COLLATION OF DESIGN KNOWLEDGE FOR SYSTEMATIC DESIGN FOR ADDITIVE MANUFACTURING AND TRIZ SYNERGISTIC APPLICATION

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Graphical abstract
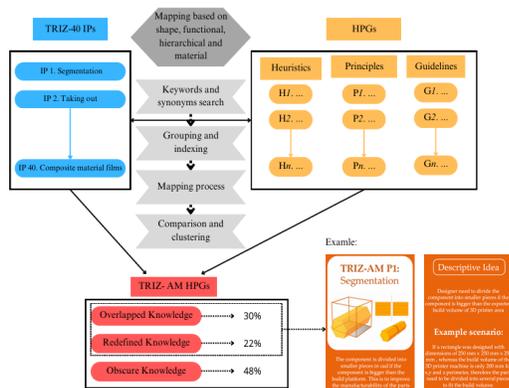
Abstract

Systematic Design for Additive Manufacturing (DFAM) information should be provided throughout the product design and development lifecycle to enable designers to capture creative design solutions. Formalized design methods were more effective to ease DFAM utilization by designers. This study aims to collate DFAM knowledge in terms of design heuristics, principles and guidelines (HPGs) that can be synergized into a structured problem-solving technique such as Theory of Inventive Problem Solving (TRIZ) using Inventive principle (IPs). The approach is by mapping the HPGs through classical TRIZ 40 inventive principles based on four AM complexities: shape, functional, hierarchical and material. Six steps procedures were performed, and the mapping process leads to four knowledge clusters categorization within TRIZ and HPGs which include overlapped knowledge, unique knowledge, redefined knowledge and obscure knowledge. The mapping outcome reached 30% for overlapping knowledge, 22% of the 40IPs requires further analysis and appropriate to be redefined to suit AM applicability and 48% for obscure knowledge potential for future AM evolution. To demonstrate the applicability between the combination of TRIZ-DFAM, a conceptual case study was proposed involving a belt roller support to illustrate how AM users can creatively design innovative AM parts using the TRIZ-AM HPGs catalogue.

Keywords: Design for Additive Manufacturing, design methods, TRIZ, Additive Manufacturing, inventive principles

Abstrak

Maklumat Rekabentuk Sistematik untuk Pembuatan Aditif (DFAM) harus disediakan sepanjang rekabentuk produk dan kitaran hayat pembangunan untuk membolehkan pereka bentuk mendapat penyelesaian rekabentuk yang kreatif. Kaedah rekabentuk formal adalah lebih berkesan untuk digunakan oleh pereka bentuk menggunakan kaedah DFAM. Kajian ini bertujuan untuk mengumpul pengetahuan DFAM dari segi heuristik reka bentuk, prinsip dan garis panduan (HPG) yang boleh disinergikan ke dalam teknik penyelesaian masalah berstruktur seperti *Theory of Inventive Problem Solving* (TRIZ) yang menggunakan prinsip Inventif (IP). Pendekatannya adalah dengan memetakan HPG melalui prinsip inventif TRIZ 40 klasikal berdasarkan empat kekompleksan AM: bentuk, fungsi, hierarki dan bahan. Enam langkah prosedur telah dilakukan, dan proses pemetaan membawa kepada empat pengkategorian kluster pengetahuan dalam TRIZ dan HPG yang merangkumi pengetahuan bertindih, pengetahuan unik, pengetahuan yang ditakrifkan semula dan pengetahuan yang tidak jelas. Hasil pemetaan mencapai 30% untuk pengetahuan bertindih, 22% daripada 40IP memerlukan analisis lanjut dan sesuai untuk ditakrifkan semula agar sesuai dengan kebolehgunaan AM dan 48% untuk potensi pengetahuan yang tidak jelas untuk evolusi AM masa hadapan. Untuk menunjukkan kebolehgunaan antara gabungan TRIZ-DFAM, satu kajian kes konseptual telah dicadangkan melibatkan sokongan penggelek tali pinggang untuk menggambarkan cara pengguna AM boleh mereka bentuk bahagian AM yang inovatif secara kreatif menggunakan katalog TRIZ-AM HPGs.

Kata kunci: Reka bentuk untuk Pembuatan Aditif, kaedah rekabentuk, TRIZ, Pembuatan Aditif, prinsip inventif

1.0 INTRODUCTION

Additive Manufacturing (AM) has revolutionized the way products can be made. It allows designers to have flexibility in creating complex geometric products with new functionalities, shapes and materials. In many instances, designers are facing great challenges in designing AM products resulting in an increasing number of design iterations along the product design phases [1]. The reason for the challenges lies mainly in the persistent use of traditional design thinking and methods which in most cases do not match the capabilities of AM [2]. With the intention to guide designers and to facilitate AM design activities using formal and structured methodologies, a new design concept called Design for Additive Manufacturing (DFAM) emerged. Originated from Design for Manufacturing (DFM) [3], DFAM aims to ease the design and production of any part or product development for AM. It allows designers to utilize a set of AM design knowledge such as design heuristics, design principles, design guidelines, and design rules during design process in a more holistic and guided way [4, 5]. DFAM knowledge is used to formalize design fundamentals so that innovative practices may be applied in future design problems, which may later be used to advance design science [6]. For the past ten years, an exponential growth was found in the DFAM-related studies which signify its importance [7, 8]. Wide spectrum of strategies, approaches and frameworks were developed to accommodate effective DFAM. In addition, the research focus varies from early up to late AM product design and development phase. Formalized AM design methods have been found to be effective in easing the utilization of DFAM especially for beginner designers [9]. Design approaches such as part consolidation [10], axiomatic design [11], topology optimization [12], integration with traditional design for manufacturing and assembly (DFMA) [13], integration with quality deployment functions (QFD) [14], combined with generative design (GDFAM) [15], restrictive design knowledge and biomimicry [16] have been used as part of the design methodology. It should be universal enough to accommodate a range of AM technologies and applications. The complete feature covers the entire range from early phase (e.g. product planning and conceptual design) to late phase (e.g. embodiment and detailed) product design and at the same time must be flexible for future design fundamentals to be extended and upgraded. Finally, practicality refers to ease of use in exploiting the correct design knowledge at the right design phase. Furthermore, looking from a design perspective, it is important to understand AM capabilities and limitations and to apply them in the right applications [17]. However, existing DFAM methods described in the literature seem to miss one or more of these features.

