9-2020

3D Printing for Solving Part Obscolescence

Ayman G. Alqarni

3D PRINTING TECHNOLOGY FOR SOLVING PART OBSOLESCENCE

THESIS

Ayman G. Alqarni, Captain, RSAF

AFIT-ENS-MS-20-S-034

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

AFIT-ENS-MS-20-S-034

3D PRINTING TECHNOLOGY FOR SOLVING PART OBSOLESCENCE

THESIS

Presented to the Faculty

Department of Operational Science

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Logistics and Supply Chain Management

Ayman G. Alqarni, BS

Captain, RSAF

October 2020

AFIT-ENS-MS-20-S-034

3D PRINTING TECHNOLOGY FOR SOLVING PART OBSOLESCENCE

Ayman G. Alqarni, BS
Captain, Royal Saudi Air Force

Committee Membership:

Dr. William Cunningham
Chair

Dr. John J. Elshaw
Member

AFIT-ENS-MS-20-S-034

Abstract

The purpose of this research was to highlight the issue of parts obsolescence and to highlight the possibility of using alternative methods to overcome parts shortage. Specifically, this thesis sought to answer the research question: is the three-dimensional printing technology (3D) an applicable approach to overcome part obsolescence.

The research question was answered through data research and survey analysis. Notwithstanding, the diminished manufacturing sources and material shortages (DMSMS) management and other existing approaches, such as forecasting, contracting, and reverse engineering (RE), were discussed briefly in the literature review and profoundly in chapter IV to differentiate among applicable existing solutions toward solving parts obsolescence.

This research qualitatively conducted a survey to identify the depth of the applicability of the 3D printing technology approach to be a solution for material shortages in comparison with other approaches to solving this matter.

Acknowledgments

First and foremost, I would like to thank God. I would like to thank my home country for believing in me and for giving me the opportunity to seek knowledge in one of the greatest educational institutions. I would like to extend my gratitude to my advisor Dr. William Cunningham, for his guidance and support, not only during my thesis writing, yet through the whole master program. In addition, I would like to extend my thanks to my Mom and Dad, may God bless them for their endless carrying and praying.

Finally, I would like to thank my wife, without her I would not be able to pull this through she has always been there for me so thank you for your support, my dear.

.

Ayman G. Alqarni

Table of Contents

Page

Abstract iv

Table of Contents vi

List of Figures viii

I. Introduction 1

1.1 Background 1

1.2 Problem Statement 1

1.3 Research Objectives and Questions 2

1.4 Methodology 2

1.5 Assumptions and Limitations 2

1.6 Chapter Summary 3

II. Literature Review 4

2.1 Chapter Overview 4

2.2 Parts Availability 4

2.3 DMSMS Management 4

2.4 Supply Chain Management (SCM) 6

2.5 Methods of Addressing Parts Shortage 8

2.6 Three-Dimensional Printing Technology (3D) 9

2.7 Chapter Summary 11

III. Methodology 13

3.1 Chapter Overview 13

3.2 Instrument Development 13

3.3 Non-experimental Instrument 14

3.4 The Sample 15
3.5 Chapter Summary 15
IV. Analysis and Results 16
4.1 Chapter Overview 16
4.2 Forecasting 16
4.3 Contracting 24
4.4 Reverse Engineering (RE) 33
4.5. Three-Dimensional Printing Technology (3D) 39
4.6 The Survey 53
4.7 Chapter Summary 59
V. Conclusions and Recommendations 60
5.1 Chapter Overview 60
5.2 Conclusion of Research 60
5.3 Recommendations for Future Research 61
5.4 Chapter Summary 62
Appendix 64
List of Symbols 64
List of Abbreviations 65
Bibliography 67

List of Figures

Figure 1. DMSMS Management Strategy and Definition

Figure 2. Making N95 Mask Using 3D Printing Technology by (GWUH)

Figure 3. Product Life Cycle Model

Figure 4. Life Cycle Using Gaussian Trend Curve

Figure 5. Supervised Learning Process

Figure 6. OPIS Regional Jet Fuel Prices

Figure 7. CNC Milling Machine

Figure 8. 3D Printer

Figure 9. Miniature Scale by Automobile Designers

Figure 10. Parts Manufactured Using 3D Technology

Figure 11. 3D Printing in the Aircraft industry – Projected Growth in Million Dollars

Figure 12. Benefits Verse Risks of Outsourcing 3D Printed Aircraft Parts

Figure 13. 3D Printing Materials and Machinery

Figure 14. AM Powder Deposition Under Laser Beam

Figure 15. 3D Printed Electric Circuit Board

Figure 16. 3D Printed Thin-Walled Hollow Pyramid Used as a Horn Antenna

Figure 17. Answers to the First Survey Question

Figure 18. Answers to the Second Survey Question

Figure 29. Answers to the Third Survey Question

Figure 20. Answers to the Fourth Survey Question

Figure 21. Answers to the Fifth Survey Question

3D PRINTING TECHNOLOGY FOR SOLVING PART OBSOLESCENCE

I. Introduction

1.1 Background

Swift changes in technology have led to an increasingly fast pace of product introductions (Jennings, Wu, & Terpenny, 2016). Since the industrial revolution, humankind evolved along with every day's inventions. However, that came at a cost; the newer inventions which do not have historical data will be difficult to predict for how long ther will be available or how many spare parts should be made to sustain that system or invention. Moreover, what if there is an update or upgrade? Will the manufacturer stop making the older parts? Furthermore, what if the manufacturer came across a financial dispute and the decision was made to close that facility or declare bankruptcy. In that case, what will happen to all the beneficiaries and users of that product.

1.2 Problem Statement

Parts shortage is a disruption that extends to many levels. In the military, it negatively impacts the aircraft's availability and readiness, as well as in any other sectors, it slows down the progress, and it will lead to asset loss. Due to the rapid movement of the wheel of inventions, overcoming part shortages is one of the most significant dilemmas in the industry we are facing nowadays. In this thesis, research will be conducted to see how good a fit is the three-dimensional printing technology (3D) along with the current options of managing parts and material shortages, such as by forecasting, contracting, and reverse engineering.

1.3 Research Objectives and Questions

The objective of this research is to acknowledge the applicability of handling part obsolescence with three-dimensional printing technology (3D).

The research question is:

1. Is the three-dimensional printing technology (3D) an applicable approach to overcome part obsolescence?

1.4 Methodology

This research is qualitative non-experimental research that will address the following subjects: forecasting, contracting, reverse engineering, and 3D printing technology. In each of these subjects, a background is drafted, which has the information about the usage and importance of that method, followed by limitations to implement that method, and the end of each section a conclusion is given with recommendations. The researcher is going to search through related articles that addressed this problem, and there will be a survey to compare all the applicable solutions for this matter, to see how does the three-dimensional printing technology (3D) fit along with other applicable options of managing parts and material shortages.

1.5 Assumptions and Limitations

There will be a minor difficulty in obtaining data regarding 3D printing technology, due to the fact that it is relatively new to the field. Thus, there is a lack of feedback and reports to utilize in this thesis. Moreover, there will be difficulty in controlling the spectrum of the respondents who will conduct a questionnaire in the analysis and result chapter.

1.6 Chapter Summary

This search is organized in five chapters format. Chapter I is the introduction and background, Chapter II is the literature review that is used to accomplish this research. Chapter II discusses the problem of diminished manufacturing sources and material shortage (DMSMS), and what are the various tools that are practical to use in order to manage DMSMS. Later, chapter III, which is the methodology where the data and analysis section of this research is. Chapter IV is going to be the result and analysis chapter of this thesis, where the comparison among the various methods of resolving the part obsolescence is conducted, such as forecasting, contracting, reverse engineering, and 3D printing technology each approach is discussed thoroughly to highlight its strength and weakness.

In addition, to determine the most appropriate solution for part obsceneness, each approach is first introduced, then limitations that prevent that approach from being the best candidate for resolving part obsceneness are discussed, and then finally, at the end of each approach, a conclusion is drafted with recommendations. Chapter V is the conclusions and recommendations, where the area for future studies and discussion can be carried on.

II. Literature Review

2.1 Chapter Overview

This section of the thesis will discuss the literature review, the historical perspectives of the part obsolescence, and briefly talks about each of the current solutions of this matter along with a proposed future solution for part shortages.

2.2 Parts Availability

Readiness and efficiency rely on parts availability, the ease of acquiring the needed part from within the organization or the ease of procuring the part from an external supplier play a tremendous roll in the race of readiness and efficiency of any institution.

Updating and maintain the organization's stock level without overwhelming the shelves or the holding cost is a critical decision that has to be made.

2.3 DMSMS Management

The issue of the part obsolescence is quite well-spread among the different industries all over the globe. The parts obsolescence has not been taken seriously enough by the decision-makers. The part obsolescence is needed to be foreseen prior to acquisition (Prophet, 2005). Furthermore, the escalating impact of the diminished manufacturing sources and material shortage has developed a number of methodologies and tools that address the obsolescence issue of a part. Forecasting future obsolescence risk is necessary for better DMSMS mitigation and management. To have effective long-term management of DMSMS, it requires addressing the issue from three different management aspects: reactive, pro-active, and strategic (Sandborn, 2008).

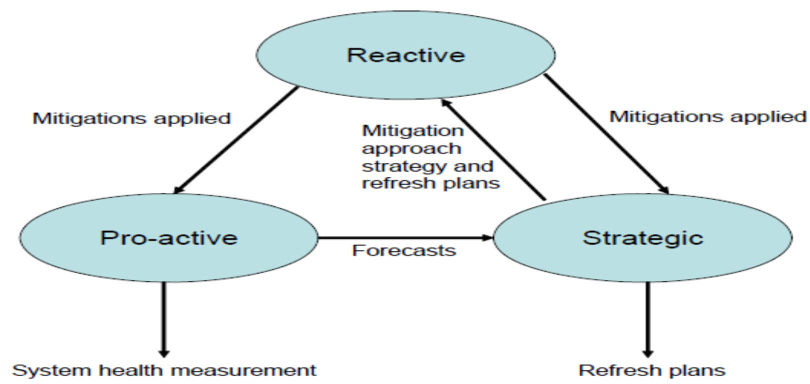


Figure 1. DMSMS Management Strategy and Definition (Sandborn, 2008)

Reactive: When parts become obsolete, determining an appropriate resolution to the issue, executing the resolution process, and track the actions taken. Next, pro-active: which is the determination of the status of the whole system with respect to DMSMS. Pro-active uses forecasting for the obsolescence risk for components, and it requires that there has to be a process for articulating, reviewing, and updating the system's status periodically, as shown in figure1.

Furthermore, strategic: which uses the status of the system, forecasted DMSMS risk, the expected demands, inventory, and spare parts to determine the mix of reactive mitigation approaches (Sandborn, 2008).

The product life cycle is defined as the time period for which the product will be acquirable from the market and can be purchased by the end-user (Meng, Thornberg, & Olsson, 2014). By contrast, obsolescence or end-of-life (EOL) is the final stage of a product's lifecycle when the vendor is no longer produce, sell, and sustain the product. The reasons for not manufacturing the product can be a technological, market, environmental, or even financial dispute. When products reach the EOL stage, the engineering department,

along with designers, receive an obsolescence notice from the vendor. In order to overcome this obstacle of shortage, a short-term or long-term strategy should be developed to solve the problem (Meng et al., 2014).

2.4 Supply Chain Management (SCM)

Supply Chain Management (SCM) has evolved into a concept which covers tactical, strategical, and operational management matters (Kok, Graves, Muriel, Simchi-levi, & Willems, 2003). One of the essential matters to SCM in the aviation sector is aircraft availability and readiness. Thus, readiness and being available when needed and ready to meet the mission's requirements are considered to be the core competency for any air force. In order to have a ready top-notch fleet, aircraft parts have to be in hand.

Parts availability plays a fundamental role in the readiness aspect. Parts for ground equipment that support the fleet of aircrafts are also essential to have and maintain regularly. The matter of running out of parts is a significant concern to the air force and aircraft operator. Methods and processes were developed to address this matter.

The manufacturers need to develop their products promptly to keep up with the competition and to maintain if not increase their market share. Besides the need for redesigning an existing product, there is an urge to adopt the newest materials and components. Products such as personal computers (PCs) and cellular telephones are updated very rapidly (Meng et al., 2014). However, some products are not as swiftly adjusting to leading-edge technology as others and do not possess the ability to catch up with the ongoing development pace of consumer products. For instance, products such as

automotive, avionics, military applications, and so forth, the desired life cycles for these systems are significantly longer than the obsolescence product cycles (Meng et al., 2014).

In 2003, the Government-Industry Data Exchange Program (GIDEP), which was built by the United States Department of Defense (DoD), started releasing information of DMSMS once a week, which indicates the seriousness that the matter has become. In 2013, according to the Silicon Expert database, more than 350,000 items were declared end-of-life (EOL) (Meng et al., 2014).

There are two categories of components: software and hardware. In the aviation industry, the life cycle of a component, for instance, an aircraft's landing gear, will go through an overhaul or refurbishment during its service in the fleet according to specific measures like, for instance, the flight hours. Moreover, the head-up display (HUD) will be upgraded prior to that phase inspection or if there is a technical change technical order (TCTO).

There is a variance among components when it comes to change a part, an upgrade, or to perform a technical change. The manufactures have a business to protect and grow, and so does the end-user. For instance, if the end-user of any product assumes to have the urge to change a part upon overhaul, and that particular part is not available in the user's inventory, and the factory of that part stops manufacturing it, what will happen? The end-user will experience the problem of part obsolescence, and the business will be affected (Prophet, 2005).

Moreover, the customer who needs that obsolete part will try to find a way to acquire that part. For instance, in 2004, the maintenance of the London underground railway system had been buying spare parts from the eBay auction website in order to keep

the older electronic system operating (Prophet, 2005). The issue of procuring parts from unapproved sources will lead to the doubt of the authenticity of that part, whether this part is genuine and fits for its purpose or not, due to the fact that counterfeit parts are becoming commonplace (Prophet, 2005).

