DESIGN FOR ADDITIVE MANUFACTURING USING TRIZ-AM PRINCIPLES IN SUPPORTING PRODUCT DESIGN AND DEVELOPMENT

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DEDICATION

This thesis is dedicated to my father, Haji Mazlan bin Hussin, who taught me that the best kind of knowledge to have is that which is learned for its own sake. It is also dedicated to my mother, Hajah Siti Khadijah binti Mohammad, who taught me that even the largest task can be accomplished if it is done one step at a time. Not to forget, my husband, Ahmad Hariz bin Mustaffa and my sister, Siti Nur Farhana binti Mazlan for the continues support in terms of moral and also financial. I thank God every day for His blessing and helps from the beginning of my study until the ends. Thank you for the endless support and endless love you give to me. I am promised to give the best that I can and provide all of you with the never-ending happiness and love. Love all of you guys so much.

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ABSTRACT

Design for additive manufacturing (DFAM) can be categorized into design and manufacturing decisions to support designers in utilizing additive manufacturing (AM) capabilities such as design freedom and complex geometry. The idea of DFAM is similar to the goals of TRIZ (Theory of inventive problem solving), where it provides tools for innovative and creative solutions to address design problems during product design and development (PDD). Past researches in connecting TRIZ and AM indicated that it can be realistically used in assisting DFAM. However, it was found that the existing 40-innovative principles (40IPs) of TRIZ could not solely provide inclusive solutions to be applied to all AM technologies and terminologies. Moreover, the usage of TRIZ 40IPs in AM is highly dependent on the available AM examples which are subjective to researchers' problem-solving viewpoints and does not cover new innovative principles represented by AM design knowledge. Therefore, this study aimed to develop a DFAM procedure integrated with TRIZ-AM by enhancing the definition of classical TRIZ inventive principles according to AM applicability and suitable AM scenario. The 40 IPs were revised according to the classifications of design heuristics, principles, and guidelines applicable to AM. TRIZ-AM cards were developed to assist designers with infographic design knowledge. In addition, a manufacturability analysis of AM-printed parts was performed for the material extrusion process using composite materials. Experimental work was conducted using carbon fiber- polylactide acid (PLA) and Wood-PLA filaments involving seven types of basic structures, and four types of lattice structures. All of the printed parts were then inspected, measured, and compared with Virgin PLA. The outcomes were based on the data obtain from computer aided design (CAD) and printed part with regard to the development of design rules. To demonstrate its applicability, a new mobile application for composite design rules (CDRs) applications was developed. Fourteen outcomes of case studies were produced, including the design modification and improvement of consumer products. Designers from various industrial backgrounds were involved to perform the design task according to the specific DFAM requirements. Resultantly, the dimensional accuracy of basic structures produced was approximately 80% to 90% closer to CAD data when compared with Virgin PLA. The strut lattice size of more than 2.00 mm produced a higher fabrication rate compared to the smaller strut lattice (< 2.00 mm). The designer also managed to improve the design up to 89% of part reductions and 50% of material reduction compared to the existing product design when using the TRIZ-AM approach. The CDRs applications were validated with capabilities such as design feature guide, size checking, either pass and fail outcomes. The case study reveals that TRIZ-AM method is beneficial in producing concept generation in early phases of PDD. In conclusion, the proposed method simplifies the design process in terms of build time, materials, weight, and prevents repetitive design iteration. It can also be useful to promote AM capabilities to amateur and professional designers based on TRIZ-AM design practice.