There is also research that focuses on integrating the Theory of Inventive Problem Solving (TRIZ) into DFAM as a structured creativity method in the design process. TRIZ was recognized for its efficiency and systematic product ideation [18]. The most commonly used TRIZ tool is the collection of the 40 Inventive Principles (40IPs) [19] deducted from thousands of patents. Each IP consists of a group of generic solutions that solve technical contradictions [20]. The premise of TRIZ is that improving one aspect of a design negatively affects another. These contradictions and suitable 40IPs can be presented using the contradiction matrix, which is also known as the Altshuller matrix [21]. The successful use of TRIZ in accommodating the design process is found in many design-related studies [18]. However, its adoption in DFAM is still at its early stage. To date, a small number of articles have been reported, as gathered by Motyl and Filippi [22]. The TRIZ tools, including inventive principles and contradiction matrix, have been applied in various studies, indicating their potential for practical application in DFAM design. There are limitations which include; (i) the usage of TRIZ is highly dependent on the available AM examples and direct usage of the classical TRIZ 40IPs which are subjective to researchers' problem-solving viewpoints; (ii) the 40IPs of TRIZ do not cover all new innovative principles represented by AM design knowledge; and (iii) the existing innovative principle of TRIZ could not solely provide inclusive solutions to be applied to all AM technologies and terminologies. Therefore, further research is required to enhance the applicability of TRIZ into AM environment.

This paper attempts to overcome the above-mentioned limitations by collating and analyzing the relevant literature related to TRIZ and DFAM. As direct answers to the limitations, the paper attempts to (i) map specific AM specific characteristics with the available DFAM knowledge; (ii) enhance TRIZ inventive principles dedicated to AM; and (iii) evaluate AM design knowledge interaction in the context of innovative problem-solving methods. This paper also presents a systematic methodological DFAM framework based on the synergistic use of TRIZ and DFAM. The rest of the paper is arranged as follows: Section 2 comprehensively discusses previous DFAM-related studies meanwhile Section 3 presents six steps procedures for collating design knowledge and the mapping process of TRIZ principles to existing DFAM problem solving methods from literature. Evaluation of the mapping approach was also given. Section 4 presents the results, analysis and discussion of the mapping and process and finally, Section 5 presents the conclusion.

2.0 DESIGN FOR ADDITIVE MANUFACTURING (DFAM)

In the context of product design, DFAM knowledge can be formalized as typologies of design heuristics, principles, guidelines, and rules, each with targeted level of knowledge representation, separated into design guidance and manufacturing process guidance

[7]. For brevity, the typologies are collectively referred to as heuristic-principle-guidelines (HPGs). The detailed definitions and types of approaches for each of these typologies as reported by Pradel *et al.* [7] are presented in Table 1.

Table 1 DFAM typologies with their approaches

Typology	Types of approach
Design heuristics (DH)	Creative product analysis, protocol analysis, comprehensive literature review, user study, qualitative analysis
Design principles (DP)	DFX/DWX, TRIZ, Axiomatic Design, Quality Functional Deployment, Biomimetic, Constructal Theory,
Design guidelines (DG)	Metrology, topology optimization, worksheet, catalogue, repository
Design rules (DR)	Part consolidation, worksheet, catalogue, repository

2.1 Grouping of DFAM knowledge

The growth in DFAM studies has increased exponentially over the past five years. The related works were categorized into five groups according to their focuses as follows:

i. Group 1 – Review or survey articles related to DFAM and basic philosophical definition of DFAM.
ii. Group 2 – Studies on DFAM guidance system development and its ontologies.
iii. Group 3 – DFAM related work with little emphasis on formal design method utilization.
iv. Group 4 – Studies on application-oriented DFAM where design methods or frameworks are specific to certain applications, domains or technologies.
v. Group 5 – Studies of DFAM framework development utilizing innovative design methods, knowledge and strategies.

Group 1 basically concerns studies related to review, survey or its general introduction. In Group 2, the research aims mainly to develop a computerized DFAM platform as an effective way to demonstrate the key success of design methodologies. Major focus ranging from assisting software developer to provide interactive DFAM platform [23], which defining the ontologies for supporting AM designers to utilize the platform at an operational level [24]. The final three groups (Group 3, 4, and 5) involve studies that relate DFAM with design methods fundamentals but with different strategies and directions. Group 3 covers basic design methods utilization related to DFAM with no formal or limited structured methods

being discussed. Group 4 emphasizes a more practical direction in implementing the available DFAM for related areas or applications. For example, development of DFAM were performed to accommodate specific AM technological requirements such metal-based printing [25, 26], tissue engineering [27], or specific materials. Finally, Group 5 focuses on DFAM framework development with the orientation to boost scientific dissemination of design methods in various design phases within AM product development phases [28]. This study examines Group 5 focuses on DFAM framework development, enhancing existing design methods, introducing new taxonomies, and applying innovative strategies for AM development scenarios.

The discussion focused on design knowledge, typologies, principles, guidelines, rules, and processguidelines, and differentiated between informal and formal design methods through in-depth discussion.

DFAM studies start to grow around 2015 with the majority of research utilizing some innovative design methodologies either formally or informally. Several design approaches have been proposed to help designers, such as modular graph technique, brainstorming, part consolidation, feature repository database [29], principle catalogue [30], worksheet [31], and even TRIZ. TRIZ is a technique for conceptual ideation and embodiment design which requires more iteration to produce successful results

because it lacks organized techniques for DFAM's practical application. Analyzing further on the reported studies, the advances of design methods and their approaches can be presented by the last three groups (Groups 3, 4, and 5), and best be viewed in a form of illustrative categorization chart given in Figure 2. The representation of research in Figure 1 was utilized to classify the research approaches taken by these studies.
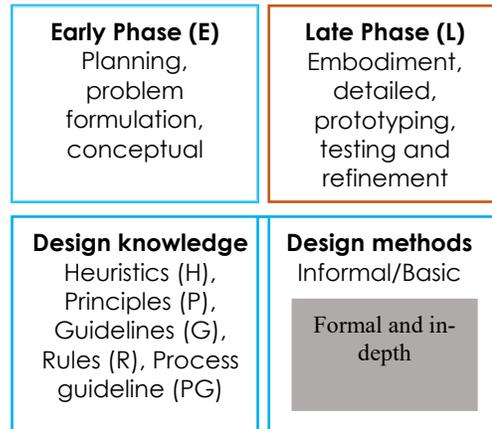

