantareddy, 2016). Additive manufacturing technologies enables incorporating these complex structures into the product design and they have already found their application in medical, automotive and aerospace industries (Petrovic et al., 2009; Iyibilgin et al., 2013). Various types of lattice structures can be achieved by changing the arrangement of the struts.

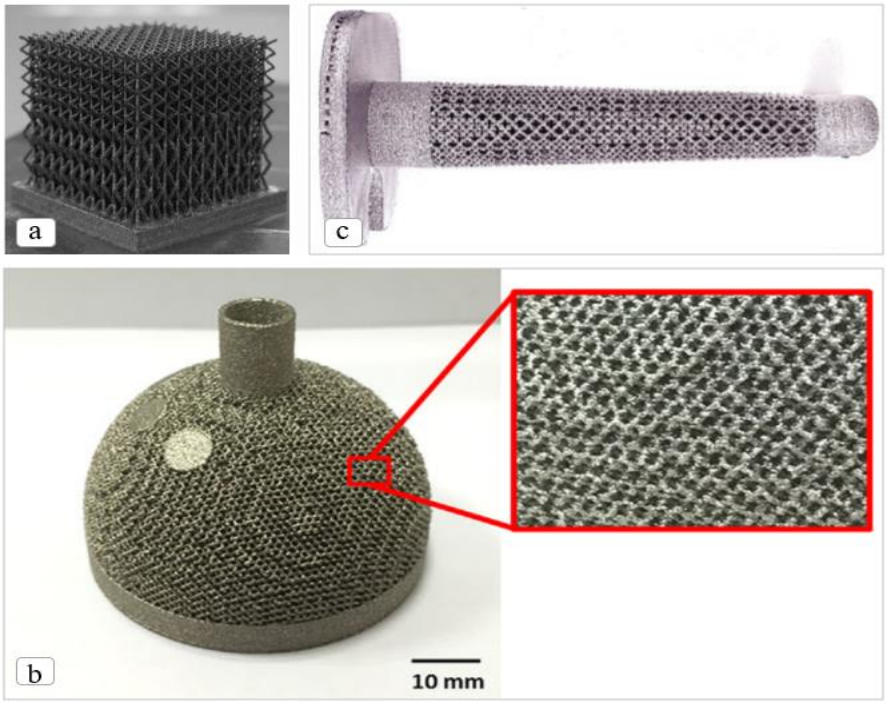


Figure 8 A lattice cell made using a laser fusion process (Petrovic et al., 2011) (a), acetabular cup with porous lattice structure (Sing et al., 2016) (b) and a tibial stem made using Electron Beam Melting process (Murr et al., 2012) (c).

These structures have high strength to stiffness ratio, good energy absorption characteristics, and acoustic insulation properties. Another reason for using these structures is to reduce the weight or the use of material (Gibson and Rosen, 2015). Lattice structures have high surface area which enables effective heat transfer from the structure to the environment (Wadley, 2006). The use of lattice structures as deployable structures (where they are stored

in compact configurations initially and are deployed when needed) has also been reported (Maheshwaraa et al., 2007). Figure 8 shows a lattice cell and its applications. Additive manufacturing processes like electron beam melting and selective laser sintering have the ability to produce metallic scaffolds with accurately controlled porosity and have been found suitable for metallic orthopedic implant applications (Murr et al., 2012) (Taniguchi et al., 2016). The porous implants promote tissue in-growth and anchor the implant to the surrounding bone, making them ideal substitutes for bones (Sing et al., 2016; Emmelmann et al., 2011).

3) Topology optimization

Topology optimization is a Finite Element Analysis (FEA) based method to optimize the geometry of the part to reduce its weight while maintaining the strength (Brackett et al., 2011). An FEA software discretizes the part into elements and then optimizes the density of each element (Kantareddy, 2016). An optimized shape of the part is generated by the software with material removed from all unstressed regions. This optimized shape is usually a complex shape that is difficult to be manufactured using conventional manufacturing process. Additive manufacturing can be used to produce these complex shapes and hence topology optimization combined with additive manufacturing can be used to produce strong light-weight components (Salonitis and Zarban, 2015; Rodrigue and Rivette, 2010; Erin, 2014; Tang and Zhao, 2015; Galjaard et al., 2015). Figure 9 shows the topology optimization process of a metal bracket.

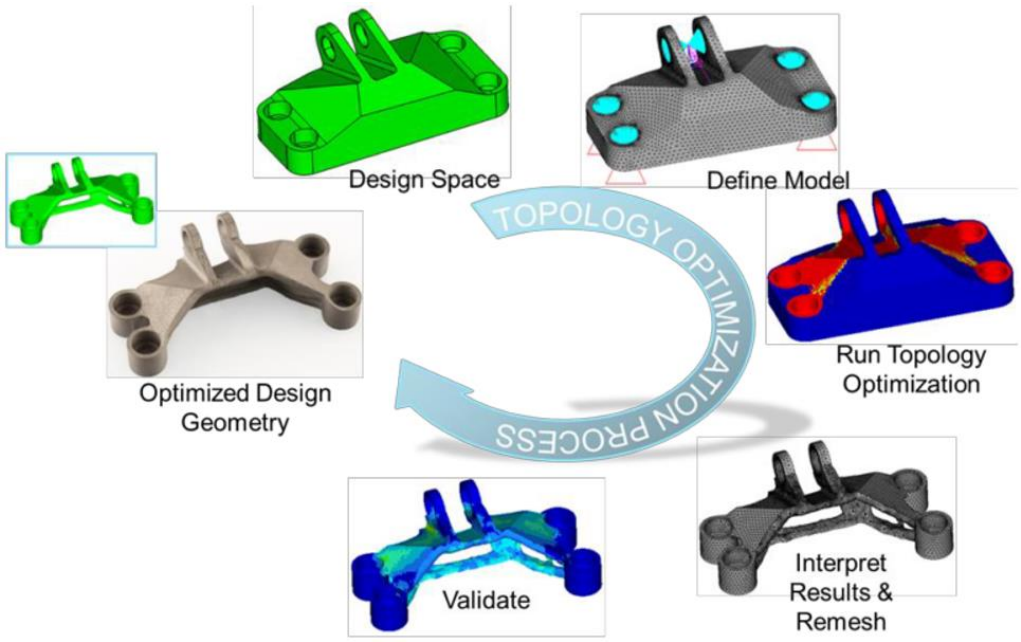


Figure 9 Topology optimization process of a metal bracket. Adopted from Komi (2014).

4) Part consolidation

The process of reducing the part count in an assembly by joining multiple parts of an assembly into one integral part is called part-consolidation. Additive manufacturing allows assemblies to be printed as one integral part. According to Yang et al. (2015), the possibilities for part consolidation in an assembly has been broadened as a result of the evolution of additive manufacturing; a process that is not bound by the constraints of conventional manufacturing. An example of part consolidation is shown in Figure 10. Consolidating parts is advantageous as it reduces the number of individual components making the assembling process easier.

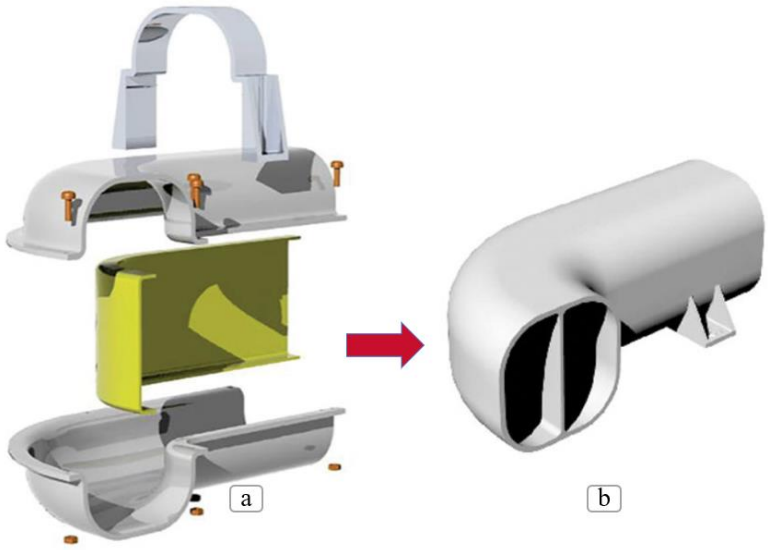


Figure 10 Example of part consolidation. An aircraft duct with 16 components (a) consolidated into a single component (b) (Gibson and Rosen, 2015).

Furthermore, removal of joints eliminates potential leak points. Schmelzle et al. (2015) redesigned a hydraulic manifold to understand the process of redesigning a multicomponent assembly and the redesigned part had a weight reduction of 60% and height reduction of 53%. The amount of benefit that can be achieved through part consolidation is directly proportional to the overall number of components and the complexity of the design (Rodrigue and Rivette, 2010).

5) Non-assembly mechanisms

Non-assembly mechanisms are operational mechanisms (with kinematic joints) that do not require assembling. Additive manufacturing enables the fabrication of non-assembly mechanisms (Gibson and Rosen, 2015; Calì et al., 2012; Koo et al., 2014; Zammori et al., 2006). This can be achieved by providing adequate clearances between the kinematic joints (Calignano et al., 2014). This ensures that enough support material fills the gap between the moving parts and prevent them from bonding together. Furthermore, any remaining interstitial material such as metal-powder and resin would have to be removed after the

manufacturing process to enable the free movement of the parts. Figure 11 shows examples for parts with movable joints made using additive manufacturing.

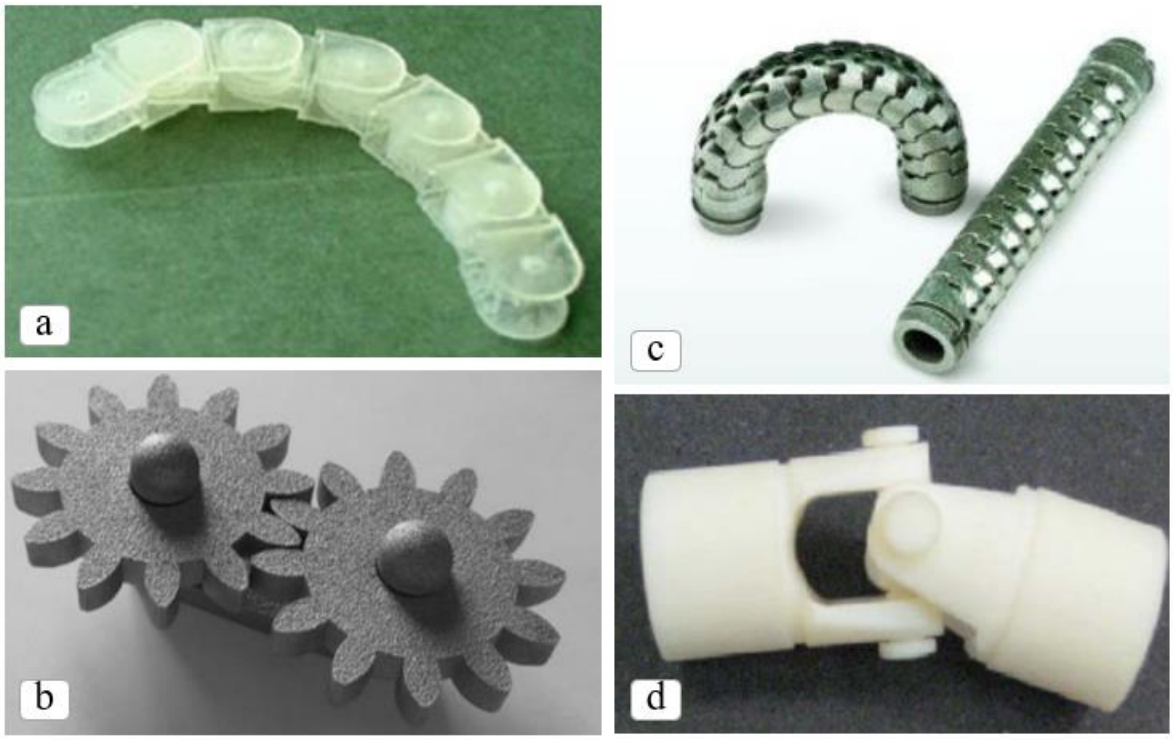


Figure 11 A pulley driven snake like robot made using stereolithography (a) (Gibson and Rosen, 2015), gear trains made of aluminum alloys with 0.8 mm clearance (b) (Calignano et al., 2014), a 13 piece articulating section made using laser sintering (c) (Zelinski, 2012) and a universal joint fabricated with Vero-white material (d) (Chen and Zhezheng, 2011)

Fabrication of non-assembly mechanisms eliminates the assembling process which, sometimes can be challenging when small, intricately moving components are involved (Zelinski, 2012). Calignano et al. (2014) studied the application of laser sintering in fabricating non-assembly mechanisms and found that the mobility and stability of the joint is dependent on the clearance which in turn is dependent on the design of the joint, the orientation on the building platform and the powder material. Chen and Zhezheng (2011) developed a systematic method to minimize joint clearance for similar non-assembly mechanisms.

6) Internal channels

Complex internal features like conformal cooling channels, air ducts, fluid channels etc. that can improve the functionality and performance of a part can be created using additive manufacturing (Gibbons and Hansell, 2005; Klahn et al., 2014; EOS GmbH, 2014; Petrovic et al., 2009). Internal channels that are difficult to be manufactured using conventional manufacturing processes can be created using AM technologies. Gibbons et al. (2005) created injection mold inserts with complex flood-cooled cooling channels using electron beam melting (EBM) process and found that the cooling efficiency was significantly higher than the un-cooled and baffled cooled inserts (See Figure 12).

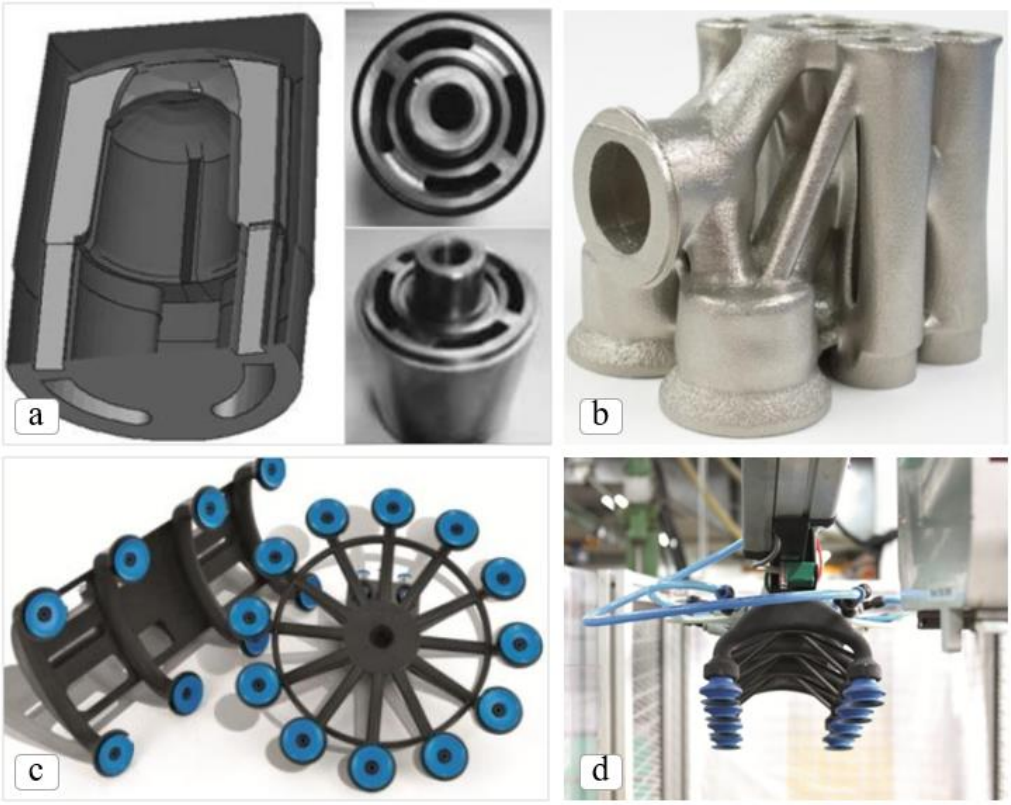


Figure 12 Injection mold insert with cooling channel (Gibbons and Hansell, 2005) (a), hydraulic valve block (b) (Komi, 2014), and robot arm with internal air ducts (EOS GmbH, 2014) (c)(d)

ASS Maschinenbau (EOS GmbH, 2014) developed a light weight robotic gripper hand with integrated air channels for the pharmaceutical industry (See Figure 12). The integrated design of air channels within the arm reduced the assembly time, weight and errors due to improper gripping. Komi (2014) manufactured a hydraulic valve block using selective laser sintering (SLS) process (See Figure 12). The valve block created using SLS had internal channels for improved flow and reduced the chance of leaks since no auxiliary channels were present (which are required if the block was manufactured by subtractive manufacturing techniques).

