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REGULAR PAPER

A Design Framework for Additive Manufacturing: Integration of Additive Manufacturing Capabilities in the Early Design Process

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Abstract
Additive manufacturing has emerged as an integral part of modern manufacturing because of its unique capabilities in various application domains. As efforts to effectively apply additive manufacturing, design for additive manufacturing (DfAM) has risen to provide a set of guidelines based on a practical design framework or a methodology during the product design process of additive manufacturing. However, most existing DfAM methods do not effectively consider the capabilities of extant additive manufacturing technologies in the early design stages, and therefore it is hard to map functional requirements from customer needs onto a product design for additive manufacturing. Moreover, available DfAM methods tend to rely on the direct application of a specific decision method rather than a systematic approach with appropriate deployment and transformation of available design decision methods considering the additive manufacturing environment. Consequently, existing DfAM methods lack suitability for use by additive manufacturing novices. To tackle these issues, this study develops a design framework for additive manufacturing through the integration of axiomatic design and theory of inventive problem-solving (TRIZ). This integrated approach is effective because the axiomatic design approach can be used to systematically define and analyze a design problem, while the TRIZ problem-solving approach combined with an additive manufacturing database can be used as an idea generation tool to generate innovative solutions for the design problem. A case study for a housing cover redesign is presented to apply and validate the proposed design framework.

Keywords Additive manufacturing · Design framework · Design for additive manufacturing · Axiomatic design theory · TRIZ · Additive manufacturing database

1 Introduction

Additive manufacturing refers to a group of technologies for building three-dimensional solid objects from their digital models by selectively accumulating material layer-by-layer [1]. 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 [2, 3].

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Additive manufacturing has emerged as an integral part of modern manufacturing because of its capabilities 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 [4, 5]. The benefits of additive manufacturing led to new design opportunities such as the fabrication of biomimetic scaffolds and artificial organs [6] and advanced design customization [7], that have not been achieved under traditional manufacturing systems.

It is necessary to have practical design frameworks or methodologies that enable designers or engineers to generate effective product designs to exploit additive manufacturing capabilities [3]. In this regard, the concept of design for additive manufacturing (DfAM) has risen to provide a set of guidelines and tools that facilitate the evaluation of constraints and additive manufacturing capabilities during a product design process [8]. However, extant DfAM approaches in the literature tend to rely on the direct application of existing methods for conventional manufacturing without their appropriate transition for additive manufacturing [5]. These DfAM frameworks do not sufficiently reflect the process capabilities and constraints of additive manufacturing in the early design phases [9]. Another limitation is that only a few DfAM methodologies make use of design decision-making tools in order to systematically analyze design problems for additive manufacturing [10]. Furthermore, there is a lack of methods that enable additive manufacturing novices to generate creative design solutions [11, 12].

The above stated limitations necessitate a design framework that can identify suitable additive manufacturing capabilities to help users to systematically analyze design problems for additive manufacturing. This study fulfills this gap by developing an effective design framework for additive manufacturing through the integration of existing design methods and a database for additive manufacturing capabilities. In the proposed design for AM framework, two proven design methods are synergistically used: (1) axiomatic design theory [13] and (2) theory of inventive problem-solving (TRIZ) [14]. In the framework, the axiomatic design approach is used to systematically define a design problem in terms of its functional requirements, design parameters, and corresponding additive manufacturing capabilities. Then, the inventive problem-solving approach based on TRIZ supports the derivation of design parameters to satisfy the functional requirements under the defined design problem structure from the axiomatic design approach. Moreover, a database system is developed to facilitate users to search appropriate additive manufacturing capabilities corresponding to the design parameters.

A design framework based on the above steps would allow designers who are not familiar with additive manufacturing to leverage its potential by considering additive manufacturing capabilities in the early design phases. In addition, such a design framework can be used to redesign existing products that were originally designed for conventional manufacturing as well as to design new products to be manufactured using additive manufacturing technologies.

The remainder of the paper proceeds as follows: Sect. 2 reviews the existing studies on DfAM and additive manufacturing capabilities. Section 3 proposes a methodology to develop a design framework for additive manufacturing by integrating axiomatic design, TRIZ, and an additive manufacturing database system. Section 4 uses the proposed DfAM framework for the redesign of two actual parts to demonstrate the application and effectiveness of the proposed framework. Finally, Sect. 5 discusses the results and provides conclusions along with limitations and future work.

2 Literature Review

2.1 Design for Additive Manufacturing

Design for additive manufacturing (DfAM) is a set of rules, guidelines, tools, and knowledge that help designers to consider additive manufacturing during the product design stage [8, 15]. DfAM enables designers to exploit the unique capabilities of additive manufacturing so as to create an additional value for manufacturers and users [16]. Kumke et al. [10] categorized DfAM approaches in the literature into DfAM for design decisions and DfAM for manufacturing decisions. DfAM for design decisions comprises of guidelines, rules, and methodologies to support designers to utilize additive manufacturing capabilities. On the other hand, DfAM for manufacturing decisions includes upstream, downstream, and other generic DfAM activities for 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.

Focusing on DfAM for design decisions, recent DfAM approaches are summarized in Table 1. The design phases included in Table 1 cover three main phases of a general design methodology for additive manufacturing [9]: (1) conceptual design phase, where basic solution principles for a design problem are identified to derive initial design concepts, (2) embodiment design phase, where the design is fleshed out by incorporating the solution principles, and (3) detailed design phase, where the design is refined to satisfy identified design parameters and requirements such as tolerance, loading conditions, and process specifications.

Different design frameworks in the literature focus on one or multiple general design phases by incorporating extant design problem analysis tools or/and idea generation tools into design frameworks. Rodrigue and Rivette [17] proposed a design methodology for additive manufacturing that combines the benefits of design for assembly and design for manufacturing. The proposed design methodology employs additive manufacturing capabilities to consolidate and optimize a product design based on the functions and characteristics of considered parts and the design failure prevention solutions identified by TRIZ. Bin Maidin et al. [18] developed an additive manufacturing design feature database, which includes 113 additive manufacturing-enabled design features, to support new product development during the conceptual design phase. Vayre et al. [19] proposed a general design methodology for additive manufacturing, involving analysis of part specifications, generation of initial shapes, analysis of these

Table 1 A summary of DfAM approaches

Literature	Design problem analysis	Idea generation	Design phase*			AMCs considered in conceptual phase?
			C	E	D	
Rodrigue and Rivette [17]	□	TRIZ	▣	■	□	▣
Bin Maidin et al. [18]	□	Design feature database	■	□	□	■
Vayre et al. [19]	Parametric optimization	□	▣	■	■	▣
Boyard et al. [20]	3D modular graph	□	■	▣	□	□
Klahn et al. [16]	□	□	▣	▣	▣	□
Laverne et al. [9]	□	Brainstorming	■	□	□	□
Salonitis and Zarban [21]	Specification analysis	□	▣	■	■	▣
Kumke et al. [10]	DfAM based on VDI2221	Catalogues, feature database	▣	▣	▣	▣
Rias et al. [12]	□	Forced association	■	□	□	□
Ko et al. [22]	Finite state automata	□	▣	▣	□	▣
Salonitis [5]	Axiomatic design	□	■	□	□	▣
Bikas et al. [23]	Topological optimization	□	▣	▣	▣	▣
Kamps et al. [24]	TRIZ	Biomimicry database	■	□	□	▣
Sossou et al. [25]	Functional analysis, additive manufacturing contextualization	□	▣	■	▣	▣
Zaman et al. [26]	Multi-criteria decision making	Material process selection database	■	□	□	▣