Figure 1 Representation of research based on different phases, typologies and methods
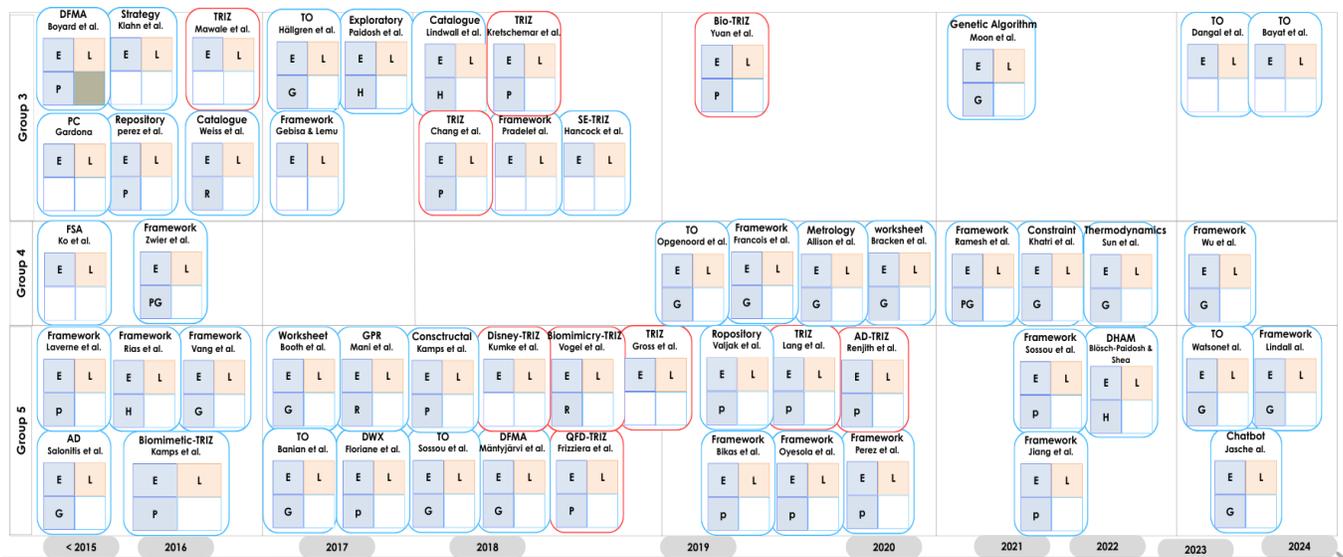

Figure 2 Overview of DFAM studies using various design methods and targeted knowledge

Figure 2 clearly indicates that quite a large amount of DFAM studies were developed for the past five years utilizing a range of design strategies and methods as well as proposing innovative DFAM frameworks. Limited research, however, was found on the specific DFAM for certain applications or technologies (Group 4) as compared to the generic DFAM implementation (Group 3 and Group 5). TRIZ-based design methods in

supporting DFAM were also found in several reported studies which highlights its significant adoption towards supporting a formal AM design process. The following will emphasize to elucidate the contributions of the research work in these three groups:

Group 3 – Earlier studies within this group mostly neither emphasize specific design knowledge nor discuss in detail the utilization of innovative design

methods. From Figure 2 it can also be seen that several design frameworks were proposed. For example, environmental impacts towards DFAM where design optimization was integrated with Life-cycle assessment (LCA) in the early design stages were proposed [32]. Pradel *et al.* [7] presented a conceptual framework for mapping current DFAM knowledge onto the typical design process based on a systematic literature review approach. Klahn *et al.* [17] presented two design strategies; manufacturing driven design strategy and function driven design strategy, in adopting the benefits of AM product development. Moon *et al.* [33] applied genetic algorithm design to metal AM to design and manufacture a three-dimensional heat exchanger (HX). Danga *et al.* [34] investigated the effect of AM constraints and three different design objectives (i.e., compliance, stress, and multi-objective) on topology optimization of structures. Series of work was conducted by Blösch-Paidosh and Shea in 2017,2019 and 2022 in presenting 25 AM design heuristics based on AM artefacts [35-37]. The work abstracted high-level design concepts and has raised attention to realize that AM heuristics have positive influence on improving the generated design in the early design phase.

The TRIZ-based studies in this group with each diversified in terms of the focus were reported by different researchers in their research work .Yuan *et al.* [38] utilized TRIZ-based design methods in generating conceptual solutions of 3D printed vibratory scaffold (3DPVS). The application of TRIZ was also applied in various AM product developments. For instance, Chang *et al.* [39] applied TRIZ for the innovation of a dashed line pen; however, the study did not employ innovative AM design methods. Five TRIZ principles were chosen to demonstrate the usage of TRIZ based on the AM development process. Hancock *et al.* [40] employed TRIZ for design improvement of heat flux for nuclear fusion, however, lacks further elaboration on how TRIZ principles were incorporated to overcome design conflicts during the concept generation process. Other reported DFAM approaches include part consolidation, repository, catalogue, and topology optimization. Hällgren *et al.* [21] demonstrated the DFAM concept, combining topology optimization with experience and design rules, but did not provide a formal design method.

Group 4 - Specific DFAM framework for Powder Bed Fusion (PBF) technology were reported by several researchers. One strategy that utilized geometry for additive part selection (GAPS) worksheet was proposed by Bracken *et al.* [25] to represent design guidelines extracted from literature. Khatri *et al.* [41] printed porous Nylon 11 material using the PBF technique, demonstrating the basic steps of design rules and fabrication constraints through the design of the lattice. For describing design guidelines, Allison *et al.* [42] utilized metrology study approach where design was focused on geometric resolution and accuracy of Selective Laser Sintering (SLS) polymer parts. Focusing on the Laser Beam Melting (LBM) process, François *et al.* [43] developed a DFAM framework that highlighted specific guidelines dedicated for microwave waveguide components. Sun *et al.* [44] proposed solutions to the phenomenon of hot cracking of metallic materials in the additive manufacturing process. Wu *et al.* [45] proposed a framework for optimized design for ceramic material 3D printing through machine learning (ML). In a design domain, Zwier and Wits [46] presented a DFAM approach for supporting the build orientation selection by using a feature-based design algorithm. The design tool offers insights into the impact of build orientation, aiding in design optimization strategies, but no formal design methodologies were discussed.