7) Segmentation

Additive manufacturing technologies can be used to print parts with interlocking features which enables a large part to be partitioned into smaller parts that can later be repeatedly disassembled and reassembled (Song et al., 2015; Luo et al., 2016). This process is called segmentation. Connecting parts by interlocking features can be advantageous because it facilitates a cost-effective way of maintenance since only a part need to be reprinted if the part breaks (rather than creating the whole object again). Other benefits of this approach are: a) segmentation of an object that can be reassembled and disassembled is conducive for storage and transportation, b) no extra connectors are required since the part are connected to each other by their geometry, c) strong inter-part connections can be achieved since the part are supported by inter blockage with their geometry, d) enables production of parts with cleaner surface without drilling and protrusions, and e) parts that are larger than the print volume of the printer can be decomposed into smaller parts and joined together later (Luo et al., 2016; Low, 2018) (Figure 13). There have also been studies where the object was portioned as smaller parts that were made using an additive manufacturing

technology and later joined together by other joining processes like welding and gluing (Meisel et al., 2017; Shapeways, 2014).

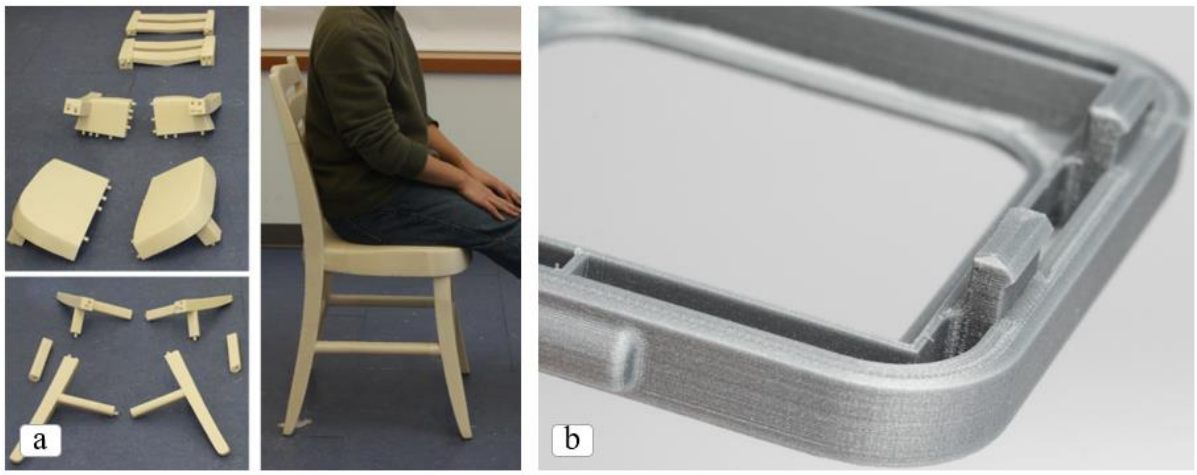


Figure 13 Printed parts of a chair and the assembled chair (a) (Luo et al., 2016). Printed cantilever snap-fit (b) (Low, 2018)

8) Embedded components

Material is added layer by layer when a part is produced using an additive manufacturing technology and this enables components to be embedded within printed parts (Gibson and Rosen, 2015; Joe Lopes et al., 2012; Ian et al., 2013). Campbell et al. (2013) manufactured an injection mold tool with conformal cooling using direct metal deposition (DMD) method. Copper cooling tubes were inserted into the substrate mold part and these were then buried using the metal deposited using DMD to create the mold die with conformal cooling channels (See Figure 14). The cooling channels improved the heat transfer and reduced the cooling time by 35%. Lopes et al. (2012) used stereolithography and direct print technologies to create parts with embedded electronic circuits. Stereolithography was used to create the mechanical structure while direct printing of conductive ink was used to create interconnections.

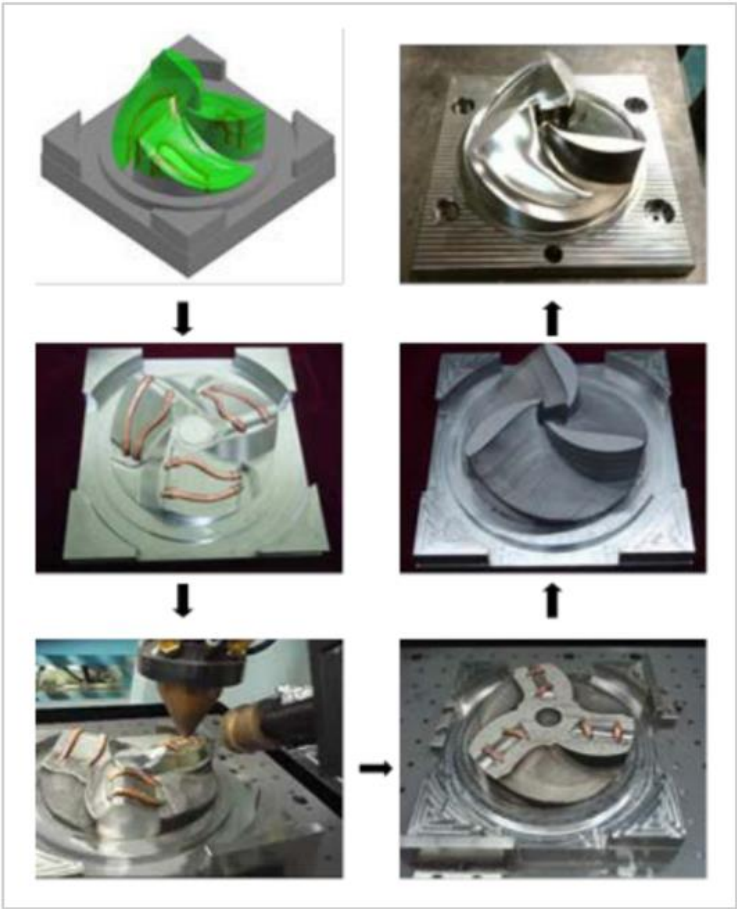


Figure 14 Mold with conformal cooling channels (Campbell et al., 2013)

9) Thin features and small features

The layer-by-layer fabrication process of additive manufacturing enables creation of small and thin features like thin walls, small holes, pins etc. and the minimum feature size is primarily determined by the x-y resolution of the 3D printer (Fabforma, 2016). High resolution additive manufacturing technologies enable fabrication of micro-scale structures and allows integration of many functions in a small volume (Ou et al., 2016; Bertsch et al., 2000; Cohen et al., 2010). A few examples of small features created using additive manufacturing technologies are shown in Figure 15.

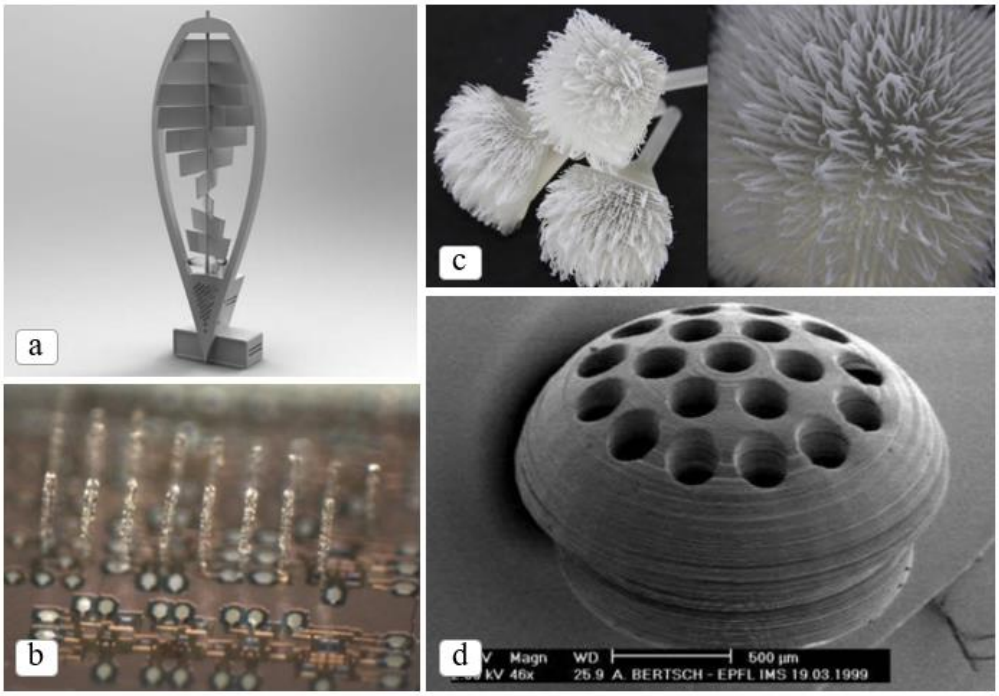


Figure 15 Wind turbine with 3D printed modular parts (Kostakis et al., 2013), dielectric pillars directly fabricated over a silicon chip (Rahman et al., 2015) (b), printed object with hair like structures (Ou et al., 2016) (c), hearing aid cap with 200µm diameter holes (Bertsch et al., 2000)(d).

The minimum feature size that can be created and the print resolution varies depending on the additive manufacturing technology and studies have been done to determine the minimum feature sizes that can be printed on different additive manufacturing technologies (Seepersad et al., 2012; Brockotter, 2018; Xometry, 2018).

10) Surface features

Additive manufacturing processes can create textured surfaces on objects and the precision of the details is determined by the resolution of the additive manufacturing machine (Thompson et al., 2016; Van Rompay et al., 2018). Some functional and cosmetic applications of surface textures is shown in Figure 16. Thomas et al. (2018) created 3D printed ice cream cups with surface textures to study the influence of surface texture on perception of the taste of ice-cream.

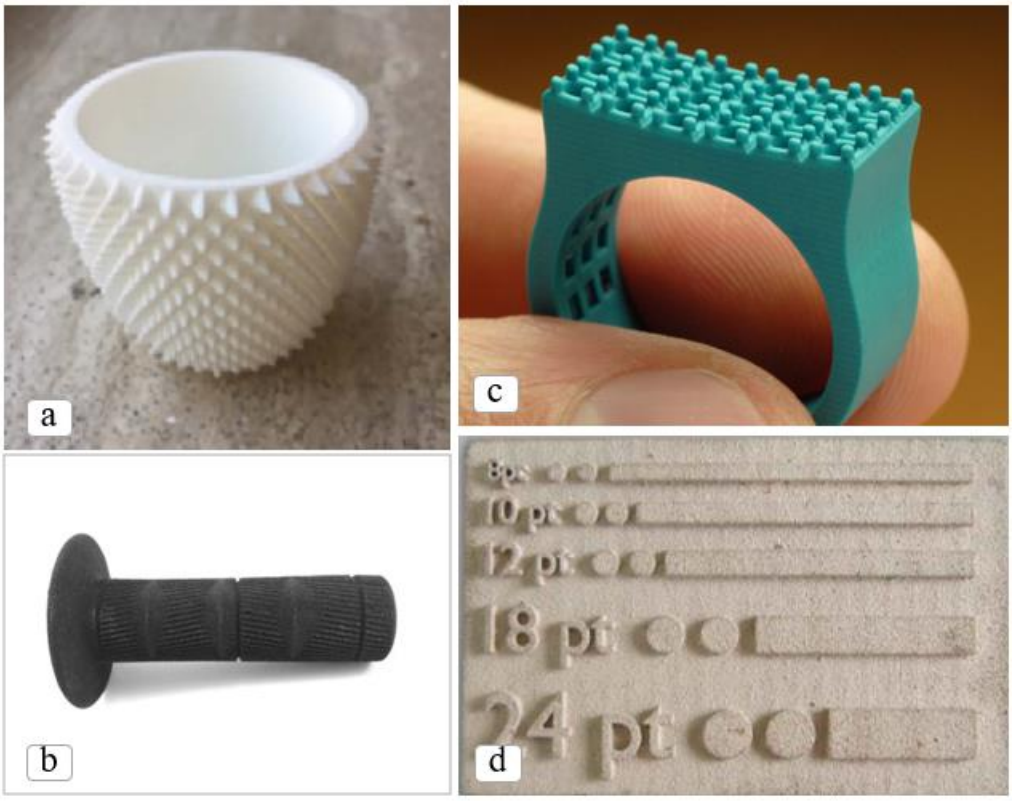


Figure 16 Ice cream cup with surface texture (a) (Van Rompay et al., 2018), 3D printed motorcycle hand-grip (b)(Moto3designs, 2017), jewelry model built on a Solidscape 3D printer (c) (Rhinojewel, 2018), 3D printed text (d) (Sculpteo, 2018).

Another application of surface textures is in designing jewelry (Rhinojewel, 2018). Lehrmitt Design Studios, a Texas based company created molds with surface textures for the chocolate industry that enables to make chocolates with intricately designed patterns on surface (3dprint, 2015).

11) Material choices

The additive manufacturing technologies are capable of processing a large variety of materials including polymers (thermoset and thermoplastic), metals, alloys, ceramic materials, sand and paper (Thompson et al., 2016; Büsgen, 2013). The users could select the material, based on its properties, that is most suitable for their application. Some of the additive manufacturing technologies are also capable of producing parts in colors, which is

usually achieved by adding color to the raw material, blending multi-colored filaments, using different colored material for different parts of the model, or by the in-process pigmentation of the raw material (Thompson et al., 2016; Stratasys, 2015; Popat and Edwards, 1996). The Senvol material database (Senvol, 2018) is one of many resources that is available on the internet that enables users to select the appropriate material based on the material properties.

	Material Supplier	Material Name	AM Process	General Material Type	Specific Material Type	Post Processed	Ultimate Tensile Strength Min (MPa)	Ultimate Tensile Strength Max (MPa)	Tensile Modulus Min (MPa)	Tensile Modulus Max (MPa)	Elongation at Break Min (%)	Elongation at Break Max (%)
Click for Details	3D Platform	3DP ABS	Material Extrusion	Polymer	ABS	No			2000	2000	9	9
Click for Details	3D Platform	3DP ABS-X	Material Extrusion	Polymer	ABS	No			2030	2030	34	34
Click for Details	3D Platform	3DP FLEX 45	Material Extrusion	Polymer	Rubber-like	No	24	24	95	95	530	530
Click for Details	3D Platform	3DP HIPS	Material Extrusion	Polymer	HIPS	No	22	22	1550	1550	50	50
Click for Details	3D Platform	3DP PET-G	Material Extrusion	Polymer	PETG	No			2020	2020	22.7	22.7
Click for Details	3D Platform	3DP PLA	Material Extrusion	Polymer	PLA	No			3120	3120	19.5	19.5
Click for Details	3D Systems	Accura 25	Vat Photopolymerization	Polymer	PP-like	No	38	38	1590	1660	13	20
Click for Details	3D Systems	Accura 48HTR	Vat Photopolymerization	Polymer		No	64	67	2800	3980	4	7

Figure 17 Example of materials suitable for 3D printing along with their properties. Copyright (Senvol LLC, 2018).

