

Developing Performance System for Evaluating AM versus TM

A Thesis Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Abhishek Chimalapati
May 2018

Copyright © 2018 by Abhishek Chimalapati
All rights reserved.

ACKNOWLEDGEMENTS

I am most grateful to my advisor, Dr. Rupy Sawhney for his guidance and support throughout the time of my dissertation research. He has been an inspirational in motivating me without which I could not have accomplished what I have in Graduate school. Special thanks to my committee members Dr. Simonton and Dr. Lee Martin who offered valuable guidance and feedback.

I wish to thank Dr. Ninad Pradhan, Carla Arbogast, Yvette Gooden and all other Industrial and Systems Engineering staff for their help and service. I would like to thank my lab mates Dr. Kaveri, Jafar, Arun, Vijay, Gajanan, Sravanthi, Waldoy, Vasanth, Vahid, Mostafa, Girish and Enrique who have supported through this Journey.

Special thanks to Mathangi, Murali and Samyucktha who have always pushed me during difficult times.

Without the blessings from my parents this wouldn't have been possible. Last but not the least thanks to my sister Swathi, Kranti and my beautiful niece Nitya for being the pillar of support.

ABSTRACT

Additive Manufacturing (AM) is a revolutionary technology that is rapidly coming into the limelight. Having been in development for over 30 years, it is expected to compete with Traditional Manufacturing in the next two decades. Federal organizations, the industry and researchers are highly focused on Additive Manufacturing (AM) and its impact once it enters main stream manufacturing. Compared to traditional manufacturing techniques like casting, forging, injection molding, and others, it has many advantages like minimal or no tooling for production, shorter and leaner supply chains, little to no distribution cost, no manufacturing lines, minimal to zero inventory, low carbon footprint, energy efficiency and its ability to produce highly complex designs. Additive technology is widely used in the aircraft industry for reasons which include its ability to produce complex assemblies and structures that would drastically reduce the weight of the components and hence increasing fuel efficiency. Additionally, it can help in reducing supply chain and logistics cost due to its potential to produce parts as required without expensive traditional setup. Automotive, space industry and the military are some of the other industries that are highly focused on this technology. Seeing its potential and growth, it is vital to focus on the softer side of additive manufacturing and its comparison to the traditional methods due to limited available research. This research focuses on the comparison and performance evaluation of additive and traditional manufacturing using supply chain and manufacturing factors/sub factors. Simulation analysis, survey from experts as an assessment tool and AHP (Analytical Hierarchy Process) are some of the tools used in this study to evaluate the two systems.

TABLE OF CONTENTS

Chapter One Introduction	1
1.1 Introduction to additive manufacturing	1
1.2 Benefits of additive manufacturing over traditional manufacturing.....	6
1.3 Impact of additive manufacturing on supply chain and logistics	7
1.4 Problem Statement.....	13
1.5 Approach.....	14
1.6 Organization of thesis	16
Chapter Two Literature Review.....	17
2.1 Main factors	18
2.2 Additive manufacturing supply chain.....	25
2.3 Performance measurement in supply chain and manufacturing	27
2.4 AHP and supply chain	29
Chapter Three Methodology.....	31
3.1 Introduction.....	31
3.2 Research methodology.....	32
3.3 Simulation model building.....	33
3.4 Simulation case study	35
3.5 Factors that will impact AM	37
3.6 DOD (Department of Defense) survey 1	38
3.7 Hierarchal structure.....	40
3.8 DOD (Department of Defense) phase 2 survey	41
3.9 Analytical hierarchy process (AHP)	44
3.10 Validation of the study.....	46
Chapter Four Results and Discussion	48
4.1 Simulation model analysis	48
4.2 Survey 1	51
4.3 AHP analysis.....	54
4.4 Final Result	64
4.5 Validation.....	64
4.6 Simulation factors vs AHP final result	67
Chapter Five Conclusions	69
5.1 Summary of research	69
5.2 Recommendations.....	70
List Of References.....	71
Appendix.....	74

LIST OF TABLES

Table 2.1: Main factors	19
Table 2.2: Cost sub factors.....	21
Table 2.3: Quality sub factors	22
Table 2.4: Time sub factors	23
Table 2.5: Flexibility sub factors	24
Table 2.6: Environmental sub factors	24
Table 2.7: Summary of Literature Review on AM supply chain.....	25
Table 2.8: Summary of Literature Review on performance measurement in supply chain and manufacturing.	27
Table 2.9: Summary of Literature Review on different studies on AHP for supply chain problems.....	29
Table 3.1: Sample size for AHP survey from studies	40
Table 3.2: Scale of Relative Importance according to Saaty (1980)	43
Table 3.3: “Example for pairwise comparison matrix”	44
Table 3.4: RCI values for different values of criteria n.	46
Table 4.1: Factor weight	54
Table 4.2: Alternative selection weights.....	57
Table 4.3: Weight of criteria and sub criteria	58
Table 4.4: Final result	65
Table 4.5: Scenarios weights	66

LIST OF FIGURES

Figure 1.1: FDM process ([5]).....	2
Figure 1.2: Uncertain demand in Traditional system.....	4
Figure 1.3: Uncertain demand in Additive supply chain	4
Figure 1.4: Weight optimization in Additive technology ([7]).....	5
Figure 1.5: Potential cost saving through AM	5
Figure 1.6: Traditional manufacturing flow.....	9
Figure 1.7: Additive manufacturing flow	9
Figure 1.8: Traditional supply chain	10
Figure 1.9: Additive supply chain.....	11
Figure 2.1: Literature review steps	17
Figure 3.1: Research methodology steps	31
Figure 3.2: Traditional AHP study methodology	33
Figure 3.3: Current research methodology	33
Figure 3.4: Overview of the simulation process	35
Figure 3.5: Part used in simulation case study.....	35
Figure 3.6: Simulation model of forged and machined process	37
Figure 3.7: Simulation model of fused deposition modeling.....	37
Figure 3.8: Breakdown of factors	38
Figure 3.9: Survey 1 response rate.....	39
Figure 3.10: Showing example connecting a node in level 2 and a node in level 3	41
Figure 3.11: Illustration of a 4 level hierarchy network	41
Figure 3.12: Recoded values as per Saaty (1980) scale of relative importance	44
Figure 3.13: Screen shot of the model in super decisions.....	46
Figure 4.1: Simulation Factors measured in both the systems.....	49
Figure 4.2: Simulation throughput.....	49
Figure 4.3: WIP output	50
Figure 4.4: Utilization of machine	50
Figure 4.5: Number of parts rejected in a shift	51
Figure 4.6: Rejection against throughput.....	51
Figure 4.7: Image showing factors and sub factors	52
Figure 4.8: Hierarchical structure constructed to five factors and twenty-three sub factors	53
Figure 4.9: Graphical representation of criteria weights	55
Figure 4.10: Graphical representation of alternative selection	59
Figure 4.11: Graphical representation of weight distribution.....	59
Figure 4.12: Graphical representation of cost weights	60
Figure 4.13: Graphical representation of quality weights.....	61
Figure 4.14: Graphical representation of time weights.....	62
Figure 4.15: Graphical representation of flexibility weights	63
Figure 4.16: Graphical representation of environment weights.....	64
Figure 4.17: Final result graphical representation	65

Figure 4.18: Graphical representation of scenario analysis	67
Figure 4.19: Simulation factors VS AHP final result	68

CHAPTER ONE

INTRODUCTION

There is a rapid paradigm shift taking place in manufacturing technology in which, Additive Manufacturing (AM) is certainly one of the key drivers of this shift in the 21st century. With its ability to convert a digital file to a functional part without having to use tools or manufacturing lines, and provide customized products at mass production prices, it is a technology that is expected to revolutionize how products are manufactured and delivered to customers. Thus, AM is of growing interest for Industries to understand what changes it would bring to world economics, Industrial operations and how AM processes can be compared to traditional manufacturing processes [1]. Supply chain and manufacturing are dominant factors in an industrial operation. With the exponential growth of AM in the last decade, it is important to study the AM system, its impact and how it can be compared to a TM systems. The following sections discuss about AM, its impact on manufacturing, supply chain and the problem statement.

1.1 Introduction to additive manufacturing

Additive Manufacturing is defined as “The process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining” [1]. AM is also termed as Rapid Prototyping (RP), 3D printing and Additive Fabrication. AM has been in existence for over three decades, mainly under the name Rapid Prototyping. In its early years it was used mainly for prototyping purposes where it first emerged in 1987 with stereolithography (SL) from 3D Systems. It is a process which builds up thin layers of ultraviolet light-sensitive polymer using a laser [2] [3]. AM has the ability to produce complex parts layer by layer from 3D

computer-aided design data using various materials such as metal alloys, titanium alloys, thermoplastics, ceramic powders among others [4]. It has been introduced to automotive and aerospace industries. Ever since, researchers and industries have been focusing on studying the benefits of AM with respect to various raw materials, area of energy, manufacturing, supply chain and logistics. Some of the cost saving potential of AM as illustrated in Figure 1.5 are:

- **Tooling:** Unlike traditional manufacturing methods, AM does not require tooling. In comparison to traditional manufacturing methods, additive technology does not require cutting fluids, tool maintenance, jigs/fixtures and storage space for tooling. An example of why tooling is not required to build parts can be seen below from FDM (Fused deposition modeling) method. In this method a temperature controller extruder is used to deposit the semi molten polymer into a platform layer by layer to produce a part in x, y and z axes [5]. This, along with several other AM processes, does not require tooling to build parts.

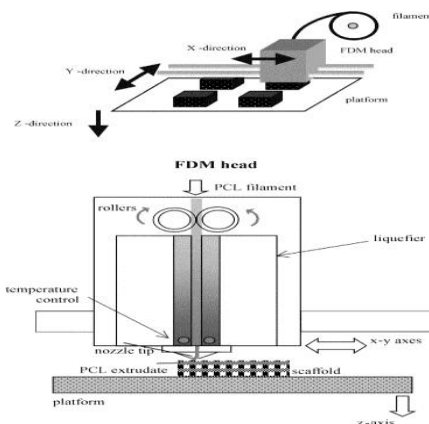


Figure 1.1: FDM process ([5])

- **Warehouse:** There is a greater requirement to shorten lead times in supply chain and to make the process leaner. The fact is nearly 50% of an industry's assets are tied up in inventories [6]. Some industries have uncertain demand, thus causing disruptions in supply chain and cash flow converted in the form of lead times in supply chain, raw material, finished goods sitting in transit and warehouse. As illustrated in Figure 1.2, we can see a current traditional model that shows the lead times caused due to uncertain demand, hence a manufacturer has to push material in the system in order to keep up with customer requirement. A customer ordering parts from a manufacturing plant causes several delays of inventory in the chain from the manufacturing plant with LT1 or lead time 1 which is production lead time to finished goods inventory, from finished goods inventory to warehouse with LT2 or lead time 2 and finally from warehouse to the customer with delivery lead time. Until the goods are delivered to the customer, the lead time and the inventory at the plant and the chain are costs that are incurred by the supplier. In comparison to this model, AM has the ability to have a leaner supply chain as there may not be a requirement for warehousing, unlike traditional systems. Suppliers using this technology can respond quickly to uncertain demand and make it a pull system as shown in Figure 1.3. This will open possibilities to deliver goods with no inventory with less lead-time, making it far less expensive for the supplier. Furthermore, the costs incurred in warehousing due to data management, taxes, property theft and insurance, can be avoided altogether in the additive systems due to no warehousing, as explained above.