ABSTRAK

Rekabentuk untuk pembuatan tambahan (DFAM) boleh dikategorikan kepada reka bentuk dan keputusan pembuatan untuk membantu pereka menggunakan keupayaan pembuatan tambahan (AM) seperti kebebasan merekabentuk produk dan penghasilan geometri yang kompleks. Idea DFAM dan TRIZ (Teori penyelesaian masalah inventif) serupa iaitu menyediakan alat penyelesaian masalah secara inovatif dan kreatif semasa reka bentuk dan pembangunan produk (PDD). Penyelidikan lepas ke atas TRIZ dan AM menunjukkan bahawa ianya boleh digunakan secara realistik dalam membantu DFAM. Walau bagaimanapun, 40 prinsip inovatif (40IPs) TRIZ yang sedia ada tidak dapat menyediakan penyelesaian secara inklusif untuk digunakan pada semua teknologi dan istilah AM. Selain itu, penggunaan TRIZ 40IPs dalam AM hanyalah berpandukan kepada contoh AM sedia ada yang hanya subjektif kepada sudut pandangan penyelidik dan tidak meliputi prinsip inovatif baharu yang mewakili pengetahuan reka bentuk AM itu sendiri. Oleh itu, kajian ini bertujuan untuk membangunkan prosedur DFAM yang disepadukan bersama TRIZ-AM dengan mengolah definisi prinsip inventif TRIZ klasik mengikut kebolehupayaan dan senario AM yang sesuai. 40IPs disesuaikan dengan klasifikasi reka bentuk heuristik, prinsip, dan panduan untuk AM. Kad TRIZ-AM telah dibangunkan melalui pengetahuan reka bentuk infografik. Kerja eksperimental dilakukan menggunakan bahan daripada serat karbon- asid polilaktik (PLA) dan Kayu-PLA, melibatkan tujuh struktur asas, serta empat jenis kekisi. Semua bahagian yang telah difabrikasi kemudiannya diperiksa dan diukur melalui perbandingan antara nilai reka bentuk terbantu komputer (CAD) dan nilai dari komponen bercetak. Bagi menunjukkan kebolehupayaannya, satu aplikasi mudah alih iaitu aturan reka bentuk komposit (CDRs) telah dibangunkan. Empat belas hasil kajian kes telah dibuat, termasuk pengubahsuaian dan penambahbaikan rekabentuk produk pengguna termasuk pereka industri dari pelbagai latar belakang terlibat dalam tugas rekabentuk menurut keperluan spesifik DFAM. Beberapa jenis struktur asas menunjukkan ketepatan di antara 80% hingga 90% lebih hampir dengan nilai CAD jika dibandingkan dengan PLA asli. Manakala, untuk kekisi yang lebih dari 2.00 mm, keputusan menunjukkan kadar fabrikasi yang lebih tinggi berbanding kekisi yang lebih kecil (< 2.00 mm). Pereka juga berjaya meningkatkan keupayaan reka bentuk produk sehingga 89% dari segi pengurangan bahagian komponen dan 50% bagi pengurangan penggunaan bahan berbanding reka bentuk produk yang sedia ada menggunakan TRIZ-AM. Aplikasi CDRs telah dibangunkan dengan keupayaan yang terdiri daripada panduan ciri reka bentuk, semakan saiz, serta informasi mengenai ciri rekabentuk samada lulus atau gagal untuk difabrikasi. Kajian kes telah membuktikan bahawa kaedah TRIZ-AM bermanfaat dalam menghasilkan konsep pada fasa awal PDD. Kesimpulannya, kaedah yang dicadangkan memudahkan proses reka bentuk dari segi masa pembangunan produk, bahan, berat, dan mengelakkan reka bentuk berulang. Ia juga membantu dalam mempromosikan keupayaan AM kepada pereka amatur serta pereka profesional berdasarkan amalan reka bentuk TRIZ-AM.

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LIST OF ABBREVIATIONS

AM - Additive Manufacturing
FDM - Fused Deposition Modeling
SLS - Selective Laser Sintering
SLA - Stereolithography
DLMS - Direct Laser Metal Sintering
HPGs - Heuristics, Principle and Guideline
DPs - Design Principle
DRs - Design Rules
DFAM - Design for Additive Manufacturing
DFMA - Design for Manufacturing and Assembly
PLA - *Polylactic Acid*
ABS - *Acrylonitrile Butadiene Styrene*
TO - Topology Optimization
PC - Part Consolidation
TRIZ - Theory of Inventive Principle
IPs - Inventive Principles
TRIZ-AM - TRIZ and Additive Manufacturing
S/N - Signal-to-Noise Ratio
DFWT - Design for Additive Manufacturing with TRIZ
CDRs - Composite Design Rules
AMPD - Additive Manufacturing Process Dependent
C-TRIZ - Classical TRIZ
AMK - Additive Manufacturing Knowledge
O-DFAM - Opportunistic Design for Additive Manufacturing
R-DFAM - Restrictive Design for Additive Manufacturing
CE - Creativity Enhancement