12) Multiple materials:

The ability to print multiple materials at the same time is another important capability of additive manufacturing. Additive manufacturing machines like the “Objet500 Connex Multi-Material 3D Printer” and “Flash forge Dreamer Dual Extrusion 3D Printer” have multiple extruders and are capable of printing multiple materials at the same time (see Figure 18 (b) and (d)).

Figure 18 GPS device prototype printed using Poly-jet multicolor printing (a) (Stratasys, 2017b), globe printed using a dual-extruder printer (b) (Hergel and Lefebvre, 2014), and a carbon fiber reinforced part with nylon outer shell (Alex Crease, 2016) (c).

The ability to print multiple materials at the same time enables the creation of composite objects that have dynamically localizable and tunable topographies (Guttag and Boyce, 2015; ORD-Solutions, 2018). 3D printers like the MarkForged Mark 1 print plastic parts, which can be reinforced with three types of material: carbon fiber, Kevlar, and fiberglass enabling users to create working prototypes and high-quality end-use products (Alex Crease, 2016). Polyjet printing is another additive manufacturing technology that enables to print multiple materials and full CMYKW colors into a single print (Stratasys, 2015b). This allows creation of parts with final-product aesthetics, fine details and smooth surfaces (see Figure 18 (a)).

13) Infill modifications

The interior structure of a 3D printed object is called infill. Additive manufacturing technologies allow users to adjust the infill of the object being printed (Baich and Manogharan, 2015; Milde and Morovic, 2016). The slicer software for the 3D printer allows the user to adjust the infill percentage and infill pattern of the object that is being printed.

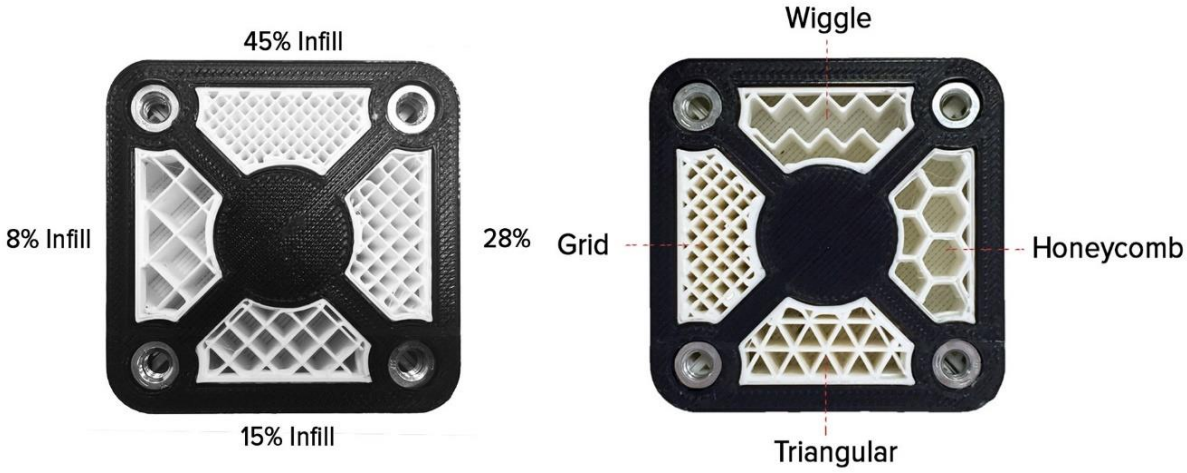


Figure 19 Infill percentages and infill patterns (3DPlatform, 2018)

If the infill percentage is 100%, the printout will be a solid model and if it is 0%, the object will be hollow. In general, the higher the infill density, the higher the material usage, weight of the object and longer the print time (Tyson, 2017). Infill density can be also used adjust the strength, porosity and buoyancy of the part (Siber, 2018; Holman and Serdar, 2018). In addition to the infill percentage, the software also allows the user to select the infill pattern. Honeycomb, triangular, linear and wiggle patterns are common patterns offered by additive manufacturing slicer softwares. Figure 19 shows various infill percentages and different infill patterns.

14) Process dependent design parameters

Even though additive manufacturing offers great design freedom and has many unique capabilities compared to traditional manufacturing methods, there are certain design parameters that are dependent on the additive manufacturing process parameters. Some of these design parameters are surface finish, accuracy, size of parts that can be printed and minimum feature size that can be printed (Renishaw, 2018a). The layer by layer material deposition causes a "stair-case" effect (see Figure 20) and is present in almost all additive manufacturing processes. This reduces the surface quality of the object and post processing is often required to improve the surface finish depending on the application (Kumbhar and Mulay, 2016; Armstrong, 2018). In general, higher the layer thickness, lower the surface finish.

Another design parameter that needs to be considered before additively manufacturing an object is the size of the object. The maximum dimensions of the object that can be printed by an additive manufacturing machine is limited the dimensions of its print bed (Nadin, 2016). The object has to be split into smaller parts if it is bigger than the maximum print volume of the printer. Another design parameter to be considered is the minimum feature size that can be printed using the additive manufacturing machine. For instance, a fused deposition modeling machine with a nozzle diameter of 0.4mm cannot print features that are smaller than 0.4mm (Francois, 2013). The minimum feature size (that can be printed) must be taken into consideration when designing thin or small features.

Figure 20 Stair-case effect on a 3D printed frog (Francois, 2013).

The additive manufacturing capabilities and the design parameters associated with each capability were identified in this section. The literature reviewed in this section is summarized in Table 2. Each study reviewed in this section has applied one or more AM capabilities to address a specific design problem and this information was used to deduce the design parameters corresponding to the AM capability. For instance, Ian et al., (2013) used additive manufacturing to embed copper tubes in an injection mold die to provide conformal cooling. Hence, conformal cooling was identified as a design parameter and the corresponding AM capability would be “embedded components”. Similarly, design parameters corresponding to each AM capability were identified and are summarized in Table 2. This information is used to create the additive manufacturing database discussed in section 3.3, which, in turn would be used by the user (of the database) to select the capability associated with the design parameter.

Table 2 Summary of additive manufacturing capabilities reviewed

Additive manufacturing capabilities	**Design parameters related to the capability identified from literature review**	**References**
Freeform shape	complex shape, customization, undercuts permissible, improve aesthetics, reduce tooling changes, avoid tooling clearances, reduce tooling	(Stratasys, 2014), (Stratasys, 2017a), (Materialise, 2008), (GM, 2018), (GE, 2014), (Evill and Evill, 2013), (Sirris, 2016)
Topology optimization	reduce weight, remove material, remove material from unstressed regions	(Tang and Zhao, 2015), (Salonitis and Zarban, 2015), (Rodrigue and Rivette, 2010), (Kantareddy, 2016), (Galjaard et al., 2015), (Komi, 2014), (Brackett et al., 2011)
Internal channels	ease of assembly, improve heat transfer, reduce leaks, remove auxiliary channels, internal channels, conformal cooling, increase surface area, reduce weight, improve flow efficiency, improve aesthetics	(Thompson et al., 2016), (Klahn et al., 2015), (Gibbons and Hansell, 2005), (EOS GmbH, 2014), (Komi, 2014), (Renishaw, 2018b), (Lemay, 2018), (Stratasys, 2015c), (Sachs et al., 2016), (EOS GmbH, 2013), (EOS GmbH, 2015)
Infill modification	reduce weight, remove material, increase surface area, porous structure, acoustic insulation, buoyancy	(Milde and Morovic, 2016), (Holman and Serdar, 2018), (Baich and Manogharan, 2015), (Siber, 2018), (Tyson, 2017), (3DMatter, 2015), (3DPlatform, 2018)
Lattice structure	reduce weight, remove material,	(Taniguchi et al., 2016), (Sing et

	improve heat transfer, acoustic insulation, high compressive strength, porous structure, deployable structure, absorb energy, high strength to stiffness ratio, increase surface area	al., 2016), (Petrovic et al., 2011), (Murr et al., 2012), (Maheshwaraa et al., 2007), (Iyibilgin et al., 2013), (Intralattice, 2018), (Emmelmann et al., 2011), (Yang, 2014), (Nguyen et al., 2013), (NTopology, 2017), (Materialise, 2016)
Thin or small features	reduce weight, improve heat transfer, increase surface area, internal channels, thin or small features	(Seepersad et al., 2012), (Xometry, 2018), (Chloe Kow, 2017), (Brockotter, 2018), (Fabforma, 2016), (Smith, 2015), (Kostakis et al., 2013)
Segmentation	segmentation, interlocking features, ease of maintenance, ease of storing, ease of transportation, increase number of parts, split the part	(Song et al., 2015), (Richardot, 2018), (Luo et al., 2016), (Lu et al., 2014), (Formlabs, 2018), (Apaza-Ag¨uero et al., 2015), (Zuza, 2018), (Low, 2018)
Part consolidation	reduce leaks, ease of assembly, reduce of number of parts, merge parts, reduce number of joints, reduce assembly error, ease of maintenance, remove material, reduce weight	(Yang et al., 2015), (Rodrigue and Rivette, 2010), (Schmelzle et al., 2015), (Cardona, 2015), (Stratasys, 2017c), (Artley, 2018), (Stevenson et al., 2017), (Materialise, 2018)
Non-assembly mechanisms	ease of assembly, movable parts, relative movement between parts, reduce assembly error, kinematic joints	(Zammori et al., 2006), (Koo et al., 2014), (Chen and Zhezheng, 2011). (Calignano et al., 2014), (Calì et al., 2012), (Maundy, 2013), (Cassaignau, 2015), (Song et al., 2015), (Cuellar et al., 2018)
Embedded components	ease of assembly, reduce number of parts, reduce number of joints,	(Cuellar et al., 2018), (Ian et al., 2013), (Joe Lopes et al., 2012),

	reduce assembly error, improve ruggedness, conformal cooling, improve IP rating, temperature resistance, impact resistance, corrosion resistance, durability	(Kataria et al., 2001), (Sbriglia et al., 2016), (Autodesk, 2015), (NTU, 2016)
Surface textures	emboss features, surface patterns, improve grip, improve friction, improve aesthetics	(Van Rompay et al., 2018), (3dprint, 2015), (Rhinojewel, 2018), (Sculpteo, 2018), (Takahashi and Miyashita, 2016), (Edman, 2015), (Moto3designs, 2017), (van Rompay et al., 2017)
Material choices	reduce weight, tensile strength, transparency, water resistance, durability, impact resistance, temperature resistance, color, corrosion resistance, material properties, density	(Protolabs, 2018), (Redwood, 2018), (GE, 2018), (ProtoLabs, 2017), (Bourell et al., 2017), (J. C. Booth et al., 2017),
Multiple Materials	multi-colored parts, multi-material parts, improve aesthetics, composite materials, transparency, tensile strength, emboss features, surface patterns, improve grip, improve friction	(Hergel and Lefebvre, 2014), (ORD-Solutions, 2018), (Stratasys, 2015a), (Stratasys, 2017b), (Willis et al., 2012), (Sugimoto, 2014), (Manufacturing, 2017), (Zmorph3d, 2018), (Alex Crease, 2016), (Stratasys, 2015b)p
AM process parameter dependent	surface finish, thin or small features, low tolerance, large sized parts	(Kumbhar and Mulay, 2016), (Renishaw, 2018a), (Postprocess, 2018), (Francois, 2013), (Nadin, 2016), (Armstrong, 2018)

CHAPTER 3. METHODOLOGY

This section discusses the proposed design framework and comprises of four sub-sections. Section 3.1 discusses the axiomatic design approach of defining the design problem; section 3.2 discusses the inverse problem-solving method; section 3.3 discusses the additive manufacturing database; and finally, section 3.4 discusses the proposed design framework by the integration of axiomatic design approach, inverse problem-solving and additive manufacturing database.

3.1 Axiomatic design approach

Axiomatic design theory forms a systematic basis to solve design problems (Suh, 1984). The axiomatic design approach interrelates functional requirements (i.e., customer needs or design objectives) for product design, design parameters and process variables. The primary focus of this approach is to map design objectives in the functional domain into the physical domain in terms of design parameters, and then to map the physical domain into the process domain in terms of process variables (Yang and Zhang, 2000). Functional requirements (FRs) are mapped into design parameters (DPs) that could satisfy the functional requirements. The DPs are then used to derive process variables (PVs) for manufacturing. The PV is then mapped back into the functional domain and a next level of FRs, DPs and PVs (Figure 21). This process is repeated, whereby a hierarchy of FRs, DPs and PVs are created, until no further decomposition seems feasible (Shirwaiker and Okudan, 2008).

This approach is used to decompose the design problem into smaller sub problems until all design objectives are clearly represented. Figure 22 shows the hierarchical structure of functional requirements and design parameters from case study of designing a tool to improve productivity (Shirwaiker and Okudan, 2008). Shirwaiker and Okudan (2008) used

axiomatic design approach to systematically define the problem and to break up the functional requirements into individual hierarchical elements.

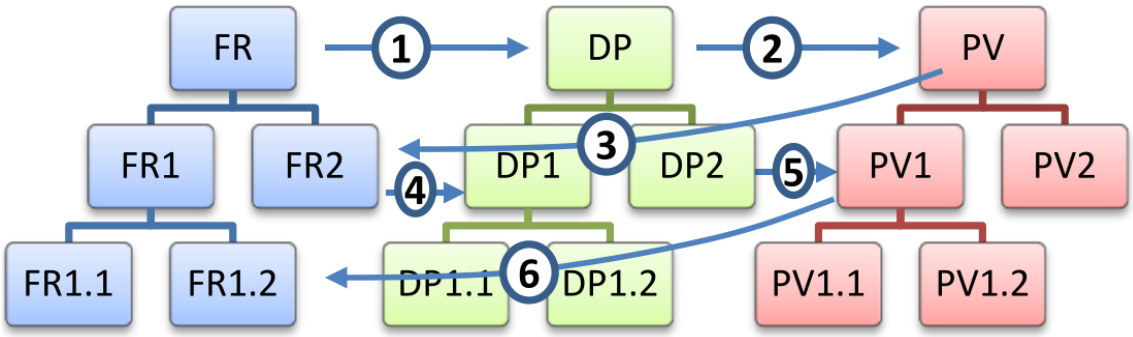


Figure 21 Axiomatic design approach of mapping functional requirements, design parameters and process variables (Salonitis, 2016)

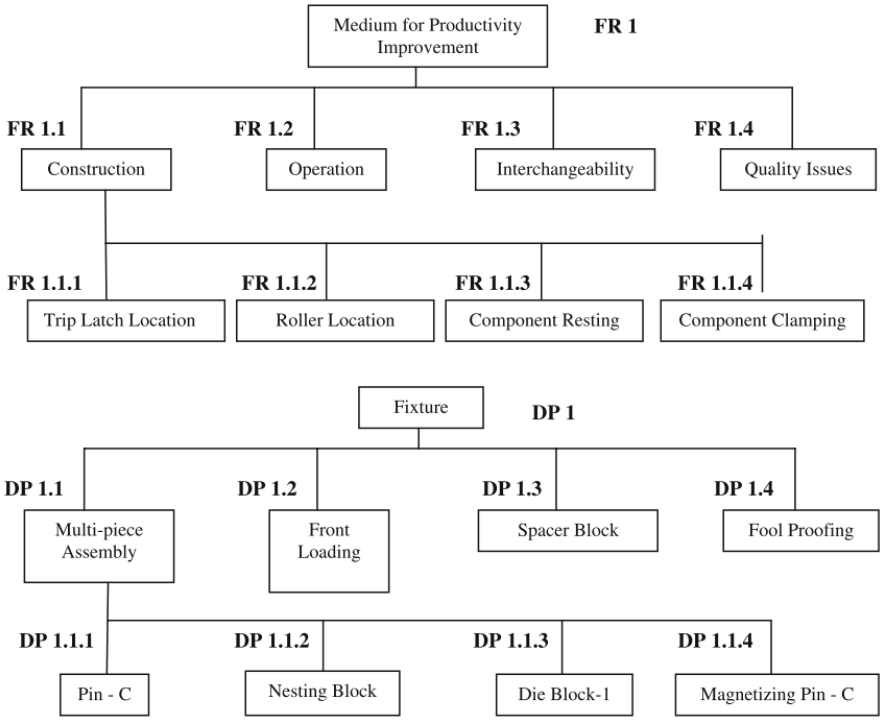


Figure 22 Hierarchical structure of functional requirements and design parameters (Shirwaiker and Okudan, 2008)

Numerous studies have reported the effectiveness of product design development based on axiomatic design, but very few studies have attempted the application of axiomatic design for the design process of additive manufacturing (Salonitis, 2016; Behdad and Oh (2017). Salonitis (2016) used the axiomatic design approach to decompose the design problem in terms of FRs, DPs, and PVs and then used the independence axiom and information axoim to select the optimal design from the concet designs. Behdad and Oh, (2017) used the independence axiom and information axiom to select the design concept and buildup alternative respectively. The axiomatic design structure of decomposing a problem in terms of the functional requirements, design parameters and process variables has been proved to be effective in defining and analyzing design problems (Kulak et al., 2010) and this approach is used in this study to define and analyze the additive manufacturing design problem in terms of functional requirements, design parameters (that would satisfy the functional requirements) and additive manufacturing capabilities (regarded as process variables for additive manufacturing herein that would satisfy the design parameter). The proposed problem definition structure is shown in Figure 23.