Group 5 – DFAM frameworks with in-depth elaboration using diversified design method approaches were found in several studies. Bikas *et al.* [47] utilized AM design aspects and considerations to define part's geometry throughout the design phases in reducing the number of design iterations. Sossou *et al.* [48] proposed an assembly-focused DFAM framework that takes advantage of AM for part integration and assembly-free mechanisms by considering structural minimization. Lindall *et al.* [49] proposed a framework for nurturing designers' creative abilities. Oyesola *et al.*[50] proposed an integrated design methodology with decision tools to assist the designers in developing new knowledge using DFM and Concurrent Engineering principles. Similarly, Floriane *et al.* [51] incorporated a traditional design perspective with DFAM development, utilizing a 'just in time' methodological approach based on Design with X, and interviewed 14 designers early in an innovative industrial project. Ranjan *et al.* [28] studied innovative design methodology for the formulation of design guidelines using feature graph-based and topology optimization. A deterministic approach using Constructal Theory was presented by Kamps *et al.* [52]. With the continuous development of computer technology, Jiang *et al.* [53] proposed a framework for integrating machine learning (ML) in AM, which utilizes ML to learn the complex relationship between design and performance space. Jasche *et al.* [54] developed a chatbot to introduce users to 3D printing and guide them through design. Watson *et al.* [55] proposed a generative design methodology using TO to achieve fast and automatic solution generation to solve the structural design problems faced by AM products. Other approaches such as design worksheet [31] and repository [56] were useful for presenting the design knowledge for designers to find potential design solutions. However, the classification and presentation of these concepts often use informal terminologies, which can lead to misinterpretation and confusion due to potential overlaps in principles and definitions.

2.2 TRIZ-DFAM: Synergistic Methodology

According to the survey by Ilevbare *et al.* [18], 85% of the industrial workers use TRIZ for technical problem solving, meanwhile, the survey significantly showed that 61% of the respondents use TRIZ for product design and innovations. Recently, a study reported by Chen

et al. [57] has described the synergizing between the human-computer interaction (HCI) with TRIZ in product innovations[57]. The literature revealed that among 444 initial findings on TRIZ, only 17 studies was reported the outcomes of synergizing related to the combination of HCI and TRIZ. However, researchers are progressively discussing the use of TRIZ in computing systems where the study on managing Artificial Intelligence (AI) are the major focus and outcomes [58]. TRIZ methodology has been successfully applied in the context of DFAM, alongside advancements in AM[59].

A recent study by Motyl and Filippi [22] verified that the increasing in interest to adopt TRIZ as a method for the resolution of design issues in AM. The article highlights TRIZ and AM combination research applications, but only a few detailed discussions detailed on methodology and strategies for formalizing AM design knowledge to aid designers. Gross *et al.* [60] proposed a TRIZ matrix for AM based on a compilation of design rules obtained from the literature, which leads to a result of 18 AM inventive principles. In our previous work, Mazlan *et al.* [19] presented 26 TRIZ-AM design principle cards adapted to AM capabilities to assist designers in the detailed design and manufacturing phases of additive manufacturing. TRIZ-AM as a result of the synergy between TRIZ and DFAM can be effective in helping designers to reduce design iterations and increase design success when designing AM products. As a DFAM design method, this study present the flow of a designer using TRIZ-AM to redesign a product is shown in Figure 3.
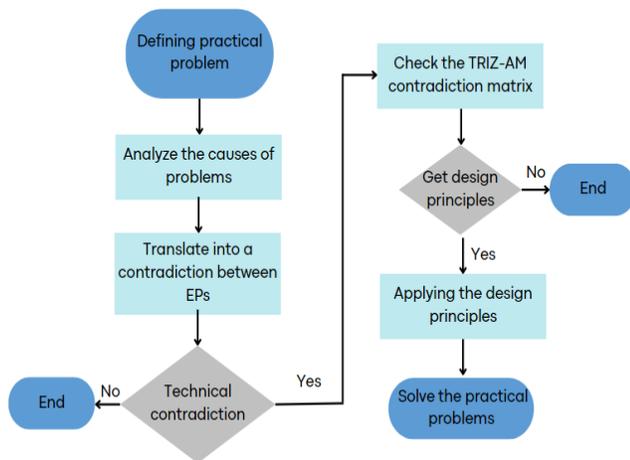

Figure 3 Flowchart for utilization of TRIZ-AM.

Besides advancing TRIZ tools for AM, some studies integrated TRIZ with other design methods such as Axiomatic Design (AD) proposed by Renjith *et al.* [61] and Quality Functional Deployment (QFD) by Frizziero *et al.* [14]. Hamzehei *et al.* [62] also compared the novel bio-inspired designs with an auxetic material and developed a bionic lattice design that has a better ability to maintain stability while providing high energy

absorption and was applied to apply to a scooter deck.

Therefore, TRIZ techniques and AM design have proven effective in increasing quality ideas, and synergizing with the DFAM method and enhanced TRIZ principles could lead to systematic design utilization.

3.0 METHOD FOR SYNERGIZING DFAM KNOWLEDGE WITH TRIZ PRINCIPLE

In this study, the HPGs interaction obtained from previous studies was used as the basic fundamental to represent the DFAM knowledge. The definition described by Pradel *et al.* [7] in differentiating the boundary of the DFAM knowledge were utilized. The overall methodology of synergizing TRIZ with DFAM knowledge in terms of HPGs was performed based on the six steps as shown in Figure 4 [63, 64].
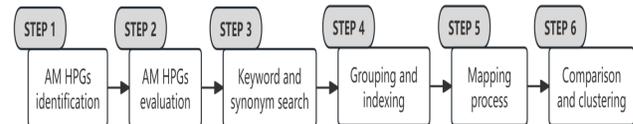

Figure 4 Six steps procedure to synergize DFAM knowledge with TRIZ principle

The six steps procedures are as follows:

Step 1: Identifying and collating the AM HPGs origins where HPGs were directly extracted and labelled.

Step 2: Evaluating the AM HPGs for their originality and consistency of terminologies.

Step 3: The study identifies keywords and synonyms in the classical TRIZ 40 inventive principles (40IPs) and AM HPGs, using variations until satisfactory results were obtained.

Step 4: Mapping and selecting potential HPGs related to 40IPs.

Step 5: Grouping and indexing of the HPGs and analyzing their connection to the inventive principles in terms of their complexities.

Step 6: Comparing and performing knowledge clustering of the compiled HPGs.

The study aims to compile AM design knowledge by identifying heuristics, principles, and guidelines (HPGs) from previous studies. The evolution of DFAM knowledge was then clarified, labelled and mapped with the classical TRIZ 40IPs. Before mapping was performed, every HPGs were studied and rephrased based on the suggested text similarity proposed by Cong and Tong [65] with some enhancements, in order to facilitate the comparison process as well as highlighting the keywords of interest. Table 2 portrayed examples of the 40IPs together with the related keywords and their synonyms.

