

BARRIER ANALYSIS APPROACH IN METAL ADDITIVE MANUFACTURING
IMPLEMENTATION WITH ENVIRONMENTAL CONSIDERATIONS

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ABSTRACT

Notwithstanding the developments in additive manufacturing technology have been set to overcome human limitations and improve efficiency in manual restoration activities, their widespread implementation as a disruptive production technology has brought various impacts on the environment, and the environmental assessment is limited in this regard. The Malaysian automotive industry has not seen widespread adoption of Life Cycle Assessment for additive manufacturing implementation. Based on the current literature review, there is a gap as the barriers for implementing Life Cycle Assessment in additive manufacturing technology within the Malaysian automotive manufacturing industry are not critically discussed. There is a need for developing appropriate approaches to weight and determine the interrelationships between these obstacles and the most prevalent ones in order to devise mitigation strategies for them. The purposes of this study are to identify various barriers of implementing Life Cycle Assessment in metal additive manufacturing within Malaysian automotive manufacturing industry and, secondly, to develop an approach to prioritize the barriers and recognize the most critical barriers. In this regard, the extant literature has critically reviewed the barriers of implementing Life Cycle Assessment in metal additive manufacturing within Malaysian automotive manufacturing industry. Fuzzy preference programming, as one of the newest and most accurate fuzzy modifications of the Analytical Hierarchy Process, was used to achieve the research purposes. Suitable Triangular Fuzzy Number has been defined and the selected data collection method was expert opinion. A total of eight industry experts from one company were involved in this research study to give their opinion on the Fuzzy Analytical Hierarchy Process pairwise comparison table. The expert opinions indicated that the main concern of industry is financial-related topic. The data collected have been analyzed using Fuzzy Analytical Hierarchy Process calculations and confirmed by the consistency check. Following the results, dominant barriers were accordingly identified and ranked in each category as well as overall. According to the results from expert opinions, the highest-ranking barrier is lack of financial resources, followed by lack of Life Cycle Assessment expertise in the additive manufacturing context, and the third rank is the lack of laws and directives for Life Cycle Assessment application in additive manufacturing. The findings may be useful to managers to develop suitable mitigation strategies and make more informed decisions with individual focus, level focus, or cluster focus. It may also contribute to the additive manufacturing literature by the weighted presentation of the barriers to implementing Life Cycle Assessment in additive manufacturing within the Malaysian automotive manufacturing industry. This study will contribute to a framework of roadmaps and strategies for sound and environmentally friendly additive manufacturing implementation in Malaysian automotive industry.