*C: conceptual phase; E: embodiment phase; D: detailed phase; □: not covered; ▣: partially covered; ■: covered in detail; AMC: additive manufacturing capability

shapes based on geometric parameters, and optimizing the shape by tuning these parameters. Boyard et al. [20] proposed a five-step design methodology including identification of functional specifications, conceptual design, architectural design, detailed design, and implementation. They performed loops of design for manufacturing (DFM) and design for assembly (DFA), in parallel, during the architectural design and detailed design stages based on a 3D modular graph to represent a product architecture. Klahn et al. [16] presented two design strategies (i.e., manufacturing-driven and function-driven) for additive manufacturing that should be selectively applied to product development depending on the operational purpose of additive manufacturing for selected parts in product development. Laverne et al. [9] developed an assembly based DfAM method to enables designers to consider additive manufacturing knowledge and constraints in early design activities for additive manufacturing, which processes development of concepts, working principles, working structures, and synthesis and conversion of data into design features. Salonitis and Zarban [21] proposed a methodology to redesign an existing part for additive manufacturing, evaluating additive manufacturing process specifications and functional requirements of the part. Focusing on the embodiment and detailed design phases, the proposed methodology performs topological optimization to derive initial concepts and multi-criteria decision analysis to evaluate design alternatives. Paying attention to the systematic utilization of additive manufacturing capabilities in the early design phase, Kumke et al. [10] developed a modular framework for DfAM that provides guidelines to integrate existing methods and tools for DfAM and general design methodologies into a design problem based on novelty in product design, user experience with additive manufacturing, and design goal. Rias et al. [12] proposed a design methodology to generate creative design concepts for additive manufacturing in five steps, including feature discovery, idea exploration, ideas evaluation, concept generation, and concept evaluation. Ko et al. [22] proposed a mathematical representation for customized design for additive manufacturing (CDFAM) that employs finite state automata (FSA) to reflect an additive manufacturing process and customer satisfaction in product design. Salonitis [5] proposed a design framework for additive manufacturing using the axiomatic design theory where functional requirements are mapped to design parameters and process variables through a zig-zag decomposition method. Bikas et al. [23] focused on transformation of structural component design for conventional manufacturing into that for additive manufacturing through three design phases (i.e., part selection for additive manufacturing, finite element analysis and topological optimization, and output analysis). Kamps et al. [24] proposed a creative design methodology that incorporates biomimicry and TRIZ for part optimization, which includes part analysis, functional analysis of the main and subfunctions of the components using TRIZ, abstract biomimetic design (i.e., database augmented analogy search for each function), and final part design. Sossou et al. [25] developed a procedural approach that integrates functional requirements and additive manufacturing constrains to derive an additively manufacturable functional architecture based on parametric optimization. Zaman et al. [26] proposed material and process selection for additive manufacturing employing existing multi-criteria decision making methods based on a database system collecting material and machine information.

Despite the benefits that can be provided by the existing DfAM frameworks and methodologies, how to enable designers to better incorporate additive manufacturing capabilities into product design has not been clearly addressed in the existing DfAM framework. As seen in Table 1, a few studies have considered AM capabilities in the early design process, and only a few among those studies considered AM capabilities in detail at the conceptual design phase. The additive manufacturing knowledge should be properly integrated into design activities for successful DfAM implementation. Although most approaches acknowledged the importance of this knowledge transfer, only a few studies explicitly provided a decision-aid system that can easily identify suitable additive manufacturing capabilities for a specific design problem. The lack of design problem analysis tools to systematically derive creative solutions for additive manufacturing can adversely affect designers who would like to effectively integrate additive manufacturing capabilities during the conceptual design phase. To tackle the above mentioned issues, it is necessarily to have a DfAM framework that enables novice designers not only to logically structure a design problem for additive manufacturing but also to creatively derive solutions by considering relevant additive manufacturing capabilities.

2.2 Additive Manufacturing Capabilities

Understanding additive manufacturing capabilities is essential for DfAM to fully exploit possible design opportunities for a specific design problem. This section summarizes common additive manufacturing capabilities that were identified from the existing literature.

- *Freeform Shapes*: Additive manufacturing, which can eliminate many constraints of conventional manufacturing processes (e.g., tooling clearances and undercuts), has significantly broadened design freedom [27]. This geometric freedom enabled by additive manufacturing provides aesthetic, functional, economical, and ergonomic benefits [8]. The capability of additive manufacturing to produce parts with complex shapes has found its applications in interior design, medicine, automotive, and aerospace industries [28].
- *Lattice Structures and Porous Objects*: Additive manufacturing can incorporate complex structures such as lattice and porous structures into the product design, and this additive manufacturing capability has been realized in various applications [29, 30]. Various types of lattice structures can be achieved by changing the arrangement of the struts. Material reduction [31], effective heat transfer [32], and tissue in-growth [33] can be achieved through additive manufacturing.
- *Topology Optimization*: Topology optimization for additive manufacturing has been considered as a critical design activity to derive an optimal design for certain design performance criteria [34]. Optimized shapes through material elimination for unstressed regions that often form complex shapes are hard to be realized in conventional manufacturing. However, additive manufacturing enables designers to produce complex shapes; and finite element analysis (FEA) has been commonly employed in many studies [17, 19, 21, 35–37] to perform topology optimization for additively manufactured parts.
- *Part Consolidation*: Part consolidation reduces the number of parts in an assembly by joining multiple parts into one integral part [38]. The additive manufacturing capability to produce parts with complex shapes is one of the means for part consolidation. Consolidating parts is advantageous not only as it reduces the number of individual components making the assembly process easier [31] but also as it eliminates potential leak points [39].
- *Non-assembly Mechanisms*: Non-assembly mechanisms are operational mechanisms (with kinematic joints) that do not require assembly. Additive manufacturing enables the fabrication of non-assembly mechanisms by providing adequate clearances between kinematic joints [40].
- *Internal Channels*: Complex internal features such as conformal cooling channels, air ducts, and fluid channels that can improve the functionality and performance of a part can be created using additive manufacturing [41, 42]. For example, Gibbons and Hansell [41] created injection mold inserts with complex flood-cooled cooling channels through additive manufacturing and found that the cooling efficiency was significantly higher than the un-cooled and baffled cooled insert.
- *Segmentation*: Additive manufacturing technologies can be used to print parts with interlocking features which enable a large part to be partitioned into smaller parts that can later be repeatedly disassembled and reassembled [43, 44]. This process is called segmentation. Connecting parts by interlocking features can be advantageous because it facilitates a cost-effective way of maintenance

in that the specific part only needs to be reprinted if a part breaks rather than creating the whole object again.