LIST OF SYMBOLS

δ - Error
D, d - Diameter
F - Force
A - Area
π - Value of Pi
h_b - Value of Height for Triangle
b - Base for Triangle
a^2 - Octagon's Side Value
V_A - Actual Value
V_E - Expected Value
Σ - Sum or Total
Y - Response Factors
n - Number of Experiments
A - Actual Measurements
N - Nominal Measurements
°C - Degrees Celsius
A - Function for Functional Quality
B - Function for Aesthetic Quality
c - Tolerances
s - Tensile Strength

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CHAPTER 1

INTRODUCTION

In the 1980s, additive manufacturing (AM) or three-dimensional (3D) printing was only an idea described by Hideo Kodama of the Nagoya Municipal Industrial Research Institute in Japan. He discovered a way to produce prototypes using layers of material concepts. Unfortunately, Kodama was unable to patent the technology. Since then, many efforts have been done to find a better way to create 3D-printed objects. Finally, in 1986, Charles Hull, an American engineer has successfully created a prototype for a process called Stereolithography (SLA) (Yakout et al., 2018). At the very beginning, Hull used photopolymers, better known as acrylic-based materials, to evolve the idea from liquid to solid using ultraviolet lights. Hull then patented the SLA printer and became the ‘father’ of 3D printing. Following SLA, other key technologies were also successfully patented, which are selective laser sintering (SLS) and fused deposition modelling (FDM). Both technologies use powder grains and filament types, respectively.

Additive manufacturing refers to the process of joining materials together layer by layer under a controlled program to develop 3D dimensional objects. AM has various commercial names. It can also be known as 3D printing (3DP), rapid prototyping (RP), layer manufacturing, and freeform fabrication. AM has grown over the last decade and it has been used to overcome the limitations in conventional manufacturing (Pereira et al., 2019). The AM plays a major role in the manufacturing industries to produce 3D geometrical intricate structures of different materials. A huge variety of polymers, ceramics, metal alloys, plastics, and composites has been used in the AM sector (Ngo, 2020). Every material contributes to different applications and sectors. For example, the medical industry uses AM to produce high-quality joint bone transplants and dentistry. Tissue engineering is also a main medical application that uses AM (Shick et al., 2019). The unquestionable advantages of the additive technique are the possibility to design parts with design freedom allowing complex shapes to be produced, improving mechanical strength properties of products, and shortening production and lead times. However, there is still a limited number of available materials and there is a need for post-processing to improve the quality of printed parts such as dimensional accuracy and surface finishing. Nowadays, a proper selection of manufacturing methods and machine tools is one of the main critical decisions in the product development process (Deja and Siemiatkowski, 2018) as well as for AM technology. Designers are facing great challenges when designing AM parts resulting in an increasing number of iterations along with the product design phases. This is because they are still adopting the use of traditional design thinking and methods, which, in most cases, do not suit the capabilities of AM (Rosen, 2014). Therefore, aiming to assist designers and to simplify AM design activities and structured methodologies, a new design concept, known as design for additive manufacturing (DFAM), was introduced.

1.1 Design for Additive Manufacturing (DFAM)

In general, DFAM is the skill to design for manufacturability using 3D printing technology. Several researchers have defined DFAM scientifically. For example, Gibson et al. (2010) define DFAM as *"maximising the product performance through the synthesis of the shapes, sizes, hierarchical structures, and also material consumptions subjected to the capabilities of AM technologies"*. According to Laverne and Anwer's (2014) perspective, DFAM is a *"set of methodology and tools that assists designers to fully specify additive manufacturing into considerations during a product design stage*". Briard et al. (2020) describe DFAM as *"a set of tools dedicated to utilising the full potential of AM technologies for design"*. According to the "ASTM standard 52910, 2018", the goal of DFAM is to design a product that is easily and economically manufactured even for a complex structure. The primary goal is to localise four DFAM unique capabilities which are shape complexity, material complexity, hierarchical complexity, and functional complexity in the designated products (Rosen, 2007). By implementing DFAM, designers can exploit the unique capabilities of additive manufacturing (AM) and benefit manufacturers and users to create an exceptional value for their product (Laverne and Anwer, 2014). Kumke et al. (2016) classify the DFAM approaches into two categories which are; DFAM decision inclusive of design and manufacturing. Since the focus of DFAM is to aid designers mainly in the design decision, the developed DFAM methodology may be reflected based on product design and development concept (PDD).