Table 2 Example of variation of keywords and synonyms used for HPGs

#	Principle	Related keywords and synonyms*
1	Segmentation	Segment, division, separate, breakdown, multiple, section
6	Universality	Universe, complete,
7	Nested doll	Interlocking joints
26	Copying	Copy, duplicate, replicate
30	Flexible shells and thin films	Thin walls, wrap
31	Porous material	Porosity, lattice, spongy material, permeable material, absorbent material, hole, cavity
34	Discarding and recovering	Discard, recover, reject, disposable, remove
40	Composite material	reinforced material, filler-added materials, compound, multi-material

The listed keywords and synonyms only represent the example of core word phrase used in a different form. For example, porous material is represented by different phrases such as "porosity", or "lattice" and universality is represented by "Universe", or "complete".

HPGs interaction mapping list procedure with respect to classical TRIZ 40 inventive principles was described (Figure 5). The inventive principles together with the obtained HPGs were grouped and briefly defined for ease of mapping process. The first group was marked with index IP1 to IP40. The group were then categorized based on four design complexities [66]; (i) material complexity, (ii) shape complexity, (iii) functional functionality, and (iv) hierarchical complexity.

It was also noted that some of the extracted HPGs were perceived as extension from the previous readily available AM knowledge. These extensions may range from extended database search, user study, observations, and experiments up to upgrading the HPGs definitions. The HPGs were interpreted as design principles or guidelines and rearranged and grouped. Interaction mapping was performed based on 40IPs, and was identified based on four clusters for comparison as listed below:

i.   HPGs with similar meaning in their descriptions or terminologies should be merged and termed as 'Overlapped knowledge'.
ii. HPGs with no common descriptions or terminologies should be further evaluated and termed as 'Unique knowledge'.
iii. 40IPs with no overlapping with any HPGs, however, applicable to AM, should be further evaluated, redefined and termed as 'Redefined knowledge'.
iv. 40IPs with no overlapped with any HPGs, however, are vague in the description and may not be applicable to AM, should be eliminated and termed as 'Obscure knowledge'.

The first comparison involves the 40IPs, taken as the benchmark, with the first HPGs group. Each of the DFAM knowledge was then compared row by row to observe any overlapping of keywords, synonyms or terms. If no overlapping was detected, the HPGs were placed at the final row for further clustering. The main reason is to highlight the visibility of unique AM HPGs that do not coincide with the classical 40IPs. This will then be useful for further evaluation and upgrade of the 40IPs relevant to AM. Secondly, the next design knowledge was compared and mapped with the 40IPs as well as other HPGs, and other subsequent design knowledge will continue to follow this comparison trend. The end of comparison will lead to a pattern of mapping and indexing where new HPGs were grouped and clustered accordingly. The final step involved merging the overlapped principles to the 40IPs in presenting new AM knowledge potential for further exploration and upgrade. The 40IPs with no match with any corresponding HPGs or vague in description in relation to DFAM were further analyzed in order to identify its suitability with AM application. The inventive principles were compared with existing DFAM knowledge, either redefined or obscured, and a final mapping list was recorded.
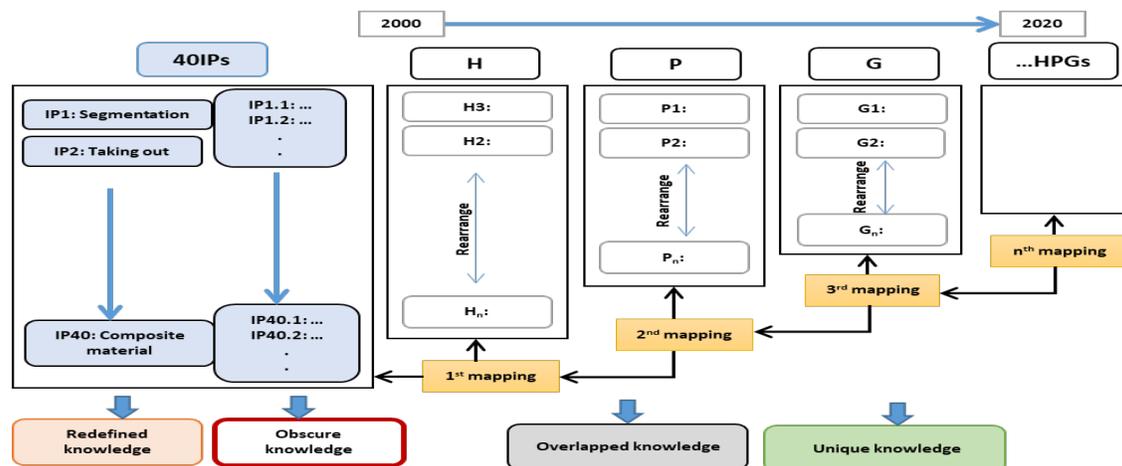

Figure 5 HPGs interaction mapping procedure.

4.0 RESULTS AND DISCUSSION

The research examines the correlation between AM-HPGs and TRIZ concepts to improve comprehension of DFAM. It also provides a conceptual demonstration showcasing the applicability of TRIZ within the context of AM HPGs.

The list of collated HPGs was mapped with TRIZ in their associated grouping is given in Table 3. A total of eight HPGs were compiled and later shortlisted to four, arranged and archived in order based on their developed timeline. Only HPGs from 2015 onwards were used for further evaluation and mapping since they are mostly being established based on previously reported AM knowledge. First heuristic group belongs to 29 AM Heuristics (29Ha) developed in 2017, extracted from over 200 AM artefacts [35]. The heuristics were first categorized into areas that are expected to fulfil the same or similar action. The term 29Ha was used to define the design heuristics. The second group involves 10 heuristics (10H) developed by Lindwall *et al.* [67] through user case study, in which results were based on reduction of the 29H that corresponds to the traditional selected DFM/A guidelines obtained from literature studies. The third heuristic group is presented by 29Hb as an improved version of the first heuristic group defined by 29Ha. The fourth heuristic group is proposed 25H[37] is further improved version from first heuristic group 29Ha [35] in 2017 and third heuristic group 29Hb [36] in 2019. The first design principle group belongs to the 23 AM principles (23P) developed by Perez *et al.* (2015). The second principle group composed of 12P reported by Booth *et al.* [31]. The

third principle group involved a work described by Valjak and Bojcetic [56]. After examination, it was found that the described principle by this study was not explicitly itemized which makes it difficult to be extracted. Valjak et al. [68] organized a design workshop in 2020 to explore the practical challenges of AM in the conceptual design phase. Then, they formalized 32 principles for AM design based on product functions [69]. Finally, the fourth principle group was obtained by a more recent work by Camburn *et al.* [70] which contains 23 unique principles specifically dedicated for AM composite design principles. The guideline group was found to be mostly embedded under the defined principles' group. Further evaluation was then performed for each of these HPGs to distinguish the appropriate heuristics, principles and guidelines for the mapping process. Furthermore, the 23 principles by Camburn *et al.* [70] were found to be mostly related to generic guidelines of composite materials development for AM and therefore were excluded from evaluation.