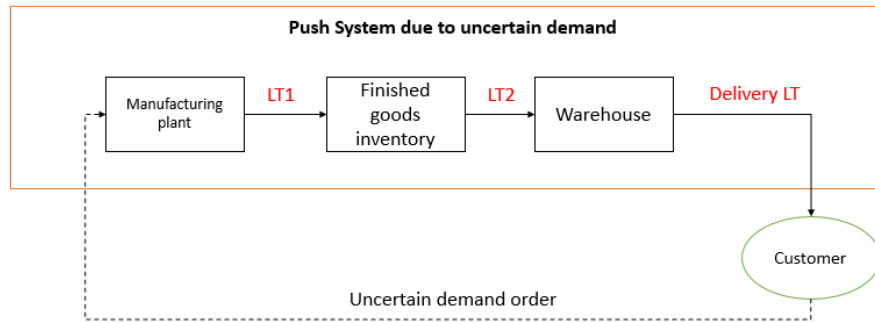


Figure 1.2: Uncertain demand in Traditional system

- Part design:** Additive technology can be used to manufacture very complex parts. Due to this, industries are now able to achieve potential cost savings through weight reduction which would lead to higher fuel efficiency and lower material wastage in complex designs that would not be possible in traditional manufacturing methods. This will also contribute to the carbon footprint as this will drastically reduce the consumption of fuel due to low weight products, especially in automotive and aerospace industries. A helicopter part designed to be produced in Additive technology with a 35% reduction in weight is shown in Figure 1.4. Such complex parts are hard or impossible to be produced using traditional manufacturing methods.

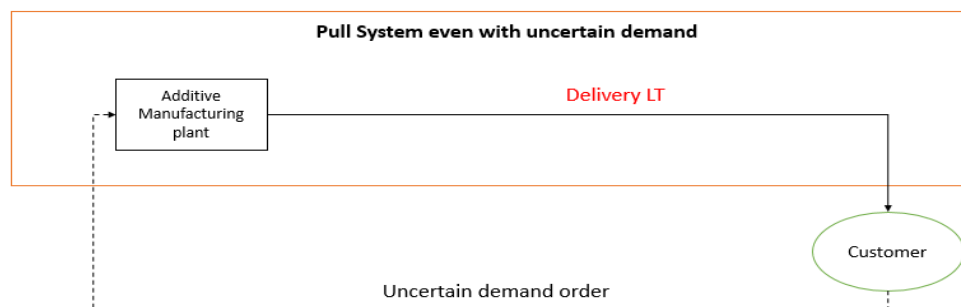


Figure 1.3: Uncertain demand in Additive supply chain

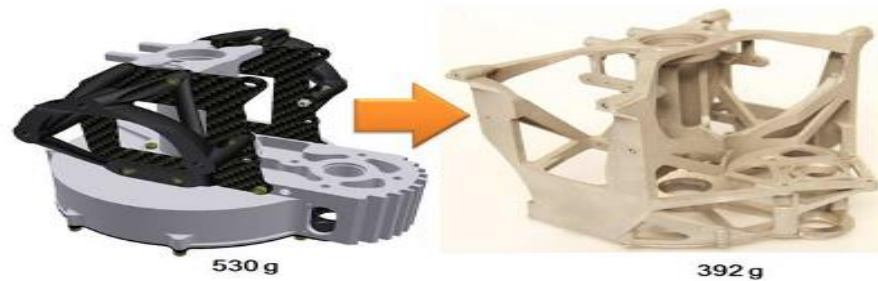


Figure 1.4: Weight optimization in Additive technology ([7])

- Investment:** Traditional manufacturing methods have long manufacturing lines where a product goes through each machine to achieve the desirable end product. In addition to this, if the product is an assembly, it requires one or several assembly lines before the final output. Additive technology can be used to produce such products in one setting as well as ability to print assemblies to a certain extent. This will lead to potential cost savings through less machines, lesser manpower, smaller production plants and lower maintenance of equipment.

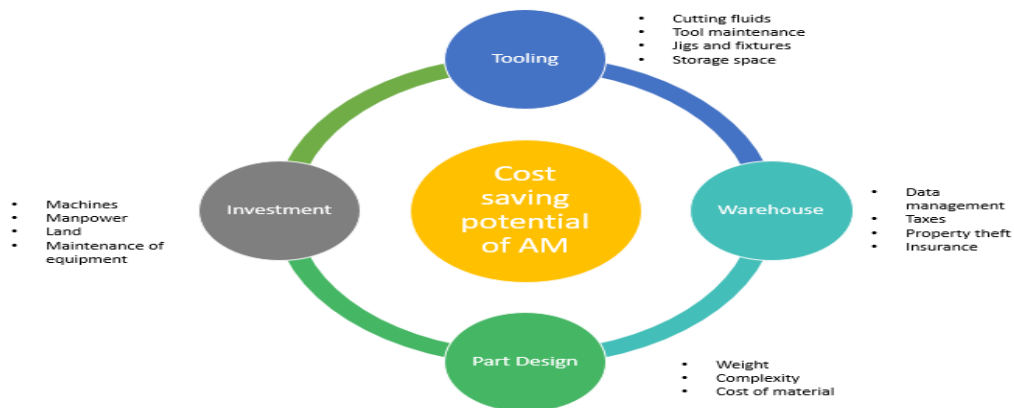


Figure 1.5: Potential cost saving through AM

1.2 Benefits of additive manufacturing over traditional manufacturing

Additive Manufacturing is a disruptive technology which revolutionizes how products are manufactured and their operations [8]. Although currently, the machines are very expensive and not feasible for mass productions due to their low speeds [9], with rapid advancements in technology it is predicted that in the future we can expect mass production of parts using AM.

Additive Manufacturing has many advantages over traditional manufacturing methods such as:

- Waste generated in subtractive manufacturing methods is very high compared to AM which has very low material waste. Unlike traditional methods where the part is cut from a solid that would generate waste, Additive technology is quite the opposite with minimal to no waste. This is because it builds the final product layer by layer with a very high yield rate.
- Products with high geometric complexity can be produced through AM; this will not only reduce the price of the product, but will also reduce waste. The automotive and aerospace industries would benefit the most as parts used in the aircrafts and vehicles will be lighter and would reduce fuel consumption. This would indirectly have an impact on environment sustainability due to lower carbon emissions [10].
- In comparison to TM processes, production tooling such as jigs, fixtures, and cutting tools, would not be required. Having little to no tools for production will reduce the manufacturing setup time and cost. This will not only reduce the heavy investment on manufacturing tools, but it will also save time for development of these tools which

would typically take about six months depending on the complexity. Once worn out, tools are stored in obsolete inventory for a certain period of time until they are scrapped, this storage costs money in the form of overhead and requires large space for storage. This can also be avoided by using AM.

- High customer satisfaction can be achievable due to AM's ability to mass manufacture customized products. Rather than buying products with less choice, customers will be able to send their own digital design to manufacturers to produce custom designed products of their choice. This will be a unique business model which would be possible only in AM, since customization in traditional manufacturing is extremely expensive and may not be available for customers to choose.
- AM can manufacture functional parts in a single print without having to be assembled like the parts manufactured by TM processes or may reduce the number of assemblies required to build the product. This will avoid large assembly lines and also reduce the labor that is required to assemble the products. However, a skilled workforce is necessary and important for the growth of this technology [11].

1.3 Impact of additive manufacturing on supply chain and logistics

The supply chain is a collection of services and operations of making products and delivering it to customers. In a supply chain, lead time is the biggest challenge; where industries try to analyze and reduce in order to avoid customer dissatisfaction and to supply goods on time in a fiercely competitive business world. To reduce the lead time, traditional manufacturers build up large amounts of raw material and finished goods inventories; this

has been a long standing problem for manufacturers and distributors as it is extremely expensive to hold these inventories. According to the state of logistics report, the inventory carrying cost for all the businesses in the United States was \$2.495 Trillion which accounted for 8.3% of the GDP [12]. The cost includes taxes, insurance, warehousing, transportation, administration, and other factors. AM can make a supply chain lean and agile, it can improve the efficiency of a lean supply chain through just-in-time (JIT) manufacturing and waste elimination, as AM only requires the digital file and raw materials in order to produce a complex part. It will also reduce the setup and changeover time, and the number of assemblies required. This in turn results in a reduction of material distribution and inventory holding for work in progress [13]. In an AM supply chain customers will play a major part in the operations of the supply chain, due to this ability for mass customization of products [8]. Customers will be able to send digital files of their product directly to the manufacturer and the manufacturer will print the part and ship it to the customer. This process will help to effectively reduce waste across the supply chain from excess material flow to help the manufacturer build to order, thus eliminating large finished goods inventory and increasing customer satisfaction. A traditional manufacturing flow process is shown in figure 1.6. The process shows an order from the customer for three different parts A, B and C, from three different suppliers. These parts are produced and stored in inventory, they are then shipped and finally assembled by the customer. This cycle repeats and is similar to most of the traditional practices in industries today. This is compared with the additive process shown in Figure 1.7, from the customer order the AM technology will be able to print/manufacture A, B and C all together, assemble and supplied

to the customer. This involves no transportation or inventory due to the flexibility of having the supplier close to the customer. Some of the benefits of AM on a supply chain are as follows.