2.5 Methods of Addressing Parts Shortage

In the beginning, forecasting is considered to be the first brick in building a well-constructed inventory. There have been enormous models to address and to predict how much to order based on dependent variables; such as, previous part consumption, expiration dates, costs, and urgency. Forecasting is well defined in business books, and there are many methods of performing forecasting.

A regression model that is associated with the prediction of uncertainty is usually developed to anticipate the need for parts. Moreover, the regression method has become the key tool for describing the relationship between the dependent variables and the independent variables (Jessen & Menard, 1996).

The second approach is contracting, which is vital among businesses and countries. Contacting is a mutually binding agreement, and there are various types of contracts. This research will consider contracts that ensure the streaming of parts, such as long term contracts, hedging contracts, forward contracts, or even creating a joint database between suppliers and the suppliers of the suppliers with the end-user to overcome part obsolescence.

On the other hand, there are other types of contracts that were not discussed because of the irrelevance to the matter of the aviation industry, such as buy-back contracts, and revenue-sharing contracts (Cachon & Lariviere, 2005).

The big question of any warehouse manager is how much to order, how to estimate the need for the next coming period, and what are the costs associated with stocking parts in the warehouse. Weighing out the holding cost verses the waiting on a part is a significant concern for decision-makers.

The next approach is the process of reverse engineering (RE) and its applications, which have been established in the industry. RE is a process of taking an existing model and reproducing its surface geometry in a three-dimensional (3D) data file on a computer-aided design (CAD) system. RE approach is based on the principle of reducing the time of fabricating and modeling of the mechanical parts, which can be detailed and complex. RE is very crucial in making parts that no longer exist. (Pandilov, Shabani, Shishkovski, & Vrtanoski, 2018).

Thus, the process of reverse engineering is considered to be one of the solutions toward resolving the issue of part obsolescence. Nevertheless, the question still stands, if this method is the best method and is it going to save the resources like money and time.

2.6 Three-Dimensional Printing Technology (3D)

The wheel of innovations keep spinning, three-dimensional printing technology, commonly known as (3D) is, in fact, an additive manufacturing (AM) method, which means the process of bonding materials, layer-by-layer, to make objects from a 3D model digital file or a scan of an existing object (Kostakis, Niaros, & Giotitsas, 2015).

There is an increasing agreement that 3D printing technologies will be one of the next essential industrial revolutions. Much work has been done as to what this technology will bring in terms of process innovation and product, little has been done on their influence upon business models (Rayna & Striukova, 2016). However, history has revealed that technological revolutions without an appropriate business model evolution are a risk for many businesses.

3D printing consists of successive stages, which are: prototyping, tooling, and digital manufacturing. Hence, 3D printing technology has the potential to alter the way business model innovation is handled by allowing adaptive business models (Rayna & Striukova, 2016).

This technology is still questionable when it comes to its ability to produce hard metallic parts or even anything besides polymers. The expenses of implementing such a technology are not cheap, and it comes with many obligations like technical obligations, and hardware necessities.

On the other hand, in the medical field, the 2019 Novel Coronavirus (COVID-19) has caused a severe reduction in the supplies of personal protective equipment (PPE) due to the unpredicted high demand. In order to address the imminent shortage of equipment including N95 masks, the George Washington University Hospital (GWUH) has developed a 3D printed reusable N95 mask respirator that can be used with multiple filtration components (Ms et al., 2020), see figure 2.

Figure 2. Making N95 Mask Using 3D Printing Technology by (GWUH) (Ms et al., 2020)

There is a promising future for this technology, and it can be implemented as one of the process manufacturing improvements in the factory floors, where it provides an alternative approach side by side with the old fashion fabricating methods.

2.7 Chapter Summary

The fact that the decision-maker or the project manager can choose among competing alternatives to produce a part is a potent tool, which provides a degree of flexibility and freedom. Furthermore, it allows choosing from two different approaches at the same time to fasten the process of manufacturing. Selecting any approach always have some level of doubt, along with the advantages and disadvantages of going in that course.

Therefore, a compromise comes into play far more often during decision making. In addition, a comparison is always present, to compare quality, speed, risks, and assets usage among all the approaches of handling parts shortages.

III. Methodology

3.1 Chapter Overview

This is qualitative research; this section of the thesis will discuss the methodology, the instrument that will be used for finding the possibility of using 3D printing as an effective method toward solving the part obsolescence.

3.2 Instrument Development

This research is conducted in a qualitative non-experimental manner. This research discussed four approaches in overcoming part shortages along with a survey. The four approaches are: forecasting, contracting, reverse engineering, and 3D printing technology, which are discussed in the data and analysis chapter profoundly. A background is drafted, which has the information about the usage and importance of each approach, followed by limitations to implementing that approach, and at the end of each approach, a summary is given with recommendations.

Supply chain management deals with various methods of handling part shortages; many articles were written in managing logistics and part availability. Thus, in order to be ahead of the game, it is mandatory to keep looking for new and more innovative ways continually. Predicting what is the customers's need is essential in the industry, and that is usually held by various types of contracts.

Moreover, starting to look at efficient methods to produce the parts that are need is a very prolonged process controlled by a lot of constraints, such as time, money, raw materials availability, quality, and then delivery. Reverse engineering and 3D printing technology have been there for a while to retrieve parts into existence after being short of

them. Reverse engineering is not meant to fabricate new parts as a 3D printer does. However, the use of 3D printing is a well-known approach in reverse engineering fabrication to save costs and time that are associated with the development of a new production line. Subsequently, this thesis provides the role and the importance of each approach, along with the possible and known challenges for that approach.

3.3 Non-experimental Instrument

This thesis will search for various solutions for overcoming part obsolescence, it will point out the most effective solution, and will answer the research question of this thesis, which is the applicability of handling part obsolescence with the three-dimensional printing technology (3D) and the obstacles associated of doing so.

A survey is conducted to correlate the search with what the respondents believe in from their expertise. The survey will be filled by a diverse spectrum of maintainers and supply technicians, along with managers in the aviation industry in Saudi Arabia. The survey will be limited for a period of two weeks, there is no target number of responses to complete the survey, yet the more response, the better results. The survey will consist of various questions in a multiple choices fashion. In addition, there will be a comment box where the respondent can add any opinions or suggestions related to parts obsolescence. The survey's findings will be in the conclusions and recommendations chapter.

The motive to conduct a survey over any other means of non-experimental tools, due to the fact that the 3D printing technology is relatively new, and during the research of this thesis, there was a shortage in feedbacks from whoever has used this technology either

they do not want to give up their trade’s secrets, or there is not enough information to offer in the form of feedbacks.

3.4 The Sample

The population of this survey is from maintainers and supply technicians, along with managers in the aviation industry in Saudi Arabia. The researcher will collect feedback from respondents and then conduct an analysis of the sample will be interpreted.

3.5 Chapter Summary

As can be seen, research followed by a survey will be conducted in this thesis in order to answer the research question. In the following chapter, the researcher will discuss in detail each of the possible solutions. The main objective is to find the answers of the research question by confirming or rejecting the idea of the 3D printing technology as a solution of the part obsolescence through searching in previous studies and conducting a survey which has questions to compare the different solutions of the part obsolescence issue from various perspectives; such as cost, difficulty to implement, and most effective approach.

Later a conclusion is drafted in the last chapter of this thesis with the interpretation of the findings. Moreover, the research question will be answered and justified. An area for possible future research will be highlighted.

IV. Analysis and Results

4.1 Chapter Overview

This chapter will discuss various methods to mitigate part obsolescence. Moreover, analysis of the different approaches to achieve effective management of the DMSMS in order to reduce the negative impact on the aircraft's availability. Later, the most efficient approach to overcome part obsolescence will be declared. Starting with forecasting, followed by contracting, after that reverse engineering, then 3D printing technology, and finally, the survey will be the last section of this chapter.

4.2 Forecasting

This section will highlight various types of forecasting in order to resolve and predict parts obsolescence. Moreover, limitations in implementing forecasting to resolve part obsolescence will be discussed. Later, recommendation, along with the conclusion, is given.

Forecasting, on the other hand, is an essential and fundamental tool. However, gathering data required for forecasting can be subjective and laborious, which can lead to inconsistencies in predictions (Jennings et al., 2016). Obsolescence takes place in all industries due to the lack of availability of alternatives, which can achieve better performance and quality, or both. In 2016, 3% of the world's electronic products became obsolete on a monthly basis due to various reasons: technical, functional, and obsolescence style (Jennings et al., 2016).

As obsolescence escalates, the need for proactive management grows because reactive strategies are often far more expensive than proactive strategies. Furthermore,

proactive strategies by the decision-makers will enable firms to have a sufficient amount of time in order to plan and react with an effective, low-cost approach. By contrast, reactive strategies require additional resources, for instance, time and materials to resolve and handle delays that negatively impacted consumer's satisfaction (Jennings et al., 2016).

The backbone of a practical, proactive obsolescence management strategy is an obsolescence forecasting methodology. Obsolescence forecasting is categorized into two methods, obsolescence risk forecasting and life cycle forecasting. The obsolescence risk forecasting is the process that predicts and foresees the probability that a particular item will become obsolete. Whereas life cycle forecasting is the process that measures the duration during which the item will be purchasable (Jennings et al., 2016).

Obsolescence forecasting is significant in two phases: the design of the item and the manufacturing life cycle of the item. Moreover, decisions that are made in the design phase are responsible for 60%–70% of the cost during a product's life cycle (Jennings et al., 2016).

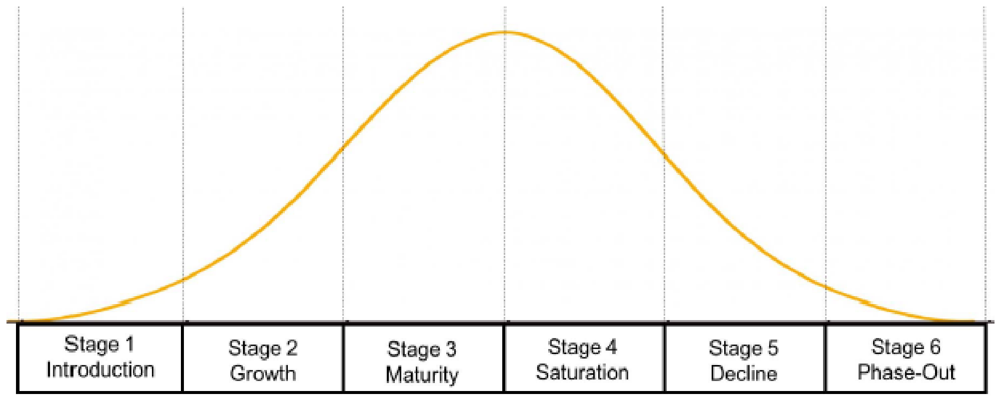


Figure 3. Product Life Cycle Model (Jennings et al., 2016)

As shown in Fig. 3, the model has six phases: introduction, growth, maturity, saturation, decline, and phase out. When sales drop that will be considered as phase-out, a large number of firms will eliminate the product, giving it unsupported and obsolete.

The main advantage of life cycle forecasting is that it enables analysts to predict and foresee a range of data when the item will become obsolete. These data allow decision-makers to set a time frame for the completion of obsolescence mitigation projects. Moreover, these data will help designers in determining when redesigning is needed and assists warehouse managers in monitoring their inventory effectively. Consequently, the life cycle forecasting will mitigate the negative impacts of obsolescence. Contemporary, the product life cycle model is used to develop most of the life cycle forecasting method (Jennings et al., 2016).

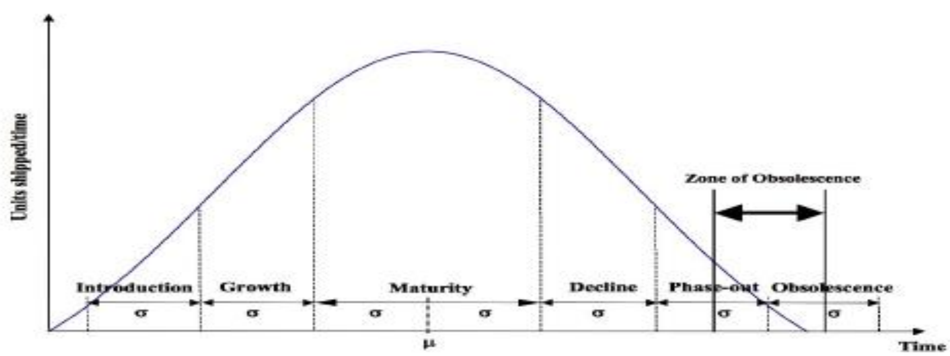


Figure 4. Life Cycle Using Gaussian Trend Curve (Jennings et al., 2016)

The obsolescence forecasting method, which identifies variables such as sales, price, part modification, usage, number of competitors, and manufacturer profits, is used to predict the life stage of an item (Jennings et al., 2016). The utilization of data mining of sales is a powerful tool that is used for life cycle forecasting of sales data of items or other parts and then fits a Gaussian trend curve -the bell-shaped curve in figure 4- to predict

future sales over time. By using the predicted sales trend curve of an item, peak sales are estimated by taking the mean (denoted as μ). Phases are then predicted based on standard deviations (denoted as σ) from the mean. Obsolescence forecasting estimates the zone of obsolescence. Next, the zone of obsolescence is given between $+2.5\sigma$ and $+3.5\sigma$ and renders the lower and upper threshold time intervals for when an item will become obsolete (Jennings et al., 2016). However, a possible shortcoming of this method is the assumption of the normality of sales.

Furthermore, another method that can be used for predicting obsolescence is the obsolescence risk forecasting. Obsolescence risk forecasting indicates the probability of a particular item becoming obsolete by using a scale (Jennings et al., 2016), for instance, the scale of product life cycle stage prediction, which uses a combination of essential aspects to identify where the item falls on a scale (Jennings et al., 2016).