The process leads to four HPGs (10H, 25H, 23P, and 12P) as summarized in Table 3. Each HPGs was indexed using alphabet A, B, C and D to differentiate the HPGs contributed from a different author. For example, for alphabet A, it was referred to the 10 heuristic list by Lindwall *et al* [67]. Thus, in order to organize the collation for these heuristics, it was referred to as A.H1, A.H2 … A.H10. The examination of collated HPGs revealed some overlap between principles and guidelines as described by the 23P and 12P guidelines. The extracted guidelines were highlighted as (G) as shown in Table 3 and were excluded from further mapping process.

Table 3 Summary of the collated HPGs with their respected indexes and description

10H (Lindwall, 2018)		25H (Paidosh, 2022)		23P (Perez, 2015)		12P (Booth, 2017)	
A.H1	Integrated design	B.H1	Consolidate parts for better functional performance	C.P1	Preserve small features by printing them in an orientation which requires no support material	D.P1	Part orientation impacts surface finish, particularly with rounded features, and strength between horizontal and vertical components.
A.H2	Internal design	B.H2	Consolidate parts to reduce assembly time	C.P2	Preserve surface finish by printing artefacts in an orientation which requires no support material	D.P2	The removal of supports decreases surface finish and increases the need for post-processing, as support structures build as layers build.
A.H3	Interlocking features	B.H3	Consolidate parts to increase robustness	C.P3	Prevent part warping by minimizing residual stresses	D.P3	Hollowing out parts - When functionally possible, thick walls and hollow interiors can reduce print time
A.H4	Embedded design	B.H4	Consolidate parts to achieve multiple function	C.P4	Improve print success by orienting a part with the lowest vertical aspect ratio	D.P4	Manufacturing features - AM, although not requiring undercuts or draft angles, often produces prototypes that will eventually be manufactured using traditional methods.
A.H5	Embedded joints	B.H5	Customize geometry to use case	C.P5	Reduce weight, material cost, and preserve stability by replacing solid volumes with cellular structures	D.P5	AM processes have a finite build space and may necessitate breaking up large parts and joining them with interlocking features later.
A.H6	Form synthesis	B.H6	Customize user interface to use case	C.P6	Eliminate assembly steps and time by printing functional joints and interfaces directly	D.P6	Reduction of part count - If the AM part is intended as a final product, the number of parts in an assembly may be reduced
A.H7	Topology optimisation	C.H7	Customize artefact with decoration	C.P7	Integrate additional functionality by incorporating components or features in unused internal volumes	D.P7	Identification marks - When a company produces many parts, it is easy to lose track of which model is which

10H (Lindwall, 2018)		25H (Paidosh, 2022)		23P (Perez, 2015)		12P (Booth, 2017)
A.H8	Anistropic structures	B.H8	Convey information with color	C.P8	Enable custom processes by identifying features that are complex or require high levels of user-based customization	D.P8	Avoid sharp edges - Removing these results in better accuracy; rounding radii correlate with outer radii of simple-curved elements
A.H9	Multiscale structure	B.H9	Convey information with geometry	C.P9	Achieve desired mechanical properties by tailoring the geometry of the mesostructured	D.P9	Round inner edges - Rounding the edges simplifies the removal of disperse support structures (e.g., powder)
A.H10	Multi materials	B.H10	Convey information with haptics	C.P10	Reduce print time by orienting the shortest dimension parallel to the slowest fabrication direction	D.P10	Blunt extreme points - Vertical points should be blunted parallel to build plane; horizontal points should be blunted orthogonal to build plane
		B.H11	Convey information with light	C.P11	Ensure printability by scaling artefacts and removing non-critical volumes	D.P11	Short overhang - This ensures robust manufacturability and prevents falling off of layers
		B.H12	Use single material to achieve recyclability	C.P12	Improve accuracy of critical curves and profiles by orienting critical curves and profiles in the plane of highest resolution	D.P12	Low island positions - This will have a significant impact on the build times
		B.H13	Use metamaterial to achieve unique and graded material propertiesl	C.P13	Satisfy alternative functional requirements by scaling the artefact		
		B.H14	Use multiple materials to achieve unique and graded material properties	C.P14	Satisfy different parametric requirements by scaling the artefact		
		B.H15	Absorb energy with small interconnected parts	C.P15	Minimize design time and effort by reusing already-designed component geometry		
		B.H16	Allow movement with small interconnected parts	C.P16	Leverage the capabilities of the selected AM technology by using comparably high resolution .STL files		
		B.H17	Use material distribution to achieve desired behaviour	C.P17	Accommodate different AM technologies' capabilities by using high-resolution .STL files		
		B.H18	Remove material to provide function	C.P18	Improve printability by designing with the resolution limitations of the selected AM process in mind		
		B.H19	Optimise structural topology or geometry	C.P19	Add function(s) to artefacts by incorporating functional features into non-functional aesthetic models		
		B.H20	Embed functional material	C.P20	Minimize assembly time and number of components by incorporating snaps fits when possible		
		B.H21	Embed functional component	C.P21	Reduce production time by standardizing the assembly process		
		B.H22	Use enclosed, functional parts	C.P22	Incorporate existing low-cost components by integrating the necessary standard interfaces		
		B.H23	Replace internal structure with lightweight lattice structure	C.P23	Improve manufacturability by dividing artefact into smaller components		
		B.H24	Hollow out artefact to reduce weight				
		B.H25	Create multi-functional artefact with reconfigurable structures				

From Table 4, it was observed that a great number of HPGs had a very close match to the 40IPs, however, the apparent similarity did not closely resemble the definition in the inventive principles. Additional meaning and terminology related to AM can be embedded in the inventive principles so a clear understanding of the principles can be presented. Certain design principles were found to be unrelated to TRIZ principles, necessitating consideration of non-associated HPGs as unique knowledge for future design iterations. Analysis showed that only a portion of the 40IPs have all their sub-principles directly overlapped to HPGs while some principles have none of their sub-principles directly overlapped to the HPGs. The remaining IPs have some of their sub-principles corresponding to the AM design knowledge and are further classified into redefined knowledge.