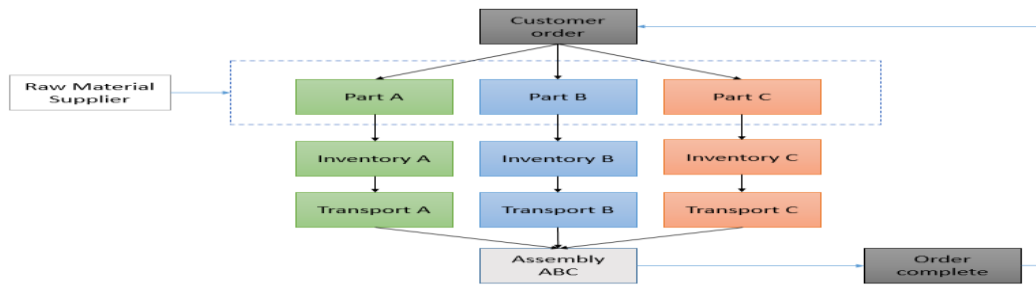


Figure 1.6: Traditional manufacturing flow

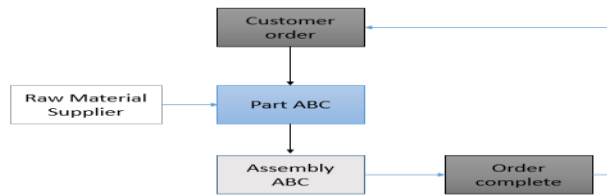


Figure 1.7: Additive manufacturing flow

Supply chain agility – In today’s world agility is the biggest challenge or assets for industries going through heavy competition in turbulent and volatile markets. Organizations are looking at agility as a key to sustainment and growth in business, making it highly critical to meet customer demand variation with shorter lead times and product flexibility. AM supply chain in comparison with TM supply chain, is more agile due to its feasibility of having a distributed production close to the market and the ability to produce

complex and innovative products. Unlike traditional manufacturers, AM would not require large manufacturing lines or assembly lines hence, can be closer to the customer. Shorter supply chains will reduce lead time, supply chain disruption, enhance flexibility and responsiveness making AM supply chain more agile and efficient. Traditional supply chain is not expected to go through a revolutionary change from its current system. Taking an example of a future state of additive and traditional supply chains illustrated in Figure 1.8 and 1.9, and as explained earlier, Figure 1.8 shows how an existing supply chain network works. A raw material supplier from Tennessee ships material to Supplier A, B and C located in Missouri, Indiana and Georgia respectively, manufacturing product A, B and C. The customer located in Texas purchases products A, B and C from the suppliers to assemble them and sell them in the market. With the additive supply chain, as shown in Figure 1.9, due to its incredible ability to make different product mixes and be closer to the customer, will be able to manufacture products A, B, and C and ship them to the customer earlier. This potential of an additive supply chain will reduce supply chain costs, inventory costs, distribution or warehouse costs and carbon emissions.

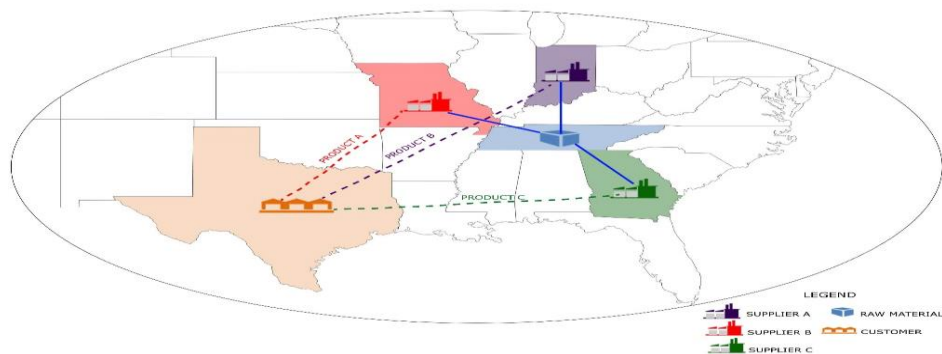


Figure 1.8: Traditional supply chain

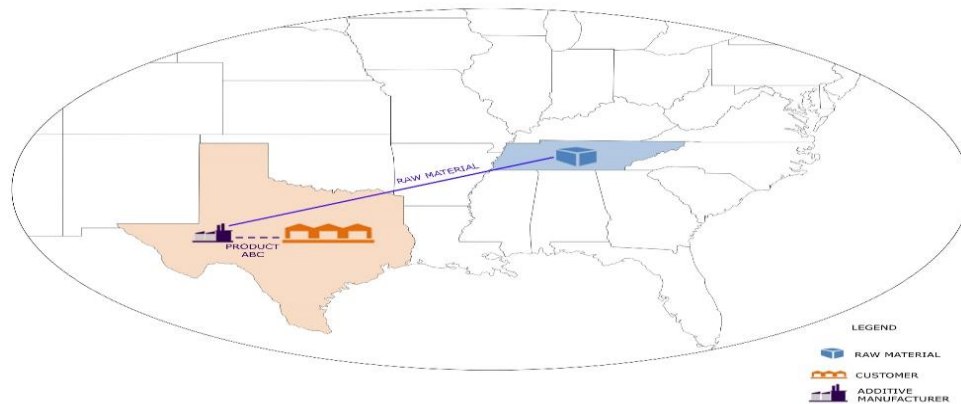


Figure 1.9: Additive supply chain

Lean supply chain – Lean is defined as doing more with fewer resources and eliminating waste or muda in the form of time, effort or materials. Lean is a philosophy that eliminates non-value added activities by continuously improving a process upon practice. AM supply chain is leaner in comparison to TM supply chain in the sense that shorter supply chains will increase the speed of the supply chain and reduce unnecessary material flow. Shorter supply chain would also mean it would require less labor, less inventories and less activities across the supply chain. The “just in time” (JIT) production is highly efficient in AM because of its proximity to the customer, instead of producing a large batch of products, manufacturers can plan smaller batch production [9] as per demand and supply without having to store finished goods. This would drastically reduce the cost of operations.

Inventory – Due to uncertain market demands, industries build inventory to provide adequate supplies to customers and to maintain customer satisfaction. Shorter supply chains can reduce lead time and AM ability to produce the parts on demand will avoid inventory. These inventories occupy physical space, buildings, and land that would require rent, utility costs, insurances, and taxes [9]. Apart from these, AM will avoid the problem

of maintaining excess documentation, labor and parts theft in the inventory. Aircraft manufacturers spend a lot of money on holding spare parts inventory, although the demand is sporadic the parts are very critical in terms of their application. Also, in TM the lead time to produce these parts is very high due to their complexity. For these reasons, aircraft manufacturers hold an abundance of inventory [14]. Aircraft industries are studying AM to tackle this issue which would result in saving millions of dollars. According to Khajavi et al. (2014) the AM decentralized production costs such as inventory obsolescence cost, initial inventory production costs, inventory carrying costs, and spare parts transportation costs are comparatively much less than centralized production[15].

Sustainable supply chain – For manufacturers, environmental aspects differ from each competitor in order to increase their competitiveness and profitability [16]. AM will provide the opportunity to manage these resources efficiently. First, there would be comparatively less water and energy consumption in manufacturing. Second, waste management would be efficient as AM will use only the required amount of material for manufacturing products as opposed to subtractive manufacturing where the material is removed from a larger solid part to get the required shape. Another advantage of AM is that micro factories can be setup close to where the market is which would reduce the transportation costs as well as increase sustainability. This would have a significant environmental advantage. Due to its ability to produce complex parts, automobile and aerospace industries will have the opportunity to produce lighter functional parts which would result in lighter vehicles consuming less fuel throughout their lifecycle, releasing less CO₂ into the atmosphere [10]. Shorter supply chains would also mean less raw

material inventory across the supply chain. Hence the energy used for maintenance of this inventory can also be avoided [17].

1.4 Problem Statement

The central idea of this research is to develop a methodology which can evaluate the performance and comparison of AM against TM supply chain and manufacturing. Manufacturing and supply chain are the two most vital components of industries. A brief overview of AM supply chain revealed that it provides compelling advantages over TM. However, there is no systematic grouping of the different performance measures in the existing literatures [18]. Thus there is a need to systematically analyze the magnitude of improvement in efficiencies and effectiveness while comparing the manufacturing and supply chain systems of AM to TM. The existing literature fails to methodically group different measures related to supply chain and manufacturing performance. Moreover, research and market reports reveal that the 3D printing industry is anticipated to reach \$8.6 billion by 2020, growing at a CAGR (Compound Annual Growth Rate) of 20.6% [19]. Keeping this exponential growth in mind, there is a need to study AM and its supply chain. It is important to understand the performance of a supply chain to be able to choose the ideal supply chain that would suit a particular type of industry.

Mokasdar S (2012) proposed a framework of two scenarios of a supply chain of an aircraft spare parts industry to compare the possible impacts of using AM [14]. Khajavi et al. (2014) evaluated the potential impact of AM improvements on the configuration of spare parts supply chain [15]. Similarly, Walter et al. (2004) highlighted the impacts of rapid manufacturing methods on supply chain management in the spare parts business and

presented new business solution examples using rapid manufacturing [20]. There is substantial work that was done in the area of AM spare parts supply chain and conceptual models in AM supply chain. There are no quantitative studies with respect to performance measurement of AM manufacturing in comparison to traditional manufacturing. This research proposes a methodology to analyze the performance of AM for a certain criteria compared to a TM supply chain taking various quantitative and qualitative performance measures into consideration.

Against the background of the growing AM and its importance mentioned above, specific research goals are classified into three parts.

- First, document, consolidate and classify factors or criteria used for analyzing supply chain and manufacturing.
- Second, rank and prioritize the important factors or criteria used for evaluating AM and TM based on expert opinion.
- Third, determine the approach to compare and quantify the different factors between the AM and TM.

1.5 Approach

The thesis contains six phases to compare both Additive Manufacturing and Traditional manufacturing systems using simulation modeling. In each chapter these phases were explained in detail.

Phase 1: Data of an automotive part was collected through lab setup of a FDM machine that was used to compare the data of the same part produced in a traditional forged and machined process. This data was used to run both the systems using simulation. The output

such as utilization, work in process (WIP), rejection rate and average time in system were then compared to understand how the systems work with in a mass manufacturing setup.

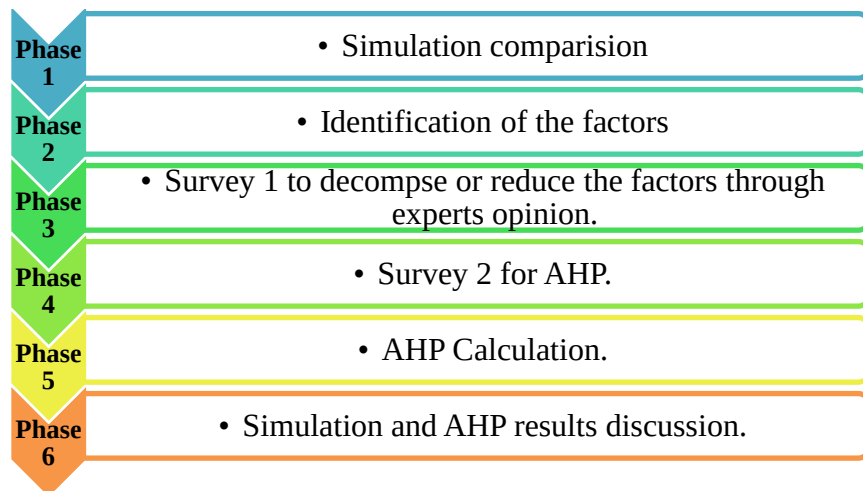
Phase 2: The simulation did not give a comprehensive comparison of the two systems, and with limited data that was expected. Through supply chain and manufacturing literature, 99 factors were identified that could be used to further study the two systems and how they perform for a given set of factors.