- *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 [45, 46]. Lopes et al. [45] used stereolithography and direct print technologies to create parts with embedded electronic circuits. Campbell et al. [46] employed a direct metal deposition method to create a mold die with conformal cooling channels.
- *Thin and Small Features*: The layer-by-layer fabrication process of additive manufacturing enables creation of small and thin features such as thin walls, small holes, and pins, and the minimum feature size is primarily determined by the x–y resolution of the 3D printer [47]. The additive manufacturing technologies that can fabricate micro-scale structures allow integration of many functions within a small volume [48, 49].
- *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 [8, 50]. For example, Van Rompay et al. [50] created 3D printed ice cream cups with surface textures to study the influence of surface texture on perception of the taste of ice-cream.
- *Material Choices*: Additive manufacturing technologies are capable of processing a large variety of materials such as polymers, metals, alloys, and ceramic materials [8]. Users can select a material that is most suitable for their application based on material properties [51]. Some of the additive manufacturing technologies are also capable of producing parts in colors, which is usually achieved by adding colors to a raw material, blending multi-colored filaments, using different colored material for different parts of the model, or implementing in-process pigmentation [8, 52].
- *Multiple Materials*: The ability to print multiple materials at the same time is another important capability of additive manufacturing [53]. The ability to print multiple materials at the same time can create composite objects that require dynamically tunable topographies [54].
- *Infill Modifications*: Additive manufacturing technologies allow users to adjust the infill of a printed object, which represents the interior structure of a 3D printed object [55]. The infill density and pattern of a printed part can not only affect its material usage, weight, and build time but also determine the strength, porosity, and buoyancy of the part [56, 57].
- *Process Dependent Design Parameters*: Design parameters such as surface finish, dimensional accuracy, and size of parts are dependent on additive manufacturing process parameters [58, 59].

3 Methodology

This paper proposes a design framework for additive manufacturing, which integrates the axiomatic design structure to the inventive problem-solving process based on TRIZ, and utilizes an additive manufacturing database to aid designers to effectively consider additive manufacturing capabilities in the early design stages. The design process during which the proposed design framework can be used comprises of three phases: (1) conceptual design phase, (2) embodiment design phase, and (3) detailed design phase. 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 the embodiment design phase by elaborating the recommended solution principles on the initial design concepts. These preliminary designs are further refined in the detailed design phase to satisfy more detailed design parameters and requirements such as tolerance, loading conditions, and process specifications. The design process in the proposed framework is described in Fig. 1. The primary focus of this study is on the conceptual design phase.

3.1 Conceptual Design Phase

This phase defines a DfAM problem based on the axiomatic design approach to decompose the design problem into a hierarchy of functional requirements (FRs), design parameters (DPs), and additive manufacturing capabilities (AMCs).

3.1.1 Design Problem Formulation through Axiomatic Design

The axiomatic design theory forms a systematic basis to solve design problems [13]. 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 [60]. The axiomatic design approach decomposes a design problem into smaller sub problems until all design objectives are independently represented [61]. The effectiveness of new product design and development based on the axiomatic design theory [62] has been also reported in its applications to the product design process of additive manufacturing [5, 63].

In the proposed design framework, the axiomatic design approach is used as a basis to structure a design problem for additive manufacturing into (1) functional requirements

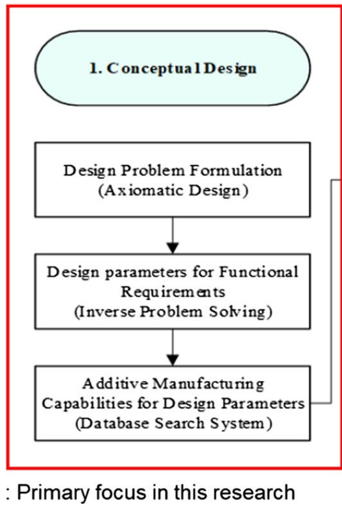


Fig. 1 Overview of proposed design framework for additive manufacturing

to satisfy customer requirements, (2) design parameters to satisfy functional requirements, and (3) additive manufacturing capabilities to satisfy design parameters (see Fig. 2).

It is recommended to create a supporting functional diagram if a deeper understanding of the part with its environment and sub-systems is essential [64]. Functional requirements in Fig. 2 represent design objectives, which are assumed to be known from customer requirements.

3.1.2 Design Parameter Derivation through Inventive Problem Solving

Given functional requirements identified for a design problem for additive manufacturing, the inventive problem-solving method based on TRIZ [65] is used to derive innovative solutions (i.e., design parameters) that satisfy the functional requirements of the problem. TRIZ is a systematic approach to generate innovative design solutions from general inventive principles [64]. Axiomatic design and TRIZ can be synergistically used to amplify their advantages. TRIZ can

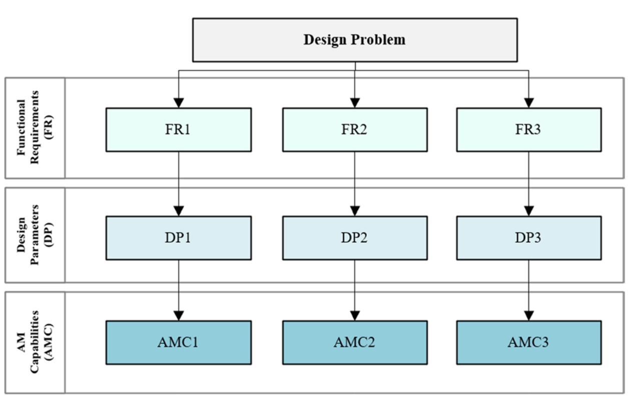


Fig. 2 Design problem structure based on axiomatic design

gnerate innovative solutions based on a design problem that is systemically structured by axiomatic design; previous studies have shown the effectiveness of the integration between the axiomatic design approach and TRIZ in solving conventional design problems [61, 66]. TRIZ has several steps to retrieve appropriate design principles for a design problem described in technical and physical contradictions between design parameters [61]. Similarly, the inventive problem-solving approach within the proposed framework has three steps: First, each functional requirement for the design problem is formulated to separate the functional requirement into a design feature to improve and its counterpart feature not to deteriorate. TRIZ is then used to generate general principles to overcome the trade-off situation between the defined features [14]. Finally, the most appropriate TRIZ principle is customized to obtain a specific design parameter that can solve the initial problem.

The application of the inventive problem-solving approach to identify a design parameter corresponding to a functional requirement is demonstrated with an example below. For a hammer design problem, let's assume that the functional requirement of the design is defined as "the hammer should not slip from the user's hand." The formulation of the above statement can be: "the hammer should not slip easily from the user's hand while maintaining original force." Then, a possible solution for the problem formulation may be to "increase the coefficient of friction on the handle." This solution is obtained from the TRIZ principle *35*: *parameter changes*, which is derived from improving the TRIZ parameter *11*: *stress or pressure*, while preserving the TRIZ parameter *10*: *force* (*intensity*). Thus, a possible solution for the actual functional requirement becomes "increasing the coefficient of friction on the handle of hammer." In this example, the design parameter for the functional requirement is identified as the coefficient of friction.

Table 2 Identified additive manufacturing capabilities and related design parameters

Additive manufacturing capability	Associated design parameters
Freeform shape	Complex shape, customization, undercuts permissible, improve aesthetics, reduce tooling changes, avoid tooling clearances, and reduce tooling
Topology optimization	Reduce weight, remove material, and remove material from unstressed regions
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, and improve aesthetics
Infill modification	Reduce weight, remove material, increase surface area, porous structure, acoustic insulation, and buoyancy
Lattice structure	Reduce weight, remove material, improve heat transfer, acoustic insulation, high compressive strength, porous structure, deployable structure, absorb energy, high strength to stiffness ratio, and increase surface area
Thin or small features	Reduce weight, improve heat transfer, increase surface area, internal channels, and thin or small features
Segmentation	Segmentation, interlocking features, ease of maintenance, ease of storing, ease of transportation, increase number of parts, and split the part
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, and reduce weight
Non-assembly mechanisms	Ease of assembly, movable parts, relative movement between parts, reduce assembly error, and kinematic joints
Embedded components	Ease of assembly, reduce number of parts, reduce number of joints, reduce assembly error, improve Ruggedness, conformal cooling, temperature resistance, impact resistance, corrosion resistance, and durability
Surface textures	Emboss features, surface patterns, improve grip, improve friction, and improve aesthetics
Material choices	Reduce weight, tensile strength, transparency, water resistance, durability, impact resistance, temperature resistance, color, corrosion resistance, material properties, and density
Multiple materials	Multi-colored parts, multi-material parts, improve aesthetics, composite materials, transparency, tensile strength, emboss features, surface patterns, improve grip, and improve friction
AM process parameter dependent	Surface finish, thin or small features, low tolerance, and large sized parts