The main metrics identified in this approach are the market share of the manufacturers, how many manufacturers, the life cycle stage, and the firm's risk level. The weights for each metric can vary based upon changes from industry to industry. Nevertheless, this metric is not a percentage, yet rather a scale from zero to three -zero being at no risk of obsolescence and three being at high risk- (Jennings et al., 2016).

Another approach introduced by Van Jaarsveld, which uses demand inputs to predict the risk of obsolescence. This approach manually segregates similar items and observe the demand over time. A formula is given to indicate how a drop-in demand escalates the risk of obsolescence. However, this approach is not able to predict far into the future due to the fact that it does not attempt to forecast out demand, which triggers the obsolescence risk to be responsive (Jennings et al., 2016).

Humans play a significant role in the process of part obsolescence risk management. Asking humans to render an opinion on every part leads to methods that are impractical for the industry. In addition, there may exist biases inherent in subject matter experts when predicting obsolescence risk within their area of expertise. Moreover, these biases are generally due to the fact that experts being so deep-rooted in their field that new products or skills may look subordinate when in fact, they may take away the expert's traditional biases (Jennings et al., 2016).

As can be seen, there are various methods and scales that incorporates how to address the obsolescence forecasting, based on different aspects such as life-cycle forecasting, obsolescence risk forecasting, sales data, and human inputs(Jennings et al., 2016).

4.2.1 Types of Forecasting and Machine Learning

The machine learning is a process that utilizes knowledge in extensive data to help automate complex systems. This made machine learning a major candidate in solving the issues of scaling obsolescence forecasting models to the needs of industries. The obsolescence risk machine learning (ORML) was the first machine learning framework in the area of forecasting by providing a risk index of each part, whether obsolete or active. The second machine learning was life cycle forecasting using machine learning (LCML), and this framework provides an estimation of the lifespan of the product (Jennings et al., 2016).

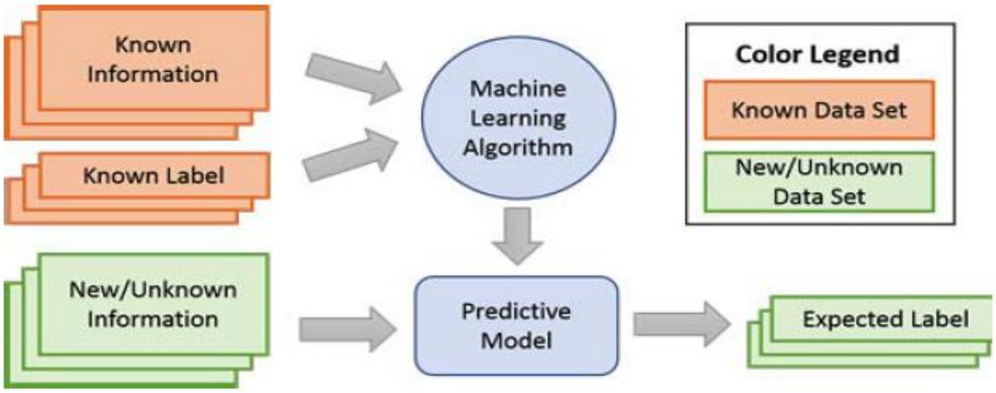


Figure 5. Supervised Learning Process (Jennings et al., 2016)

An essential distinction in machine learning is among "supervised" and "unsupervised" learning approaches, as can be seen in figure 5. In supervised learning, the purpose is to estimate one or more outputs associated with a given sample. In addition, supervised learning approaches are subdivided into two main categories: classifiers, which aim to predict sample classes, and regressors, which is responsible for predicting numerical quantities (Zampieri, Vijayakumar, Yaneske, & Angione, 2019).

By contrast, unsupervised learning enables the examination of data collections through deconstructing variation or correlations between samples. Unsupervised learning approaches are classified as either association algorithms, which reveal unused trends in data, or clustering algorithms, which groups samples based upon their built-in and hidden characteristics.

The most general approaches for data dimensionality reduction are principal components analysis (PCA), which reduces data into low-dimensional representations by summarizing maximum variance among variables; factor analysis, which decomposes data based upon unused relationships describing the correlation among variables; and matrix

factorization, which breaks down data matrices into denoised components (Zampieri et al., 2019). Finally, the clustering approaches, which are the most widespread ones, fall within the k-means and hierarchical clustering families, yet various other algorithms are available with diverse applications (Zampieri et al., 2019).

4.2.2 Limitations of Forecasting

Like any other system, obsolescence forecasting frameworks and models have limitations and issues that may affect and compromise the validity of the prediction. This section addresses these issues and limitations.

First, the initial issue that may arise from the beginning, during data collection, is the data reliability. The data do not have to be complete, yet the more complete the data are, the more accurate and reliable the estimation is going to be. In addition, there will be no uniform indicator between industries. Furthermore, an excellent metric to measure obsolescence, for instance, for flash drives is the memory size, and for cellular telephones, the metric to measure the obsolescence will be the screen resolution. When cellular telephones were first invented, connectivity was the metric of measuring obsolescence, and little emphasis was on the features. Nowadays, connectivity is given, and the features will determine the obsolescence. Hence the metrics change over time.

Another limitation is the accuracy of the data used to build the model. If the data is not up to date, a machine learning or statistical obsolescence model will not be able to predict the jump in technology a new innovation will cause (Jennings et al., 2016).

Furthermore, the usage of machine learning includes human inputs in the process of data cleaning from the outliers, which consumes time and money. Furthermore, if the forecasting is fixed upon demand, this approach is not going to be able to foresee into the

future, which is a limitation presented in the Van Jaarsveld's forecasting model (Jennings et al., 2016).

4.2.3 Summary of Forecasting

There are two types of obsolescence forecasting: obsolescence risk and life cycle. Each of them was tested for its ability to scale using the three aspects: requiring sales data for all items in each component's market, human inputs for each item, and the capability of handling multifeatured components. Machine learning was introduced as a technique to utilize knowledge in large data sets in order to help organize data and automate complex systems. Consequently, this made machine learning as the best candidate in solving the issues related to scaling obsolescence forecasting models to the need of the industries (Jennings et al., 2016).

The first machine learning was obsolescence risk forecasting using machine learning (ORML), which gave the risk index of any product being obsolete or active. The second machine learning was life cycle forecasting using machine learning (LCML), which estimated the lifespan of an item (Jennings et al., 2016).

Then the limitations of applying these models to current obsolescence forecasting systems were addressed for a better understanding of the implications. Furthermore, obsolescence is negatively impacting almost every industry- including aviation- reducing the cost of that impact will result in a better saving for the resources such as time and money as well as readiness and availability. The best way to reduce the negative influence is by sustaining parts and obsolescence mitigation planning in the earlier phases of design and supply chain management. As can be seen, machine learning is a highly effective solution for obsolescence forecasting (Jennings et al., 2016).

4.3 Contracting

This section will study various types of contracting, along with its importance in order to resolve parts obsolescence. Moreover, limitations to contracting in the overcoming of part obsolescence will be discussed. Later, recommendation, along with the conclusion, is given.

Contracting is a well-known matter; it has been used since the beginning of the human race. It comes in various forms and shapes, for instance, verbal and documented contracts. There are numerous definitions when it comes to defining contracting; it is an agreement between two parties or more for doing or not doing specified things. This agreement is enforced by law. Business people usually tend to understand contracts as legal documents, crafted by attorneys to protect the firm from any potential risks and to formulate them for any possible litigation in the worst-case scenario (Nystén-Haarala, Lee, & Lehto, 2010).

4.3.1 Types of Contracts

One of the most fundamental kinds of contracting is hedging, which is the procurement of future contracts that ensure a fixed price. The concept of hedging began to be used in International Relations (IR) (ALAGÖZ, 2017). In another term, hedging is looking for opportunities to manage risk. Furthermore, hedging is an essential tool in facing parts obsolescence. Hedging can overcome fluctuation of prices if planned well, as Southwest Airlines did in hedging their aircraft's fuel between 1999 and mid-2008 (D. A. Carter, Rogers, & Simkins, 2011).

When fuel prices skyrocketed, Southwest managed to save a lot of money. At the same time, rivals from other airlines were losing money on the high jet fuel prices. Airlines

senior managers knew that it is generally impossible to pass higher fuel prices on to passengers through raising ticket fees due to the highly competitive nature of the airline industry; whereas, Southwest Airline kept offering the lowest fees for their tickets because Southwest was benefiting from its strategy of buying fuel for coming years at a fixed rate regardless of the current price fluctuation of the jet fuel as can be. Figure 6 shows the fluctuation of jet fuel prices from 1994 to 2011.

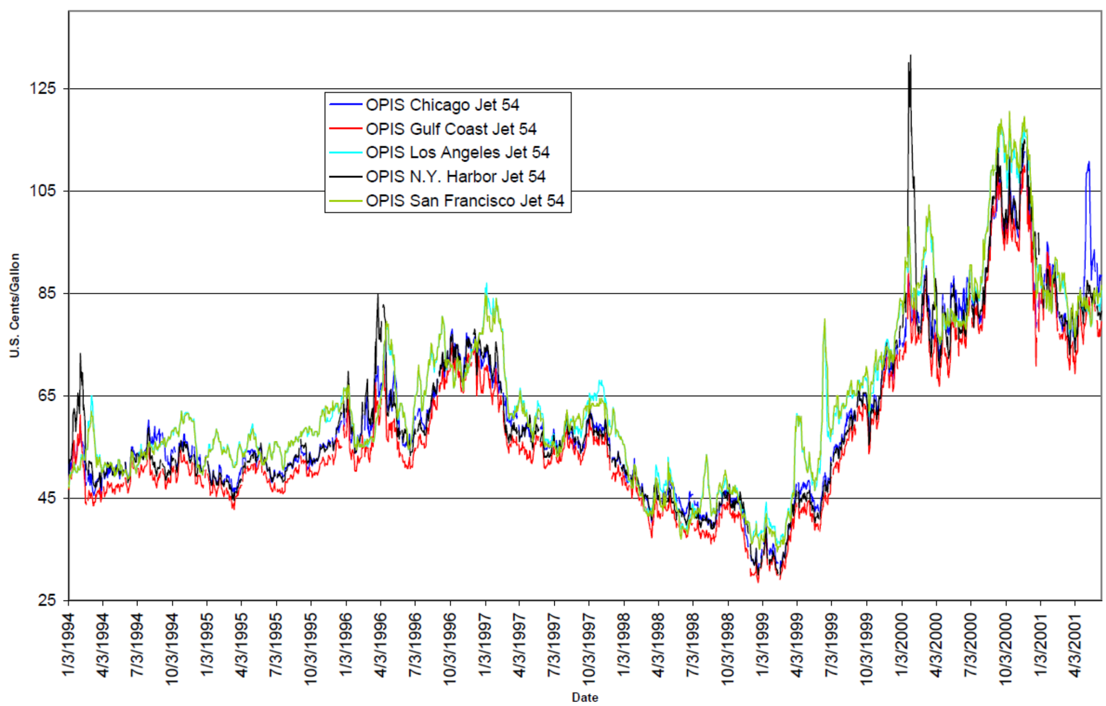


Figure 6. OPIS Regional Jet Fuel Prices (D. A. Carter et al., 2011)

Thus, hedging is a useful tool to face the uncertainty of parts obsolescence, by attempting to buy the wanted commodity at today's price over a period of time to ensure the continuity and the sustainability of the operation. It should not be misconstrued with buying in bulk, because buying in bulk will add holding cost to the buyer, unlike the hedging which requires minimal holding cost, due to the fact that the commodity or parts

are not delivered at once. In fact, delivery will be divided over a period of time upon the agreement.

Another type of contracts is the futures contracts, which are an agreement to purchase or sell a specified quantity and quality of a part for a specific price at a designated time in the future. Future contracts are traded on an exchange, which specifies standard clauses for the contracts; for instance, quantity, quality, and delivery. In addition, futures contracts guarantee their performance. Instead, the buyers and the sellers of futures contracts generally offset their position (D. A. Carter et al., 2011).

Forward contracts are similar to futures contracts except for two major differences. First, futures contracts are standardized and traded on organized exchanges; on the other hand, forward contracts are generally customized and not applicable to an exchange. The second difference, futures contracts are marked daily to the market; on the other hand, forward contracts are fixed at the maturity phase only. For the future contracts, each day within the length of the contract, there is a daily cash deal depending upon the current value of the commodity being needed to be hedged. (D. A. Carter et al., 2011).

As mentioned above, in order to be able to trade futures contracts, they have to be standardized in many ways; for instance, the size of one contract, its length, and delivery date. By contrast, forward contracts can be fitted to the client's requirements, for most of the aspects that are fixed in the case of future contracts. As a result, this form the main advantage of forward contracts (Taušer & Čajka, 2014).

What differs future and forward contracts from hedging is that the strategy of hedging is basically the attempt to reduce the amount of risk due to the volatility of prices for the needed item or commodity.

Long-term contracts are one of the solutions toward resolving the part obsolescence. In fact, many obsolete parts are the result of closing factories, or the manufacturer of that part was forced out of business. Therefore, the long-term contract can prevent factory closures as well as part obsolescence. The presence of monetary disturbances can negatively impact employment and output. A related conclusion is that feedback governs for monetary policy can be an effective stabilization tool. The stability of the labor market can influence productivity as well as the continuity of the product (Barro, 1977). Upon signing the contract, for example, with a new aircraft, it is wise to include clauses of the part obsolescence issue along with part sustainment plan, and what are the alternatives for the user to overcome this matter swiftly.

In addition, many firms and factory close their production lines of an item due to the fact that it is not cost-effective to keep producing that part, and the best approach to overcome this matter is by having a long-term contract which protects every one's interest between the manufacturer and the user.