Phase 3: In this phase, a survey method was used to identify the most important factors within the list of 99 factors. This is to narrow down the scope of the study and use the most influential factors according to experts in the field. A survey was then sent out to experts.

Phase 4: AHP questionnaire was designed and sent to the same experts.

Phase 5: From phase 5, AHP results were analyzed, pair wise comparisons were done and each factor was rated by the expert comparing both the manufacturing systems.

Phase 6: The final results were compared with the simulation results for conclusions.



1.6 Organization of thesis

This work is presented in five chapters. A brief of the content of the work is presented below

1. The first chapter consists of the introduction, problem statement, conceptual framework, general approach and organization of the thesis.
2. The second chapter consists of a literature review on performance measurement in supply chain and manufacturing, Additive Manufacturing supply chain, and AHP used in various supply chain problems.
3. The third chapter describes the methodology followed to identify the factors and sub factors, developing a first phase survey to identify the most vital criteria, decompose the criteria to various levels and finally an Analytical Hierarchy Process (AHP) to calculate weights to compare and measure the performance of a supply chain and manufacturing of AM and TM.
4. The fourth chapter discusses the results
5. The fifth chapter summarizes the conclusions and future work.

CHAPTER TWO

LITERATURE REVIEW

This chapter is divided into three sections of the literature review. The first section focuses on main factors and sub factors, also known as the performance measures in the study. The second section focuses on the existing research on AM supply chain. The third section focuses on performance measurements in manufacturing and supply chain. Finally the fourth section focuses on AHP studies on the supply chain. Due to limited research in the field of Additive manufacturing and its comparison to Traditional manufacturing in the field of manufacturing and supply chain, a new methodology was developed where key performance measures were used to compare both these systems. The main factors were decomposed in several sub factors through literature search, various literature on performance measurement, supply chain and AHP were reviewed to come up with a new methodology for the study.

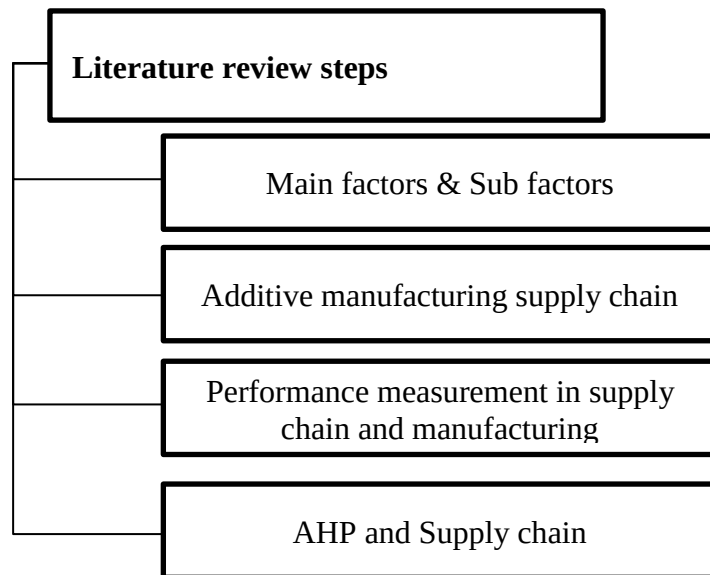


Figure 2.1: Literature review steps

2.1 Main factors

There are many conceptual framework on manufacturing and supply chain performance measurements in literature, but there is a lack of availability of case studies in this field [21]. Many firms identify the importance of performance measures in supply chain but often find it difficult to identify the most effective performance measures or factors that would suit their supply chain and business model [22]. Factory Physics second edition, as well as literature, was used as a reference to scientifically select the factors for the study. Manufacturing and supply chain are very important parts of industries. In their operations, factors or performance measures such as cost, quality, and speed or time are very vital for global competition. Cost is a critical performance measure in all supply chain models [21]. Cost is a very important factor to be competitive, “Efficient utilization of labor, material, and equipment is essential to keeping costs competitive”, similarly quality and speed/time are important factors to compete and sustain in a heavily increasing global competition. Quality is a key for competition, “external quality that is seen by a customer, has always been a concern in manufacturing”. Speed or time is next in line to quality and cost. Customers expect firms to rapidly develop new products coupled with quick delivery of the products. These three dimensions are central to operations of a firm and are applicable to most of the manufacturing industries [23]. In volatile markets, flexibility is an asset. Customers expect manufacturers to adopt JIT (Just in time) manufacturing which lowers inventory costs. This can be related to AM since it is expected to be highly flexible and JIT manufacturing with its ability to produce customized parts [24]. Cleaner production and sustainability are crucial in manufacturing setups since a great amount of energy and materials are consumed [25]. AM has the potential to reduce the consumption of energy

relative to traditional methods by eliminating engineered scrap and producing higher material yield [16].Environment sustainability in supply chain and manufacturing are of great interest to many researchers studying carbon foot print and energy utilization in additive technology. With environmental degradation in current times, it is extremely necessary for industries to adopt sustainability as a responsibility and policy.

Table 2.1: Main factors

	Main factors
Financial and Non-Financial factors	Cost
	Quality
	Time
	Flexibility
	Environmental Sustainability

Sub factors: Several sub factors or performance measures were chosen for the case study that have both financial and non-financial impact to a supply chain. There are many performance measures in literature, when selecting a performance measure or factors the questions that should come to one's mind are if **both financial and non-financial factors are taken into consideration? Do the factors fit in the case study? Do the factors influence the performance of a firm? Do they provide long term or short term benefit? Do they focus on customer satisfaction?** Many organizations have acknowledged the importance of financial and non-financial performance measures, however they failed to categorize and understand them in a balanced framework [22]. Cost associated with sub

factors like WIP, incoming stock in inventory and finished goods in transit are cash converted to assets and have a larger impact on a company's cash flow unless they are optimized. These performance measure or factors can be related to the factor "Total cash flow time" which according to Stewart, 1995 [26] is the average number of days required to convert cash invested in assets to cash recovered from the customer. Reduction in "order lead time" increases supply chain responsiveness [22], similarly order lead time, planned process cycle time, delivery speed, time to make changeovers also influence in supply chain responsiveness. All of which are also related to customer satisfaction. Buyer supplier relationship has gained tremendous attention amongst researchers and industries [22]. There is a greater need for this to ensure a strong partnership between the stake holders in the chain. Partnership influencing factors such as cost reduction activities, extent of mutual planning cooperation leading to improve quality, supplier cost saving initiatives, compliance with cost analysis systems, mutual trust and prompt response would yield a higher customer satisfaction. At an operational level suppliers must address OEE, throughput, cycle time and short setup time, in order to improve their internal productivity and profitability. According to Slack et al, 1995 [27], the speed and responsiveness to customer is affected by capacity utilization directly. Measuring this factor can lead to flexibility gains, lead time and deliverability can be achieved [22]. Simultaneously, Environmental factors must not be ignored since sustainability is an expectation from customers and federal bodies globally. Sustainable suppliers also viewed to be more competitive in the market. Conventional manufacturing methods such as castings, forgings and machining, produce hazardous gases as well as oil spills which pose a great threat to

the working environment and people working on these processes. Exposure to oil mist can cause from minor to fatal health hazards [16]. All the questions mentioned above have been addressed while selecting factors for the study.

Table 2.2: Cost sub factors

Main Factor	Sub Factor	Source
Cost	Net profit vs productivity ratio	Bhagwat et al 2007 [28], Boone et al 2012 [29], Mark Davidson 2013 [30], Gunasekaran et al 2001 [31], Gunasekaran et al 2004 [21], Gunasekaran et al 2001 [31], National research council 1999 [32], Shepherd 2010 [33] Sarkis et al [34]
	Rate of return on investment	
	Variation against budget	
	Manufacturing cost as a percentage of revenue	
	Net operating profit	
	Average unit contribution margin	
	Return on asset and return on net assets	
	Compliance with cost analysis system	
	Compliance with sectorial price behavior	
	Supplier cost saving initiatives	
	Labor efficiency	
	Cost variance from expected cost	
	Low initial price	
	productivity in revenue per employee	
	cost per operation hour	
	information carrying cost	
	incoming stock inventory	
	WIP inventory	
	Scrap level inventory	
	Finished goods in transit	
	Total manufacturing cost per unit excluding materials	
	Energy cost per unit	
	Cost reduction activities	

Table 2.3: Quality sub factors

Factor	Sub factors	Source
Quality	Conformance quality	Bhagwat et al 2007 [28], Boone et al 2012 [29], Mark Davidson 2013 [30], Gunasekaran et al 2001 [31], Gunasekaran et al 2004 [21], Gunasekaran et al 2001 [31], National research council 1999 [32], Shepherd 2010 [33] Sarkis et al [34]
	Quality philosophy	
	Level of suppliers defect free deliveries	
	Extent of Mutual planning cooperation leading to improve quality	
	Extent of mutual assistance leading in problem solving efforts	
	Delivery performance	
	Suppliers quality incoming	
	Supplier rejection rate	
	Delivery reliability	
	Percentage of wrong supplier delivery	
	Mutual trust	
	Satisfaction with knowledge transfer	
	Suppliers assistance in solving technical problems	
	Quality of perspective taking in supply networks	
	Order entry methods	
	Effectiveness of delivery invoice methods	
	Buyer supplier partnership level	
	Distribution of decision competences between supplier and customer	
	quality of delivery documentation	
	quality of delivered goods	
	Achievement of defect free deliveries	
	Yield	
	Information accuracy	
	Information availability	
	Quality and frequency of exchange of logistics information between supplier and customer	
	Consistent delivery	
	Prompt response	

Table 2.4: Time sub factors

Factor	Sub factors	Sub factor
Time	Partnership formation time	Bhagwat et al 2007 [28], Boone et al 2012 [29], Mark Davidson 2013 [30], Gunasekaran et al 2001 [31], Gunasekaran et al 2004 [21], Gunasekaran et al 2001 [31], National research council 1999 [32], Shepherd 2010 [33] Sarkis et al [34]
	Supplier lead time against Industry norm	
	Total supply chain cycle time	
	Total cash flow time	
	Customer query time	
	Order lead time	
	Delivery lead time	
	Downtown in proportion to operation time	
	Planned process cycle time	
	Manufacturing cycle time	
	OEE	
	Engineering change order cycle time	
	throughput	
	Product development time	
	Purchase order cycle time	
	Percentage of late deliveries	
	Information timeliness	
	Efficiency of purchase order cycle time	
	Delivery Speed	
	time to make change overs	
	Suppliers booking in procedure	