Figure 1.1 presents the overall idea of DFAM development inspired by a group of researchers (Maidin et al., 2012; Doubrovski et al., 2016). It starts with the requirements from customers. Then, the designer needs to apply the design heuristic and principle influenced by the idea generations. In the embodiment design, design guideline is applied, influencing the geometry and the product layout. The detailed design emphasises the design rules and specifications mainly influenced by the geometry such as part shapes and sizes. Once completed, the design is ready for fabrication and manufacturing. The DFAM route is compromised with design and manufacturing sections. The design sections consist of conceptual to detailed design phases, while the manufacturing section, the part programming, and finishing, is included as important phase to produce the parts.

The manufacturing section in Figure 1.1 is divided into part programming as well as manufacturing and finishing. Factors influencing the AM process and criteria in selecting the suitable AM process are also reviewed. Part programming can also be known as the slicing process (Sikder et al., 2014). In a slicing process, a few factors need to be considered. These include build orientation, support, and tool path optimisation, as well as parameter optimisation (included in process planning and optimisation). For manufacturing and finishing, support removal, the quality of the finishing process, and reduction of unwanted part defects, such as warping and shrinkage, must also be reviewed. The idea of DFAM also includes the factors affecting AM selection and the criteria to select proper AM technology for users. In general, the rate of successful manufacturability of the printed part depends on the AM process selections (Alkahari et al., 2017).

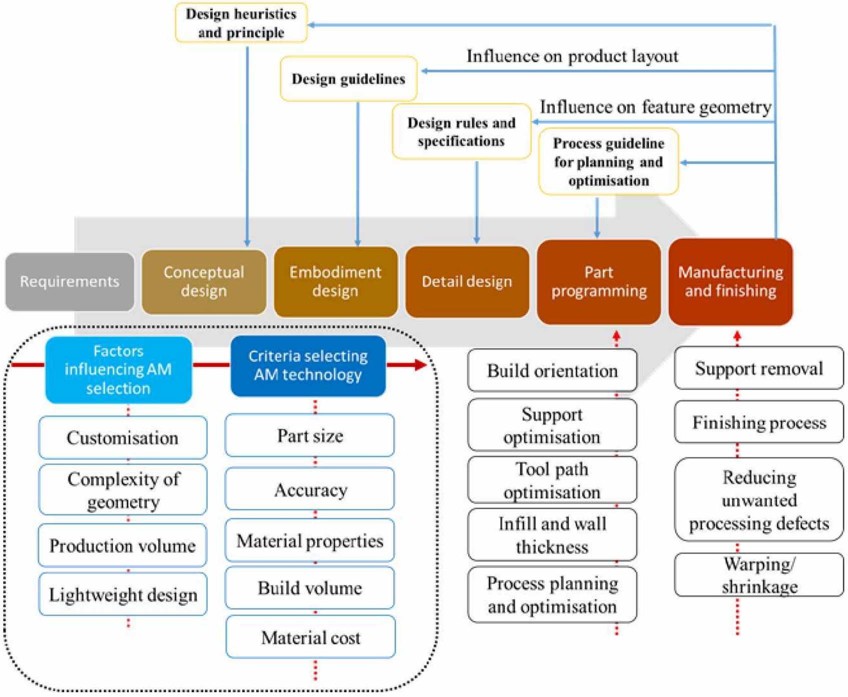

Figure 1.1 DFAM synergistic with PDD

PDD for AM using the DFAM concept is essential to drive the commercialisation and growth of AM in the manufacturing sector. To capitalise on the current and future market opportunities in AM, designers, and manufacturers should focus on PDD strategies by utilising customer requirements. In DFAM, product design may involve adopting new products or may require the refinement or upgrading of the features of existing designs to improve the parts' functionality, performance, or aesthetic quality. Despite the abilities of DFAM in producing lightweight and complex designs, a few unsettled issues in DFAM require additional support to enhance its visibility, especially in the industry. Therefore, this research is motivated to give the inter-relationship and understanding of DFAM comprising of design knowledge, design methodology, and design tools, all integrated into a newly developed DFAM procedure. This development would allow designers with no AM knowledge as well as novices to consider AM abilities in the early design phases for better AM utilisation.