In the case of aviation, many parts are replaced on a daily basis either for preventive maintenance, corrective maintenance, or overhaul phase inspection due to flight hours according to the technical orders (T.Os) of each aircraft. For instance, the F-15 Eagle model C and D began entering service with the Air Force in June 1979, these platforms are still in service, and still flying (King & Massey, 1997). Boeing company does not make all the parts for these aircrafts; they outsource many of them like any other company. Outsourcing of parts is a well-known practice in the industry of aviation. One of the main reasons for outsourcing is to focus more on the core competency and get the parts that will make the product as a whole from other companies that make that only produce within their core

competency. As a result, a well-designed product that is desirable and qualified for its purpose will be obtained.

There are other advantages in not trying to make a product from start to finish. Instead of having a vertically integrated structure, a supply chain that incorporates innovative smaller firms that have proved themselves in the competition that they are the best in their class. As well as, suppliers who are focused on their core competencies of their own are preferabl, continually striving to make additional value in everything they perform (Cove, 2004).

Long-term contracts, assist in the initiation of the products as well as the continuity of the product, and it can be a win-win situation for both ends. The launching of Boeing 7E7 Dreamliner was a game-changer. It was the first large aircraft built with a composite fuselage and wings, which provided an incredibly economical and comfortable feature. However, that could not have happened without the big order from the leading international carriers to launch this program. Due to the high cost of this aircraft and the need for finical flow for the manufacturing company to make payments to their employees and to outsource the necessary parts from the suppliers in order to build this aircraft (Cove, 2004).

For offshore outsourcing, to the consumer's eyes, it is all about the price or the features the venders offer upon selling the product. For instance, once known as an inexpensive and pleasant brand that offered a comprehensive warranty to make up for mechanical shortcomings and failures, Hyundai has become a respected brand and a smart buy (Taylor III, 2010). Hyundai was known for its low prices, average quality, and a 100,000-mile warranty. Consequently, that what the buyer is looking for, an affordable

brand-new product and commitment to repair and fix the product if it breaks, and that what Hyundai has been doing since entering the U.S market.

Getting all the parts outsourced locally is nearly impossible, due to various reasons, such as quality, price, and labor. Simply put, self-sufficience is difficult and costly. Trades among companies is very common; the supplier's relationship is crucial and critical for continuity as well as productivity. In the Boeing company, 70% of the value-added in most of the products that carry the Boeing name was put there by suppliers, not by Boeing company employees (Cove, 2004).

Since most of the manufacturers rely on suppliers for most of their products, there has to be a way to protect that interaction in order to maintain the flow of production and parts availability. Therefore, long-term contracts among vendors and producers are fundamental. It does not end between supplier and buyer, it goes beyond that, and that is vastly obvious in the foreign military sales (FMS) contracts. Where the other countries purchase their military weapons and equipment via the department of defense (DoD), later, the DoD has to fulfill these purchases via contracting with local companies, like Boeing. If one of the suppliers of that company stops making a specific part, and that part is still in use from other countries, what will happen?

As a result, the whole chain of logistics will be affected, and the end-user will have to wait for that part to be acquired by the manufacturing company- in this case, Boeing- and the user will be informed of that via the DoD. As extended as it looks, things can get lost, and the level of readiness can be jeopardized due to the lack of assured long term contracts which satisfy the ongoing flow of parts and part obsolescence prevention, among

all the parties involving making a particular product, from supplier to the supplier of the supplier toward the end-user.

Foreign military sales (FMS) is one of the forms of long-term contracts between the United States government and its allies. Alliance and coalition partners that use the U.S. made products will develop a closer relationship with the American military, its industry, and through them with the American people as well, and that can be achieved via the commitment of long-term contracts (Mckinley, 2016).

On the other hand, manufacturers have to offer better options for their customers' database, with various differentiation, in order to create a long-lasting contract that can benefit both parties and flourish the economy. Long-term contracts mean job security, and that will influence the performance of the labor force and will enhance the sense of belonging on the factory floor.

Another form of contracts is called the offsets contract, which is associated with foreign military sales. Offsets contracts or agreements come into view to be common in defense sales of aircrafts, radars, and other electronic devices, to foreign allies. In addition, it seems that the offset agreements are the typical trend in such transactions (Waller, 2003).

There are two distinctive types of offsets; which are: co-production and licensed production contracts. The co-production contract is nation to nation basis, which provides the importation of arms to acquire the technical data to facilitate the start of building the parts within the buyer’s industry. Whereas, the licensed production contracts, is basically building the artilleries and their parts overseas under a commercial contracts between the selling firm and the foreign nation or the producer (Uttley, 2001).

In a typical offsets arrangement, the buying country, which usually has a formal offsets rules and policy to govern offsets, requires the selling party to come up with economic offsets for having acquired the foreign-made product or system. The offsets can involve purchases by the selling party from the acquiring country, as well as technology transfers to the buying party (Waller, 2003). Often the more substantial the contract, the higher the offset (Jones, 2002).

Moreover, the selling party may concur to produce a portion of the product in the buyer's homeland. Thus, the value of the offset agreements by the buying country often equals to the value of the defense purchases. In addition, the time required to accomplish the offset agreements can be more than the delivery time for the purchased equipment (Waller, 2003).

The benefit of the offsets agreements is that it will ensure the ongoing of most of the parts; the obstacle of having obsolete parts will be minimal, as well as this approach will keep the user in a closer relationship with the seller. In addition, the approval cycle for most of the items will be shorter. Thus, the offset contracts or the localizing the industry can be a vital solution to part obsolescence. Furthermore, the employment rate will be positively influenced by the offsets agreements for both the importer and exporter (Department of Commerce, 2013).

4.3.2 Limitations of Contracts

Like any other approach, hedging has a limitation to be implemented, and that can be seen from what many airlines have done by limiting the strategy of fuel hedging operations, due to that fact there is uncertainty to guarantee generating enough cash flows to finance futures margin deposits or option premiums. In fact, Delta Airlines, in 2004,

began with fuel hedging strategy, yet it was forced to abort the strategy to finance their flight operations (Cobbs & Wolf, 2004).

Moreover, the offset contracts can be limited to the original agreement that was agreed upon, which dictates a partial transfer of the technology. Thus, the risk of the possibility of running into an obsolete part is still standing (Jones, 2002).

4.3.3 Summary of Contracts

The long-term contracts process consumes a lot of time. As a result, someone else with a much shorter approval cycle possibly will step up and be a competitor for the venders, and the buyer could benefit from that leverage in reducing prices (Mckinley, 2016).

One shortfall of contracts is that firms get sold by other larger companies, or two great companies merge together, which results in changing policies and editing of terms and conditions with the customers. Nothing is guaranteed in the line of business. Hedging is a great technique, yet what if the commodity's price that needed to be hedged went down instead of going up. That means, there will be losing of money since there is a binding contract.

Companies declare bankruptcy quite often these days due to the heat of the competition among rivals. Therefore, this brings us back to the same point, what type of approach to resolve part obsolescence should contracting be embraced, and if so what type of contracting might be most suitable.

4.4 Reverse Engineering (RE)

This section will inquire about the methodology of reverses engineering along with its role in resolving parts obsolescence. Moreover, limitations to reverses engineering in overcoming part obsolescence will be discussed. Later, recommendation, along with the conclusion, is given.

The concept of reverses engineering was first introduced in the early 1990s (Miiller et al., 2000). There were many definitions of reverse engineering, yet all were poured into one source. Reverse engineering is defined as analyzing a subject system to identify its current components, subcomponents, and their dependencies, as well as to extract and create system abstractions and design information (Miiller et al., 2000).

Many reverse engineering tools focus on extracting the structure of a legacy system with the purpose of transferring this information into the minds of the software engineers in order to re-engineer or reuse it (Miiller et al., 2000). The process of reverse engineering can be one of the effective solutions of the part shortages.

Reverse engineering is a tool in itself in facing such an obstacle of part obsolescence. As the name implies, it is simply taking something already was made and trying to take it apart piece by piece to fabricate a new part or to upgrade the existing one. The reverse engineering method requires the right hardware and software along with the capable labor force in order to adequately comprehend the mechanism and the software of the product needed to be reverse-engineered.

Often times, the attempt to reverse engineer software is a bit complex than reverse engineering hardware, because usually, the software comes in codes and these codes are

hard to obtain, or there have been a lot of undocumented changes on that code, which makes it difficult to either retrieve it to its genuine status or even reverse engineer it.

4.4.1 The Process of Reverse Engineering

Reverse engineering includes extracting design artifacts from the source code for the building of abstractions, which are less implementation-dependent than the source code (Müller, Orgun, Tilley, & Uhl, 1993). The source code is the core of reverse engineering, where the software engineer pours his heart in making the script. In contrast, the main purpose of forward engineering is to produce the quality of the code (Miiller et al., 2000).

Moreover, the importance of the code level is emphasized in legacy systems where major business rules are embedded in the code. During the development of software, change is applied to the source code, for various reasons such as fixing defects, adding a function, and enhancing the quality. In the case of systems with poor documentation, the code source is the only authentic source of information about that system. Thus, the process of reverse engineering has focused on comprehending the code (Miiller et al., 2000).

Nonetheless, the code does not have all the needed information. Commonly, knowledge about architecture and the design tradeoffs, engineering limitations, and the application domain is only found in the minds of software engineers. As time passes, memories fade, people leave, documents vanish, and the level of complexity increases. Therefore, the gap arises among known necessary information and the required information needed to enable the software change. Simultaneously, the gap can be too broad to be easily expressed by traditional programming tools (Miiller et al., 2000).

For long-term maintenance of large software projects, logical for design decisions are usually not available because the people who could trace back the history of changes

are no longer with the same project. Similarly, design files can be inconsistent with respect to the genuine source code because of the undocumented corrections, improvements, or even enhancements.

This type of evolution is typical and can considerably result in complications for the maintenance tasks. Most of the time, the source code is the only valid mean for a maintainer to be able to make the decision on how a software system is to be modified upon the implementation of a desired enhancement or change. However, the size of the source text usually prevents a complete and comprehensive analysis of all probable impacted components and dependencies. Similarly, small editing can result in an inconsequential change that can be unforeseen and sometimes devastating. Therefore, the results of any modification must be considered cautiously, not only locally, yet throughout the entire code of the system (Müller et al., 1993).

The code source is important to have in hand prior to reverse engineer an item to program it in the Computer Numerical Controlled (CNC) machine. CNC machine is an instrument that performs a subtractive process where the material is removed from stock depending on the code; usually, it is called G-code (Farouki, Manjunathaiah, & Yuan, 1999). CNC simultaneously allows the transformation of the digital design -usually from the AutoCAD program- into a physical part (Xu & He, 2004). CAD systems began in the early 1980s and enabled designers to create geometric models of the product more conveniently than on paper (Lee, Ma, Thimm, & Verstraeten, 2008).

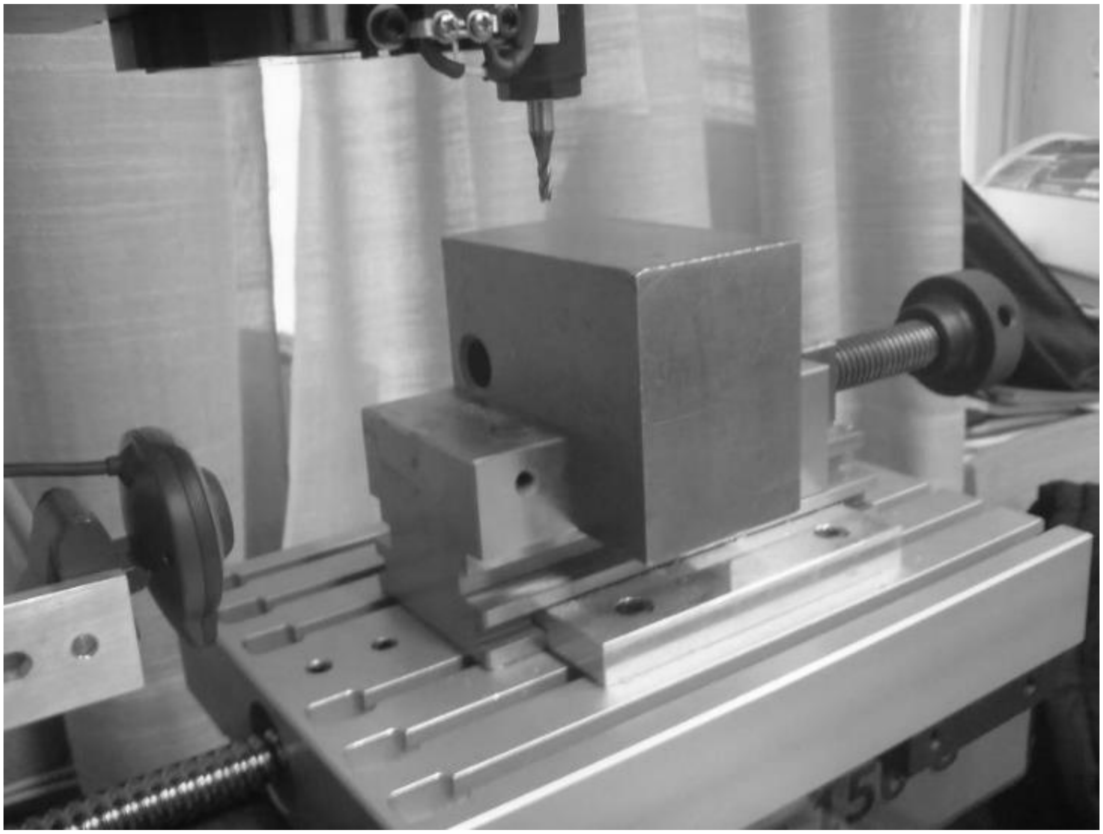


Figure 7. CNC Milling Machine (Klančnik & Šenveter, 2010)

Moreover, as can be seen from figure 7, the CNC machine is faster, with higher precision comparing to manual alternatives. The precision is within thousand of an inch referred to as thou (Carver, 2016). The importance of this machine is its axis; it comes in 3 axes and in 5 axes, which simply referred to the degree of freedom a machine can make a cut. The 3 axes CNC moves in the X, Y, Z directions; where, the 5 axes CNC can move in the X, Y, Z axes along with two additional rotational axes (Sencer, Altintas, & Croft, 2008).