Table 2.5: Flexibility sub factors

Factor	Sub factors	Source
Flexibility	Level of customer perceived value of product	Bhagwat et al 2007 [28], Boone et al 2012 [29], Mark Davidson 2013 [30], Gunasekaran et al 2001 [31], Gunasekaran et al 2004 [21], Gunasekaran et al 2001 [31], National research council 1999 [32], Shepherd 2010 [33] Sarkis et al [34]
	Flexibility of service systems to meet particular customer needs	
	Buyer-Supplier partnership level	
	Range of products and service	
	Product volume and variability capabilities	
	Accuracy of forecasting techniques	
	Responsiveness to urgent deliveries	
	Rate of new product introduction	
	Conflict resolution	
	Service capability	
	Supplier ability to respond to quality problems	
	Response to product changes	
	Materials variety (Number of materials available)	
	Product volume changes	
	Frequencies of delivery	
	capacity utilization	
	Short setup time	

Table 2.6: Environmental sub factors

Factor	Sub factors	Sub factor
Environmental	Environmental cost savings	Bhagwat et al 2007 [28], Boone et al 2012 [29], Mark Davidson 2013 [30], Gunasekaran et al 2001 [31], Gunasekaran et al 2004 [21], Gunasekaran et al 2001 [31], National research council 1999 [32], Shepherd 2010 [33] Sarkis et al [34]
	Reportable Environmental incidents	
	Environmental relationship and cooperation level	
	Waste generated from products and materials	
	Energy efficiency of systems	
	Environmental cost performance variance	
	Amount of environmental penalties	
	Length to time to implement environmental programs	
	Meeting environmental program implementation period	
	Mutual trust on environmental issues	
	Mutual planning for environmental improvements	

2.2 Additive manufacturing supply chain

The supply chain is a very important component in any manufacturing industry. Conventional manufacturing processes have a need to invest a lot of money in holding inventory in the supply chain due to very high lead time [14]. Additive Manufacturing will revolutionize how products are manufactured and supplied. The sales in this industry could potentially reach \$3.7 billion worldwide by 2019 [3]. Many organizations have identified the benefits of AM supply chain. One such example is a company Digital tooth cap, optimizing their supply chain from analogue global dental production to local digital production has saved 85% of their logistic steps, reducing the production and energy consumption for production by 80% [35]. Over the years many authors have analyzed AM supply chain and its comparison to TM supply chains. A brief summary of the literature review that describes various methods used to compare both the manufacturing systems supply chains is shown in Table 2.7.

Table 2.7: Summary of Literature Review on AM supply chain

Author(s)	Methods	Year
Khajavi et al.	Additive manufacturing in spare parts supply chain	2013
Tuck et al.	Rapid manufacturing-impact on supply chain methodologies and practice	2007
Walter et al.	Rapid manufacturing and its impact on supply chain management	2004
Mashhadi et al.	Impact of Additive Manufacturing Adoption on Future Supply Chains	2015

- Khajavi et al. (2013) evaluated the impact of additive manufacturing on spare parts supply chain using the case study of an F-18 Super Hornet fighter. Out of the four scenarios used, it was found that with the current AM technology, current AM machine

specifications were compared to future assumed AM machine specifications to calculate the cost of investment, production supply chain and inventory. After analyzing the cost analysis, it was concluded that centralized production compared to the existing distributed production is much more cost effective and preferred supply chain configuration for the F-18 Super Hornet fighter spare parts. However, once AM machines become less capital intensive, autonomous and achieve lower production lead times, decentralized spare parts production become practical [15].

- Tuck et al. (2007) talk about how Rapid Manufacturing (RM) is used in various industrial sectors, its flexibility and what impact Rapid Manufacturing (RM) will have on manufacturing and Supply Chain paradigms such as lean, agile, leagile and how it integrates with mass customization. The paper is concluded with three case studies related to an automotive component, Renault F1 case study and hearing aid industry[24].
- Walter et al. (2004) talk about how rapid manufacturing impacts a supply chain. How the technology produces parts without the need of tools or setup of the process. How rapid manufacturing can reduce supply chain cost, reduce lead time and increase responsiveness through an example of an air craft industry spare parts logistics problem [20].
- Mashhadi et al. (2015) discuss the major advantages and benefits of Additive Manufacturing. The paper discusses the changes that an AM supply chain would bring to a traditional supply chain. Agent based Simulation (ABS) and System Dynamics

(SD) were used to show the possibility of lead time reduction and the potential for less “Pipeline” effect respectively in AM supply chain [36].

2.3 Performance measurement in supply chain and manufacturing

The supply chain is a very important component in a manufacturing industry. With the increasing competition in the market, companies are often looking at various tools to identify key performance factors in a supply chain. Performance metrics in a supply chain are used to analyze the performance and determine ways to increase its efficiency. Many authors have addressed a way to analyze performance and performance measures of a supply chain. We will briefly discuss the literature below.

Table 2.8: Summary of Literature Review on performance measurement in supply chain and manufacturing

Authors(s)	Methods	Year
Gunasekaran et al.	Performance measures and metrics in a supply chain environment	2001
Gunasekaran et al.	A framework for supply chain performance measurement	2004
Hong et al.	Supply Chain Dynamic Performance Measurement Based on BSC and SVM	2013
Bhagwat et al.	Performance measurement of supply chain management: A balanced scorecard approach	2007

- Gunasekaran et al. (2001) talk about the importance of the need for performance measurement and metrics in a supply chain. It is vital to understand the type of metrics and measures required to be able to improve or enhance the productivity of a supply chain. In this study, the two important reasons to study a supply chain are the lack of a balanced approach and the lack of a clear distinction between metrics at a strategic,

tactical, and operational levels. The author develops a framework that defines three levels of performance metrics such as strategic, tactical, and operational; these are again distinguished between financial and non-financial metrics [22].

- Gunasekaran et al. (2004) explain the role and importance of performance metrics that effect the supply chain's organizational strategic, tactical and operational planning and control. The motivation of the study is due to a lack of empirical analysis and case studies on performance metrics in a supply chain environment. A methodology was developed where the performance measures were divided into strategic, tactical and operational. A 150 questionnaire was sent out to various companies in the UK to evaluate strategic planning, order planning, supplier, production and delivery performance metrics by their level of importance. The performance was then evaluated based on a mean score which was converted to percentages [21].
- Hong et al. (2013) explain that most traditional supply chain performance is a static evaluation while the actual supply chain is a dynamic system. To meet the dynamic supply chain overall performance evaluation, a five Balanced Scorecard was used instead of a four Balanced Scorecard. In this study a Fuzzy Analytic Hierarchy Process was used to measure each performance index value, simultaneously using the number of inputs that were reduced Support Vector Machine (SVM) by using a classification method. The final performance evaluation results were derived using a Least Square Support Vector Machine (LS-SVM) which provides rational analysis and decision making of the supply chain [37].

- Bhagwat et al. (2007) identified the need to help managers evaluate supply chain in a balanced way by proposing a performance measurement system to map and analyze Supply Chains. A balanced scorecard was developed to measure a supply chain day-to-day business operation from four different perspectives such as finance, customer, internal business process, learning and growth. This was supported by three case studies demonstrating ways in which the BSC can be applied in a small and medium sized enterprises (SMEs) in India [28].

2.4 AHP and supply chain

Several authors have integrated Supply Chain and AHP for decision making. AHP is a multi-criteria decision making tool used to solve complex decision problems [38]. Shown in table 2.9 are authors who worked on AHP for supply chain problems.

Table 2.9: Summary of Literature Review on different studies on AHP for supply chain problems

Authors(s)	Methods	Year
Chan	Performance Measurement in a Supply Chain	2003
Gaudenzi et al.	Managing risks in the supply chain using the AHP method	2006
Sarkis	A strategic decision framework for green supply chain management	2002

- Chan (2003) explains how important supply chain is in logistics development for all industries and the non-existence of a systematic grouping of performance measures in existing literature. Criteria such as cost, quality, resource utilization, flexibility, visibility, trust and innovation are categorized into qualitative and quantitative

performance measures for easy understanding and representation. Analytical Hierarchy Process (AHP) is the tool used to make decisions based on the priority of supply chain performance measures. The model is tested with the case study of an electronic industry [39].

- Gauden et al. (2006) propose a methodology to evaluate a supply chain risks using AHP. An AHP model was used to identify various risks in the supply chain that would affect the objective of customer value. A case study was presented with two evaluations from the sales manager and a logistics manager [40].
- Sarkis (2002) describes the importance of green supply chain and how industries are now integrating environmental practices into their company's strategic plans. With the growing markets, it is often challenging for companies to keep up with environmental regulations in their supply chain. A dynamic non-linear multi attribute decision model known as ANP model is used for decision making to analyze the elements of a green supply chain and how they serve as a basis for the decision framework [41].

CHAPTER THREE

METHODOLOGY

3.1 Introduction

Motivation was derived from introduction on additive manufacturing to further expand the scope of the study and compare both the systems using real-time data. In order to compare the systems manufacturing setup, an automotive part was considered for the study. The real-time data for the automotive part that is manufactured in traditional forged and machined process was provided by a Tier 1 automotive supplier. The data for the Additive part was collected by setting up a simple lab experiment and some assumptions. From the simulation five key performance factors were compared in both the systems. Since this is too limited to conclude a study, the scope was further expanded where five key factors were selected, and were decomposed to over 100 performance sub factors through literature. Since working with over 100 factors seemed difficult, time consuming and may not be relevant to the study, a survey was designed to choose the most influential factors for the comparison of both systems. Experts from DOD and industry were requested to take part in the study. Once survey one was complete, AHP survey was designed to run AHP analysis on the factors and sub factors with AM and TM as alternatives. Final results were then compared to simulation performance factors.