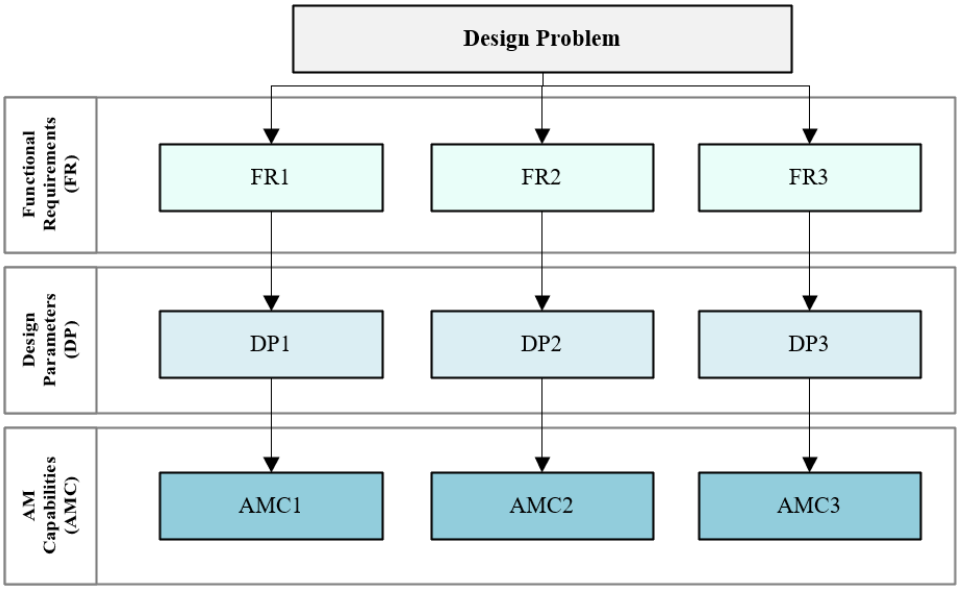


Figure 23 Defining the design problem in the axiomatic design structure in terms of FRs, DPs and AMCs.

The functional requirements are the design objectives. This study assumes that the design objectives (functional requirements) are known (or provided by the customer). The process of identifying the design parameter corresponding to the functional requirement is elaborated in the next section and the process of mapping the design parameter to the appropriate additive manufacturing capability is discussed in section 3.3.

3.2 Inverse problem-solving approach based on TRIZ

In the previous section, the axiomatic design approach, involving mapping of functional requirements, design parameters and additive manufacturing capabilities, was discussed. This section describes the process of identifying the design parameter corresponding to each functional requirement.

TRIZ is a systematic approach to generate innovative design solutions (Cascini and Rissone, 2004; Ogot and Kremer, 2004). An inverse problem-solving method based on TRIZ

(Meylan, 2007)(Rodrigue and Rivette, 2010) is used in this study to identify the design parameters corresponding to the functional requirements. Previous studies have shown compatibility of axiomatic design approach and TRIZ and their effectiveness in solving design problems (Shirwaiker and Okudan, 2008; Yang and Zhang, 2000). The inverse problem-solving approach, which is similar to "reverse- brainstorming" (Souder and Ziegler, 1977), is effective because, it focuses on what causes the problem which in turn helps the person understand the problem and come up with ideas that could solve it (Elmansy, 2018; Mulder, 2018)(Rodrigue and Rivette, 2010). The inverse way of approaching the problem enables one to deliberately go outside the actual situation and generate creative, robust solutions (Vieira et al., 2012; Souder and Ziegler, 1977). The inverse problem-solving approach has four steps (Figure 24). First the functional requirement of the part is formulated (i.e., the failure mode that needs to be avoided or the characteristic that need to be improved is determined). Next, the functional requirement is inversely formulated (i.e., question how to amplify the problem mentioned in the previous step), and its solution (i.e., the solution that will amplify the initial problem) is obtained. Finally, the inverse solution is used to obtain specific solution (i.e., the inverse of the inverse-solution could solve the initial problem) for the initial design problem.

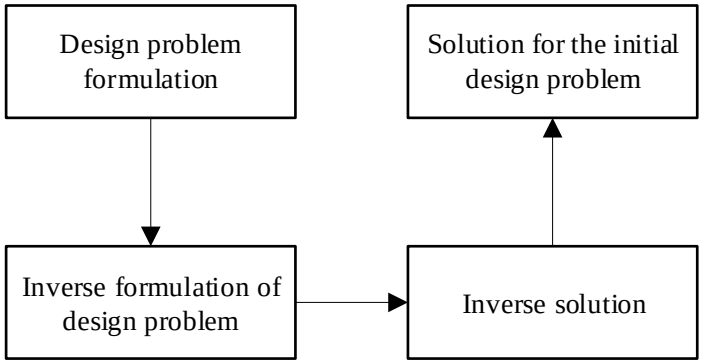


Figure 24 Inverse problem-solving approach. Adapted from Rodrigue and Rivette (2010).

The inverse problem-solving approach of identifying the design parameter corresponding to the functional requirement is demonstrated with an example below. Assume that the functional requirement for a hammer is that it should not slip from the user's hand. The functional requirement of the part is formulated first which is "the hammer should not slip from the user's hand." The inverse formulation of the above statement will be: "the hammer should slip easily from the user's hand." The inverse solution for the inverse formulation will be: "decrease the coefficient of friction on the handle (gripping)" and the solution for the actual functional requirement will be: "increase the coefficient of friction on the handle of hammer." Hence the design parameter for the functional requirement will be (increasing) coefficient of friction. This process is summarized in Table 3. The additive manufacturing capability corresponding to this design parameter is identified using the additive manufacturing database discussed in section 3.3.

Table 3 Inverse problems solving method

Formulation (Functional Requirements)	**Inverse formulation**	**Inverse solution**	**Solution (Design Parameter)**
Hammer should not slip	Hammer should easily slip	Decrease the gripping (coefficient of friction)	Increase the coefficient of friction

3.3 Additive manufacturing database

Additive manufacturing capabilities that can satisfy design parameters are searched for using an additive manufacturing database. For this study, a Microsoft Access-based database was built to store the general additive manufacturing capabilities identified from the literature review in section 2.2. A total of 14 general capabilities were identified from the literature review as summarized in Table 2. Each of these capabilities were added to the database along with its description, design parameters associated with it, pictures and case studies where the capability has been used in existing literature. This section discusses the database in detail.

The additive manufacturing capabilities identified from the literature review were converted into a tabular form in Microsoft Access (see Appendix A). Each capability is associated with an identification number (amc_id), a short description (amc_description), a detailed description, case studies related to the capability, a set of images related to the application of the capability, design parameters associated with the capability and links to webpages containing additional information related to the capability. A “query” was created that would search the design parameter entered by the user or selected from the drop-down box in the database home page shown in Figure 25.

If a match was found between the keyword searched and the design parameters of capabilities in the database, the capability (or capabilities, if there are more than one capability associated with the design parameter entered by the user) would be displayed in the search results. If the search yields more than one result, then the user is expected to select the most suitable capability for their design based on the description of the capability displayed from the database. If the database could not find a capability associated with the keyword entered, it will display all the capabilities stored in the database and the user can go through each one of the capabilities to find the one that is most appropriate for their design.

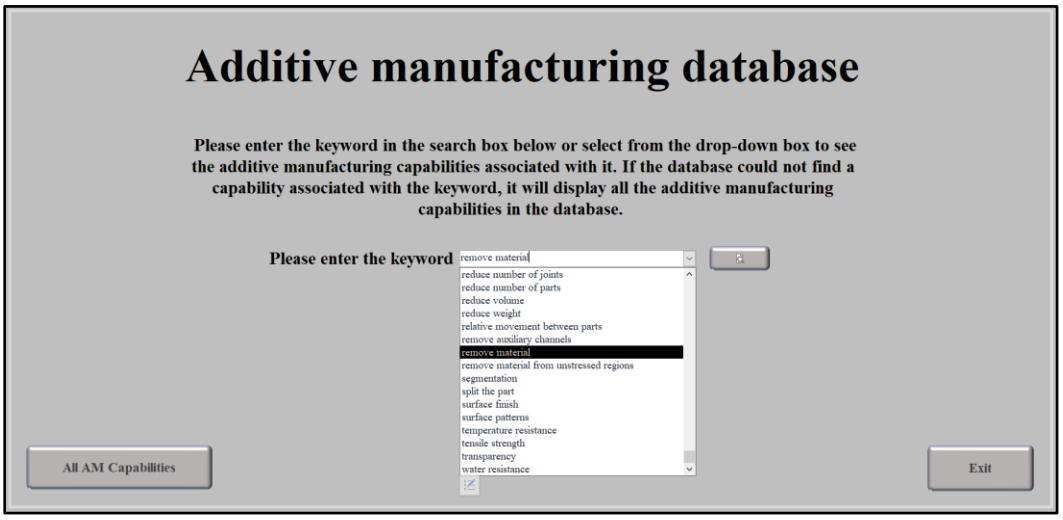


Figure 25 Home screen of the database with "search" feature

An example of the keyword search is shown in Figure 25. The design parameter “remove material” was selected by the user from the drop-down menu on the database home page. The search results for the keyword is shown in Figure 26. There are three additive manufacturing capabilities associated with the design parameter “remove material.” Now, the user can click on the “GO TO > Database” button at the top of the search results and view each of the capabilities in detail. The detailed information screen for “Topology optimization” is shown in Appendix B.

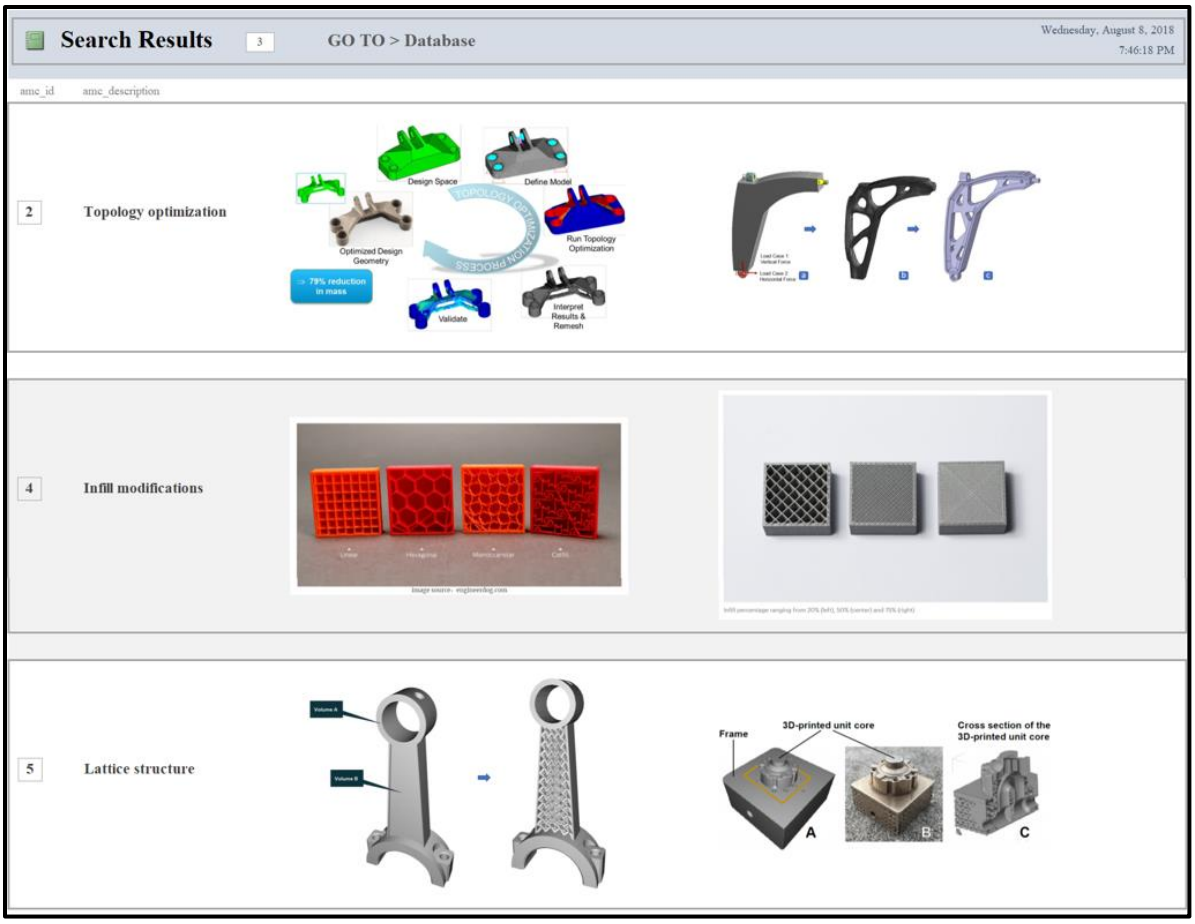


Figure 26 Search results for "remove material" shown in Figure 25.

The screen shown in Appendix B has detailed information about the capability including a description of how to apply the capability into the design, case studies and images of the capability from literature and links to webpages that has additional information (tutorials, case studies etc.) about the capability. This approach is expected to benefit the designers who are additive manufacturing novices in identifying the additive manufacturing capability that would satisfy the corresponding design parameter and incorporating it into the product design. Additive manufacturing is evolving at a rapid pace and additive manufacturing machines with newer and better capabilities are launched into the market every day. The database structure is advantageous since the capabilities and associated

design parameters can be updated easily to keep up with the advancements taking place in additive manufacturing domain.