One of the most practical CNC machines is the milling machine, which involves the use of a rotary cutting tool in order to remove material from a stock piece of any material from plastic to Titanium (Ti). Therefore, the CNC machine operator has to adjust

the tool selection, the revelation per minute (RPM), and coolant flow accordingly with each stock of material (Rubery, 1988). The CNC machine is a fundamental tool for reverse engineering; thus, it has been used widely in the industry to achieve the required product (Sokovic & Kopac, 2006).

In the ongoing fight with the problem of part shortages, the method of reverse engineering defines two distinct information about a product; which are: the identification of the components, and the extraction of system design information. As a result of the information produced by this method, it will be a firm ground for system comprehension and analysis (Müller et al., 1993). This method involves all of the subsystem’s levels of a product, along with their interactions with each other.

Once the structural characteristics and properties of the system are identified using the reverse engineering method, the impact of local changes can be traced effectively by analyzing the resources changed between subsystems at different levels of detail (Müller et al., 1993).

Identifying subsystems is a predecessor in establishing hierarchical subsystem structures. During the design phase, subsystem structures are usually used to split the task into work assignments for managing the design and the implementation of the task. At integration time, subsystem decompositions may serve as testing and integration objectives. Therefore, constructing hierarchical configuration structures is important for long-term maintenance, and during the preliminary design stages (Müller et al., 1993).

In the aviation industry, the average life of the fleet is around 30 years. A lot can happen over three decades, many factories switched their production line to more innovative and cost-effective products, and newer technology arises every day (Lee et al.,

2008). As a result, old aircraft parts will vanish due to the frequent consumption by the user along with the dry supply of these parts from the manufacturer. A compromise is needed to keep the fleet ongoing and to not lower the level of readiness by the usage of reverse engineering for the obsoleted parts.

An aircraft will be grounded and band from performing a mission if it has any missing or unreliable part. It is a big waste to prevent an aircraft from flying over out of reach part, and the only way to get the aircraft flying again is by obtaining this part; thus, reverse engineering will be a vital solution for such a dilemma.

4.4.2 Limitations of Reverse Engineering

The frequent need to replace the expensive drill pits of the CNC machine along with periodic calibration is a vital limitation, especially the 5 axes CNS.

The electronic devices with programming and complicated software usually harder to reverse engineer due to patent rights along with the complexity of tracing back the original code the programmer encrypted. Reverse engineering requires permission from the manufacturer or the owner of the part, and that is not an easy task to acquire, because rarely someone will give up the secrets of his trades.

The set-up cost of a new operation to reverse engineer a part is not cost-effective compared to locating an alternative part, because the cost does just not end in setting up a factory floor, there will be associated costs, like operation costs, holding costs, and transportation cost. Many parts in the industry are under contracts, which basically define the usage window for the user and the process of repairing the product if it is unrepairable or if it reaches its end of the life cycle.

4.4.3 Summary of Reverse Engineering

As can be seen, reverse engineering is the process of retrieving someone's else steps to make a product or to enhance one. Reverse engineering is very beneficial in resolving the matter of part obsolescence, and it can restore the performance of disabled mechanisms or software.

The main approach of reverse engineering of a product is to have its genuine source code and try to work on creating a product out of that code. The second approach, which is for the hardware products, is done by taking the measurements of each and every subassembly of that product. After that, drawing the parts using one of the automated drawing programs like AutoCAD, and import the drawing to a CNC machine after preparing the right martial according to the specifications of the original martial.

Therefore, reverse engineering can be significantly done for structural items more than the software items. The patent rights can be an obstacle for the implementation of reverse engineering, the grant of copyrights from manufacturing firms can be prolonged process especially for firms who are no longer in the market game, or firms who declared bankruptcy.

4.5. Three-Dimensional Printing Technology (3D)

This section will explore the methodology of three-dimensional printing technology commonly known in the industry as 3D printing, along with its applicability role in resolving parts obsolescence. Moreover, limitations to 3D printing technology in overcoming part obsolescence will be discussed. Later, recommendation, along with the conclusion, is given.

4.5.1 Background

3D printing technology is an additive manufacturing (AM) process essentially functioning in reverse from a digital file or scan of the item needed to be fabricated (Manda, Kampurath, & Msrk, 2018). The procedure of joining substance, film-by-film, or layer by layer to make a final product from 3D model data (Kostakis et al., 2015).

3D printing has the potential to positively impact the world by simplifying the construction process, shortening the supply routes and distribution chains, facilitating assembly, creating jobs, and customizing products to persons' desire and need (Hornick, 2018).

3D printing technology enables the mass customization and eliminates the need for tool production, and reduces waste in the downstream. Due to these advantages, 3D printing technology has been progressively used in many areas, including medical, construction, automotive, and aviation (Yossef & Chen, 2015).

This technology has many applications; for instance, an architect can print in 3D the design of a building or an automobile engineer can print a prototype of a part for further finishing of the design. This technology has been adopted by the aerospace industry and health care to make useful products for the human race (Kostakis et al., 2015).

3D printing technology brought many changes to logistics and supply chain management and product sustainability. The factories can fabricate to accurate customer's specifications, better material efficiency and effective use of resources in the production lines, enhance global production capacity by practicing standardized 3D printing methods, and rapid modification for the prototypes until the satisfactory product is reached with less consumption in resources and minor impact to the environment (Manda et al., 2018).

Furthermore, 3D printing depends on computer-aided design software, where an operator inputs the drawing of the needed to be manufactured item into the 3D printer along with the substance (Kostakis et al., 2015). This technology is mainly focusing on forming the nonmetallic substance, such as synthetic polymers or Polyethylene (PE) commonly known as Plastic, and carbon fibers together toward making the desired part. These printers differ in sizes, however they share the same principle, as in figure 8.

The carbon-fiber is vastly used in the racing cares due to its rigidity and lightweight and be made using 3D printing technology (M. R. Carter, 2018) (Desai & Singh, 2004).

Figure 8. 3D Printer (M. R. Carter, 2018)

4.5.2 Applications of 3D Printing Technology

The three-dimensional printing enables mass production, increases production speed along with fewer resources waste such as material, time, and labor (Yossef & Chen, 2015). This technology has proven itself in a lot of areas, and it has various benefits such as, one of the main benefits of using 3D in the early designing stage is the ability to start

small and scale up swiftly, prior assessment before the part reaches the assembly line so changes can be made before making the final product, which can save the manufacturer a ton of money and time (M. R. Carter, 2018).

Moreover, the use of 3D printing technology enables designers to examine multiple forms as well as numerous functions of the product as in figure 9, where designers can scale up or down the prototype of the product. Therefore, this will bring designers closer to an ultimate design far more rapidly and costly efficient (M. R. Carter, 2018). By contrast, 3D printing technology saves resources, such as time and money, better than the conventional method of fabrication (M. R. Carter, 2018).

Figure 9. Miniature Scale by Automobile Designers (M. R. Carter, 2018)

3D printing technology is proven indispensable in the design shops, as well as on the factory floor simultaneously. As a cost-effective solution for improving measurement, functional testing, customization, optimization, and swift tooling, adopting and optimizing

3D printing is essential for engineers, designers, and plant workers, aiming to stay ahead of the competition. In addition, with new applications being revealed, tested, and implemented substantially every day, the potential impact on the industry by the implantation of 3D printing technology is just the tip of the iceberg (M. R. Carter, 2018).

In the aviation industry, the implementation of 3D printing technology to fabricate parts has become an industrial necessity. Due to the fast pace the aviation industry is going, the 3D printing technology is highly sufficient and capable to keep up with that rhythm.

Moreover, the research question of this thesis is: Is the three-dimensional printing technology (3D) an applicable approach to overcome part obsolescence?

Is the usage of 3D printing technology in producing aircrafts' parts capable of achieving the mechanical and material property an aircraft requires with the high level of safety requirements to be maintained?

Moreover, can the 3D printing of parts undergo the stress-strain test, shear test, and resist change in physical and chemical properties at high-temperature spots, like around the engine bay of an aircraft or a shuttle. These questions have to be answered in order to consider or not the possibility of enrolling the three-dimensional printing technology as the newer capable approach in resolving part obsolescence.

The arising of 3D printers steers the wheel of new geometric problems that control the quality of the fabricated parts. The main goal of the 3D printing is to have low material cost and low weight of an object while providing a sustainable printed part that can resist impact as well as external forces (Lu et al., 2014).

The honeycomb structure, which provides a minimal cost of material as well as high tensile strength. The strength to weight ratio, along with minimal material waste is the core of the 3D printing technology (Lu et al., 2014).

The usage of this technology in making aircraft and shuttle parts is the new challenge, due to the higher specifications and safety requirements of these parts. 3D printing in the aviation industry has brought in a prospective side by side with challenges setting new approaches and innovative methodologies to match the global standards (Manda et al., 2018).

Nonetheless, experts predicted that 3D printing is going to play a more crucial role in aircraft manufacturing and avionics in the coming years if the present scenario is in line with the industrial requirements (Manda et al., 2018).

The zero-waste of materials, the minimal impact on the environment along with the great opportunity of local manufacturing these parts, and the possibility of just in time (JIT) delivery are all potential benefits of the 3D technology, (Manda et al., 2018). As can be seen from figure 10 various shapes of polymers were made which can be used vastly in the industry.

Figure 10. Parts Manufactured Using 3D Technology (Manda et al., 2018)

3D printing technology is leading towards growth and expansion. The world's aerospace 3D printing market is estimated to flourish from USD 714.5 million in 2017 to USD 3,057.9 million by 2022, as shown in Figure 11.

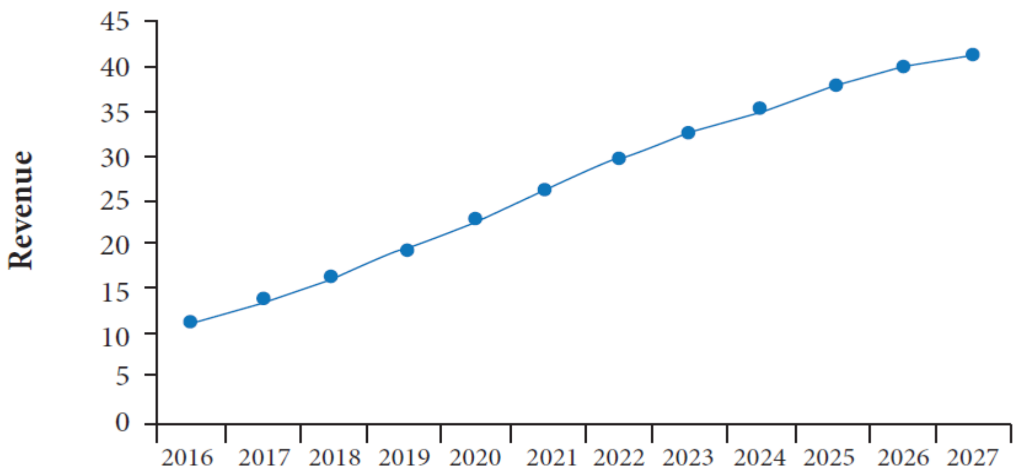


Figure 11. 3D Printing in the Aircraft industry – Projected Growth in Million Dollars (Manda et al., 2018)

There are various materials when it comes to making aircraft parts; structural components differ from the engine bay components and from the hydraulic lines as well. The promising forecast of the growing usage of 3D printing technology in making aircraft

parts is very bright. Thus, the expansion of using this technology locally as an alternative of purchasing parts from overseas has enormous benefits. The most important advantage for implementation of the 3D printing method for aircraft parts production is the reduction of the lead time which it takes to get a specific variety of material, as well as the mitigation of transportation and servicing bottlenecks (Manda et al., 2018).

On the other hand, a similar approach yet considered to be cheaper is to outsource the 3D aircrafts' manufactured parts instead of owing high-end 3D equipment and tooling due to the fact that this technology takes years to become going to be economically feasible.

Moreover, outsourcing will boost economies of scale for the outsourcing companies and maximize the number of parts which can be printed (Manda et al., 2018). Figure 12 illustrates follow chart of the pros and cons of outsourcing 3d printed aircraft parts.

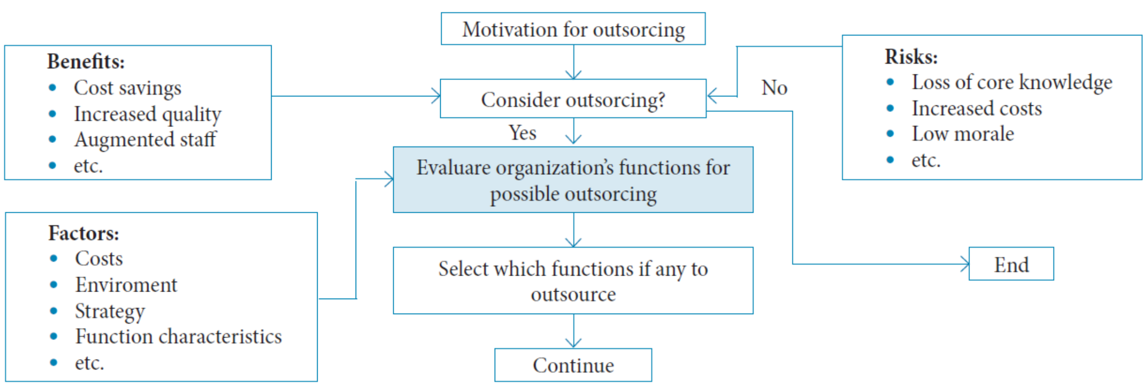


Figure 12. Benefits Verse Risks of Outsourcing 3D Printed Aircraft Parts (Manda et al., 2018)

4.5.3 3D Technology for The Aviation Industry

The digital file is an integrated part of additive manufacturing, which has all the information and instructions about the part being manufactured; it basically tells the printer

what sort of action to take or perform (Manda et al., 2018). The printer's software will read the digital file and consequently prints the layers, layer by layer, and that will result in the final needed part. Each layer is very thin, which allow for very detailed part to be made with high precision. In addition, the orientation of a product is optimized to increase mechanical strength when fabricated with additive manufacturing (Umetani & Schmidt, 2013).