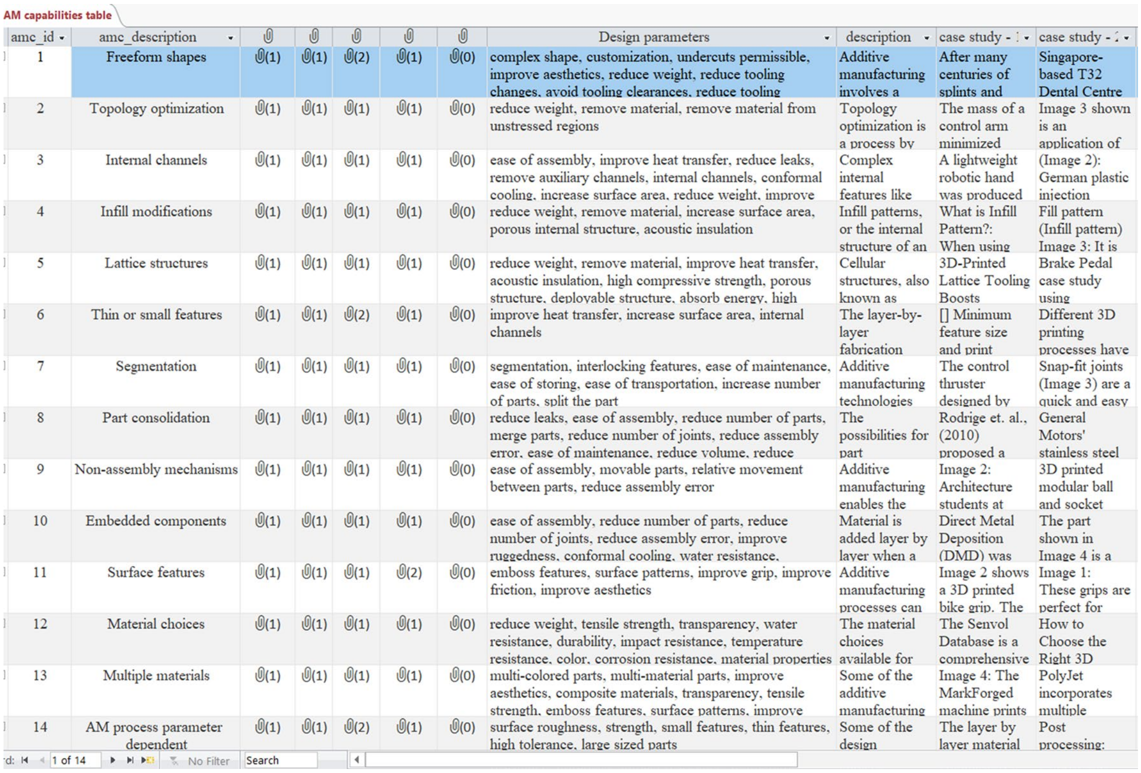
3.1.3 Identification of Additive Manufacturing Capabilities for Design Parameters

After the parameters of a design problem are identified using the inventive problem-solving approach, additive manufacturing capabilities that can satisfy the design parameters are searched using the developed additive manufacturing database. The database organizes general additive manufacturing capabilities and their associated design parameters from the extant literature for easy retrieval. From the literature review performed in Sect. 2.2, general additive manufacturing capabilities and their associated design parameters were identified as summarized in Table 2. It is noted that in the curation of material for the database research publications were carefully reviewed with specific attention given to additive manufacturing capabilities. This information was used to deduce the design parameters corresponding to each additive manufacturing capability.

In total, 14 general additive manufacturing capabilities identified from the literature were converted into a tabular form in Microsoft Access to create an additive manufacturing database (see Fig. 3). 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.

Users are required to directly input a keyword or to select a design parameter from the drop-down box of the database home page shown in Fig. 4. If associated manufacturing capabilities in the database are found for the keyword, resultant capabilities are displayed. If the search yields more than one result, then the user is expected to select the most suitable capability for the product 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 so that the user can go through each capability to find the most appropriate one for the product design. An example of the keyword search is described as follows. If the design parameter "remove material" is selected by the user from the drop-down menu on the database home page as seen in Fig. 4, the search results of the keyword is displayed as shown in Fig. 5. There are three additive manufacturing capabilities associated with the design parameter "remove material." 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. For example, the detailed information screen for "Topology optimization" is displayed in Fig. 6.

The screenshot shown in Fig. 6 has detailed information about the capability including a description of how to



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 error, ease of maintenance, reduce volume, reduce	The possibilities for part	Rodrige et. al., (2010) proposed a	General Motors' stainless steel
9	Non-assembly mechanisms	(1)	(1)	(1)	(1)	(0)	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:

1 of 14 No Filter Search

Fig. 3 Information table for additive manufacturing database

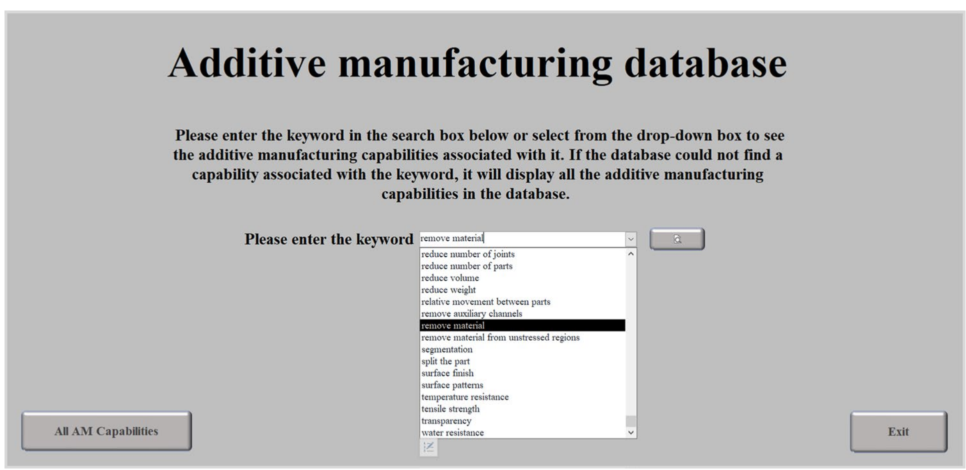


Fig. 4 Home screen of additive manufacturing database

apply the capability on a design, case studies and images of the capability from the literature, and links to webpages with additional information (e.g., tutorials and case studies) about the capability. This approach is expected to benefit designers who are additive manufacturing novices in identifying additive manufacturing capabilities that would satisfy the corresponding design parameter. 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 the additive manufacturing domain.