1.2 TRIZ Evolution: Current Status and Issues of Concern

T, R, I, Z in TRIZ (/'tri: z/) is the English acronym for the Cyrillic words pronounced as "*Teoriya Resheniya Izobretatelskikh Zadatch*", translated as Theory of the Solution of Inventive Problems. TRIZ is commercially known as Theory of Inventive Problem Solving developed by G. Altshuller in 1946. He was a Russian patent engineer who discovered that problems, solutions, and patterns of technical evolution were repeating over the industries and sciences. Based on the study, over 200,000 patents were narrowed down to 40,000 innovative patents. Therefore, the TRIZ principle was invented to support engineers and scientists to solve problems using the knowledge of former inventors. The essence to support this solution was consolidated into 40 Inventive Principles (Lin and Wu, 2016). The definition of TRIZ was accordingly defined as a philosophy, a process, and a series of tools primarily based on the concept of resolving contradictions (Yeoh and Song, 2009).

There are several reasons to use TRIZ as a problem-solving tool. The reasons are; (i) TRIZ uses the concept of the world's knowledge, (ii) it is systematic and repeatable, (iii) it is based on proven successful patents, and (iv) it is designed not just for engineers and engineering, but for universal applications. TRIZ tools have been developed to allow the users to oversee the solutions to the given technical problems. In the TRIZ tool, 39 engineering parameters are extracted which usually cause a conflict when designing a product. They are also known as the 39-contradiction matrix. According to the survey made by Ilevbare et al. (2013), 85% of the respondents used technical problem solving (using 40 inventive principles), while 61% of the respondents used product and technology innovation. In business management and technology strategy, only 24% and 37% of respondents used TRIZ, respectively. The TRIZ process flow is shown in Figure 1.2. The first three steps of the TRIZ process flow are extracted from the typical problem-solving process to complement TRIZ requirements and recognised as the TRIZ problem-solving tool as shown in Figure 1.2. After a problem has been identified, the user can apply the TRIZ tool to generate the TRIZ general solution. After the general solution is introduced, the user can apply the TRIZ model of the solution to enhance the idea so that the specific solution can be moulded and designed.

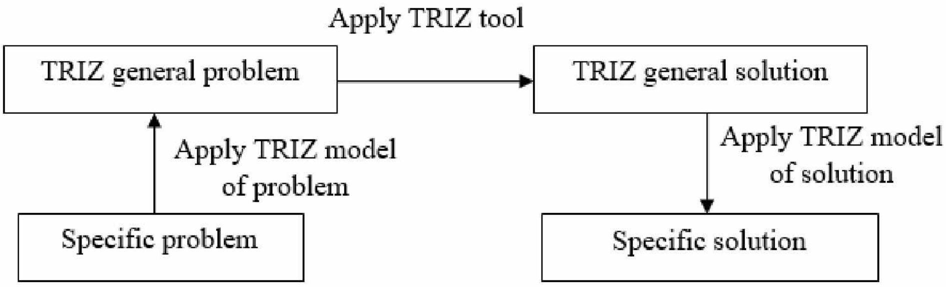

Figure 1.2 TRIZ problem-solving process (Yeoh and Song, 2009)

TRIZ can be considered as a set of all methods to solve an inventive problem from the beginning to the end. Many approaches have been developed by combining TRIZ with other methods. A total of 200 case studies have been found where TRIZ had been used throughout the industry (Spreafico and Russo, 2016). There have been successful attempts to apply TRIZ methodology in the context of DFAM (Kretzschmar and Chekurov, 2018). TRIZ was first invented in 1946, hence, there are concerns about whether the 'universal' concepts of TRIZ can be applied to AM technology, considering the 40-year technological gap between TRIZ and AM. Thus, the pathway for synergising TRIZ and AM (TRIZ-AM) may not be clearly explained concerning AM capabilities and complexities. The discussion on the applicability between TRIZ and DFAM will be further discussed in Chapter 2 and Chapter 4.