ABSTRAK

Perkembangan teknologi di dalam sektor pembuatan tambahan bukan sahaja telah mengatasi had keupayaan manusia, bahkan telah juga meningkatkan kecekapan aktiviti manusia dalam kehidupan seharian. Namun begitu, teknologi ini turut mendatangkan pelbagai kesan negatif kepada alam sekitar, dan penilaian kesan teknologi ini terhadap alam sekitar adalah sangat terbatas. Penilaian Kitar Hayat dalam pembuatan tambahan jarang dilaksanakan di kalangan industri automotif di Malaysia. Hingga ke hari ini, halangan untuk melaksanakan Penilaian Kitar Hayat dalam teknologi pembuatan tambahan di kalangan industri pembuatan automotif di Malaysia tidak dibincangkan secara kritikal dan meluas. Pendekatan yang sesuai perlu diambil untuk menentukan kaitan antara halangan-halangan ini supaya dapat merangka strategi mitigasi yang bersesuaian. Tujuan kajian ini adalah untuk mengenalpasti pelbagai halangan untuk melaksanakan Penilaian Kitar Hayat dalam pembuatan tambahan logam di kalangan industri pembuatan automotif di Malaysia. Di samping itu, kajian ini juga bertujuan untuk menentukan kaedah yang sesuai bagi mengutamakan halangan serta mengenalpasti halangan yang paling kritikal. Kajian terdahulu yang terperinci dan menyeluruh berkaitan halangan-halangan untuk melaksanakan Penilaian Kitar Hayat di dalam sektor pembuatan tambahan logam di kalangan industri pembuatan automotif di Malaysia telah dilakukan. Pendekatan Logika Kabur, yang merupakan salah satu Proses Hirarki Analitik yang terbaru dan mempunyai ketepatan yang tinggi, telah digunakan sebagai metodologi utama untuk mencapai objektif penyelidikan ini. Nombor Kabur Segi Tiga yang sesuai telah ditentukan dan kaedah pengumpulan data yang terpilih adalah berdasarkan dari pandangan para pakar sedia ada. Seramai lapan orang pakar dari satu syarikat dalam sektor industri telah terlibat dalam kajian penyelidikan ini. Pakar-pakar tersebut dikehendaki untuk memberi pendapat mereka dalam jadual perbandingan berpasangan bagi Proses Hirarki Analitik Kabur. Hasil perbincangan oleh para pakar telah menunjukkan bahawa keutamaan industri adalah sektor kewangan. Pengiraan Proses Hirarki Analitik Kabur telah digunakan untuk menilai maklumat yang diperolehi. Tambahan pula, konsistensi keputusan turut disemak secara terperinci. Analisa keputusan telah menunjukkan serta menerangkan halangan dominan bagi setiap kategori dan juga secara keseluruhannya. Hasil kajian daripada pandangan para pakar menunjukkan bahawa halangan yang utama adalah kekurangan sumber kewangan. Manakala, halangan yang kedua adalah kekurangan sumber pakar yang memahami Penilaian Kitar Hayat dalam sektor pembuatan tambahan, dan seterusnya adalah kekurangan undang-undang kerajaan untuk mewajibkan Penilaian Kitar Hayat dalam sektor ini. Hasil kajian ini amat berguna terhadap pengurus-pengurus sektor berkenaan untuk merangka strategi mitigasi yang sesuai dan membuat keputusan yang sewajarnya. Hasil kajian ini telah mengenalpasti halangan-halangan untuk melaksanakan Penilaian Kitar Hayat dalam pembuatan tambahan logam di kalangan sektor pembuatan automotif di Malaysia. Kajian ini akan dapat menjadi rujukan penting untuk memberi bantuan sewajarnya dalam menentukan pelan dan strategi dalam pelaksanaan pembuatan tambahan yang terbaik serta mesra alam dalam kalangan industri automotif di Malaysia.

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LIST OF ABBREVIATIONS

3D	-	Three Dimensions
AHP	-	Analytic Hierarchy Process
AI	-	Artificial Intelligence
AM	-	Additive Manufacturing
ANP	-	Analytical Network Process
ASTM	-	American Society for Testing and Materials
CAD	-	Computer-aided Design
CI	-	Consistency Index
CLAD	-	Construction Laser Additive Direct
CM	-	Conventional Manufacturing
CNC	-	Computer numerical control
CO ₂	-	Carbon Dioxide
COA	-	Center of Area
COG	-	Centre of Gravity
COPRAS	-	COMplex PROportional ASsessment Method
CP	-	Compromise Programming
CR	-	Consistency Ratio
DED	-	Directed Energy Deposition
DFE	-	Design For Environment
DMD	-	Direct Metal Deposition
EISS	-	Environmental Impact Scoring Systems
ERMD	-	Environmental and Resource Management Data
FAHP	-	Fuzzy Analytic Hierarchy Process
FDM	-	Fused Deposition Modelling
FL	-	Fuzzy logic
FMM	-	Federation of Malaysian Manufacturers
GDP	-	Gross Domestic Product
GHG	-	Greenhouse Gases
GRA	-	Grey Relation Analysis
IEA	-	International Energy Agency