Table 4 TRIZ-HPGs mapping catalogue

40 IPs	Heuristics/ Principles/ Guidelines (HPGs) List	Referenced HPG codes
IP1. Segmentation	Improve manufacturability by dividing artefact into smaller components	C.P23
	Remove material to provide function	B.H18
IP2. Taking out	Eliminate assembly steps and time by printing functional joints and interfaces directly	C.P6
	Hollowing out parts - where functionally possible, scaling artifacts and trimming or removing non-critical volumes and unnecessary parts such as thick walls and hollow interiors can reduce print time.	B.H24, D.P3
IP3. Local Quality	Multiscale structures by applying customized material distribution	A.H10, B.H13-14
	Replace internal structure with lightweight cellular/lattice structure	A.H2, B.H23, C.P5
IP4. Asymmetry	Anisotropic structures	A.H8
	Part orientation - Orientation impacts surface finish, particularly with rounded features, and strength between horizontal and vertical components.	D.P1
IP26. Copying	Enable custom processes by identifying features that are complex or require high levels of user-based customization	C.P8
	Minimize design time and effort by reusing already-designed component geometry or integrating standard geometry (e.g. standard threads, holes) into the design	B.H2, C.P15, C.P22
	Minimize assembly time and number of components by incorporating snaps fits when possible	A.H3, C.P20
IP27. Cheap short living	Minimize design time and effort by reusing already-designed component geometry	C.P15
	Traditional processes produce low-cost or wear-prone parts that are more cost-effective than 3D direct printing due to their standard interface design and ease of maintenance.	B.H2, B.H3, C.P22
IP28. Mechanics substitution	Convey information with haptics	B.H10
IP31. Porous materials	Replace internal structure with lightweight cellular/lattice structure	A.H2, B.H23, C.P5
	Reduce weight, material cost, and preserve stability by replacing solid volumes with cellular structures	
IP32. Color changes	Convey information with color	B.H8
IP34. Discarding and recovering	Add function(s) to artefacts by incorporating functional features into non-functional aesthetic models -Avoid sharp edges	C.P19 D.P8
	Removing these results in better accuracy; rounding radii correlate with outer radii of simple-curved elements	D.P8
	Blunt extreme points - Vertical points should be blunted parallel to the build plane, while horizontal points should be blunted orthogonal to the build plane.	D.P10
IP35.Parameter changes	The AM process employs various materials for various applications, such as utilizing elastic materials for energy absorption and flexible filaments for easy stretching or bent parts.	A.H10, B.H13-14
IP37. Thermal expansion	Multi-materials and use material distribution to achieve desire behavior	B.H14, B.H17
IP40. Composite material	Multi-materials/ Use multiple materials to achieve variable material properties	B.H13-14

Table 5 AM unique knowledge

Suggested 40IPs	Description
Use biomaterial	• Can be applied specifically to Tissue Engineering application of AM
Use biodegradable material	• Can be applied for Design for Environment and Sustainable Manufacturing application in AM
resolution limitations	• Improve printability by designing with the resolution limitations of the selected AM process in mind • Improve accuracy of critical curves and profiles by orienting critical curves and profiles in the plane of highest resolution
Use AM features such as low island, short overhang, etc.	• Introduction of AM unique features enables designers to spot AM capabilities
Printing orientation	• Preserve small features by printing them in an orientation which requires no support material • Preserve surface finish by printing artefacts in an orientation which requires no support material

Table 5 summarized some of the uniquely suited for additive manufacturing knowledge that cannot be integrated with 40IPs.

As shown in Figure 6, the mapping revealed that the AM HPGs that can overlap with 40IPs amounted to 30%, and 22% requiring further analysis and redefinition to suit AM applicability. The redefined knowledge can be associated further to match the AM design knowledge in the following indirect ways:

i.   Integrate the redefined knowledge as specific interpretation in the inventive sub-principles.

ii. Integrate the redefined knowledge with unique knowledge from the HPGs as a new interpretation of the inventive principles.

iii. Fit the redefined knowledge into relevant keywords or synonyms related to the HPGs which have more general AM interpretation.

Finally, about 48% of the obscure knowledge obtained from the 40IPs were found to have a vague relation to the AM at the current state of AM design knowledge which indicates potential for evolution.
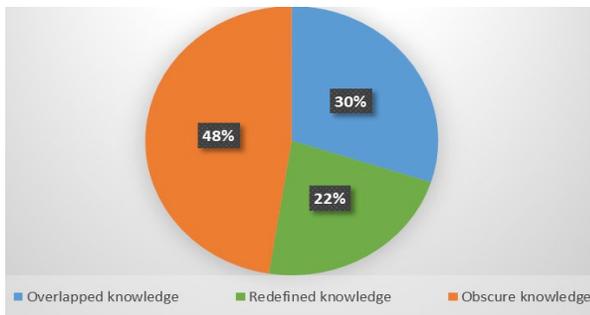

Figure 6 Percentage distribution of the knowledge cluster

4.1 Case Study

The applicability of the developed TRIZ-AM HPGs method was demonstrated based on an example on how the original design of the belt roller support can be improved (Figure 7).

Part consisted of;
• Bracket (2x)
• Base (1x)
• Shaft (1x)
• Bushing (2x)
• Washer (4x)
• Screw (4x)

Total part counts: 14

Figure 7 Original design of belt roller support

Figure 8 presented the evolutionary concept design of the belt roller support. It is anticipated that, by using the AM knowledge, the part can be greatly reduced from 14 to 4. The modified concept now consists of a bracket with a base, two screws and a shaft. The major change in the concept can be observed when the merging principle is used to the two brackets with a base to produce a single component. In AM, a part can be merged with the neighboring parts, especially if they can be produced with the same materials as per bracket with base and does not require any movement relative to each other. This is also a standard design for assembly considerations when designing parts for AM.
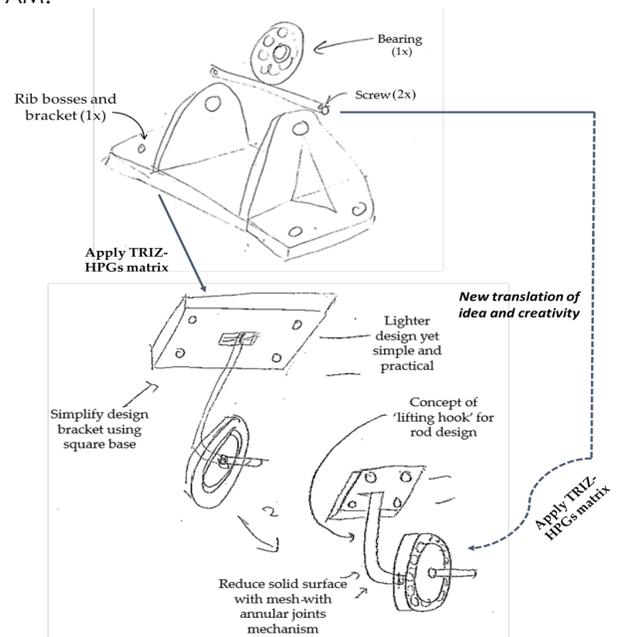