1.3 Problem Statement

DFAM is a set of rules and tools designed to make the AM constraint and capability easier to manage during the product design stages. Therefore, the practical methodology is necessary to assist the designers and engineers to generate effective product design for AM (Newell et al., 2019). Existing DFAM methodology is rarely found in a way that is accessible to novice designers. Most methodology assume that the designer has extensive prior knowledge of the process, applies to only a few AM technologies, has very specific applications, or describes the benefits of the technology that novice designers already know.

In DFAM, the design method plays a significant role to produce the AM-printed part based on a principle given. Examples of design methods in AM include topology optimisation, part consolidation, axiomatic design, and TRIZ. TRIZ has attracted the AM community to assist product development and can be used as a method for generating new ideas and solutions (Renjith et al., 2020). Past research connecting TRIZ and AM indicates that it can be realistically used in assisting DFAM. However, there are limitations which include; (i) the usage of TRIZ which 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. Thus, further research is required to enhance the applicability of TRIZ into AM environment (Gross et al., 2018; Lang et al., 2019; Yuan et al., 2019).

Design knowledge is also important to establish DFAM. Available design knowledge in DFAM is the design rules. According to Mani et al. (2017), gaps exist in the design process because designers are challenged with a lack of understanding of AM capabilities, process-related constraints, and their effects on the final product development. Focusing on the process-related constraint, designers are uncertain of the limitations and possibilities of the AM process (Adam and Zimmer, 2014). Therefore, according to Schmidt and Fornasini, (2015), designers tend to apply and design the parts using incompatible design rules from familiar manufacturing processes such as injection moulding or other traditional manufacturing process guidelines.

Other than design method and design knowledge in DFAM, material is also a component that drive the successful of fabrications. Composite material has been recently introduced to fulfil the niche of 3D printing applications in the industry especially on producing lightweight composite parts for automotive and aerospace. The existing research on the composite material in AM mainly addresses the mechanical properties of the printed part and rarely discussed on the geometrical limitations and manufacturability of the AM-composite featured design including the AM lattice design. In conjunction to the AM-featured lightweight design, Kessler, et al. (2017) state that the product-oriented with lattice structure is becoming more challenging to produce as the industry's demand for lattice application are keep on growing. As a result, designers often perform trial-and-error investigations before attaining the optimal outcomes for their printed parts in order to meet the demand. This is because composite filaments are complicated to handle with, especially for inexperienced users. Therefore, this research intends to focus on the manufacturability analysis of the composite materials involving the AM-design feature to assist on the design rule developments for composite parts.

1.4 Significance of the Study

The findings of this study will contribute greatly towards designers and AM practitioners by considering the importance of AM role. In Malaysia, particularly, AM has become a key technology that drives the Industrial Revolution 4.0 and can potentially contribute to Malaysia's economy. The findings specifically align with the *'Application of the 10-10 MySTIE framework to the energy socio-economic driver'* where 3D printing has become an important element to drive the IR 4.0. In the current technology highlighted by MySTIE, 3D printed respirators, face shields, and PPEs have been used to combat the shortage of medical protection equipment supply. Other than that, the study has introduced the TRIZ-AM cards that can help designers to use virtual 3D designs and printing for rapid prototyping in engineering and creative arts as stated in MySTIE. It is also beneficial to assist the industry in an assembly line where the spare parts are automatically 3D-printed and installed by robots.

Therefore, designers who apply the recommended design methodology derived from the results of this study will be able to systematically practice the overall DFAM procedure and can help them to speed up the research and development (R&D) process. Designers will also be guided on the geometrical constraint to improve fabrications performance using the developed design rules. On the other hand, the results of this study will help researchers uncover critical areas in the DFAM, especially on the design method that is still adapting from the concept of conventional design thinking. Thus, the design method for DFAM will be explored more comprehensively.

1.5 Research Questions

Based on the problem statement, the research questions are identified to achieve the research objectives and goals of this study. The research questions are listed as follows:

i. How designers can adopt TRIZ-AM inventive principle with the combinations between AM complexity and unique capabilities during product design and development stages?
ii. How to ensure the success of design rules development in design knowledge to produce AM parts?
iii. How to ensure the effectiveness of TRIZ-AM method and design rules to produce AM parts?