IoT	-	Internet of Things
IR4.0	-	Fourth Industrial Revolution
ISO	-	International Organization for Standardization
LCA	-	Life Cycle Assessment
LCI	-	Life Cycle Inventory
LCIA	-	Life Cycle Impact Assessment
LENS	-	Laser Engineered Net Shaping
LMD	-	Laser Metal Deposition
LOM	-	Laminated Object Manufacturing
MADM	-	Multi-Attributes Decision Making
MAUT	-	Multiple Attribute Utility Theory
MCDA	-	Multi-Criteria Decision Analysis
MCDM	-	Multiple Criteria Decision Making
MDDM	-	Multi-Dimensions Decision Making
MITI	-	Ministry of International Trade and Industry
Mt	-	Million Tonnes
NAIADE	-	Novel Approach to Imprecise Assessment and Decision Environment
PBF	-	Powder Bed Fusion
RI	-	Random Index
SAW	-	Simple Additive Weighting
SDG	-	Sustainable Development Goals
SETAC	-	Society of Environmental Toxicology and Chemistry
SLA	-	Stereolithography
SLM	-	Selective Laser Melting
SLS	-	Selective Laser Sintering
STL	-	Standard Tessellation Language
TFN	-	Triangular Fuzzy Number
TOPSIS	-	Technique for Order Preferences by Similarity to Ideal Solutions
TRL	-	Technology Readiness Level
UNEP	-	United Nations Environment Program
WCED	-	World Commission on Environment and Development

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CHAPTER 1

INTRODUCTION

1.1 Overview

This chapter begins with an overview of the research, which is followed by a description of the research objectives, research questions, research scope, and importance of the research. The chapter concludes by presenting the structure of the thesis.

1.2 Research Background

Industrial metabolism, defined as the conversion of matter, energy, and labour into goods, services, waste, and ambient emissions, has generated significant value while contributing to rising environmental impact (Peng et al., 2018). At a global level, energy consumption by industry accounted for 22% of the world's total in 2012 (IEA, 2017) and is one of the most critical sectors for sustainable development (WCED, 1987). One of the most essential factors in determining whether a technology is viable and sustainable is its environmental impact. The field of additive manufacturing (AM), also known as 3D printing or rapid manufacturing, has been gaining momentum recently. This is primarily due to the technological advantages provided by the manufacturing of complex and customised products using modern manufacturing methods, including the ability to produce items not previously possible or practical using traditional manufacturing methods (Gibson et al., 2021; Conner et al., 2014). In comparison to conventional methods, AM has the potential to improve material efficiency, reduce life cycle impacts, and enable greater engineering functionality by reducing the need for specialised tooling in part fabrication, speeding up tool production, and material waste reduction. Hence, AM has been dubbed a green

technology (Peng et al., 2018; Bechmann, 2014). Subsequently, the time and cost of manufacturing individual and small-volume parts could be reduced.

"Process of combining materials to create parts layer by layer from 3D model data, totally different from subtractive manufacturing" is how ASTM International Committee F42 on AM Technologies defines additive manufacturing (ASTM, 2009). AM processes are vastly distinct from conventional manufacturing processes, including machining, casting, and forming. Typically referred to as '3D printing', AM entails a collection of computerized procedures tasked with fabricating 3D parts layer upon layer based on computerized design models that utilize materials made out of metal, plastic, ceramic, composite, or biological substances. Such technologies are superior to other manufacturing processes for many reasons, including: the parts can easily be customized and personalized based on demand; non-requirement of specific tooling in the fabrication of the parts; less material waste; reduced manufacturing time and cost for single parts and small-quantity production; easy fabrication of new components and complex geometries and heterogeneous structures for certain AM technologies; as well as drastic compression of the supply chain (Frazier, 2014).

Following its mid-1980s introduction, AM has since progressed to incorporate multiple processes such as laser metal deposition (LMD), direct metal deposition (DMD), selective laser melting (SLM), selective laser sintering (SLS), laminated object manufacturing (LOM), fused deposition modelling (FDM), stereolithography (SLA), inkjet printing, and many others. 3D printing has been transformed by contemporary improvements in materials and processes, revolutionizing it from rapid prototyping to rapid production, which enables production at or near the point of use and "on demand" as well as a drastic reduction of inventories and waiting times. Consequently, the AM market is now experiencing exponential growth since its inception. The report by Wohlers Associates (2013) stated that the compounded annual growth rate (for a 25-year period) of the global revenues for all AM products and services was 25.4%, with a growth rate of 27.4% over the 2010-2012 period, leading to a revenue of \$2.2 billion in 2012. There was an increase of 19.3% in the unit sales of industrial AM systems (unit price > \$5000), i.e., to 7771 units in 2012, and an

increase of 46.3% in the unit sales of 3D personal printers (unit price \leq \$5000) i.e., to 35,508 units also in 2012 (Frazier, 2014).