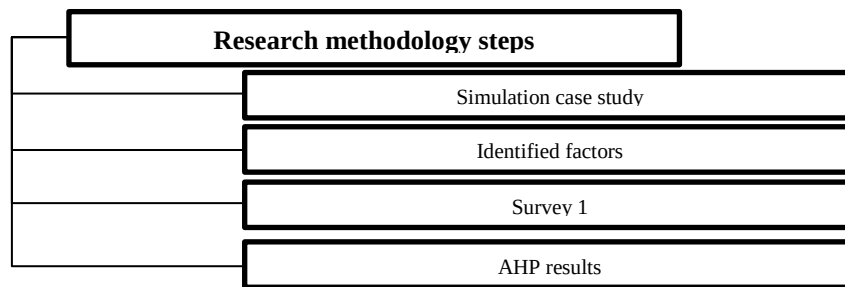


Figure 3.1: Research methodology steps

3.2 Research methodology

This chapter explains, in detail, the methodology developed to address the comparison and performance of AM with traditional manufacturing supply chain. The study consists of two surveys, a general survey and an AHP survey [42]. The methodology is scientifically structured as shown in Figure 3.1. The first activity done in the methodology of this study was the initial simulation analysis of a manufacturing process of a part in fused deposition modeling. The following section, scientifically the main factors such as cost, quality, time, flexibility and environment, were selected for the study. Various sub-criteria were compiled from literature. The criteria were then classified into several groups, and a questionnaire was developed to choose the most important criteria. AM experts from DOD and Oak Ridge National Laboratory were chosen as a target audience for the questionnaire. A hierarchy network was constructed consisting of different criteria, sub criteria and alternatives. A phase two survey is then developed based on the results of the first survey. AHP (Analytical Hierarchy Process) tool was used to analyze the comparison and performance of the AM and TM supply chain and manufacturing. Expert opinion and historical data with respect to qualitative and quantitative measures were used. The literature review in chapter two highlights some of the work done in the field of AM supply chain mainly in the spare parts segment. Due to lack of quantitative studies in additive manufacturing and supply chain, there is a need to integrate additive manufacturing supply chain and performance measures to understand how AM and supply chain performs under certain criteria under certain circumstances. The methodology in this study was modified against most of the established traditional AHP models in literature as shown in Figure 3.2, a traditional AHP model and Figure 3.3, current study methodology.

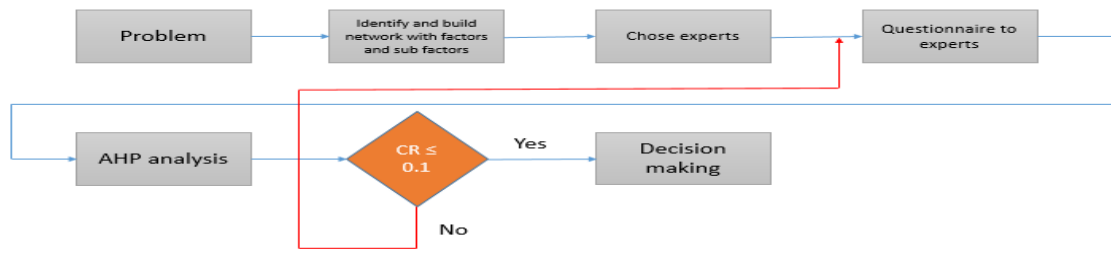


Figure 3.2: Traditional AHP study methodology

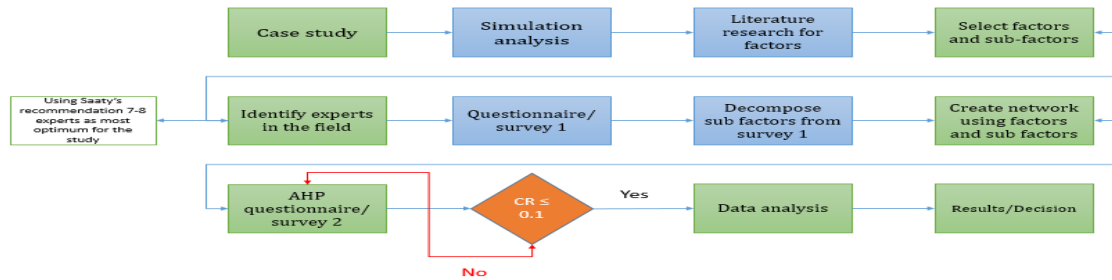


Figure 3.3: Current research methodology

3.3 Simulation model building

The two manufacturing systems, traditionally forged versus if the same part, as shown in Figure 3.5, were to be manufactured using additive technology and were compared on a macro level using simulation software ANYLOGIC. The forged part was compared with Fused Deposition Modeling technology (FDM). According to Stratasys, “FDM builds three dimensional parts by melting and advancing a fine ribbon of plastic through a computer-controlled extrusion head, producing parts that are ready to use” [43]. FDM was considered for the study due to the availability of multiple size FDM machines at the University of Tennessee as well as to its popularity among industrial and commercial sectors. The functionality of this part was not compared as it is not within the scope of this study. This

comparison study was done to compare the five key performance factors, to get a better understanding of the difference in the manufacturing setups of AM and TM, the flow of parts and supply chain. This gives a more comprehensive understanding of the differences between the two systems. The data of the Forged part was shared by a company in South Asia which is primarily a forged and fabrication automotive supplier. Data for the Additive Part was collected from an experiment that was conducted at a laboratory using a FDM (Fused Deposition Modeling) machine and also by interviewing an additive manufacturing company based out of Knoxville, Tennessee. The Forged part data consists of the actual layout of the plant that was shared by the company and this was used to construct the model in the software. Due to unavailability of the same for AM, a conceptual model was constructed with the inputs received from the AM Company. The core idea of the simulation was to analyze the areas AM can be used, where there are opportunities for AM in the future and how this can be compared to TM. The simulation model gives an accurate replica of the real manufacturing environment and the outcome of the model can be seen in the next section. As seen in Figure 3.4, the following steps were followed to build the simulation model.

1. Data collection for the forged part.
2. Data collection for the additive part.
3. Assumptions for missed data.
4. Building simulation model using AnyLogic.

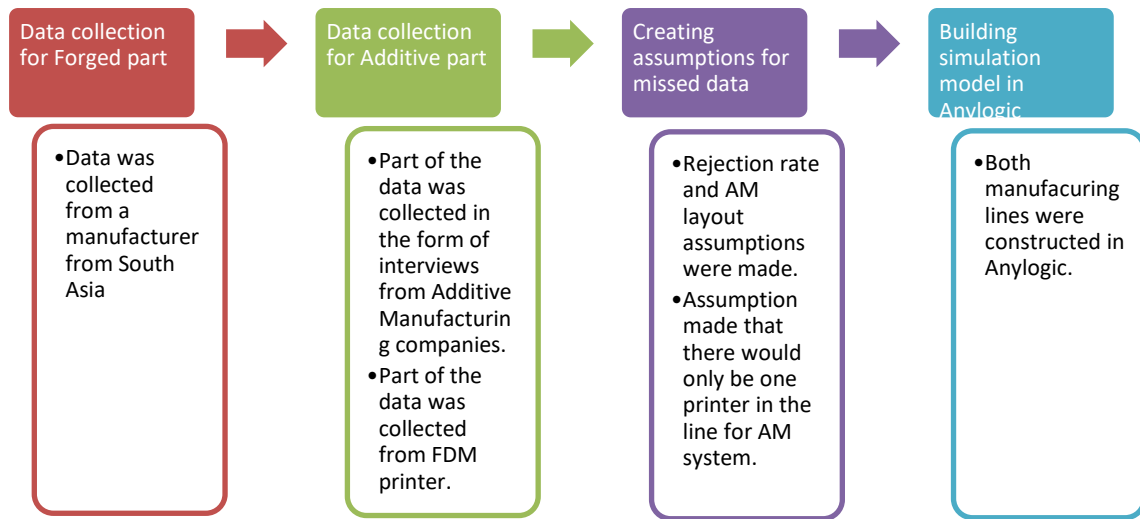


Figure 3.4: Overview of the simulation process

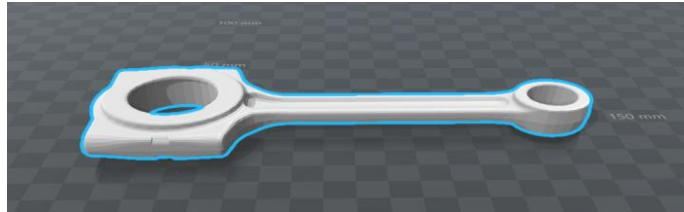


Figure 3.5: Part used in simulation case study

3.4 Simulation case study

The core idea of the simulation was to analyze the areas where AM can be used, where there are opportunities for AM in the future and how this can be compared to TM. The simulation model gives an accurate replica of the real manufacturing environment. Data of the Forged part was shared by a company in South Asia who is primarily a forged and fabrication automotive supplier. The Forged part data consists of the actual layout of the plant, which was used to construct the model in the software. Due to unavailability of the

same for AM, a conceptual model was constructed with the inputs received from the AM Company.

The two manufacturing systems, traditionally forged and additive manufactured part were compared on a macro level using simulation software “AnyLogic”. The forged part was compared with Fused Deposition Modeling technology (FDM). FDM according to Stratasys “FDM builds three dimensional parts by melting and advancing a fine ribbon of plastic through a computer-controlled extrusion head, producing parts that are ready to use” [43]. This comparison study was done to get a better understanding of the difference in the manufacturing setups of AM and TM, the flow, variation and disruptions. This gives a more comprehensive understanding of the differences between the two systems.

The motivation behind this comparison is to have a basic understanding of what AM is and how it can be compared with TM. To briefly explain the process of the forged automotive part, the manufacturer purchases forged billets from a TIER 2 supplier and machines them according to the requirement of the customer before shipping it to the customer. The billet undergoes operations in 11 different machines before the part is finally inspected and shipped. Data such as cycle time, takt time along with other relevant information of each operation was shared by the manufacturer. Similarly, based on literature research and inputs from an AM company, assumptions were made to a manufacturing setup of an AM facility; as it was explained in the introduction, AM would not need as many processes as a traditional manufacturing set up since one machine can produce the entire part by itself. Figure 3.6 shows the simulation model of forged and fabricated process in AnyLogic and Figure 3.7 shows the simulation model of FDM.

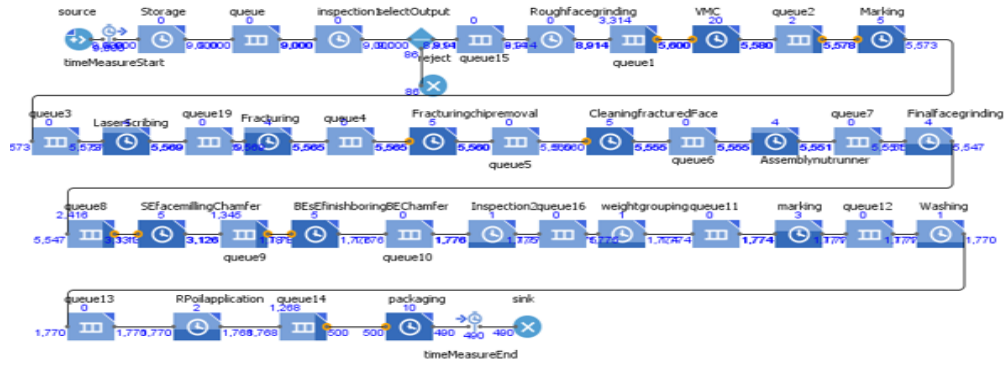


Figure 3.6: Simulation model of forged and machined process

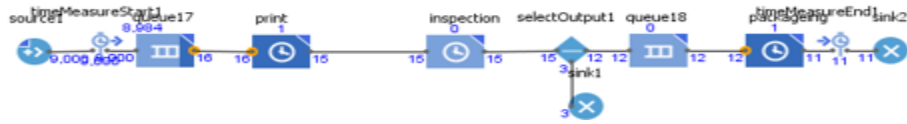


Figure 3.7: Simulation model of fused deposition modeling

3.5 Factors that will impact AM

In this section, a general framework is developed. After the simulation model is complete, various factors are identified that will impact AM. A panel of experts was identified to decompose these factors into the most critical factors. The factors were further categorized into various sub factors.