1.6 Research Objectives

The research objectives are made to answer the previous research questions. Accordingly, the three objectives of this study are:

i. To develop design for additive manufacturing procedure integrated with AM process capability and TRIZ-AM inventive principle
ii. To evaluate the DFAM design knowledge using manufacturability analysis in assisting design rule applications
iii. To verify and validate the effectiveness of the TRIZ-AM method and design rule using case studies

1.7 Research Scopes

To conduct this study, a few boundaries have been identified. The research scopes have been described as follows:

i. Only 40-classical TRIZ inventive principle has been used to synergise with the AM capability and limitations.
ii. ISO/ASTM (52910) standard has been used as the guideline for the DFAM strategy and architecture.
iii. Seven AM feature designs inclusive of basic design structures are developed. They are thin walls, slots, small hole diameters, maximum hole diameters, overhang lengths, overhang angles and bridges.
iv. An AM-lightweight feature design involving only four types of strut lattice designs is also developed. They are square strut, circle strut, triangle strut, and octagon strut.
v. All designs are fabricated using PLA-based composite materials of carbon fibre reinforced PLA and Wood-PLA as well as Virgin PLA.
vi. The process parameter optimisation is conducted using Taguchi. The analysis uses Minitab software where S/N ratio, and ANOVA are also performed.
vii. The dimensional accuracy of AM fabricated parts is measured using an image analyser to inspect the quality or defects of the printed parts.
viii. All designs are fabricated using the material extrusion technique to assist the design rule development.
ix. Digital design rules are developed using *Android Studio* to ease the modification process.
x. An evaluation of case studies focuses only on creativity enhancement involving custom geometries or combinations of special features as well as characteristics for various products.
xi. The case study involves fifteen (14) participants consisted of an experienced designer and novices' designer with the industrial experiences between 2 to 8 years, respectively.

1.8 Thesis Outline

The work presented in this thesis consists of the development of a DFAM procedure integrated with the extended version of classical TRIZ known as the TRIZ-AM inventive principle. The DFAM procedure consists of design rules development using a composite material of AM-featured design. The particular focus in this thesis is to develop a systematic design approach and tool, especially for AM novice designers. This thesis is divided into 7 chapters. In Chapter 2, a comprehensive literature review of the design for additive manufacturing (DFAM) is presented. DFAM knowledge, which is HPGs (Heuristics, Principles, and Guidelines), is proposed. The main goal is to identify the gaps in knowledge where the TRIZ-AM definition can be performed. Aside from this, DFAM's earlier developments were discussed to identify potential areas of research development that are likely to be applicable in industry.

In Chapter 3, a detailed discussion on the research methodology is presented. The chapter begins with the general flowchart consisting of 4 phases. Phase 1 covers the development of the DFAM procedure, Phase 2 includes the manufacturability analysis and setup, Phase 3 discusses the fabrication and testing using the composite material, and Phase 4 describes the composite design rule development (CDR). Chapter 4 describes the TRIZ-AM integrated into the DFAM procedure which is first introduced in the product design phase (PDD). The procedure is known as DFAM with TRIZ (DFWT) targeted to promote AM technology among TRIZ users and vice versa. The case studies to demonstrate the feasibility and validity of the TRIZ-AM method are presented in Chapter 5. Two major tasks involving four types of products (hanging shelf with a roller, PCB casing, belt roller support, and multipurpose box) are used for creativity enhancement demonstration. The tasks include *Case Study A: Part consolidations with TRIZ* and *Case Study B: Creativity enhancement with TRIZ.*

In Chapter 6, the manufacturability analysis is described, presenting the results and discussions of the composite fabricated features together with the development of composite design rules in the form of flashcards and mobile applications. To demonstrate the applicability of CDR applications for AM content and creativity, *Case study C: Innovative design* is performed. Lastly, in Chapter 7, the conclusions, intellectual contributions, and future works are described.

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Book Chapter

1. Additive Manufacturing for Process Optimization Using Architecture Lattice Structures (2020) – Indexed in WOS
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