3.4 Proposed design framework

This section proposes a design framework for additive manufacturing by integrating the axiomatic design approach, inverse problem-solving, and additive manufacturing database. The proposed design framework comprises of three design phases: 1) conceptual design phase, 2) embodiment design phase, and 3) detailed design phase (see Figure 27). In the conceptual design phase, basic solution principles for a design problem are identified to derive initial design concepts. Then, preliminary designs are created in an embodiment design phase by elaborating the solution principles on the initial design concepts. These preliminary designs are further refined in a detailed design phase to satisfy more detailed design parameters and requirements such as tolerance, loading conditions, and process specifications, and a detailed description of the proposed design framework is given below. The primary focus of this study is on the conceptual design phase.

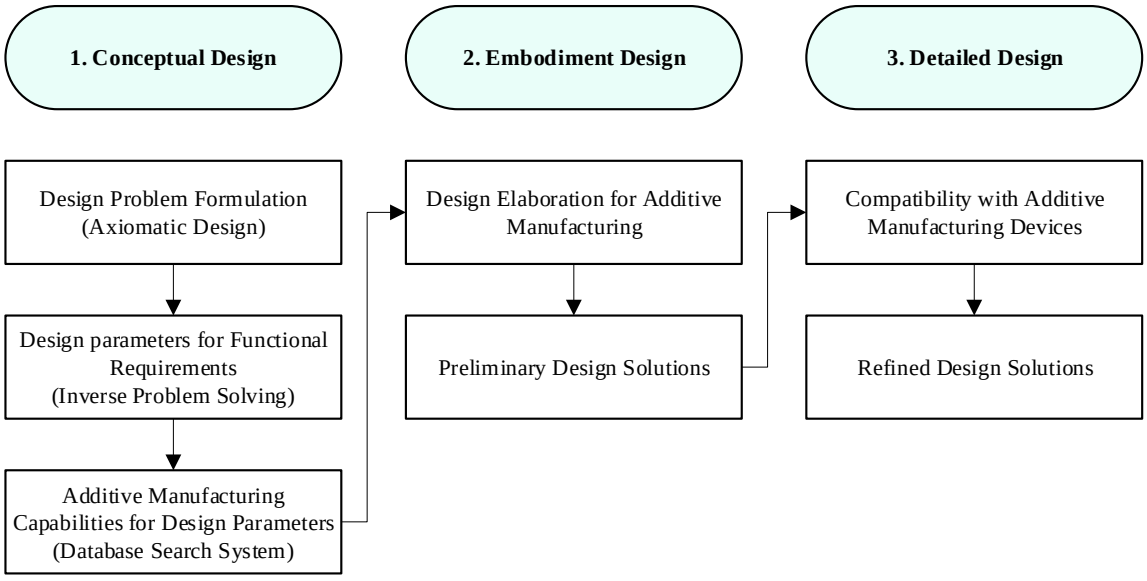


Figure 27 Flowchart of the proposed design framework

3.4.1 Conceptual design phase

This phase defines a design problem in the axiomatic design framework to decompose the design problem into a hierarchical design process of Functional Requirements (FRs), Design Parameters (DPs), and Additive Manufacturing Capabilities (AMCs) for additive manufacturing. It is recommended that a functional diagram of the part be created if a deeper understanding of the part with its environment and its sub-systems is necessary (Cascini and Rissone, 2004). A functional diagram is a schematic representation of all the components (of a part) and the action they carry out along with their interactions with other parts. A functional diagram of a wheel is shown in Figure 29. This study assumes that the functional requirements of the part are known. Given the functional requirements of the part, the inverse problem-solving method based on TRIZ is used to derive innovative solutions (design parameters) to satisfy the FRs of the problem.

Additive manufacturing capability that can satisfy design parameter identified from the inverse problem-solving is searched using the additive manufacturing database. Each identified design parameter is entered as a keyword (or selected from a list) in the database, which in turn displays its relevant additive manufacturing capabilities. If the search yields more than one result, then the user is expected to select the most suitable capability for their design based on the description of the capability displayed from the database. An illustration of the database search system is shown in Figure 28.

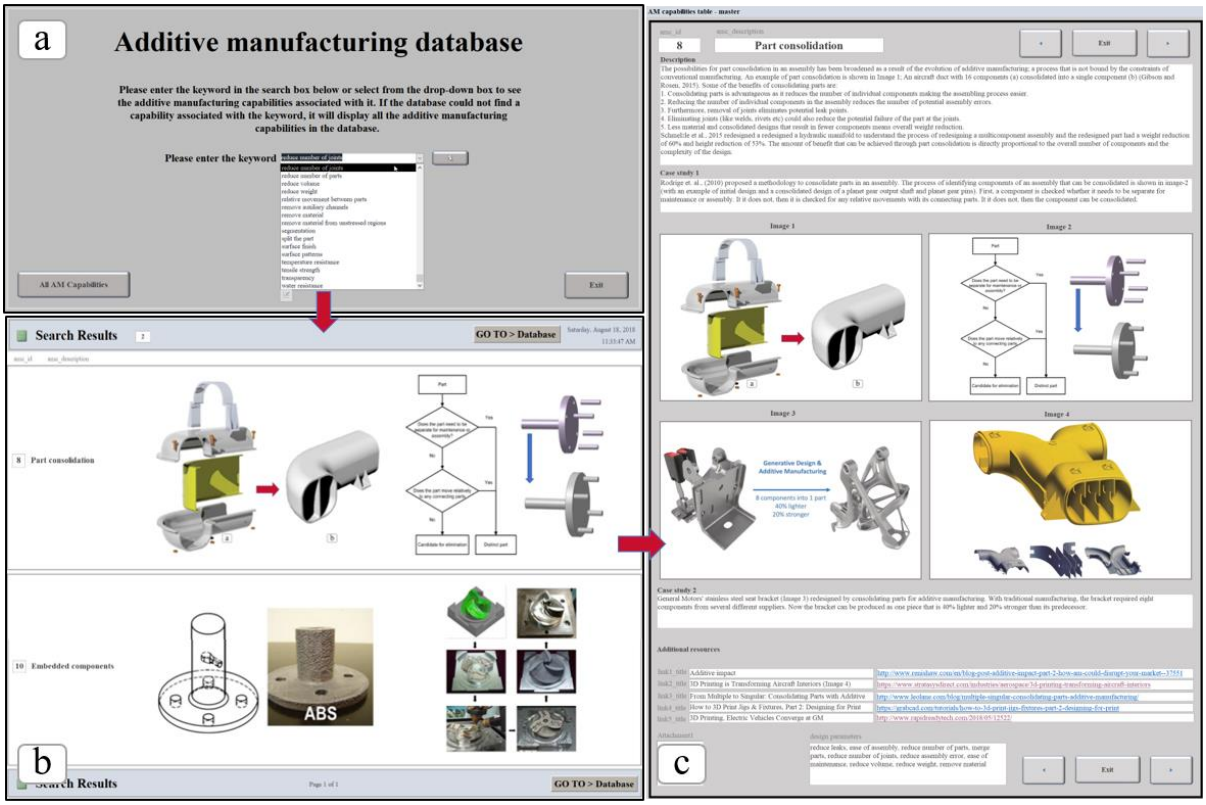


Figure 28 Searching the keyword in the additive manufacturing database (a), search results (b) and detailed description of the additive manufacturing capability (c).

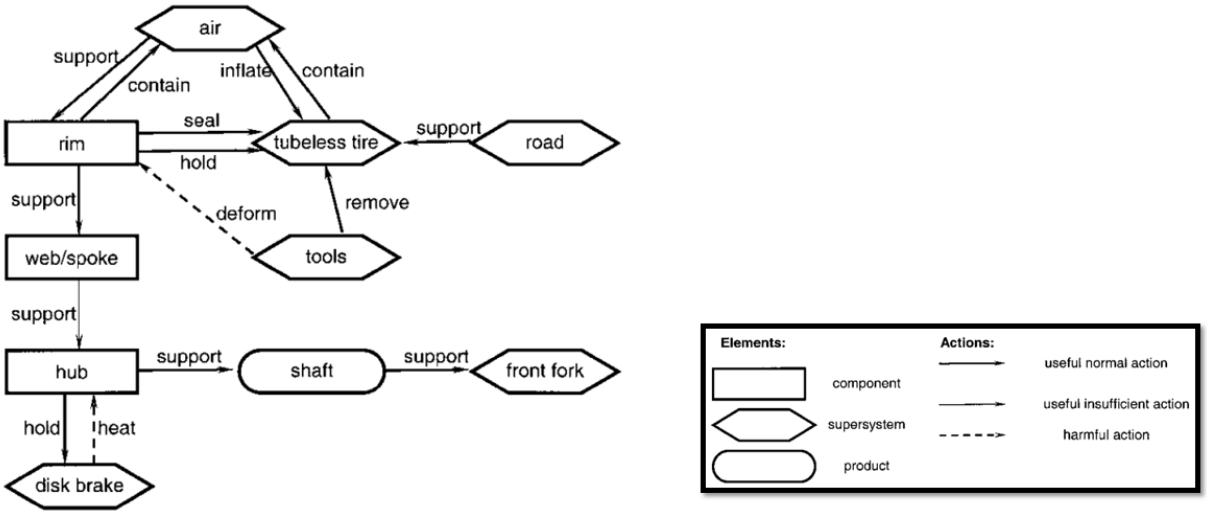


Figure 29 A functional diagram of a wheel by Cascini et al. 2004. The components of wheel (rim, spoke and hub), their actions and their interactions.

3.4.2 Embodiment design phase

Preliminary designs are created by incorporating the additive manufacturing capabilities identified in the previous phase. The additive manufacturing database can be used to obtain more information about these additive manufacturing capabilities if required. The user can make use of this information to incorporate the additive manufacturing capability into their design. This study assumes that the user of this framework has the basic design engineering knowledge and hence would be able to apply the AM capability into the product design with the information provided in the database.

For instance, the database-search example in Figure 28 displays “part consolidation” as the associated additive manufacturing capability. The database has information regarding the process of identifying components that can be consolidated (Figure 28 c). According to the database, the parts that do not need to be separate for maintenance or assembly and the parts that do not need to move freely relative to any connecting parts, are candidates for part-consolidation. The designer could use this information to identify the components that could be consolidated in the product that is being designed.

Another example for applying the AM capability into the product design can be demonstrated from the example in Figure 39. “Topology optimization” is the AM capability identified in this case and the database has information on what topology optimizing is and how it can be applied to a product. According to the database topology optimization is done using a Finite Element Analysis software (examples of software available in the database). The FEA software discretizes the part into elements and then optimizes the density of each element. An optimized shape of the part is generated by the software with material removed from all unstressed regions. This optimized shape is usually a complex shape that is difficult

to be manufactured using conventional manufacturing process. The designer can use this optimized shape as a reference and modify the initial design of the part.

3.4.3 Detailed design phase

The preliminary designs created in the previous phase are refined by considering the additive manufacturing process constraints and specifications (e.g., tolerances, minimum feature size that can be produced, layer thickness, etc.). This information can be collected from the additive manufacturing machine manufacturer or from existing literature. Another additive manufacturing database that has information about these process constraints would be useful in this phase and this will be part of the future work. The refined designs will also be evaluated using a Finite Element Analysis (FEA) software to ensure that they would be able to withstand the mechanical forces that they would be subjected to (Salonitis and Zarban, 2015)(Kumke et al., 2016). FEA is a computerized method for predicting how an object will react when it is being subjected to physical forces (i.e., force, pressure, heat etc.) (Autodesk, 2018). The software simulates the physical conditions on the Computer Aided Design (CAD) model of the object and shows whether the object will break or work the way it was designed. If the FEA analysis reveals that the loading requirements have not been met, the designer should redesign the refined design and re-evaluate it using the FEA software.

CHAPTER 4. CASE STUDIES

In this section two case studies are presented to illustrate the proposed methodology.

4.1 Case study 1: Redesigning a housing cover

A housing cover (Figure 30) is redesigned using the proposed methodology. The functional analysis (functional diagram) of the housing cover is shown in Figure 31. The main parts of the housing cover are the cover, the gasket and the threaded socket. The components that directly interact with the housing cover assembly are the housing, the shaft bearing, and the shaft, and are considered as the super-system to the housing cover system.

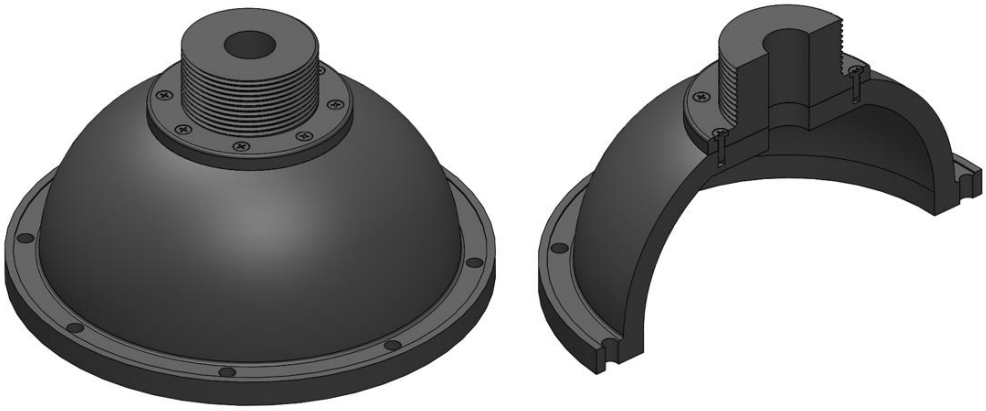


Figure 30 Initial design (isometric view on the left and cross-sectional view on the right) of the housing cover

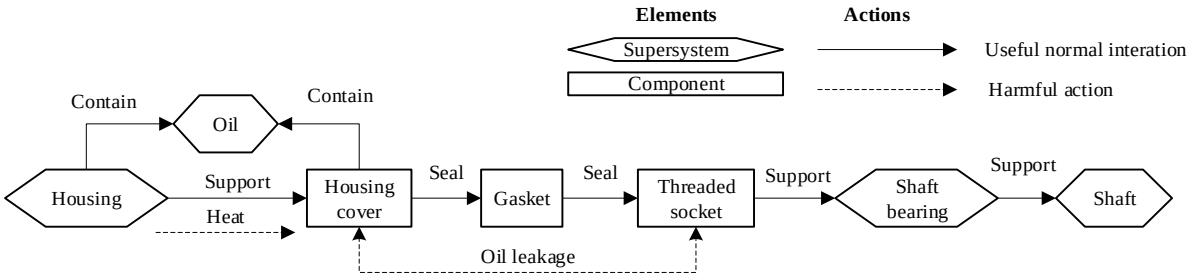


Figure 31 The initial design of the part and the functional analysis of its components (Housing cover, gasket and threaded socket)

Furthermore, the continuous line indicates a useful interaction and a dashed line indicate a harmful interaction. The customer requires the weight of the housing cover to be reduced and the leakage to be prevented. Furthermore, the heat generated inside the housing needs to be effectively removed to the environment. This requires redesigning the housing cover and the redesign process of the part using the proposed design framework as described below.

4.1.1 Conceptual design phase

The main functional requirements of the part are: 1) preventing the leakage, 2) facilitate heat removal, and 3) reducing the weight of the part without compromising its strength. The process of mapping these functional requirements to corresponding design parameters, and to additive manufacturing process capabilities is explained below and summarized in Figure 34.

Functional Requirement-1, Preventing leakages: The functional analysis diagram (Figure 31) of the system shows that there can be leaks between the housing cover and the threaded socket. The functional requirement is to prevent this leakage. The inverse formulation of the same is: “to increase the leakage” and its solution is “by increasing the gap between the joining parts.” Hence, the solution for the functional requirement is “by avoiding the gap between the parts or joining the parts altogether” and “number of joints” would be the design parameter. The database search system for additive manufacturing is used to identify an additive manufacturing capability directly related to this functional requirement and design parameter. The additive manufacturing capability identified from the system is “part consolidation” as shown in Figure 28.