3.2 Embodiment Design Phase

This phase incorporates the additive manufacturing capabilities identified in the previous phase to preliminary designs. The additive manufacturing database can be used to obtain more information about these additive manufacturing capabilities if needed. This study assumes that

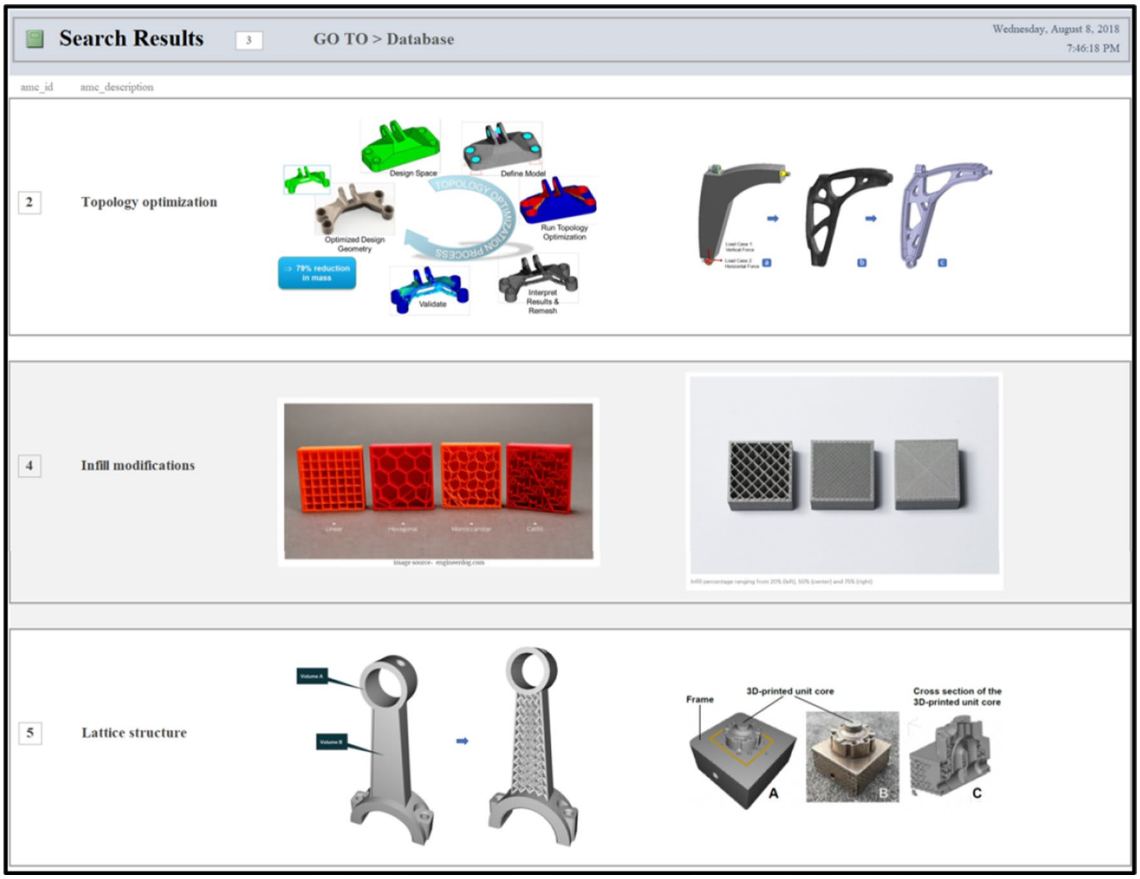


Fig. 5 Search results for "remove material" in additive manufacturing database

the user of this framework has basic engineering design knowledge and hence would be able to apply the information relevant to an additive manufacturing capability retrieved from the database to the design under consideration. For example, the database search results of "topology optimization" in Fig. 6 provide information about what topology optimization is and how it can be applied to product design. The designer then performs topology optimization using a finite element analysis software by referencing examples available in the database.

3.3 Detailed Design Phase

The preliminary designs created in the previous phase are refined by considering additive manufacturing process constraints and specifications (e.g., tolerances, minimum feature size that can be produced, and layer thickness). This information can be collected from machine manufacturers or from existing literature. The refined designs can also be evaluated using a finite element analysis (FEA) software to ensure that they would be able to withstand the mechanical forces [10, 21]. 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.) [67]. The software simulates physical conditions on the computer aided design (CAD) model of an object and shows whether the object will break or work the way it was designed. If the FEA analysis reveals that the loading requirements are not satisfied, the designer should redesign the refined design and re-evaluate it using the FEA software.

4 Results

Based on the proposed design framework for additive manufacturing, a design case to redesign a housing cover for traditional manufacturing is presented to illustrate the proposed methodology.

4.1 Case Study: Hosing Cover Redesign

A housing cover in Fig. 7 was redesigned using the proposed methodology. The functional analysis (i.e., functional diagram) of the housing cover of a motor system is shown in Fig. 8. The main parts of the housing cover are cover, gasket, and threaded socket. The components that directly interact

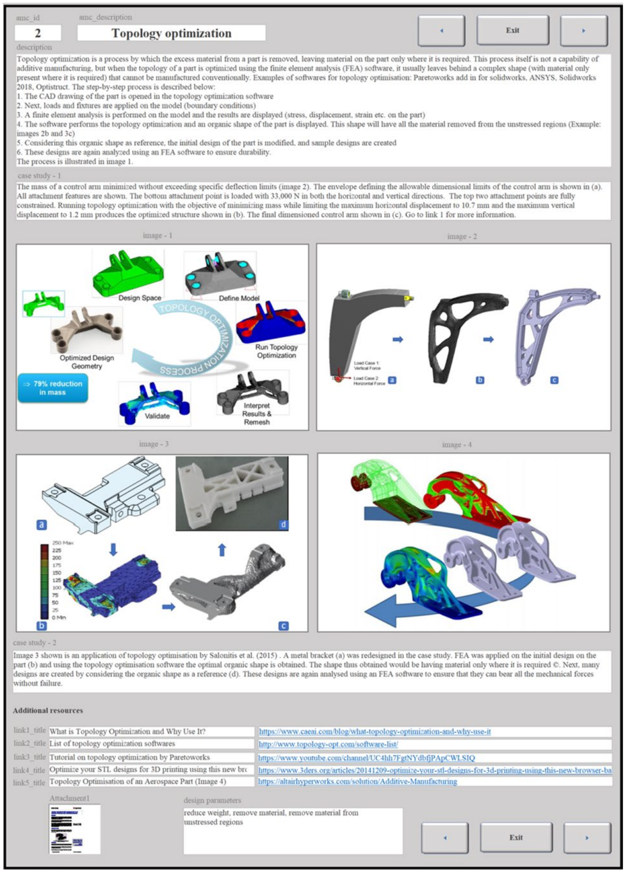


Fig. 6 Example of detailed information for an additive manufacturing capability

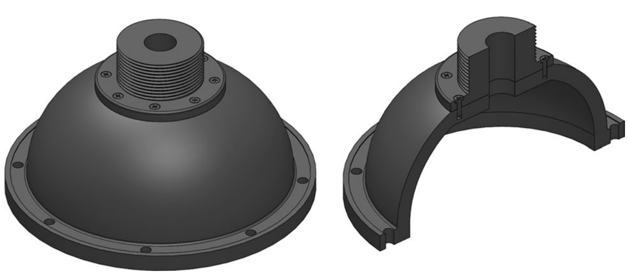


Fig. 7 Initial design (left: isometric view, right: cross-sectional view) of a housing cover

with the housing cover assembly are housing, shaft bearing, and shaft. They are considered as a super-system of the housing cover system.