Figure 8 Evolutionary design sketches using TRIZ-AM HPGs catalogs

The following IPs of *#5 Merging, #34 Discarding and recovering,* and also *#13 The other way around* was found to be beneficial in simplifying the design of the bracket and the base. These three IPs were used to merge the ribs and boss features and convert them into modular units which is a square base with extruded-boss features. Innovatively, a base to mount the shaft and change the orientation from horizontal to vertical axis. By changing the orientation, the mechanism to mount the shaft is also different. This is mainly influenced from IP *#7 Nested doll* where the interlocking joints concept was utilized to mount the shaft at the square base. Furthermore, by using a snap-fit concept, it allows the individual parts to be easily attached and detached from other parts. For the shaft design using TRIZ- AM HPGs, instead of using cylinder tube-looked design, a concept of 'lifting hook' can be embedded, inspired from mechanical eye-hook design for the rod. In the upgraded shaft concept, IP *#27 Short-cheap* lived objects mimic the simple 'hook' design that was applied, literally to allocate the design for spare parts. Similar to the others evolutionary design, IPs *#8 Anti-weight* is used to replace the solid surfaces of the square base with mesh surface such as honeycomb and IP *#31 Porosity* is used by hollowing out the space inside the rod-hook design and generating the lattice structure. The original design, which consisted of two separate brackets and one base, was consolidated into a single integrated base with brackets (Part 1). Additionally, interlocking joints were introduced to mount the shaft without the need for two bushings (Part 2). A snap-fit mechanism was also implemented to replace four screws and four washers, resulting in a simplified assembly which requires only two screws to secure the bearing and bracket (Parts 3 and 4). As a result the design was improved with a 71.4% reduction in part count which greatly simplify and improved the assembly efficiency.

4.2 Discussion

The case study aims to understand the efficiency of a TRIZ-AM HPGs method on industry professionals' creativity in a DFAM task. The main findings from the results were summarized as follows;

i. The TRIZ-AM approach has a positive influence on designers to improve the functionality of the product into unique components without separating them into other parts.

ii. TRIZ-AM approach has a positive influence on the uniqueness and overall creativity of the designs by encouraging the creative solutions to solve the design problems

The study reveals that DFAM has transformed the conventional design production approach, presenting unique challenges in the transition from DFMA to DFAM. Therefore, the synergized approach of DFAM and TRIZ seems relevant. However, the derivation of 40 IPs can't be directly translated and adapted to AM because there are some principles that were at glance, not suitable to be directly adopted to AM applications. Therefore, in order to decide which principle is superior to potential for DFAM and AM applications, HPGs were accumulated and allocated among the suitable inventive principles. From the study, it was found that obtaining HPGs requires a large research effort and should be well synchronized, analyzed and archived in order to facilitate their usage for better utilization and interpretation. The collation and mapping process performed in this study demonstrated that the synergy of TRIZ and AM is promising. The foundations of DFAM knowledge representation based on TRIZ intends to demonstrate how the designers can apply unique AM capabilities in a more guided way and at the same time, encourage them to boost their creativity during the design process.

The study however demonstrates the possibility of combining DFAM and TRIZ based on the classical TRIZ 40IPs which over the years have undergone series of enhancement. Definitions of the HPGs may also vary which leads to several interpretations. Design knowledge and their typologies must be well defined to distinguish their relevant usage along the product design phase so that only relevant knowledge was extracted at a particular design phase. In most cases, the interpretation of design heuristics, principles, guidelines and rules can sometimes be used in a different context, misleading definition which leads to confusion. Therefore, proper taxonomies of the DFAM knowledge must be made available to assist DFAM developers to strictly use the correct definition. For example, design knowledge representation as described by Mani *et al.* (2017) based on the guideline-principle-rule methods can be taken as a guide to represent DFAM knowledge with a more inclusive knowledge. Furthermore, all of the collated HPGs are also based on generic principles.

Thus, further expansion of the HPGs can be useful to include specific principles, guidelines or even rules, for example, principles that are dedicated for composite can be found in a reported study by Camburn *et al.* (2019) can be used to represent the Composite principle of the 40IPs (Principle #40 along with its sub-principles). Therefore, any relevant principles related to the composite design or materials can become meaningful and easily accessible for designers upon usage. In order to resolve some of these issues, further studies on evaluating the usage of TRIZ in the context of DFAM have to be performed by novice designers that are either familiar with TRIZ or have the intention to utilize TRIZ as the design practice. Overlapped and unique knowledge can directly be utilized to observe how the principle guidance influences the designers' creativity. Redefined knowledge can be further evaluated to obtain a modified AM description applicable to TRIZ. And finally, the obscure knowledge can be used to alert the designers that

there is a transition of design thinking from a traditional DFMA approach to DFAM concept. By this way, inventive principles specifically dedicated to AM can be developed.

5.0 CONCLUSION

The study integrates DFAM knowledge with TRIZ inventive principles, promoting creative design and manufacturing practices, and unifying AM design knowledge for developers and TRIZ users. Even though the problems associated with design knowledge interactions are complex, it is believed that their solutions through systematic and structured frameworks such as TRIZ can offer major advantages in the exploitation of future DFAM knowledge development. The study successfully compiled and mapped AM design knowledge with 40 inventive principles of TRIZ, thereby expediting design decisions among TRIZ users. The results indicated that a large number of AM knowledge overlapped within the 40 inventive principles (30%) with some requiring slight enhancement in the definition (22%). It was found that, to date, there is only a small amount of knowledge that is unique to AM. However, the study reveals that they are still principles that are inadequate when dealing with the wide range of AM capabilities. At the current state of DFAM, this knowledge is still vague in the description and not applicable to AM (48%). In addition, purely relying on textual descriptions are insufficient to visualize particularly when attempting to convey the practical application of these design principles.It becomes challenging for designers especially those who are new in the field to fully grasp these principles into useful real-world design contexts. Misapplication of these applications due to confusion can hinder the smooth execution of the design process. Therefore, it is suggested that future research should include graphical examples to clearly demonstrate how the principles can be applied supported with a clearly defined framework or decision support system to assist the designers in choosing the right design principles.

In conclusion, there is a promising research avenue by integrating TRIZ and AM, enabling users to utilize AM design knowledge in a systematic method for innovative product development. An effective understanding of the design process along with the systematic methodology to cater for AM, will result in a great transition from traditional design thinking into a more practical way of design thinking, taking AM design freedom as the main benefit of technology

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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