Functional Requirement-2, Removing heat: The operation of the motor generates heat within the housing and this heat needs to be dissipated to the environment. The inverse

formulation of the functional requirement is “to reduce the heat transfer to the surroundings” and its solution is by reducing surface area or reducing temperature gradient.” Hence, the solution for the functional requirement is “increasing surface area or increasing temperature gradient.” By increasing the surface area on the surface of the housing cover the convective heat transfer can be improved and therefore a database search for “surface area” was performed. The additive manufacturing capability associated with surface area was “thin or small features.” Additive manufacturing technologies can create features like thin walls (heat fins), blades, hair like structure etc. than can increase the surface area of an object. Hence, “thin wall” was selected as the additive manufacturing capability corresponding to the design parameter surface area.

Functional Requirement-3, Reduce weight of the pump housing cover: “how to increase the weight of the object” is derived as the inverse formulation of this functional requirement, and its solution is “by increasing the quantity of material or by increasing density of the material.” Hence, the solution for the functional requirement would be: “decrease the quantity of material or decrease the density of the material” and the related design parameter becomes “material removal.” A database search for the design parameter is performed, and three additive manufacturing capabilities (i.e., topological optimization, lattice structure, composite materials) are identified. In this case, “lattice structure” is selected. Topology optimization is not suitable since the shape of the cover cannot be changed due to design requirements and composite material is not suitable due to the metal requirement of the part. The process of performing the database search is shown in Figure 39. The process of deriving the design parameters is summarized in Table 4.

Table 4 Deriving solutions using inverse problem-solving approach

Formulation (Functional Requirements)	**Inverse formulation**	**Inverse solution**	**Solution (Design Parameters)**
Reduce leakage from the joint	Increase leakage	Increase the number of joints in the assembly	Reduce number of joints
Increase heat transfer to surroundings	Reduce heat transfer to surroundings	Reduce surface area	Increase surface area
Reduce the weight of the housing cover	How to increase the weight of the part?	Increasing the quantity of material or density of the material	Decrease the quantity of material or density of the material

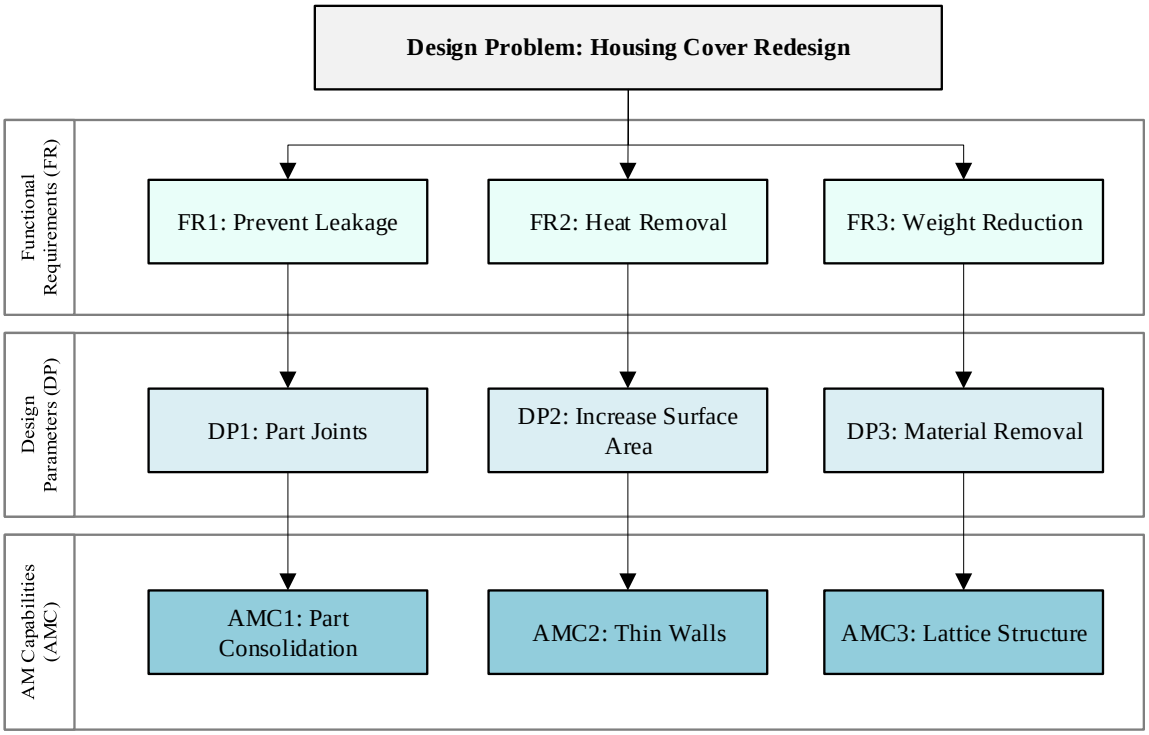


Figure 32 Hierarchical structure of functional requirements, design parameter and process variables

4.1.2 Embodiment design phase

Three additive manufacturing capabilities were identified in the conceptual design phase; part consolidation, thin walls and lattice structure. These capabilities are incorporated in consecutive order into the product design in this phase and preliminary designs are created.

The first step in this phase is to incorporate the “part consolidation” capability into the product design. The additive manufacturing database has information regarding the process of identifying components that can be consolidated (Figure 28 c). According to the database, the parts that does not need to be separate for maintenance or assembly and the parts that does not need to move freely relative to any connecting parts, are candidates for part-consolidation. Based on this information, housing cover and threaded socket could be combined as a single part. The initial design and the consolidated design of the housing cover is shown in Figure 33.

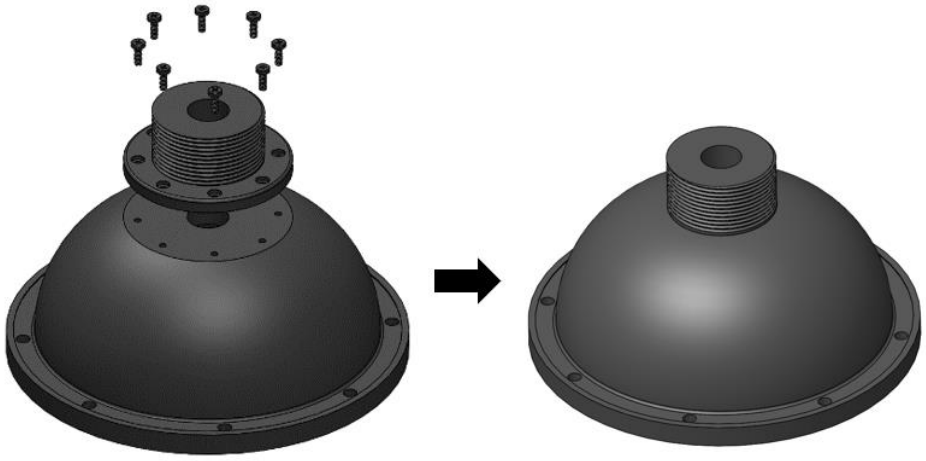


Figure 33 Initial design of the housing cover (left). Consolidated design of the housing cover (right)

The second additive manufacturing capability identified was “thin walls”. According to the database, AM technologies can create small and thin features like thin walls, small

holes, pins etc. and the minimum feature size is primarily determined by the x-y resolution of the 3D printer. This capability is used to create thin fins on the housing cover. These fins would increase the surface area and promote the convective heat transfer between the housing cover and the surroundings. The consolidated part design from the previous step and the modified design with thin fins on the housing cover is shown in Figure 34.

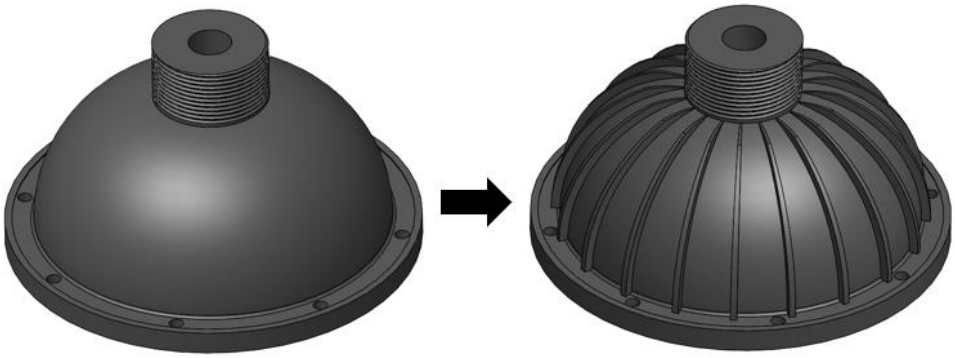


Figure 34 Consolidated design of the housing cover (left). Modified design of the housing cover with thin fins (right)

The third additive manufacturing capability identified was “lattice structures.” The additive manufacturing database provides detailed information about this capability. According to the database, lattice structures are a network of struts with high strength to stiffness ratios. The database also provides examples of softwares that can be used to incorporate lattice structure into the CAD model of the object. The design created in the previous step (with fins) is modified by incorporating lattice structure to the internal structure of the housing cover (see Figure 35). The lattice structure was generated using the “nTopology Element” software.

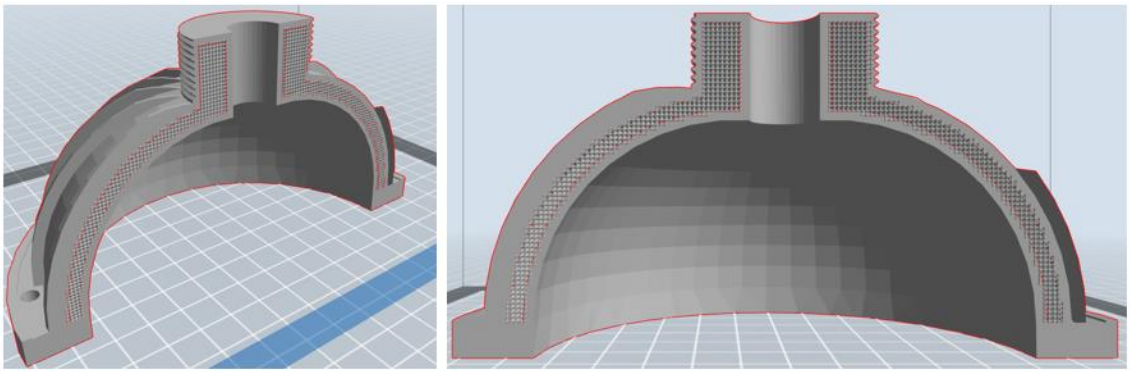


Figure 35 Modifying the internal structure of the part by adding a lattice structure (cross-sectional view of the housing cover).

4.1.3 Detailed design phase

The preliminary part design is refined by considering the process constraints and specifications of tolerance, minimum feasible feature size, and support structure. Fillets are added to the edges to avoid stress concentration. The design is analyzed using a Finite Element Analysis (FEA) software to compare the thermal loads on the new and old designs (See Figure 36). The analysis shows that the steady-state temperature distribution is more uniform in the new design.

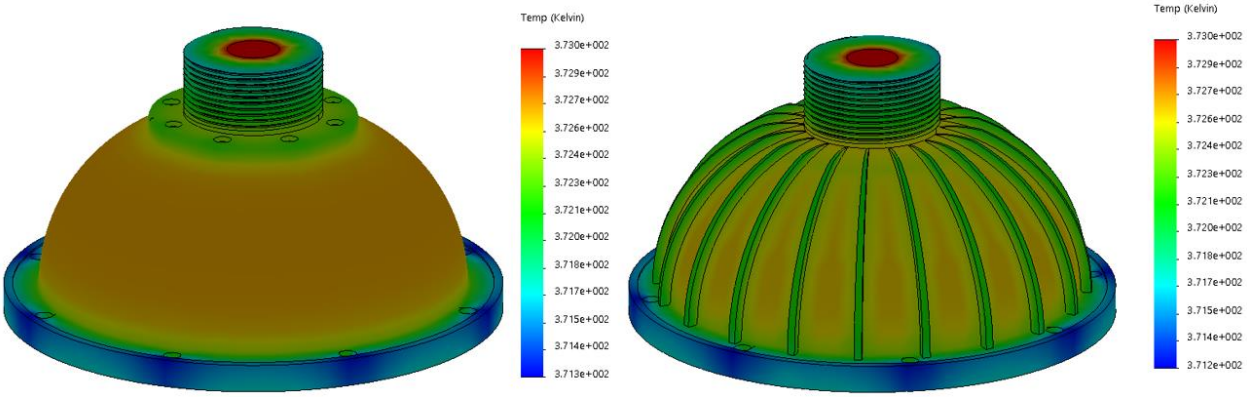


Figure 36 Thermal analysis on the design without fins and with fins

Table 5 shows changes in design properties between the original part and the redesigned part. The redesigned part is less susceptible to a leakage between the housing cover and the threaded socket since both these parts have been combined as a single part in the new design. Furthermore, there has been a reduction in the amount of material and the number of individual components (from 11 components in the initial design to one part in the final design). The surface area on the outer surface of the cover has increased in the redesigned part which is conducive for better convective heat exchange with the surroundings and for a uniform temperature distribution. The weight of the redesigned part is lesser compared to the original part (34% reduction). The redesigned part satisfies all the functional requirements.

Table 5 Comparison between original and redesigned parts

Properties	**Original Design**		**Redesigned part**		**Change**
No. of parts		10		1	-9 90% reduction
Surface area (mm^2)		276412		278939	2527 1% increase
Mass (*g*)		360.8		237	-123.8 34% reduction

4.2 Case study 2: Redesigning a link-pin assembly

The proposed methodology is demonstrated using a case study of part design in this section. The part considered for the case study is a link-pin assembly in the control unit of a hydraulic pump (see Figure 37). This part is a legacy part (low-volume) and needs to be manufactured using a metal additive manufacturing technology. The part is required to have light weight, high strength, and high-quality surface. The part is made of low carbon steel (i.e., C-1008). The resultant redesign process of this part through the proposed design framework is described below and it aligns with the preliminary study by Renjith et al., (2018).

4.2.1 Conceptual design phase

The main functional requirements of the part are: 1) improving the reliability of the assembly, 2) reducing the weight of the part without compromising its strength, and 3) creating a high-quality surface at certain portions. The process of mapping these functional requirements to corresponding design parameters, and to additive manufacturing process capabilities is explained below and summarized in Figure 38.