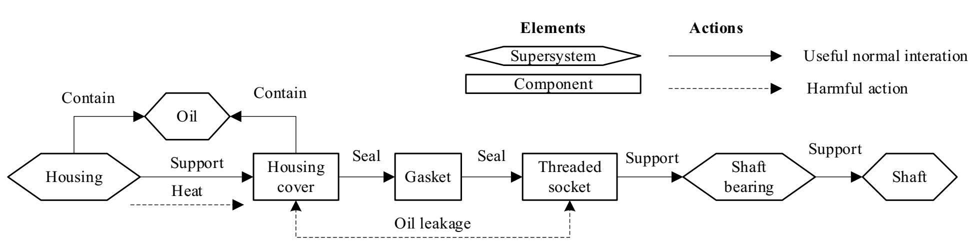
In Fig. 8, the solid arrow line indicates a useful interaction, and a dashed arrow line indicates a negative interaction. The customer requires the weight of the housing cover to be reduced and the leakage to be prevented. In addition, the heat generated inside the housing needs to be effectively removed to the environment. This requires 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) facilitating heat removal, and (3) reducing the weight of the part without compromising its original volume. Each functional requirement was first transformed to corresponding design parameters, which are derived by the inventive problem-solving through TRIZ. Then, each identified design parameter was entered using the keyword list of the additive manufacturing database, which in turn displays relevant additive manufacturing capabilities. The process of mapping these functional requirements to corresponding design parameters and design parameters to additive manufacturing process capabilities is explained below.

- *Functional Requirement 1* (*Preventing Leakage*): The functional analysis diagram (see Fig. 8) shows that there can be leaks between the housing cover and the threaded socket. The first functional requirement is to prevent this leakage. The problem formulation of the functional requirement is to "avoid the leakage while maintaining the stability of the part," and this design problem is expressed as a contradiction between the TRIZ parameters *23*: *Loss of substance* and *13*: *Stability of the object*. Herein, the TRIZ principle *2*: *Taking out*, defined as "separate an interfering part or property from an object, or single out the only necessary part property of an object" [68], of all possible solutions is found applicable to the design problem. Hence, a solution for the functional requirement inferred from the TRIZ solu-

Fig. 8 Functional diagram of a housing system



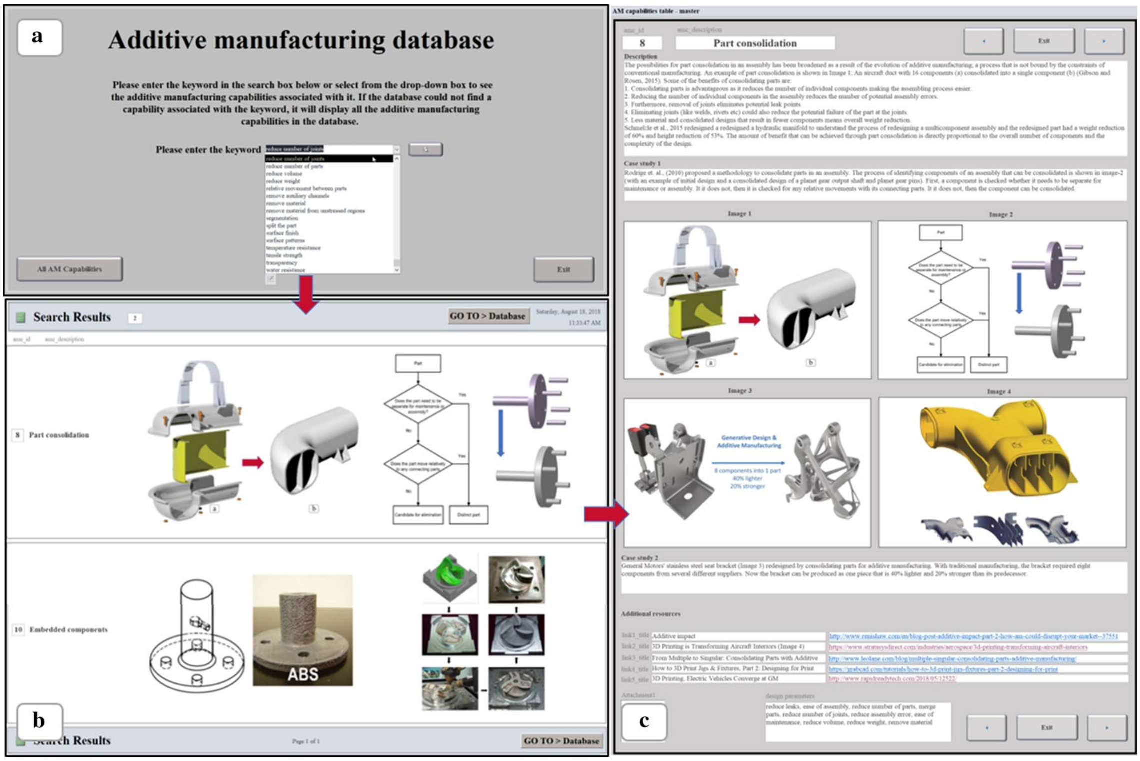


Fig. 9 Derived additive manufacturing capability (reduce number of joints—part consolidation)

tion can be to "avoid the gap between the parts or joining the parts altogether," and this can be further simplified as "reducing the number of joints." The database search recommends two possible additive manufacturing capabilities (i.e., part consolidation and embedded components); "part consolidation" is finally selected as the design parameter that is directly related to the functional requirement (see Fig. 9).

- *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 formulation of the second functional requirement is to "increase the heat transfer to surrounding area while maintaining the stability of the part." Then, its solution can be to "increase surface area or reduce temperature gradient" inferred from the TRIZ principle *35*: *Parameter changes*, defined as "change an object's physical state, and change the temperature" [68]. This TRIZ principle is obtained as a solution for the contradiction between the TRIZ parameters *17*: *Temperature* and *13*: *Stability of the object*. By increasing the surface area on the housing cover, the convective heat transfer can be improved. Therefore, its relevant design parameter can be to "increase surface area." The most related additive manufacturing capability associated with this parameter is "thin or small features" among four possible capabilities (i.e., internal channels, infill modifications, lattice structures, and thin or small features) identified from the additive manufacturing database. Additive manufacturing technologies can create features such as thin walls (heat fins) and blades that can increase the surface area of an object. Hence, "thin or small features" is selected as the additive manufacturing capability corresponding to the design parameter as shown in Fig. 10.
- *Functional Requirement 3* (*Reducing Weight*): The formulation of the third functional requirement is to "decrease the weight of the object while maintaining the original volume of the part," and its solution is to "decrease the quantity of material or density of the material" inferred from the TRIZ principle *35*: *Parameter changes* (i.e., "change an object's physical state" [68]) for the contradiction between *2*: *Weight of stationary* and *13*: *Stability of the object*. Hence, the solution for the functional requirement can be to "decrease the quantity of material or decrease the density of the material," and the related design parameter becomes "material removal." Three additive manufacturing capabilities (i.e., topological optimization, lattice structure, and composite materials) are identified from the database, and "lattice structure" is selected as the additive manufacturing capability (see Fig. 11). Topological optimization and composite material are not suitable for this case since