Moreover, since the additive manufacturing (AM) will allow for the use of fewer materials, lightweight alloys, and minimal time cycle for swift prototyping will be produced (Manda et al., 2018). The use of AM will result in less waste, a better address for complex geometries, and an improvement in strength-to-weight ratio. However, currently, the AM cost centers are more expensive than CNC machining, and the production rate is slower than the CNC machine as well (Manda et al., 2018). Nevertheless, 3D printing technology of aircraft parts allows the reduction of the manufacturing cycle time from a year to a month and a half, along with other benefits; such as lightweight, simplicity of design, better convoluted cooling pathways, and support joints with stronger robustness (Manda et al., 2018).

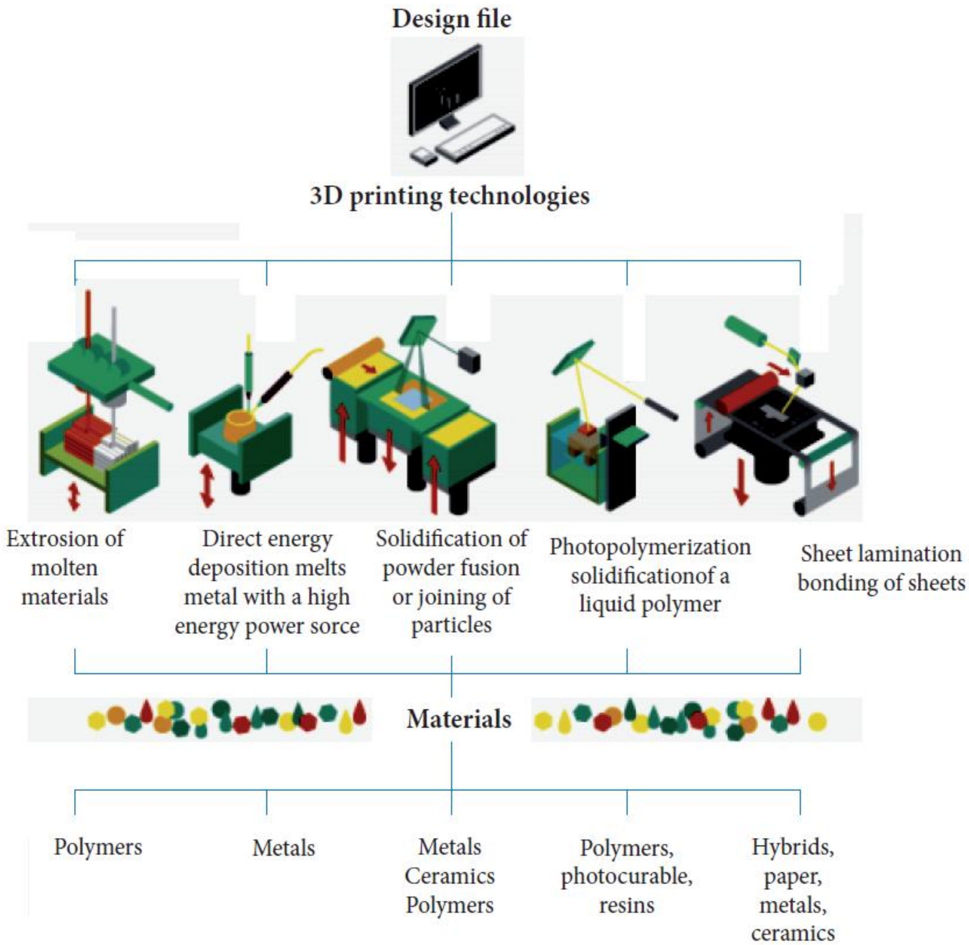


Figure 13. 3D Printing Materials and Machinery (Manda et al., 2018)

Figure 13 illustrates the process of how a 3D printer works, and it states the various materials that can be used in the printing process. Titanium (Ti) and its alloys, especially Ti–6Al–4V, are used widely in the aviation sector, due to their high strength, low density, and excellent corrosion resistance. However, there are massive challenges in casting, machining, and forming titanium, which result in end products that are quite more expensive than their aluminum or steel rivals. Powder-based additive manufacturing is a final shape production method, where components are built by melting consecutive films of metal against a workpiece.

In the AM process, a laser beam is scanned in a preprogrammed behavior to melt the metallic material in order to produce the desired shape. Materials will be delivered to the workpiece by spreading and selectively melting individual powder films in a powder bed fusion (PBF) process. Thus, AM can manufacture a dense three-dimensional part with highly detailed features.

Moreover, AM allows fabricating parts with different shapes and compositions by using the same tolling machine, making the additive manufacturing method desirable for short production runs, which would otherwise require prohibitively high-priced tooling. AM manufacturing of Titanium can be contaminated by Oxygen (O2), and that will affect the grain structure of the metal; thus, an oxygen sensor is placed inside the isolated box to prevent the contamination as can be seen in figure 14 (Carroll, Palmer, & Beese, 2015).

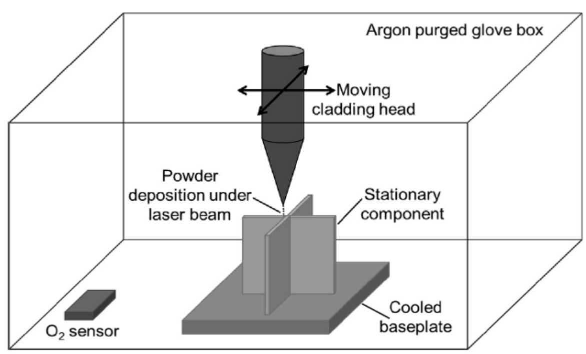


Figure 14. AM Powder Deposition Under Laser Beam (Carroll et al., 2015)

Various electronic parts were made using 3D printing technology, such as sensors and conductive (Leigh, Bradley, Pursslell, Billson, & Hutchins, 2012).

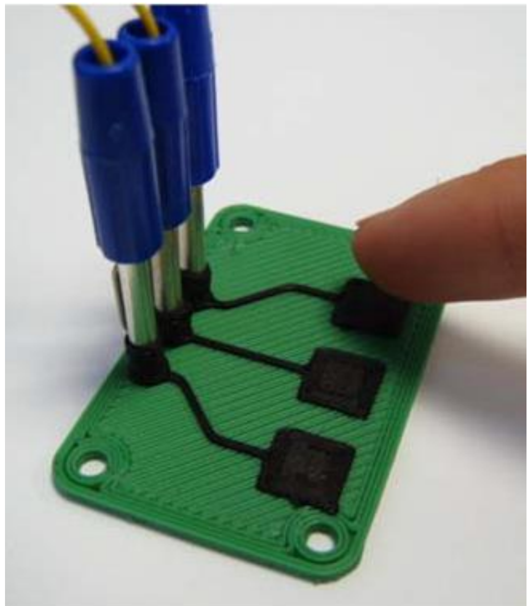


Figure 15. 3D Printed Electric Circuit Board (Leigh et al., 2012)

Figures 15 and 16 show different outputs of 3D printed parts. These outputs are the first step towards having a library of 3D printed electronic parts with sophisticated designs, and the required properties (Flowers, Reyes, Ye, Kim, & Wiley, 2017).

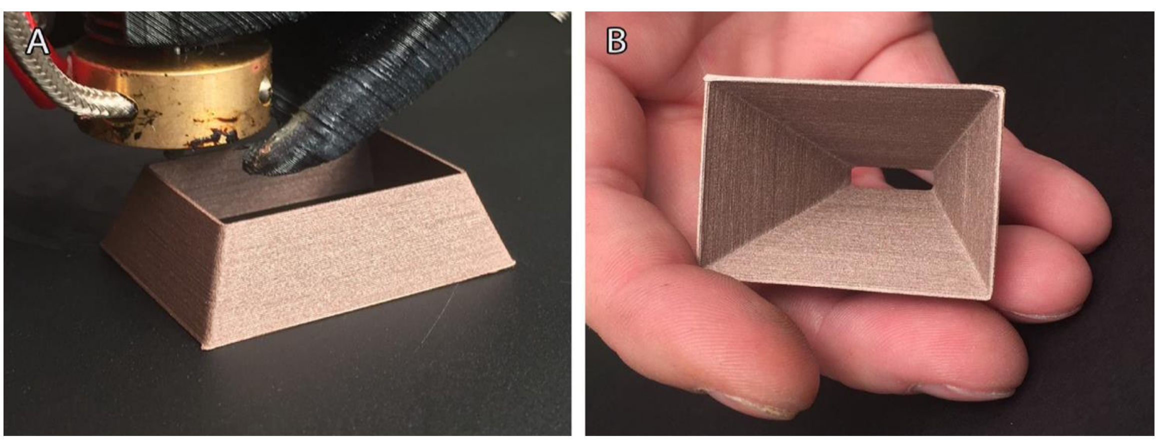


Figure 16. 3D Printed Thin-Walled Hollow Pyramid Used as a Horn Antenna (Flowers et al., 2017)

4.5.4 Challenges to The Implementation of 3D Printing in The Aviation Industry

There are mechanical and martial specifications that can get in the way of implementing or fully benefit from the 3D printing technology in the aviation industry. The aviation sector requires high detailed parts that can withstand high temperature due to the heat generated from the engine or the drag when flying at high velocity. In addition to the other fundamental mechanical tests, such as tensile, shear, hardening, and ductility tests. Flying places, a significant amount of stress on the airplane parts, which are in addition needed to be lightweight yet sturdy. Thus, there has to be high tolerance in manufacturing all parts. However, this approach of achieving high tolerances and quality will consume time (Axtman & Wilck, 2015).

The aviation industry is subjected to complex internal and external loadings, such as gravity and wind. Thus, it is challenging to have a suitable printing tool for such a mission. Therefore, 3D printing technology is still in the primitive phase. (Yossef & Chen, 2015).

By comparison to the construction industry, which is similar to the aviation industry when taking into consideration loads that act on a building is relatively similar to the loads that are acting an airplane. The usage of 3D printing for constructions showed some challenges that can be taken into consideration, such as automated manufacturing is challenging to implement for large scale products. There is a limitation for material usage by the automated machines, and expensive automated machines tend to be economically not efficient (Yossef & Chen, 2015).

4.5.5 Summary of 3D Printing Technology

3D printing technology automatically makes parts from different materials such as plastics, metals and alloys, and ceramics. The additive manufacturing technology has served the aerospace industry, automotive manufacturing, and the medical sector. From printing parts in plastic and metals to bioprinting of transplantable organs. The 3D technology is evolving on a daily basis, which is a breakthrough innovation, garnered by the swift growth in the core technology (Anandan, 2016).

The growing appearance of 3D printers illustrates how quickly high-tech industries and markets can be changed via innovation, collaboration. In addition, it is estimated that innovation by user communities will be increasingly seen in more industries in the future. Because of several exotic trends, including the understanding of modular design, and decreasing design costs because of cheaper and more reliable computerized design instruments. Indeed, these factors are all drivers behind the emergence of open 3D printing, yet they will also influence other industries in the future. Smart companies should begin rethinking their innovation management practices accordingly (Jong & Bruijn, 2013).

Furthermore, the Titanium-based parts were produced in AM manner in the powder deposition process, which shows that quasi-static uniaxial tensile mechanical properties similar to the traditionally produced Ti–6Al–4V (Carroll et al., 2015). Since the titanium (Ti) is one of the highest used metals in the aviation industry, this gives hope for additive manufacturing to overcome part obsolescence.Titanium metal tends to be very rigid, which makes it susceptible to be brittle. The ductility test is crucial for any metal to test the metal's deformation or elongation, the ductility causes the presence of grain boundary, which prolongs as a path along resulting damage that can lead to fracture (Carroll et al., 2015).

4.6 The Survey

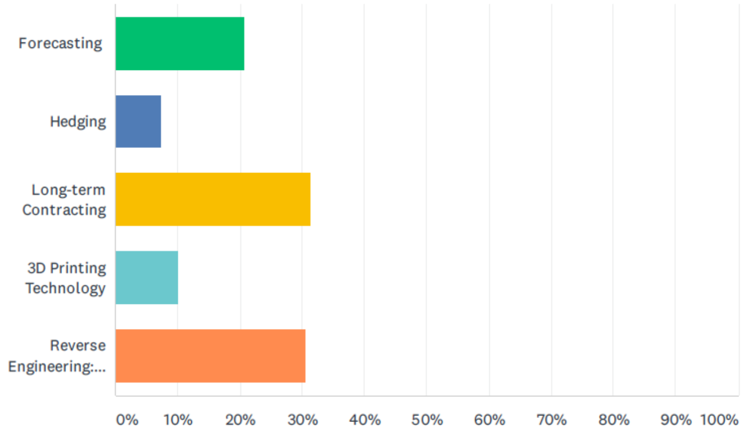
This section of the thesis will address the questions and answers of the survey. The survey will add some insight and influence to the decision-maker. Moreover, conducting a survey will help to answer the research question about whether three-dimensional printing technology going to be an applicable approach in overcoming part obsolescence?

4.6.1 The Survey Format

The survey was sent to a diverse spectrum of maintainers and supply technicians, along with managers in the aviation industry in Saudi Arabia. The survey was conducted over a period of two weeks. The total responses were 421, the completion rate of the survey was 95% the with 400 completed responses. The survey consisted of five questions, which were in a multiple choices fashion.