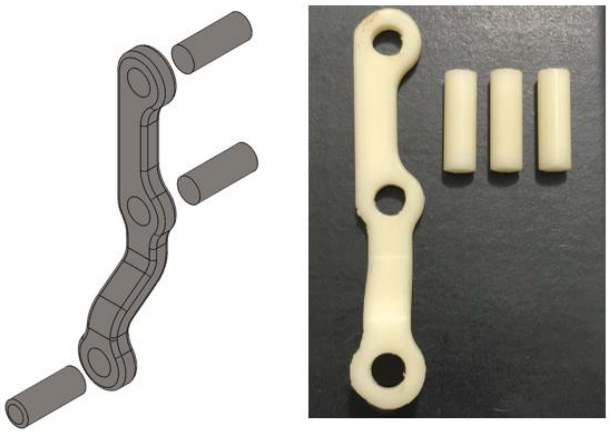


Figure 37 CAD Design and polymer 3D printing example for a link-pin assembly in a hydraulic pump

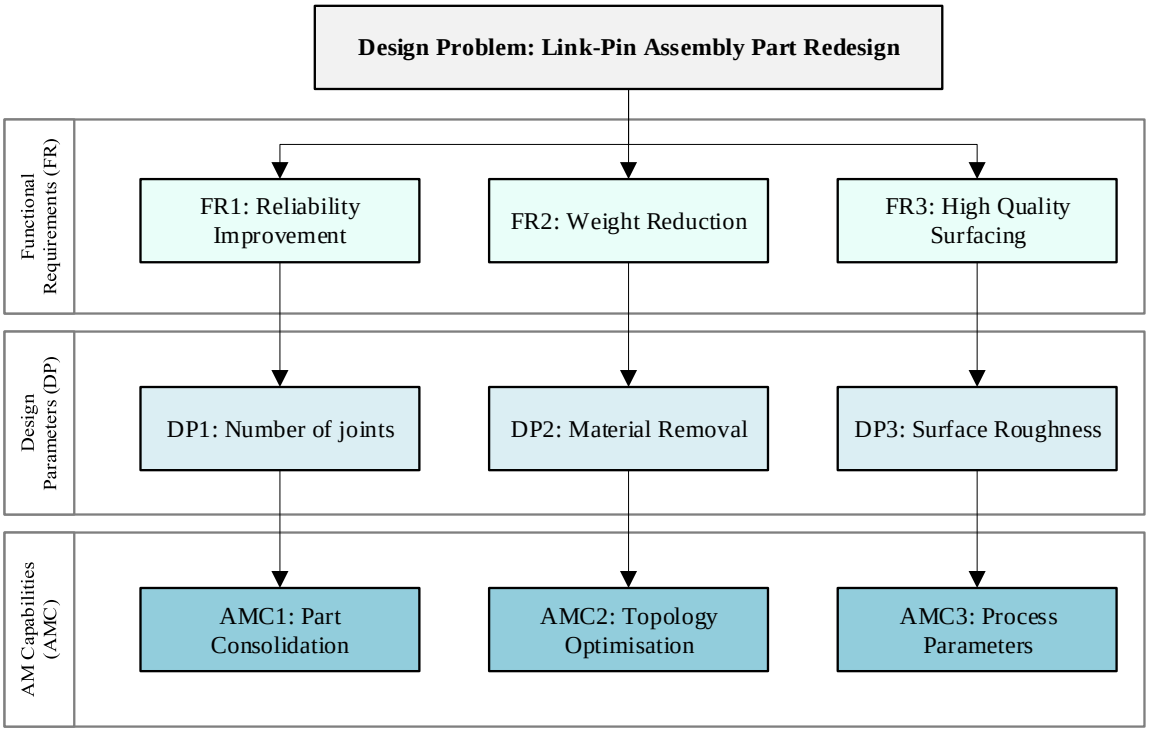


Figure 38 Result summary of conceptual design phase

Functional requirement-1, Reliability improvement: Using the inverse problem-solving method, “how to decrease the reliability of part”? is derived as the inverse

formulation of the functional requirement. The solution for the inverse formulation would be: “by increasing the number of welded parts in the assembly.” As shown in Figure 37, the assembly part can fail if one of the three welds (between the pins and the link) is defective. Hence, the solution for the functional requirement would be:” to decrease the number of welded parts or decrease the number of parts altogether,” and “number of parts” becomes the design parameter related to this solution. The database search system for additive manufacturing is used to identify an additive manufacturing capability directly related to this design parameter. The database search is shown in Figure 28. The additive manufacturing capability identified from the system is “part consolidation.”

Functional requirement-2, Weight reduction: “how to increase the weight of the object” is derived as the inverse formulation of this functional requirement, and its solution is “by increasing the quantity of material or by increasing density of the material.” Hence, the solution for the functional requirement would be: “decrease the quantity of material or decrease the density of the material” and the related design parameter becomes “material removal.” A database search for the design parameter is performed, and three additive manufacturing capabilities (i.e., topological optimization, lattice structure and infill modifications) are identified. For this case study, “topology optimization” is selected since both the lattice structure and infill modifications cannot support the link-pin assembly due to the very low thickness and the metal requirement of the part (see Figure 39).

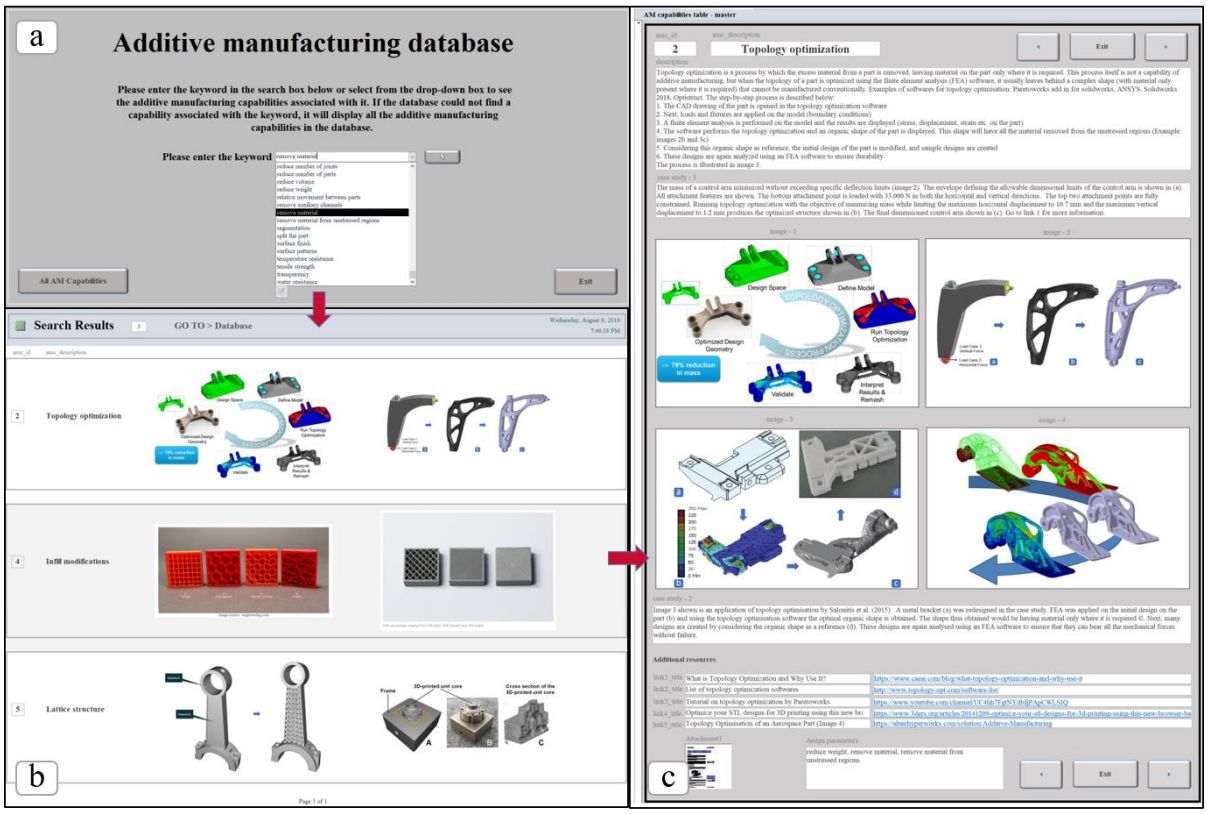


Figure 39 Derivation of an additive manufacturing capability for material removal

Functional requirement-3, High quality surfacing: The corresponding design parameter is surface roughness. A database search for surface roughness shows that surface roughness is an additive manufacturing process dependent parameter, which is dependent on process parameters like layer thickness and the additive manufacturing technology being used. Metal additive manufacturing technologies are not capable of producing high quality bearing surface finish and hence, post processing is required to achieve the required surface roughness. Therefore, this functional requirement would be separately considered in the pre and post-manufacturing stages to adjust the layer thickness and select the appropriate post processing method. The process of deriving the design parameters is summarized in Table 6.

Table 6 Deriving solutions using inverse problem-solving approach

Formulation (Functional Requirements)	**Inverse formulation**	**Inverse solution**	**Solution (Design Parameters)**
Increase reliability of the link-pin assembly	How to decrease the reliability of the part?	Increase the number of welded joints in the assembly	Reduce number of joints or parts
Reduce the weight of the link-pin assembly	How to increase the weight of the part?	Increasing the quantity of material or density of the material	Decrease the quantity of material or density of the material
High surface finish at certain areas of the link-pin assembly	How to decrease the surface finish of the part?	Increase the surface roughness	Decrease the surface roughness

4.2.2 Embodiment design phase

Based on the identified additive manufacturing capabilities, the preliminary design in Figure 41 (d) is created by applying these capabilities to the initial part design in consecutive order. First, part consolidation is applied on the product design. According to the database, the parts that does not need to be separate for maintenance or assembly and the parts that does not need to move freely relative to any connecting parts, are candidates for part-consolidation. Based on this information, the link and the pins can be consolidated into one integral part. The part- consolidated CAD design shown in Figure 40 (b) is created by following the guidelines in the database search system.

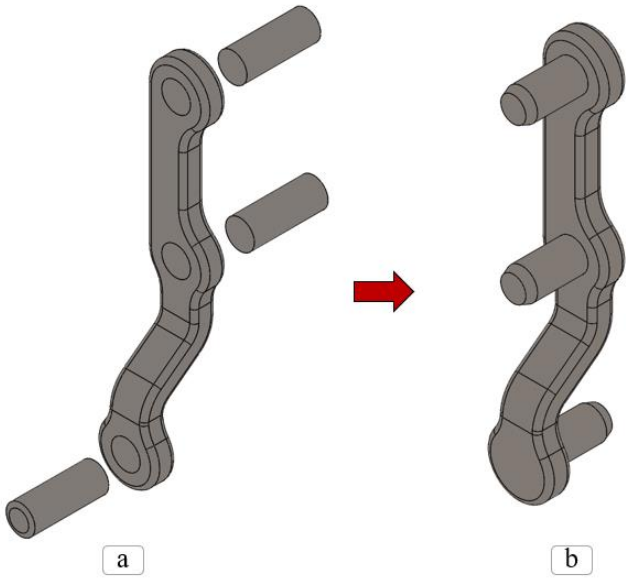


Figure 40 Initial design of the assembly (a) and consolidated design of the assembly (b)

Next, the consolidated design on the link-pin assembly is topologically optimized. According to the database topology optimization is done using a Finite Element Analysis software. An optimized shape of the part is generated by the software with material removed from all unstressed regions. This optimized shape is usually a complex shape that is difficult to be manufactured using conventional manufacturing process. This optimized shape can be used as a reference to modify the initial design of the part. The unstressed regions of the consolidated part design are found through the Finite Element Analysis (FEA) on the initial design (see Figure 41 (b)). Then, the shape of the part is optimized through the topology optimization process by which excessive materials from the part design is removed (See Figure 41 (c)). Finally, the preliminary design of Figure 41 (d) is derived by material removal from the unstressed regions.

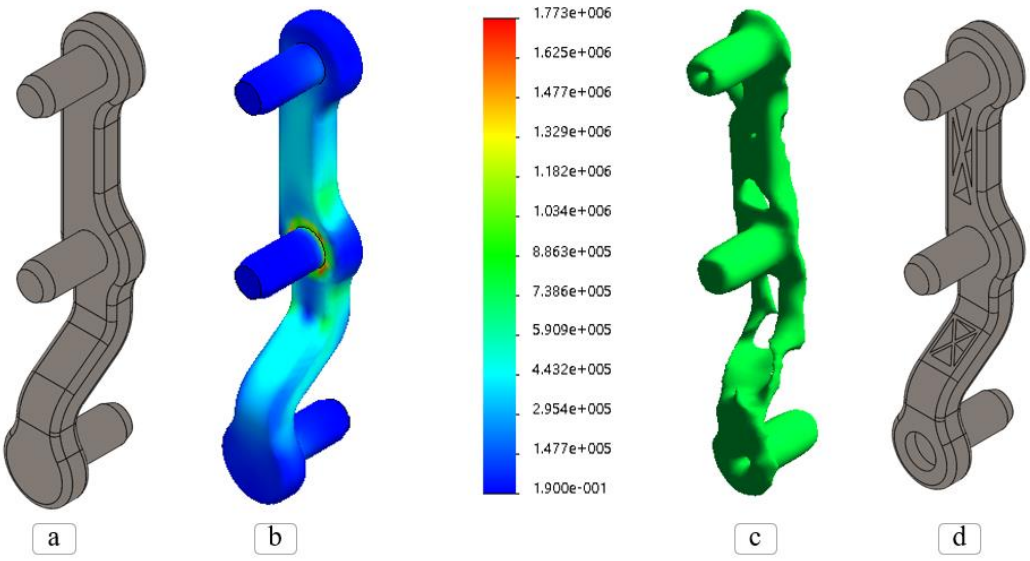


Figure 41 Consolidated design of the assembly (a), finite element analysis on the consolidated design (b), topologically optimized shape of the part and the design after material removal (d)

4.2.3 Detailed design phase

The preliminary part design is refined by considering the process constraints and specifications of tolerance, minimum feasible feature size, and support structure (See Figure 42 (a)). Fillets are added to the edges to avoid stress concentration. The design is then analyzed using the FEA software to ensure that is satisfies the loading conditions (See Figure 42 (b)).

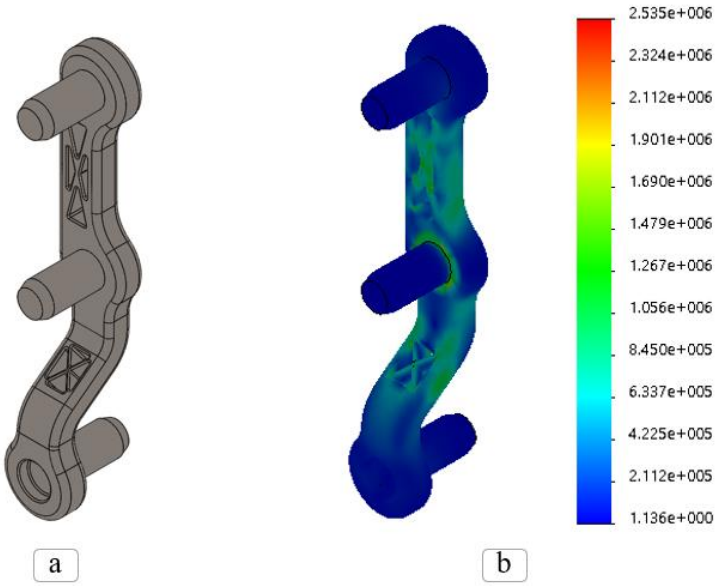
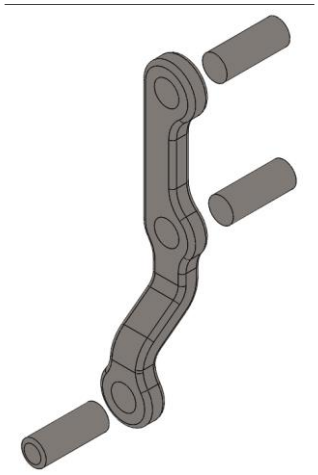
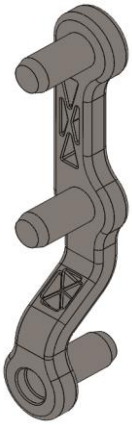


Figure 42 Final part design derived in detailed design phase

Table 7 shows changes in design properties between the original part and the redesigned part. The redesigned part does not have any welded joints since the link and the pins were consolidated into a single part. Hence, the possibility of failure due to an improper weld is eliminated in the redesigned part, making the redesigned part more reliable. Furthermore, there has been a reduction in the amount of material and the number of individual components (from 4 to 1). The weight of the redesigned part is lesser by 11% compared to the original link pin assembly. The redesigned part satisfies all the functional requirements.