AM processes have also been examined under the lens of environmental impacts (Ford & Despeisse, 2016). Gebler et al. (2014) conducted a comprehensive sustainability assessment of 3D printing by examining the impacts of additive manufacturing on the three sustainability pillars, i.e., the economy, society and the environment. The authors focus on highlighting the associated costs and environmental impacts of various 3D printing scenarios and their prospective reductions over the course of the next 10 years. Kellens et al. (2017b) published a comprehensive overview of published studies on the AM's environmental impacts, highlighting production circumstances whereby the AM offers environmentally valuable contributions. As AM processes involve the usage of metal-based components, several studies have been published regarding the environmental effects of electron beam melting (Baumers et al., 2017; Le et al., 2017), Direct Additive Laser Manufacturing (DALM) (Le Bourhis et al., 2013) and Selective Laser Melting (SLM) (Faludi et al., 2017). In terms of polymers, Yang and Li (2018) published a study on the environmental characterization of stereolithography. Meanwhile, Song and Telenko (2017) and Griffiths et al. (2016) have studied the material and energy efficacy of Fused Deposition Modelling (FDM). Kellens et al. (2014) conducted a Life Cycle Assessment (LCA) on the polymer's Selective Laser Sintering (SLS). Further investigations into the environmental effects of AM are still called for (Frazier, 2014). According to Rejeski et al. (2018), AM carries an environmental footprint due to the emissions generated from materials and energy consumption. Analyzing the environmental effects of additive manufacturing is difficult and expensive because of the wide range of factors that influence AM, such as the materials, feedstock forms, processes, locations, and post-processing options. These factors all influence AM.

In most of the studies, only the energy usage of the printing process was taken into consideration (Lifset, 2017). For Powder Bed Fusion, Faludi et al. (2017) conducted a Life Cycle Assessment (LCA) to examine the environmental impacts of AM machines and powder production. The use of the component was not included in a comprehensive evaluation of various construction orientations and machine cycles.

The environmental effects of Directed Energy Deposition (DED) and conventional wind turbine high-speed gear manufacturing were compared in another study by Liu et al. (2018), and they also excluded the use of components and technological development. Contrastingly, a comprehensive study was carried out by Huang et al. (2017) to investigate and compare the Powder Bed Fusion (PBF) environmental and economic impacts for injection molding, comprising the cradle-to-grave impacts and taking into consideration circumstances for the development of technology in the future. Correspondingly, Mami et al. (2017) conducted a study to calculate the cost and life cycle impact of using Powder Bed Fusion from cradle to grave in the production of aeroplane parts. By adopting experimental measurement, Sreenivasan et al. (2010) presented a sustainability analysis of Selective Laser Sintering (SLS) from an energy perspective. Balogun et al. (2014) studied Fused Deposition Modelling (FDM) and a generic model for direct energy demand in layered manufacturing. However, existing research asserts that realizing such potential remains beyond reach. As such, this study motivates research towards more environmentally benign AM technology.

1.3 Problem Statement

Around 100 years after the industrial revolution, the manufacturing industry began to address the issue of sustainability. There is a more than 50-year gap between the introduction of numerical control machining and mass production and the focus on environmental responsibility today (Peng et al., 2018). Despite the fact that extensive studies are being conducted to minimize the effects of existing manufacturing practices, many of their consequences are difficult to measure, evaluate, or mitigate. Thus, research efforts on sustainability in additive manufacturing (AM) should be made to guide better industrial adoption and implementation of AM since it also entails several disadvantages, including high energy usage for a slow printing process (Gutowski et al., 2017). For mass production, the slow printing process will cause problems (Kellens et al., 2017a). In the development and implementation of AM, potential environmental and resource consequences should be assessed. According to Arvidsson et al. (2018), the mentioned assessments are difficult due to the inherent

uncertainties. Moreover, the current literature and quantitative studies on metal AM's environmental impacts are limited. In most of the studies, only the energy usage of the printing process was taken into consideration (Lifset, 2017). In other words, the overall development of AM needs further assessment in this context (Huang et al., 2017).