The performance measures or factors chosen for the study are categorized into financial and non-financial measures. The financial measures were categorized into cost, time, and quality while the non financial measures were categorized into flexibility and environment. Factors such as time, cost and quality indicate the potential to deliver high customer service in supply chain and manufacturing, while flexibility is important to cope with rapid changes in the demand [33]. Environmental factors help us in optimizing supply chains to

be more environmentally friendly. Cost, time, quality, flexibility and environmental factors were decomposed into several sub factors, based on the consideration of literature and 99 of such factors were collected. The output of this section is the list of criteria. The factors cost, quality, time, flexibility and environment were categorized into financial and non-financial factors as shown in Figure 3.8.

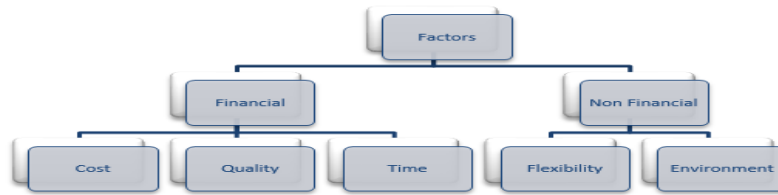


Figure 3.8: Breakdown of factors

3.6 DOD (Department of Defense) survey 1

This section explains the survey development procedures used for selecting the important criteria used for comparing the two types of systems. Hauser et al. said, “Choosing the right metrics is critical to success, but the road to the right metrics is fraught with pitfalls” [44]. Factors are to be developed to suit a particular study or industry. For that purpose, a phase one survey assessment tool was developed with experts in the field of Additive Manufacturing as respondents. To understand the factors that would impact the performance of a supply chain and manufacturing, picking the right criteria is very important since several factors are complex, time consuming, and may not necessarily be suited for a particular supply chain and type of manufacturing. Thus, a survey was developed using Qualtrics web surveys software to filter the 99 sub factors that were taken

from literature which can be found in the appendix. Thirteen AM experts belonging to various DOD (Department of Defense) AM research facilities across the United States and two experts from other AM industries were chosen for the study. The experts are highly qualified in their field with experience ranging from four to fifteen years in the field of rapid manufacturing. Saaty et al. (2015) clarify that seven to eight experts would be optimum for a study provided the experts are knowledgeable in the field, and one needs to make sure that the selected judges have both knowledge and practical experience in the field [45]. Similarly, there are authors who have done various studies using AHP with survey, interviews or questionnaires where the sample size was less than eight as shown in Table 3.1. Multiple choice questions are chosen for this section. In the questionnaire, experts were asked to pick the top 10 sub factors that are most important to a supply chain and manufacturing.



Figure 3.9: Survey 1 response rate

Table 3.1: Sample size for AHP survey from studies

Sample size for AHP survey	Year published	Reference
3	2008	[46]
6	2004	[47]
4	2006	[40]

3.7 Hierarchal structure

The expected conclusions from the result of the phase 1 survey and, the criteria are grouped together to build a hierarchical network. In our case there are four levels of the hierarchy diagram where level 1 is the goal or the objective of the problem; level 2 is the attribute level that consists of the variables cost, quality, time, flexibility and environment; level 3 is the sub-attribute level which consists of the criteria as per the results from phase 1 survey. As shown in Figure 3.10 an example of the construction of level 2 cost factor to level 3 manufacturing cost, which is a sub factor of cost. The final, level 4, consists of the alternatives. In the network from level 1 to level 3, the factors are connected to the sub factors in the lower level. Sub criteria in level 3 are connected to alternatives which are AM and TM in this case in level 4. An example of the hierarchy network is shown in Figure 3.11.

In order to successfully construct a hierarchy close to the problem one has to:

1. Identify the goal or what you want to accomplish.
2. Identify the attributes that would have an influence on the goal.
3. Identify all the sub-attributes that are relevant to the criteria.
4. Filter the sub-criteria that are most influential through expert opinion.
5. Identify the alternatives.

6. Draw a hierarchal network diagram connecting goal to each of the criteria, to relevant sub-criteria and connecting each sub-criteria to each of the alternatives.

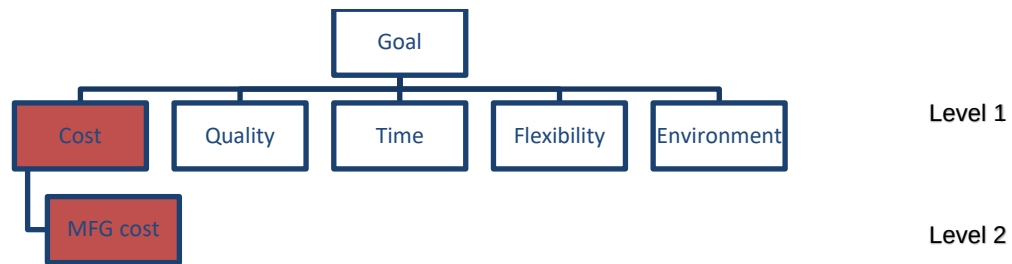


Figure 3.10: Showing example connecting a node in level 2 and a node in level 3

Level 3

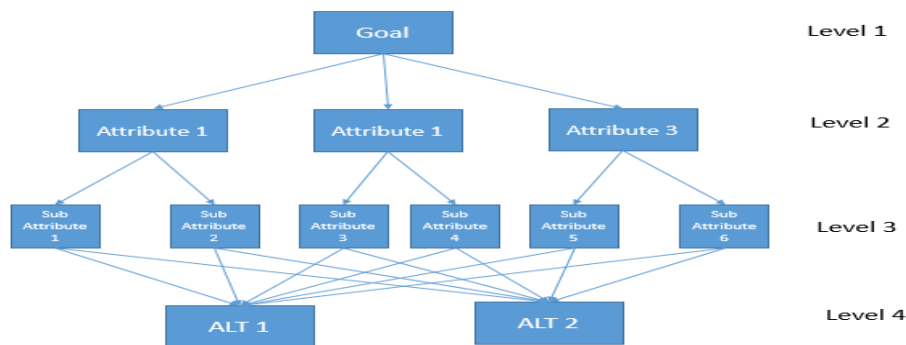


Figure 3.11: Illustration of a 4 level hierarchy network

3.8 DOD (Department of Defense) phase 2 survey

The phase two survey was developed using Qualtrics web survey software. This survey is basically used to construct a set of pairwise comparisons between each factor and sub factor in level 2 and level 3 in the hierarchy network. The alternatives at level 4 are also compared with each other for each of the criteria in level 3. The pairwise comparison is used to find the relative importance of the alternatives with respect to the criteria. The objective of

pairwise comparison is to calculate the relative importance of the criteria and their sub criteria using the scale of intensity proposed by Saaty (1980) [48] as shown in Table 3.2. The experts who took part in the phase 1 survey were also asked to participate in the phase 2 survey. In this survey each expert was asked to choose an alternative which would have a better performance measure or factor. As an example the experts were asked to choose a manufacturing system that would have a better “Rate of return on investment”, and the alternatives are Additive Manufacturing and Traditional Manufacturing. A display logic was added that would display the consecutive question based on the expert’s choice; if the expert chose the alternative Additive Manufacturing, the software would display the next question as shown in the appendix, similarly the same logic was applied if the expert chose the second alternative Traditional Manufacturing. The experts were asked to choose the intensity of importance in terms of each factor involved as per the scale of relative importance according to the scale in Table 3.2. The Saaty’s scale of importance was recorded in the background of the question. It was assumed that no compromise would be needed, hence the scales 2,4,6,8 were not included in the option. Finally, the last few questions in the questionnaire are to make a pairwise comparison between each element in the hierarchy; each sub factor is then compared with one another and to get this we ask the expert to compare a factor against another based on scale of importance. The scale of importance is recoded in the software as shown in Figure 3.12. The experts were asked to rate whether a sub factor is either extremely strong, very strong, strong, moderately strong or equally strong against another performance measure. An example of a pairwise comparison is shown in Table 3.3 which compares cost, quality and time for factors in a

supply chain in a 3X3 matrix. In this example the cost was scaled 3 as per intensity scale against quality and 9 as per the intensity scale against time, quality was scaled 7 as per the intensity against time.

Table 3.2: Scale of Relative Importance according to Saaty (1980)

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Weak importance of one over another	Experience and judgement slightly favor one activity over another
5	Essential or strong importance	Experience and judgement strongly favor one activity over another
7	Demonstrated importance	An activity is strongly favored and its dominance demonstrated in practice
9	Absolute importance	The evidence favoring one activity over the another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgement	When compromise is needed
Reciprocals of above non zero	If activity i has one of the above nonzero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	

Recode Values

☒ Recode Values
☐ Variable Naming
☐ Question Export Tags

9

7

5

3

1

3

5

7

9

Rate of return on investment

Rate of return on investment

Rate of return on investment

Manufacturing cost as percentage of revenue

Manufacturing cost as percentage of revenue

Total Manufacturing cost per unit excluding materials

Manufacturing cost as percentage of revenue

Total Manufacturing cost per unit excluding materials

Cost per operation hour

Cost per operation hour

Cost per operation hour

Figure 3.12: Recoded values as per Saaty (1980) scale of relative importance

Table 3.3: “Example for pairwise comparison matrix”

Criteria for supply chain performance	Cost	Quality	Time
Cost	1	3	9
Quality	1/3	1	7
Time	1/9	1/7	1

3.9 Analytical hierarchy process (AHP)

The Analytical Hierarchy Process (AHP) was developed by Thomas Saaty in 1980 [48]. In its existence of over 20 years it was applied to numerous fields, and is a tool that is used for solving multi criteria decision making (MCDM) problems. AHP was applied to a wide variety of supply chain areas such as supplier selection, purchasing strategy, green supply chain, collaborative supply network, performance measurement, supply chain design, warehousing network and much more [49]. In this study, Super Decisions version 2.6.0 software was used to conduct the analysis. A screen shot of the hierarchical structure constructed in the software, as shown in Figure 3.13, shows give factors and 22 sub factors. The factors were represented by alphabets and a number in the suffix for easier construction. The geometric averaging of the scores was calculated before inputting the

results of phase 2 in the software for mathematical calculation of the weights [50]. The weights are then used to conclude how an AM and TM supply chain performs under a given set of criteria. We will see step by step how the software would mathematically run the analysis. Once the scales of the pairwise comparison is obtained from the survey phase 2, the next steps would be:

1. There will be n number of elements and $n(n-1)/2$ comparisons, where n is the number of elements with considerations that diagonal elements are equal or “1” and the other elements will be reciprocals of earlier comparison [51] [47]. Each element is compared with the other on the same level and to the higher level above.
2. The next step is calculating the weights of the elements in the matrix which is the eigenvector and is also called the priority vector; this is obtained by averaging across the rows of the matrix.
3. Next, check if the pairwise comparison is adequately consistent, the consistency ratio [33] has to be less than 0.10, $CR \leq 0.1$, according to Saaty (1980) [48]. The consistency index (CI) is calculated by the formula $CI = \lambda_{max} - n / (n - 1)$ where λ_{max} is the maximum eigenvalue. The consistency ratio [33] is obtained by dividing the CI by the Random Consistency index (RCI), $CR = CI/RCI$. The RCI are values calculated from a sample of 500 randomly generated matrices based on the scale of intensity by Saaty (1980). The RCI scale as per Table 3.4. If CR value is satisfied, then the decision can be taken based on the weights. If no further investigation into the problem is required.