Table 7 Comparison between original and redesigned parts

Properties	**Original Design**		**Redesigned part**		**Change**
Number of components		4		1	-3 75% reduction
Number of welds		4		0	-4 100% reduction
Mass (*mg*)		34,117		30,504	-3,613 11% reduction

CHAPTER 5. DISCUSSION & CONCLUSIONS

Additive manufacturing has emerged as an integral part of modern manufacturing because of its unique capabilities like the ability to fabricate complex shapes, to consolidate parts in an assembly and to fabricate non-assembly mechanisms. In order to take full advantage of the capabilities offered by AM technologies, Design for Additive Manufacturing (DfAM) has risen to provide tools and guidelines during the product design process. A thorough review was conducted on the DfAM approaches in literature and the review revealed that there is a lack of design frameworks that could enable the designer to consider the additive manufacturing capabilities into the product design in the early design phase. To address this issue, this study presents a design framework for additive manufacturing based on the synergetic use of the axiomatic design approach and inverse problem-solving method supported with an additive manufacturing database. Under the proposed framework, the design problem is systematically defined in terms of functional requirements, design parameters and additive manufacturing capabilities using the axiomatic design approach. The Inverse Problem-Solving method is used to identify the design parameter corresponding to each functional requirement and an additive manufacturing database that contain information about the general additive manufacturing capabilities is used to identify the additive manufacturing capability corresponding to the design parameter. The proposed design framework would enable designers to appropriately reflect additive manufacturing capabilities into their design in the conceptual design phase.

Two redesign case studies, redesigning a link- pin assembly and redesigning a housing-cover, were presented to demonstrate the proposed design framework. The functional requirements for the housing-cover were leakage prevention, improved heat

removal and weight reduction, and that of the link-pin assembly were weight reduction, reliability improvement and high-quality surfacing. The design problems were systematically decomposed, in terms of functional requirements, design parameters and additive manufacturing capabilities, in the conceptual design phase. The design parameter for each functional requirement was identified using the inverse problem-solving method and the additive manufacturing capabilities corresponding to the design parameter was identified using the AM database. The parts were then redesigned by applying the AM capabilities in the embodiment and detailed design phases. The redesigned housing-cover and link-pin assembly satisfied the functional requirements. The results showed that the redesigned parts had improvements in terms of its properties and that the proposed design framework can be effectively used to transform original product designs for traditional manufacturing into new designs suitable for additive manufacturing by incorporating the additive manufacturing capabilities into the product design. Furthermore, the additive manufacturing database with its search system is expected to be beneficial for additive manufacturing novices.

Additive manufacturing technologies are evolving at a fast pace and 3D printers with better capabilities are launched into the market every day. Hence, the additive manufacturing database needs to be constantly updated with new capabilities. Even though additive manufacturing technologies offer certain unique capabilities, the cost of producing parts, in most cases, using additive manufacturing technologies is higher than that by conventional manufacturing methods. This is primarily due to the higher cost of raw material and the low machine productivity (compared to conventional manufacturing methods) (Douglas and Stanley, 2014). Nevertheless, studies have shown that AM can be cost effective for low-volume production and it is expected that the cost of raw material will reduce with the

increased adoption of additive manufacturing. Furthermore, the technological advancements in the field of AM technologies is expected to lower the prices and improve the productivity of AM machines (Baumers et al., 2016). Additive manufacturing is still maturing and hence, this study has not considered cost-reduction as a functional requirement. The current study is aimed at improving the design of the part under consideration by leveraging the capabilities offered by AM technologies. This study focuses on the conceptual design phase and the primary objective is to support the designer by facilitating the consideration of additive manufacturing capabilities in the conceptual design phase. The DfAM approaches reviewed in the literature have not described a direct method to map the functional requirement to the corresponding additive manufacturing capability, (in comparison to the database approach used in this study) and for this reason, this study has not compared the proposed framework with other DfAM approaches.

For future work, this study will be extended to additionally support a design decision process to consider various additive manufacturing conditions like process selection, part-selection, and selection of the optimal design if there are more than one design that satisfies the functional requirements. The current study focuses on the conceptual design phase. The detailed and embodiment design phases will also be covered in detail in the future study. Another additive manufacturing database with information about the design rules and process specific constraints will be created to support the user during the embodiment and detailed design phases.

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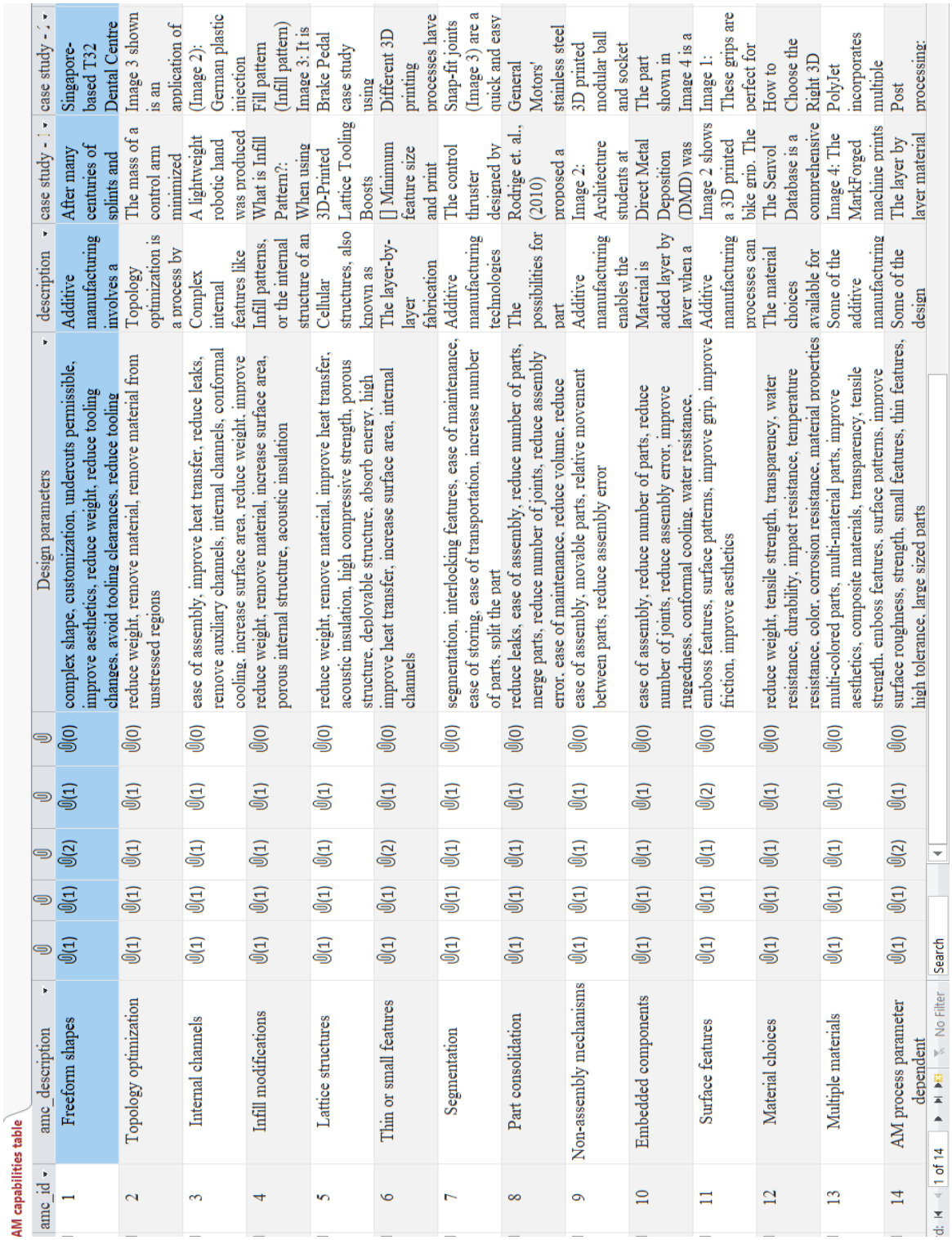
APPENDIX A.



AM capabilities table

amc_id	amc_description						Design parameters	description	case study - 1	case study - 2
1	Freeform shapes	(1)	(1)	(2)	(1)	(0)	complex shape, customization, undercuts permissible, improve aesthetics, reduce weight, reduce tooling changes, avoid tooling clearances, reduce tooling	Additive manufacturing involves a	After many centuries of splints and	Singapore-based T32 Dental Centre
2	Topology optimization	(1)	(1)	(1)	(1)	(0)	reduce weight, remove material, remove material from unstressed regions	Topology optimization is a process by	The mass of a control arm minimized	Image 3 shown is an application of
3	Internal channels	(1)	(1)	(1)	(1)	(0)	ease of assembly, improve heat transfer, reduce leaks, remove auxiliary channels, internal channels, conformal cooling, increase surface area, reduce weight, improve	Complex internal features like	A lightweight robotic hand was produced	(Image 2): German plastic injection
4	Infill modifications	(1)	(1)	(1)	(1)	(0)	reduce weight, remove material, increase surface area, porous internal structure, acoustic insulation	Infill patterns, or the internal structure of an	What is Infill Pattern?: When using	Fill pattern (Infill pattern) Image 3: It is
5	Lattice structures	(1)	(1)	(1)	(1)	(0)	reduce weight, remove material, improve heat transfer, acoustic insulation, high compressive strength, porous structure, deployable structure, absorb energy, high	Cellular structures, also known as	3D-Printed Lattice Tooling Boosts	Brake Pedal case study using
6	Thin or small features	(1)	(1)	(2)	(1)	(0)	improve heat transfer, increase surface area, internal channels	The layer-by-layer fabrication	[] Minimum feature size and print	Different 3D printing processes have
7	Segmentation	(1)	(1)	(1)	(1)	(0)	segmentation, interlocking features, ease of maintenance, ease of storing, ease of transportation, increase number of parts, split the part	Additive manufacturing technologies	The control thruster designed by	Snap-fit joints (Image 3) are a quick and easy
8	Part consolidation	(1)	(1)	(1)	(1)	(0)	reduce leaks, ease of assembly, reduce number of parts, merge parts, reduce number of joints, reduce assembly	The possibilities for part	Rodrige et. al., (2010) proposed a	General Motors' stainless steel
9	Non-assembly mechanisms	(1)	(1)	(1)	(1)	(0)	error, ease of maintenance, reduce volume, reduce ease of assembly, movable parts, relative movement between parts, reduce assembly error	Additive manufacturing enables the	Image 2: Architecture students at	3D printed modular ball and socket
10	Embedded components	(1)	(1)	(1)	(1)	(0)	ease of assembly, reduce number of parts, reduce number of joints, reduce assembly error, improve ruggedness, conformal cooling, water resistance,	Material is added layer by layer when a	Direct Metal Deposition (DMD) was	The part shown in Image 4 is a
11	Surface features	(1)	(1)	(1)	(2)	(0)	emboss features, surface patterns, improve grip, improve friction, improve aesthetics	Additive manufacturing processes can	Image 2 shows a 3D printed bike grip. The	Image 1: These grips are perfect for
12	Material choices	(1)	(1)	(1)	(1)	(0)	reduce weight, tensile strength, transparency, water resistance, durability, impact resistance, temperature resistance, color, corrosion resistance, material properties	The material choices available for	The Senvol Database is a comprehensive	How to Choose the Right 3D
13	Multiple materials	(1)	(1)	(1)	(1)	(0)	multi-colored parts, multi-material parts, improve aesthetics, composite materials, transparency, tensile strength, emboss features, surface patterns, improve	Some of the additive manufacturing	Image 4: The MarkForged machine prints	PolyJet incorporates multiple
14	AM process parameter dependent	(1)	(1)	(2)	(1)	(0)	surface roughness, strength, small features, thin features, high tolerance, large sized parts	Some of the design	The layer by layer material	Post processing:

Figure 43 Table in MS Access with additive manufacturing capabilities.

APPENDIX B.

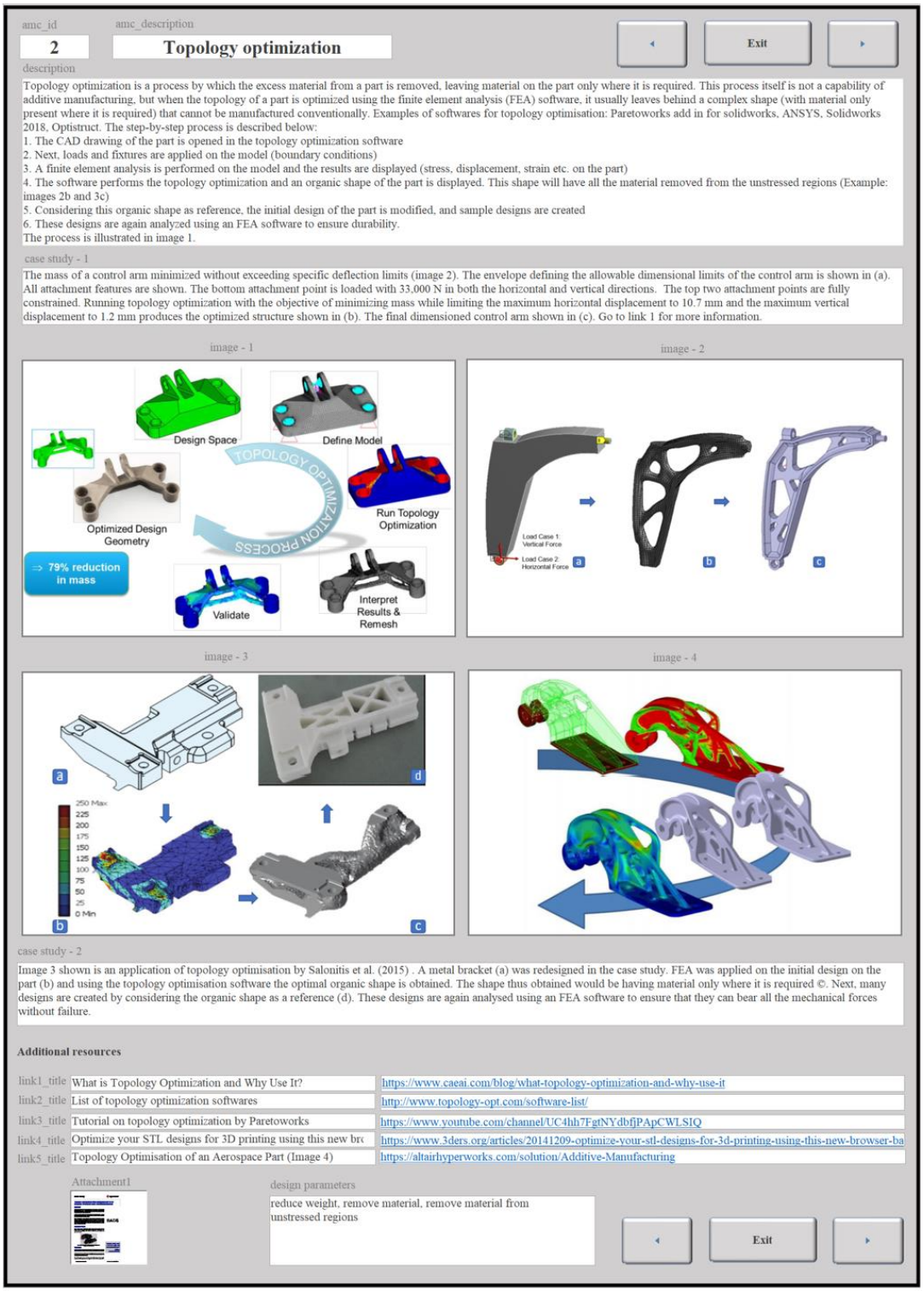


Figure 44 Additive manufacturing capability with detailed information.