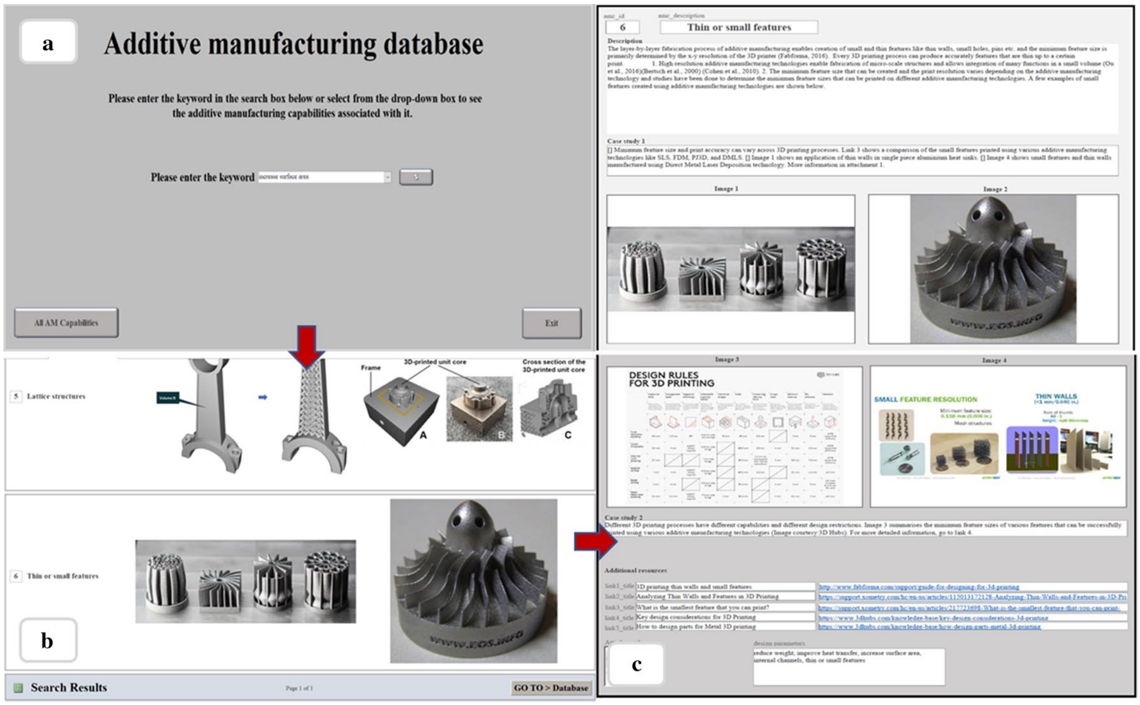


Fig. 10 Derived additive manufacturing capability (increase surface area—thin or small features)

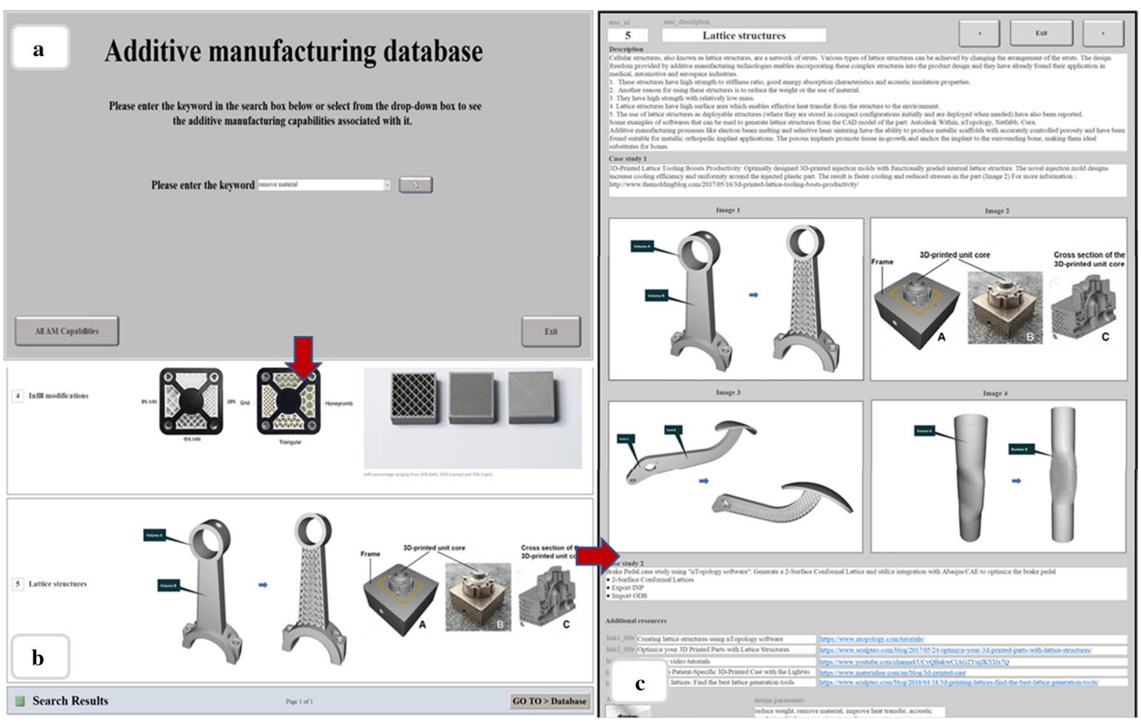


Fig. 11 Derived additive manufacturing capability (material removal—lattice structure)

the shape of the cover cannot be changed. In addition, composite material is not suitable due to the material property requirements of the part.

The resultant functional requirements, corresponding design parameters, additive manufacturing process capabilities demonstrated are summarized in Fig. 12.

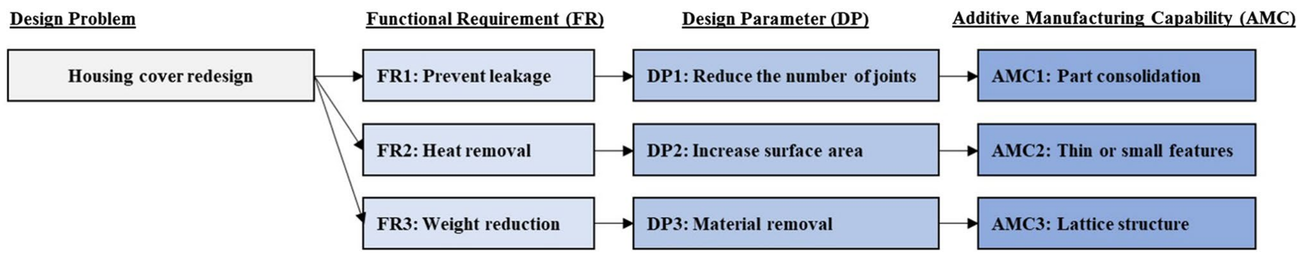


Fig. 12 Summary of derived design considerations for hosing cover redesign

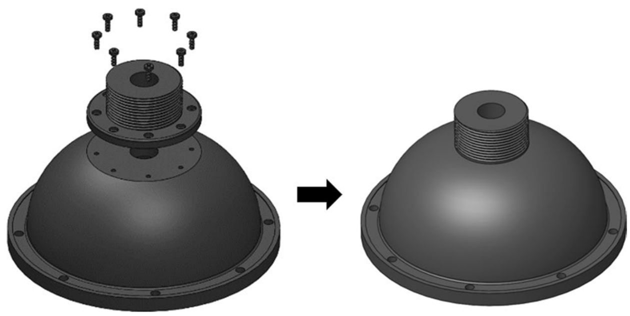


Fig. 13 Initial design (left) and consolidated design (right)

4.1.2 Embodiment Design Phase

Three additive manufacturing capabilities were identified in the conceptual design phase: part consolidation, thin or small features, and lattice structure. These capabilities were incorporated consecutively into the product design to create a preliminary design.

The first step in this phase was 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 (see Fig. 9). According to the database, parts that do not need to be separated for maintenance or assembly are candidates for part consolidation. Based on this information, housing cover and threaded socket are decided to be combined as a single part. The initial design and the consolidated design of the housing cover are shown in Fig. 13.