4.6.2 The Survey Questions

The first question was: which of the following methods is the best approach toward solving the shortage of spare parts? The respondent would choose form (forecasting, hedging, long-term contracting, reverse engineering, or 3D printing). Figure 17 illustrates the results of the first question.

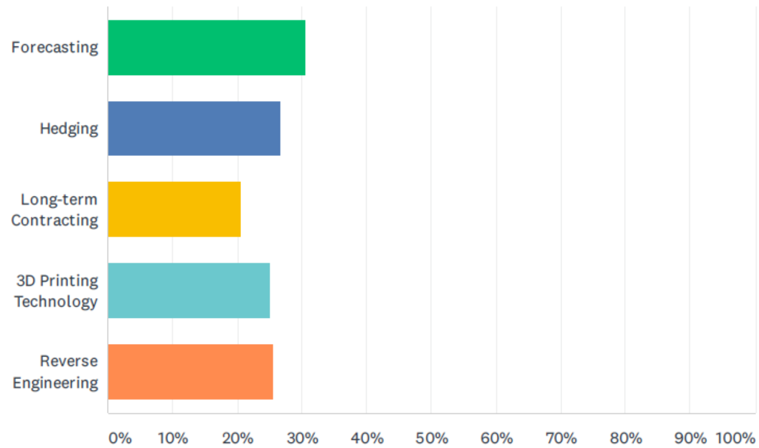


ANSWER CHOICES	RESPONSES	
Forecasting	20.67%	87
Hedging	7.36%	31
Long-term Contracting	31.35%	132
3D Printing Technology	9.98%	42
Reverse Engineering	30.64%	129
TOTAL		421

Figure 17. Answers to the First Survey Question

As can be seen, the total responses for this question were 421 out of 421 with a 100% completion rate for this question form the respondents. Long- term contracting is neck to neck with the reverse engineering, long- term contracting was the best approach to solve the issue of part obsolescence, and hedging came to be the least preferred approach according to the respondents.

The second question was: which of the following options is the most difficult solution to implement toward solving the shortage in spare parts? The respondent would choose form (forecasting, hedging, long-term contracting, reverse engineering, or 3D printing). Figure 18 illustrates the results of the second question.

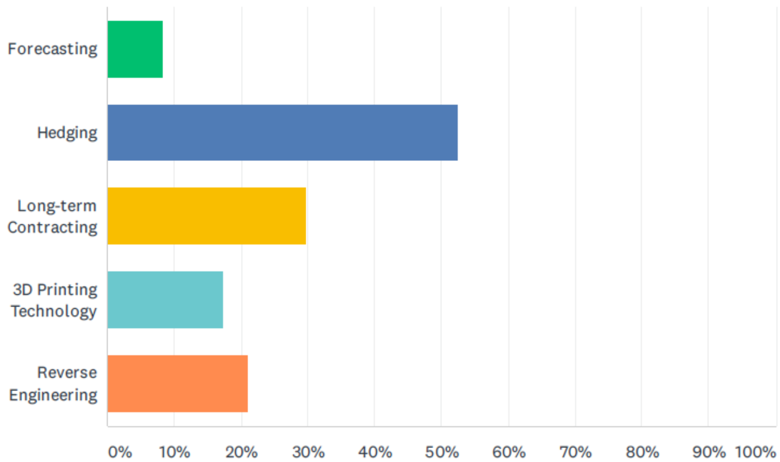


ANSWER CHOICES	RESPONSES	
Forecasting	30.51%	126
Hedging	26.88%	111
Long-term Contracting	20.58%	85
3D Printing Technology	25.18%	104
Reverse Engineering	25.42%	105
Total Respondents: 413		

Figure 18. Answers to the Second Survey Question

As it can be seen, the total responses for this question were 413 out of 421, with a 98% completion rate for this question form the respondents. Forecasting was the most difficult solution for solving the shortage in spare parts, and the long-term contracts came to be the least difficult solution for solving the shortage in spare parts according to the respondents

The third question was: which of the following options is going to be the most expensive solution in solving the shortage in spare parts? The respondent would choose form (forecasting, hedging, long-term contracting, reverse engineering, or 3D printing). Figure 19 illustrates the results of the third question.

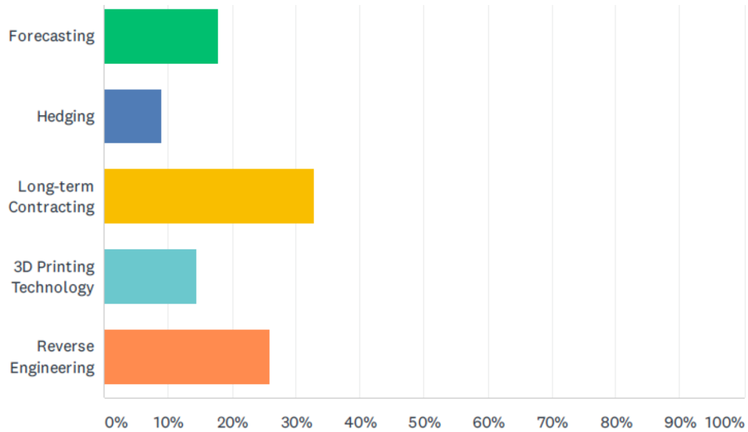


ANSWER CHOICES	RESPONSES	
Forecasting	8.33%	34
Hedging	52.45%	214
Long-term Contracting	29.66%	121
3D Printing Technology	17.40%	71
Reverse Engineering	21.08%	86
Total Respondents: 408		

Figure 19. Answers to the Third Survey Question

As can be seen, the total responses for this question were 408 out of 421, with a 97% completion rate for this question form the respondents. Hedging was the most expensive solution for solving the shortage in spare parts, with more than half of the respondents chose that. Forecasting was the least expensive solution for solving the shortage in spare parts, according to the respondents.

The fourth question was: which of the following options is going to be the most effective solution toward solving the shortage in spare parts? The respondent would choose form (forecasting, hedging, long-term contracting, reverse engineering, or 3D printing). Figure 20 illustrates the results of the fourth question.

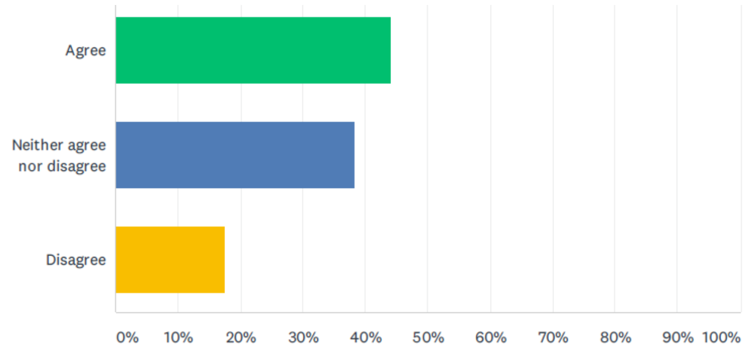


ANSWER CHOICES	RESPONSES	
Forecasting	17.80%	73
Hedging	9.02%	37
Long-term Contracting	32.93%	135
3D Printing Technology	14.39%	59
Reverse Engineering	25.85%	106
TOTAL		410

Figure 20. Answers to the Fourth Survey Question

As can be seen, the total responses for this question were 410 out of 421, with a 97.4% completion rate for this question form the respondents. Long-term contracting scored 32.9%, which made it the most effective solution for solving the shortage in spare parts, according to the respondents. By contrast, hedging scored less than 10%, which made it the least effective solution for solving the shortage in spare parts, according to the respondents.

The fifth question was the research question of this thesis: is the 3D printing technology going to be the newer technology toward solving the shortage in spare parts for old machinery and aircraft? The respondent would choose from three answers (agree, neither agree nor disagree, or disagree). Figure 21 illustrates the results of the fifth question.



ANSWER CHOICES	RESPONSES	
Agree	44.23%	184
Neither agree nor disagree	38.22%	159
Disagree	17.55%	73
TOTAL		416

Figure 21. Answers to the Fifth Survey Question

As can be seen, the total responses for this question were 416 out of 421 with a 98.8% completion rate for this question form the respondents. 44.2% of the respondents agreed with the possibility of having 3D printing technology to be the newer approach of solving the shortage in spare parts. Next, 38.2% of the respondents were neutral, and 17.5% of the respondents disagreed with the possibility of having 3D printing technology to be the newer approach of solving the shortage in spare parts.

4.6.3 Summary of the Survey

The respondents were well educated; whereas, their level of knowledge differs from one to another. Thus, the level of credibility of this survey is fairly acceptable. Moreover, surveys are usually subjective and biased, yet it provides an excellent indication to be taken into consideration when it comes to decision making or manufacturing.

4.7 Chapter Summary

First, the process of forecasting is very fundamental in order to predict what needed to be produced without having excess capacity or loss of assets, and that can be accomplished after looking into the orginzation’s historical trend, and there will always be a margin of prediction error.

Next, the process of contracting, signing a valid profitable contract with a detailed clause that assures a continuum of supply for all the involved parties can assist in minimizing the sudden or unwanted shortage of parts. After that, the reverse engineering process, which brings vanished part back to existence, is quite unique.

In addition, reverse engineering process exerts a good amount of time, it needs the original blue-prints with the right tools, and the exact description of martial that was used in the vanished part along with written authorization from the owner pefrore producing a part without having the intellectual property of it.

After that, 3D printing technology was the last approach which was discussed, 3D printing is relatively new to the game, it has a lot of areas to be improved at, and it can be used to produce parts other than polymers based.

Finally, a survey was conducted at the end of this chapter right after the 3D printing section. Five questions were answered by a sample of maintainers, supply technicians, and managers in the aviation industry from Saudi Arabia. The survey supports the level of optimism that the 3D printing technology is an applicable approach toward overcoming parts obsolescence. The next chapter is going to draft the summary of this thesis, along with recommendations.

V. Conclusions and Recommendations

5.1 Chapter Overview

The purpose of this section of the thesis is to summarize the final thoughts and findings as well as to point out the possibility of future research to be carried for much profound analysis.

5.2 Conclusion of Research

This research was conducted in a comparison fashion among valid existing solutions of part obsolescence, such as forecasting, contracting, reverse engineering, along with the search of using 3D printing as a next valid candidate toward solving part shortages.

One of the main obstacles of implementing 3D printing is the lack of historical data that reveals reliable feedback by whomever have utilized it in their industry. Moreover, 3D printing has to undergo various psychical tests, such as ductility, tensile, and hardening test to prove applicability and reliability for the usage.

In the past 3D printing technology was constrained to polymers; however, a part made from Titanium, which is one of the strongest metals, was successfully produced using 3D printing by the powder deposition process (Carroll et al., 2015). Moreover, composite materials became known to the 3D printing technology (Leigh et al., 2012), which is clearly good evidence that 3D printing technology is applicable in various parts regardless of the raw material that part is made of. Subsequently, there is a tremendous amount of optimism according to the rapid adoption and acceptance among the industry sector, which indicates the success of the usage of 3D printing technology as a viable solution toward overcoming part obsolescence.

In addition, around 45 % of respondents to the survey that was conducted in this thesis, concur to the research question of this thesis: is the 3D printing technology going to be the newer technology toward solving the shortage in spare parts for old machinery and aircraft? While only 17% of respondents were skeptical, and the rest of the respondents were neutral.

5.3 Recommendations for Future Research

The future is predicted to be brighter for 3D printing technology as it gets more used and adopted in private and military sectors. More feedbacks from the users will be available; thus, a robust effective study will be carried out to overcome any flaws in this technology according to the suggestions and feedbacks of the users.

Moreover, as this technology spreads among manufactures, it will be easy to compare the cost of using it more accurately, and it will be easier to compare its cost with other means of overcoming part obsolescence. 3D printing technology may need more time to become viable from an investment point of view (Axtman & Wilck, 2015). However, that does not lower its potential nor its applicability toward solving part shortages.

Furthermore, since the data collection and feedbacks of this technology are going to be the game-changer, which allows modification and updates to the customer’s satisfaction. Consequently, for a future researcher finding a way to make this technology more affordable to implement on the factory floor is vital toward the spread of 3D printing technology.

5.4 Chapter Summary

Parts make a whole, and part obsolescence is a disruption of the wheel of aircraft availability, the project progresses, and the entire industry sector. Ways to overcome this matter vary, and it depends on various factors.

There has been a very profound discussion of the methods to overcome part shortages in this thesis. Regardless of the approach of addressing part shortages, they all pour in the same valley. Some of the methodologies of addressing part shortages are proactive, such as forecasting and contracting. Nevertheless, some of the methodologies of addressing part shortages are reactive, such as reverse engineering, and 3D printing. Thus, integration among the above solutions will solidify against the chances of having a shortage in the stock.

Three-dimensional printing technology is used in the industry, yet its applicability for part shortages was the question to look for in this research. Thus, 3D printing is applicable in using to overcome part obsolescence; it has been used in many areas in the industry, it was used in fabricating electronic parts, in the medical field to overcome medical supplies shortages, in the construction to erect housings, and in the aerospace applications to make various parts from different raw materials.

However, the technology is not well-analyzed from a cost standpoint. The near future will be brighter for this technology, and its usage will be broader as more manufacturers will adopt this technology. Since cost is essential in the scope of any project, and that will assist the decision-makers to evaluate possible alternatives. Consequently, studying the cost analysis of 3D printing technology will be very fundamental toward implementing and accepting the use of it.

Moreover, there is always invention appearing on the surface every day, and there is always a modification for an existing method or tool to be improved, and the researcher believes the 3D printing technology will be brought to another level of excellence, it is just a matter of time.