Life cycle assessment (LCA), which was first developed in the 1990s, is a widely accepted approach for measuring the environmental impact of various business operations and products (Gungor & Gupta, 1999; ISO, 2006). For subtractive manufacturing, a large number of life cycle analysis studies have been conducted (e.g., Duflou et al., 2012; Peng & Xu, 2014; Cai et al., 2016; Schudeleit et al., 2016; Seow et al., 2016; Hu et al., 2017). However, very few studies have examined the environmental impacts of this technology using LCA, particularly in the entire life cycle of metal AM production in the automotive industry (Bekker et al., 2016; Bekker & Verlinde, 2018). Because of its size and impact on the ecosystem, the automotive industry is an ideal setting for studying the adoption of AM technology. The use of AM technology in the automotive industry is expected to grow rapidly, reaching USD 4.3 billion by 2025, with savings of up to USD 10 billion per year by 2030 caused by a shortened supply chain (Frost & Sullivan, 2015). Metal fabrication contributes significantly to various forms of environmental harm (Norgate et al., 2007). Hence, the industrial sector, specifically metal component manufacturers, plays a crucial role in this regard. Such an industry poses a significant impact on the automotive industry because substantial spare parts demand in the automotive industry has resulted in a large bulk of unused and non-recyclable stocks. On top of that, the effects of metal manufacturing on the environment are difficult to identify as the associated values are typically incorporated into the material production stage (Ingarao et al., 2018). AM has also been evolving in Malaysian automotive manufacturing systems. However, being an interdisciplinary technological area, understanding the energy and environmental impact of AM from a life cycle perspective is challenging. Due to the fact that there are major barriers, there are difficulties in implementing the AM technology and in giving an insightful interpretation of the long-term effects of its use from a life cycle perspective.

Yet, the automotive industry has not seen widespread adoption of LCA for AM implementation as a result of a number of major barriers (Wohlers & Gornet, 2014; Dwivedi et al., 2017). These issues need to be dealt with in an appropriate manner. According to Lorek and Fuchs (2013), companies that already have management and employee commitment to sustainability values and business practises based on assumptions about environmental protection will be able to successfully utilize LCA in the AM context. One of the major barriers in this context is regarded to be the lack of LCA readiness in the automotive manufacturing system (Rejeski et al., 2018). According to critics, the environmental knowledge required by LCA is too advanced for design engineers to possess (Bhander et al., 2003). Based on Igos et al. (2019), a greater emphasis on uncertainty communication is needed to ensure the credibility and transparency of LCA studies as well as to keep non-expert stakeholders from making skewed interpretations of the data. Often, these barriers are interrelated or carry a lot of weight. Therefore, there is a need to develop appropriate approaches to weight and determine the interrelationships between these obstacles and the most prevalent ones in order to devise mitigation strategies for them.

1.4 Research Questions

The questions of the research are:

- (a) What are the barriers of implementing LCA in metal AM within Malaysian automotive manufacturing systems?
- (b) How are the AM implementation-related barriers prioritized and evaluated?

1.5 Research Objectives

The objectives of the research are:

- (a) To identify various barriers of implementing LCA in metal AM within Malaysian automotive manufacturing systems.
- (b) To develop an approach to prioritize the barriers and recognize the most critical barriers.

1.6 Research Scope

The metal industry plays a large role in the vehicle sector; the high demand for spare parts has resulted in a significant accumulation of unused and non-recyclable stocks. MITI (2018), through the National Policy on IR4.0, promoted the future of the manufacturing industry through enabling IR4.0 technologies such as AM in order to "make things better". Since the AM production in the Malaysian automotive manufacturing industry have become a trending focus of current and future development, the environmental impacts caused by this advanced technology should not be neglected. The aforementioned context has not yet seen widespread adoption of LCA for AM implementation due to the fact that there are a number of major barriers.