The second additive manufacturing capability identified was "thin or small features." According to the database, AM technologies can create small and thin features such as thin walls, small holes, and pins. The minimum feature size is primarily determined by the x–y resolution of the 3D printer. This capability was used to create thin fins on the housing cover. These fins can increase the surface area, and thereby 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 are shown in Fig. 14.

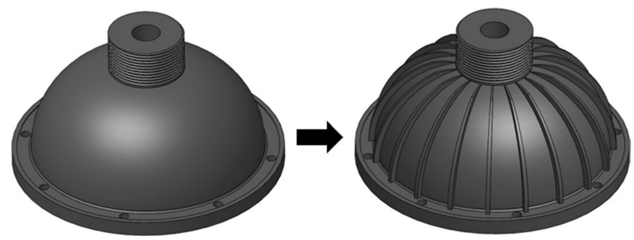


Fig. 14 Consolidated design (left) and modified design with thin fins (right)

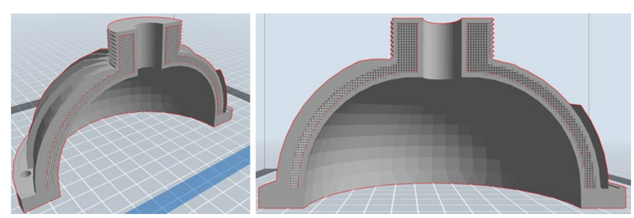


Fig. 15 Modified internal structure by adding a lattice structure

The third additive manufacturing capability identified was "lattice structure." The additive manufacturing database shows that a lattice structure is a network of struts with high strength to stiffness ratios. The database also provides software information that can incorporate lattice structure into a CAD model. The design created in the previous step (with fins) was modified by incorporating a lattice structure to the internal structure of the housing cover (see Fig. 15). The lattice structure was generated using *nTopology Element* [69].

4.1.3 Detailed Design Phase

The final preliminary design was refined by considering the process constraints and specifications for tolerance, minimum feasible feature size, and support structure. Fillets were added to the edges to avoid stress concentration. The refined design was analyzed using finite element analysis (FEA) software [67] to compare the thermal loads on the original part and the redesigned part (see Fig. 16). Figure 16

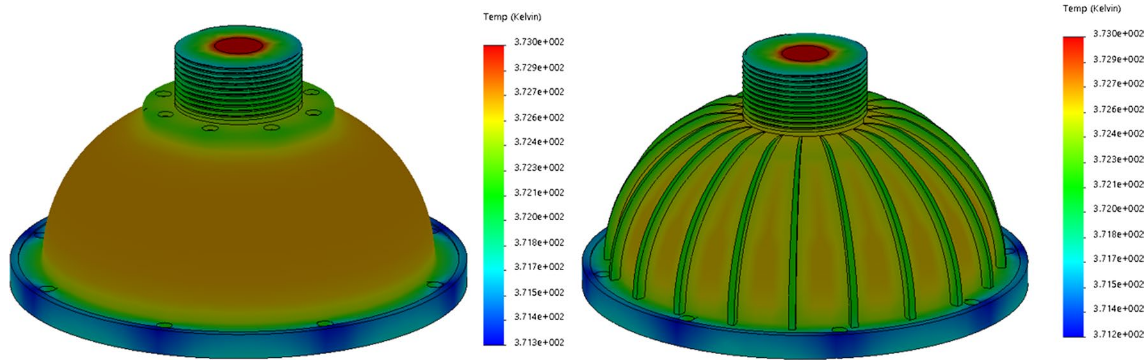


Fig. 16 Thermal analysis between original design (left) and new design (right)

Table 3 Comparison between original design and redesign

Properties	Original design	Redesigned part
Design		
Number of parts	10	1
Surface area (mm^2)	276,412	278,939
Mass (g)	360.8	237

shows that the steady-state temperature distribution is more uniform in the new design.

Table 3 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 these parts have been combined as a single part in the new design. Furthermore, the number of individual components is reduced from 10 components in the initial design to one part in the final design. The surface area on the outer surface of the cover increases in the redesigned part which has better convective heat exchange with the surroundings and a uniform temperature distribution. The weight of the redesigned part is also less compared to the original part (i.e., 34% reduction).

5 Discussion and Conclusions

Additive manufacturing has emerged as an integral part of modern manufacturing because of its unique capabilities. In order to take full advantage of the capabilities offered by additive manufacturing technologies, DfAM has risen to provide tools and guidelines during the product design process. However, there is a lack of design frameworks in the existing DfAM approaches to effectively infuse additive manufacturing capabilities into product design during the early design process. To address this issue, this study presents a design framework for additive manufacturing based on the synergetic use of axiomatic design and TRIZ supported with an additive manufacturing database. Under the proposed framework, a design problem is systematically defined in terms of functional requirements, design parameters, and additive manufacturing capabilities in an axiomatic design structure. The inventive problem-solving approach of TRIZ is used to identify the design parameter corresponding to each functional requirement, and an additive manufacturing database that contains information about general additive manufacturing capabilities is used to identify the specific additive manufacturing capabilities corresponding to the design parameters.

A case study for housing-cover redesign was presented to demonstrate the proposed design framework. The functional requirements of the housing-cover were leakage prevention, improved heat removal, and weight reduction. The design problem was systematically decomposed into functional requirements, design parameters, and additive manufacturing capabilities in the conceptual design phase. The design parameter for each functional requirement was identified using TRIZ, and the additive manufacturing capabilities corresponding to the design parameters were identified using the additive manufacturing database. The original part was then redesigned by applying the additive manufacturing capabilities in the embodiment and detailed design phases. The results showed that the redesigned part has improvements in structural properties, and the proposed design framework can be effectively used to transform an original product design for traditional manufacturing into a new design suitable for additive manufacturing by incorporating the additive manufacturing capabilities into the product design. Furthermore, the additive manufacturing database with its search interface is beneficial for additive manufacturing novices.

Additive manufacturing technologies are evolving at a fast pace with the development of 3D printers having better capabilities. 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 through additive manufacturing technologies tends to be higher in comparison to most conventional manufacturing methods. This is primarily due to the higher cost of raw materials and the relatively low machine productivity in 3D printing [70]. However, the technological advancements in the field of additive manufacturing technologies are expected to lower the prices and to improve the productivity of additive manufacturing machines [71]. Additive manufacturing is still maturing, and thus this study has not considered cost-reduction as a primary functional requirement. The current study is aimed at improving the design of a part under consideration by leveraging the capabilities offered by AM technologies. This study focuses on the conceptual design phase, and its primary objective is to support a designer by facilitating the consideration of additive manufacturing capabilities in the conceptual design phase. The DfAM approaches reviewed in the literature have not widely discussed a direct method to map functional requirements to additive manufacturing capabilities.

For future work, this study could be extended to consider various additive manufacturing conditions such as process selection and optimal design selection if there are more than one design that satisfies the functional requirements. Since the current study focuses on the conceptual design phase, the embodiment design and detailed design phases should be further improved to provide more effective guidelines for users to refine initial concepts from the proposed design framework. Although possible trade-offs between additive manufacturing capabilities are not addressed in the current study, another additive manufacturing database with information about the design rules and process specific constraints could be created to support users during the embodiment and detailed design phases. For example, a new TRIZ database system that can generate design solutions from a contradiction matrix of additive manufacturing capabilities may be very helpful for the selection of specific additive manufacturing capabilities.

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