Appendix

List of Symbols

1. The Mean (denoted as $\boldsymbol{\mu}$)
2. Standard Deviations (denoted as $\boldsymbol{\sigma}$)
3. Titanium Element (Ti)
4. Polyethylene (PE)
5. Oxygen Element (O_2)

List of Abbreviations

1. Supply Chain Management (SCM)
2. Diminished Manufacturing Sources and Material Shortages (DMSMS)
3. Diminishing Manufacturing Sources (DMS)
4. Reverse Engineering (RE)
5. End-of-Life (EOL)
6. The Government-Industry Data Exchange Program (GIDEP)
7. Life Time Buy (LTB)
8. Personal Computers (Pcs)
9. The United States Department of Defense (DoD)
10. Technical Change Technical Order (TCTO)
11. Principal Components Analysis (PCA)
12. Obsolescence Risk Forecasting Using Machine Learning (ORML)
13. Life Cycle Using Machine Learning (LCML)
14. International Relations (IR)
15. Oil Price Information Service (OPIS)
16. Technical Orders (T.Os)
17. The Foreign Military Sales (FMS)
18. The Royal Saudi Air Force (RSAF)
19. Computer Numerical Control (CNC)
20. Automagical Computer-Aided Design Program (CAD)
21. The Revolution Per Minute (RPM)

22. The Three-Dimensional Printing (3D)

23. United States Dollar (USD)

24. Just-In-Time (JIT)

25. Additive Manufacturing (AM)

26. Powder Bed Fusion (PBF)

27. Research and Development (R&D)

28. 2019 Novel Coronavirus (COVID-19)

29. Personal Protective Equipment (PPE)

30. George Washington University Hospital (GWUH)

Bibliography

ALAGÖZ, E. A. (2017). Blue-Water Navy Program as a part of South Korea's Hedging Strategy. *Güvenlik Stratejileri Dergisi*, *13*(25), 65–97.

Anandan, K. (2016). Preface. In *Advances in 3D Printing and Additive Manufacturing Technologies*. https://doi.org/10.1007/978-981-10-0812-2

Axtman, S. J., & Wilck, J. H. (2015). A review of aviation manufacturing and supply chain processes. *International Journal of Supply Chain Management*, *4*(4), 22–27.

Barro, R. I. (1977). *LONG-TERM CONTRACTING, STICKY PRICES, AND MONETARY POLICY Robert .I. BARRO*. 3*, 305–316.

Cachon, G. P., & Lariviere, M. A. (2005). Supply chain coordination with revenue-sharing contracts: Strengths and limitations. *Management Science*, *51*(1), 30–44. https://doi.org/10.1287/mnsc.1040.0215

Carroll, B. E., Palmer, T. A., & Beese, A. M. (2015). Anisotropic tensile behavior of Ti-6Al-4V components fabricated with directed energy deposition additive manufacturing. *Acta Materialia*, *87*, 309–320. https://doi.org/10.1016/j.actamat.2014.12.054

Carter, D. A., Rogers, D. A., & Simkins, B. J. (2011). Fuel Hedging in the Airline Industry: The Case of Southwest Airlines. *SSRN Electronic Journal*, (503). https://doi.org/10.2139/ssrn.578663

Carter, M. R. (2018). Transforming. In *Arts Education and Curriculum Studies* (pp. 69–130). https://doi.org/10.4324/9781315467016-7

Carver, C. N. C. P. (2016). *CNC Pumpkin Carver*. (April).

Cobbs, R., & Wolf, A. (2004). Jet Fuel Hedging Strategies: Options Available For

Airlines And A Survey Of Industry Practices. *Working Paper (Finance 467)*, 1–22. Retrieved from http://www.kellogg.northwestern.edu/research/fimrc/papers/jet_fuel.pdf

Cove, C. (2004). *VITAL SPEECHES OF THE DAY Outsourcing THE REAL ISSUE*. 664–668.

Department of Commerce, U. S. (2013). Offsets in Defense Trade - Seventeenth Study. *The DISAM Journal*, *2099*(February), 57–97. Retrieved from papers2://publication/uuid/6FB0B4BE-BB51-458E-8274-A6D21334C0AD

Desai, S. M., & Singh, R. P. (2004). Surface modification of polyethylene. *Advances in Polymer Science*, Vol. 169, pp. 231–293. https://doi.org/10.1016/S0927-7757(03)00242-5

Farouki, R. T., Manjunathaiah, J., & Yuan, G. F. (1999). G codes for the specification of Pythagorean-hodograph tool paths and associated feedrate functions on open-architecture CNC machines. *International Journal of Machine Tools and Manufacture*, *39*(1), 123–142. https://doi.org/10.1016/S0890-6955(98)00018-2

Flowers, P. F., Reyes, C., Ye, S., Kim, M. J., & Wiley, B. J. (2017). 3D printing electronic components and circuits with conductive thermoplastic filament. *Additive Manufacturing*, *18*(2017), 156–163. https://doi.org/10.1016/j.addma.2017.10.002

Hornick, B. J. (2018). *Dangers and Benefits of 3D Printing*.

Jennings, C., Wu, D., & Terpenny, J. (2016). Forecasting obsolescence risk and product life cycle with machine learning. *IEEE Transactions on Components, Packaging and Manufacturing Technology*, *6*(9), 1428–1439. https://doi.org/10.1109/TCPMT.2016.2589206

Jessen, H. C., & Menard, S. (1996). Applied Logistic Regression Analysis. *The Statistician*, *45*(4), 534. https://doi.org/10.2307/2988559

Jones, W. E. (2002). The Value of Military Industrial Offsets. *The DISAM Journal*, pp. 108–118.

Jong, J. P. J. De, & Bruijn, E. De. (2013). Innovation Lessons From 3-D Printing. *MIT Sloan Management Review*, *52*(2), 43–52. Retrieved from http://sloanreview.mit.edu/files/2012/12/819a3bcb5e.pdf

King, D., & Massey, D. (1997). History of the F-15 Program: A Silver Anniversary First Flight Remembrance. *Air Force Journal of Logistics*, (Winter).

Klančnik, S., & Šenveter, J. (2010). Computer-based workpiece detection on CNC milling machine tools using optical camera and neural networks. *Advances in Production Engineering & Management*, *5*, 59–68.

Kok, A. G. De, Graves, S. C., Muriel, A., Simchi-levi, D., & Willems, S. P. (2003). *Techniques for Strategic and Tactical Models Supply Chain Design : Safety Stock Placement and Supply Chain Configuration Supply Chain Coordination with Contracts*. 757.

Kostakis, V., Niaros, V., & Giotitsas, C. (2015). Open source 3D printing as a means of learning: An educational experiment in two high schools in Greece. *Telematics and Informatics*, *32*(1), 118–128. https://doi.org/10.1016/j.tele.2014.05.001

Lee, S. G., Ma, Y. S., Thimm, G. L., & Verstraeten, J. (2008). Product lifecycle management in aviation maintenance, repair and overhaul. *Computers in Industry*, *59*(2–3), 296–303. https://doi.org/10.1016/j.compind.2007.06.022

Leigh, S. J., Bradley, R. J., Purssell, C. P., Billson, D. R., & Hutchins, D. A. (2012). A

Simple, Low-Cost Conductive Composite Material for 3D Printing of Electronic Sensors. *PLoS ONE*, *7*(11), 1–6. https://doi.org/10.1371/journal.pone.0049365

Lu, L., Sharf, A., Zhao, H., Wei, Y., Fan, Q., Chen, X., … Chen, B. (2014). Build-to-last: Strength to weight 3D printed objects. *ACM Transactions on Graphics*, *33*(4). https://doi.org/10.1145/2601097.2601168

Manda, V. R., Kampurath, V., & Msrk, C. (2018). 3D printing and its effect on outsourcing: A study of the Indian aircraft industry. *Journal of Aerospace Technology and Management*, *10*. https://doi.org/10.5028/jatm.v10.862

Mckinley, C. R. (2016). *Foreign Military Sales More Vital Than Ever*.

Meng, X., Thornberg, B., & Olsson, L. (2014). Strategic proactive obsolescence management model. *IEEE Transactions on Components, Packaging and Manufacturing Technology*, *4*(6), 1099–1108. https://doi.org/10.1109/TCPMT.2014.2316212

Miiller, H. A., Jahnke, J. H., Smith, D. B., Storey, M. A., Tilley, S. R., & Wong, K. (2000). Reverse engineering: A roadmap. *Proceedings of the Conference on the Future of Software Engineering, ICSE 2000*, 47–60. https://doi.org/10.1145/336512.336526

Ms, D. P., Rao, Y. J., Mitic, K., Obaid, S. N., Pierce, D., Huckenpahler, J., … Loew, M. H. (2020). *Rapid Prototyping of Reusable 3D-Printed N95 Equivalent Respirators at the George Washington University*. (March), 1–9. https://doi.org/10.20944/preprints202003.0444.v1

Müller, H. A., Orgun, M. A., Tilley, S. R., & Uhl, J. S. (1993). A reverse-engineering approach to subsystem structure identification. *Journal of Software Maintenance:*

Research and Practice, *5*(4), 181–204. https://doi.org/10.1002/smr.4360050402

Nystén-Haarala, S., Lee, N., & Lehto, J. (2010). Flexibility in contract terms and contracting processes. *International Journal of Managing Projects in Business*, *3*(3), 462–478. https://doi.org/10.1108/17538371011056084

Pandilov, Z., Shabani, B., Shishkovski, D., & Vrtanoski, G. (2018). Reverse Engineering – an Effective Tool for Design and Development of Mechanical Parts. *Fascicule, 2*, 113–118.

Prophet, G. (2005). Tracking down obsolete parts. *EDN*, *50*(3), 17.

Rayna, T., & Striukova, L. (2016). From rapid prototyping to home fabrication: How 3D printing is changing business model innovation. *Technological Forecasting and Social Change*, *102*, 214–224. https://doi.org/10.1016/j.techfore.2015.07.023

Rubery, E. D. (1988). Evaluation Procedures. *Radionuclides in the Food Chain*, 264–281. https://doi.org/10.1007/978-1-4471-1610-3_19

Sandborn, P. (2008). Strategic management of DMSMS in systems. *DSP Journal*, (June), 24–30.

Sencer, B., Altintas, Y., & Croft, E. (2008). Feed optimization for five-axis CNC machine tools with drive constraints. *International Journal of Machine Tools and Manufacture*, *48*(7–8), 733–745. https://doi.org/10.1016/j.ijmachtools.2008.01.002

Sokovic, M., & Kopac, J. (2006). RE (reverse engineering) as necessary phase by rapid product development. *Journal of Materials Processing Technology*, *175*(1–3), 398–403. https://doi.org/10.1016/j.jmatprotec.2005.04.047

Taušer, J., & Čajka, R. (2014). Hedging techniques in commodity risk management. *Agricultural Economics (Czech Republic), 60*(4), 174–182.

Taylor III, A. (2010). Hyundai smokes the competition. *Fortune*, *161*(1). Retrieved from http://money.cnn.com/2010/01/04/autos/hyundai_competition.fortune/index.htm

Umetani, N., & Schmidt, R. (2013). Cross-sectional structural analysis for 3D printing optimization. *SIGGRAPH Asia 2013 Technical Briefs, SA 2013*. https://doi.org/10.1145/2542355.2542361

Use, T., & Sales, F. M. (2003). *N / A*.

Uttley, M. (2001). Defence Offsets, Weapons Proliferation and Emerging Security Challenges. *Defence Studies*, Vol. 1, pp. 172–182. https://doi.org/10.1080/714000009

Xu, X. W., & He, Q. (2004). Striving for a total integration of CAD, CAPP, CAM and CNC. *Robotics and Computer-Integrated Manufacturing*, *20*(2), 101–109. https://doi.org/10.1016/j.rcim.2003.08.003

Yossef, M., & Chen, A. (2015). Applicability and Limitations of 3D Printing for Civil Structures. *Conference on Autonomous and Robotic Construction of Infrastructure*, 11.

Zampieri, G., Vijayakumar, S., Yaneske, E., & Angione, C. (2019). Machine and deep learning meet genome-scale metabolic modeling. *PLOS Computational Biology*, *15*(7), e1007084. https://doi.org/10.1371/journal.pcbi.1007084

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 074-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From – To)*
15-09-2020	Master's Thesis	August 2018 – October 2020

TITLE AND SUBTITLE	
3D PRINTING TECHNOLOGY FOR SOLVING PART OBSOLESCENCE	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	**5d. PROJECT NUMBER**
Ayman, Alqarni., Captain, RSAF	**5e. TASK NUMBER**
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(S)	**8. PERFORMING ORGANIZATION REPORT NUMBER**
Air Force Institute of Technology Graduate School of Engineering and Management (AFIT/ENS) 2950 Hobson Way, Building 640 WPAFB OH 45433-8865	AFIT-ENS-MS-20-S-034
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Intentionally left blank	**10. SPONSOR/MONITOR'S ACRONYM(S)** **AFRL/RHIQ (example)**
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
DISTRUBTION STATEMENT A. APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The purpose of this research was to highlight the issue of parts obsolescence and to highlight the possibility of using alternative methods to overcome parts shortage. Specifically, this thesis sought to answer the research question: is the three-dimensional printing technology (3D) an applicable approach to overcome part obsolescence.

The research question was answered through data research and survey analysis. Notwithstanding, the diminished manufacturing sources and material shortages (DMSMS) management and other existing approaches, such as forecasting, contracting, and reverse engineering (RE), were discussed briefly in the literature review and profoundly in chapter IV to differentiate among applicable existing solutions toward solving parts obsolescence.

This research qualitatively conducted a survey to identify the depth of the applicability of the 3D printing technology approach to be a solution for material shortages in comparison with other approaches to solving this matter.

15. SUBJECT TERMS
Part Obsolescence; DMSMS; 3D Printing; Forecasting; Contracting; Reverse Engineering

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Dr. William Cunningham, AFIT/ENS
U	U	U	UU	82	**19b. TELEPHONE NUMBER** *(Include area code)* (937) 255-6565 x4283 Wiliam.cunningham@afit.edu

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18