Thus, the scope of the study is limited to the automotive manufacturing sector, with a focus on analyzing key barriers hindering adoption of LCA for AM implementation in such an industry in Malaysia. To do so, this study uses the Fuzzy Analytic Hierarchy Process (FAHP) method to analyze barriers vis-à-vis extant literature and further scrutinize the identified barriers, followed by validating the data and results. To collect the data, the eight experts who have considerable industrial and managerial experience in the automotive manufacturing industry are tasked with expressing their views on the understudied context.

1.7 Research Significance and Deliverables

It is highly crucial for AM implementation to be endorsed in environmental policies due to its environmental sustainability, capability to reduce material waste,

and capacity to repair and restore, thereby extending the life cycle of products. This solidifies the country's commitment to the Sustainable Development Goals (SDG) ratified by the United Nations. The development of the policy should be a cooperative effort between government authorities, including the Department of Environment, MITI, and the Remanufacturing and Aftermarket Industry. It should be a framework of roadmaps and strategies for sound and environmentally friendly AM implementation and of the role of the consumer or society in boosting awareness and knowledge of re-manufacturable AM products.

Environmental studies such as the current one can enable stakeholders entailing the likes of MITI, FMM, and Industry Association to establish a clear visualization and roadmap on how to deploy AM in such a way that can transform the industry into a smart manufacturing industry from the environmental LCA standpoint. Despite having been discussed in the National Policy & Industry Revolution 4.0, the technology's substantial up-front investment needs to be justified along with its technological, economic, and environmental effects on the industry in particular and the nation in general. A sustainable environment is indeed favorable for society. Environmentally friendly production of high quality and reliable secondary automotive parts is 40-60% less expensive than the production of new components.

There is a dearth of research on the effects of metal AM on the environment. Throughout most of the studies, only the printing process's energy consumption was considered (Lifset, 2017). To put it another way, the overall development of AM necessitates further evaluation in this context (Huang et al., 2017). AM processes have been exposed to a series of life cycle assessments (LCA) to decrease energy and material consumption, as well as transportation and packaging system for achieving environmental sustainability. Rarely have the environmental effects of this technology, particularly in the context of automotive metal AM production over its entire life cycle, been examined in research to date (Bekker et al., 2016; Bekker & Verlinde, 2018). As a result of a simplified supply chain, AM in the automotive sector is expected to grow rapidly to a value of USD 4.3 billion by 2,025 and USD 10 billion annually by 2,030 (Frost and Sullivan, 2015). Malaysian automotive manufacturing systems are also incorporating advanced AM technology, but the implementation of this advanced

technology is hindered by some environmental constraints. The automotive industry has not seen widespread adoption of LCA for metal AM implementation due to certain barriers that need to be properly addressed and mitigated (Wohlers & Gornet, 2014; Dwivedi et al., 2017).

To this end, this study contributes to identifying dominant barriers in the understudied context and developing an appropriate approach to weight and prioritize barriers. Individual, level, or cluster-level managers may find the findings useful in developing appropriate mitigation strategies and making more informed decisions.

1.8 Thesis Structure

This thesis comprises of five chapters. Chapter 1 lays the foundation for the thesis. Following a critical overview of the study, the research background and problems are discussed. At its core, it outlines the research objectives and questions, which are then followed by a discussion of the significance and contributions of the research.

Chapter 2 elaborates the theoretical concepts on the under-researched domains, i.e. – Sustainable Development Goals (SDG), Fourth Industrial Revolution (IR 4.0), Additive Manufacturing (AM), environmental aspects of AM, barriers to implement LCA in AM and reviews on methodologies. Chapter 3 details the research methodology, entailing the applications of fuzzy systems and the Analytic Hierarchy Process (AHP). Chapter 4 reveals the results and findings derived from the data analysis according to the research's methodological framework. A comprehensive discussion of the research findings is described in detail, allowing for a more in-depth understanding of the thesis statements. Chapter 5 outlines the final conclusions as well as recommendations for further investigation.

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LIST OF PUBLICATION

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