Table 3.4: RCI values for different values of criteria n.

N	1	2	3	4	5	6	7	8	9
RCI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45

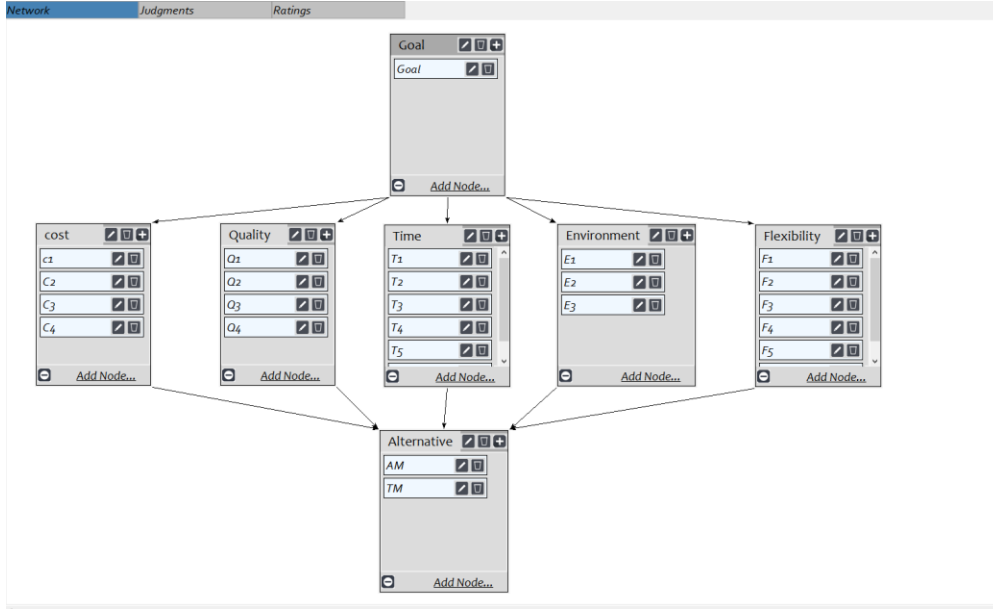


Figure 3.13: Screen shot of the model in super decisions

3.10 Validation of the study

In this section, a validation study was developed in order to test and validate the model.

The essence of the validation is to understand how different combinations could change the final result. This is very important to understand since it gives us an overview of how each of the factors influences the performance of the final result. Different combinations of the variables Cost (C), Quality [50], Time (T), Flexibility (F) and Environment (E) were

calculated using a formula of combinations $\frac{N!}{(N-R)!R!}$, where N is the number of variables and R is the number of combinations required per case. Each combination is run in software and, the results are recorded. By doing this, we can see the varying performance of the

alternatives with each combination. A table was developed with the number of scenarios, different combinations and scores for the alternatives.

CHAPTER FOUR

RESULTS AND DISCUSSION

In this chapter results will be discussed in the following phases:

- 4.1 Phase 1: Simulation results analysis.
- 4.2 Phase 2: Talks about the outcome of survey 1
- 4.3 Phase 3: AHP survey results. Final result Validation Study
- 4.4 Simulation output vs AHP final result

4.1 Simulation model analysis

The outcome of the simulation model tells us that some factors have better results in AM while others are in TM. From the analysis, as shown in Figure 4.1, we understand that AM has a better Average time in system and Rejection Rate. On the other hand, TM has a better WIP, Utilization. The reason behind AM having a disadvantage compared to TM is due to the slow print time and absence of a robust quality system when compared to the traditional manufacturing systems. One of the advantages identified with AM is that the manufacturing may not have to go through multiple machines for a finished product. AM has the capability to directly advance from the design phase to the manufacturing phase [52]. AM has less setups, less WIP and higher utilization of the machines. The output of the simulation model was limited and lead to further examination into various other factors for comparison. Due to limited availability of literature and studies in this field, a unique methodology was developed in the following chapters. Further analysis of the simulation results can be seen in detail below.

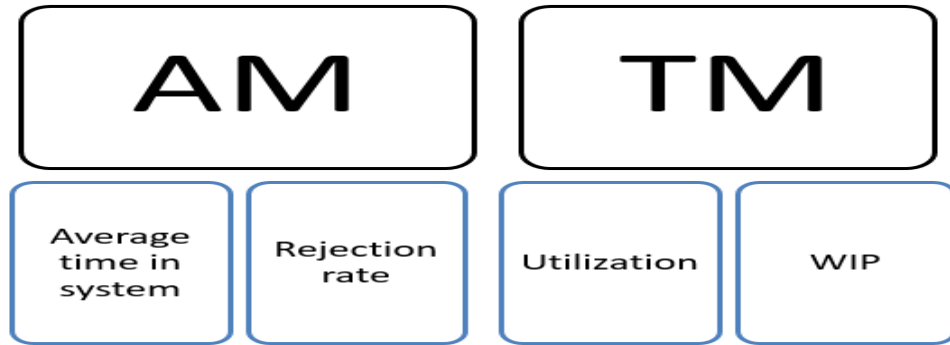


Figure 4.1: Simulation Factors measured in both the systems

Average time in the system – Average time in the system for AM is 10,608 seconds while the average time of TM is 12,927 seconds, as shown in Figure 4.2.

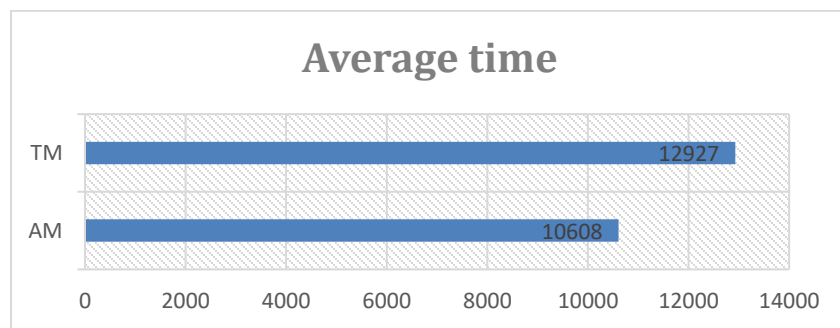


Figure 4.2: Simulation throughput

WIP (Work in Process) – In Lean manufacturing terms, WIP is Muda or waste. As shown in Figure 4.3, the WIP of AM is 8,989, 479 more entities or unfinished parts in the system as TM which is 8,510. It is important to mention that maximum WIP of AM was in the queue before the print. As explained, if the print time of the system is improved in the future, this would be a far lower number. The slow print time is causing raw material inventory stack up before being loaded in the printer for manufacturing. The purchase of

the raw material can certainly be controlled or by installing several printers in the line, would reduce WIP drastically. For TM, due to the entities or unfinished products, products go through several machines before a finished product comes out. Improving machine speeds might reduce WIP.

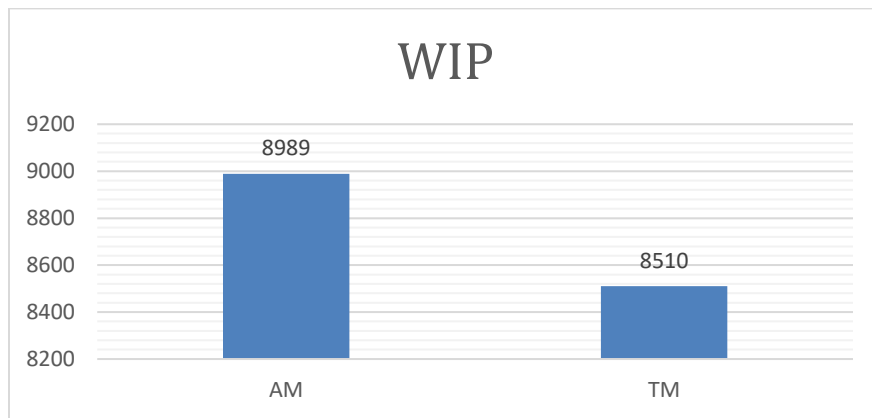


Figure 4.3: WIP output

Utilization – Utilization of AM is 1 compared to the utilization of TM which is 1.07, as shown in Figure 4.4. TM certainly has a better utilization. One important factor that should be considered is that the model was constructed with only one printer in the AM system.

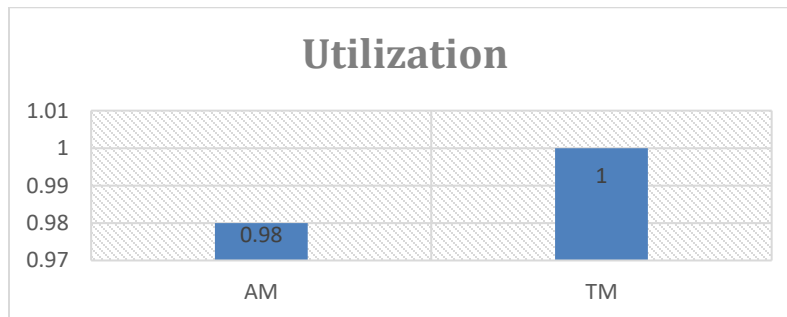


Figure 4.4: Utilization of machine

Rejection – The number of rejected parts in AM is 3 against 86 in TM as shown in Figure 4.5. This was compared against the throughput, the results as shown in the graph below,

rejection rate of AM against throughput was 27.27% and 17.55% for TM as shown in Figure 4.6. Although both seem quite high, TM has a lower rejection rate than AM. It is understood that there are no proper quality standards defined for AM at the present time. In the future, it is expected to be more competitive with traditional manufacturing systems.

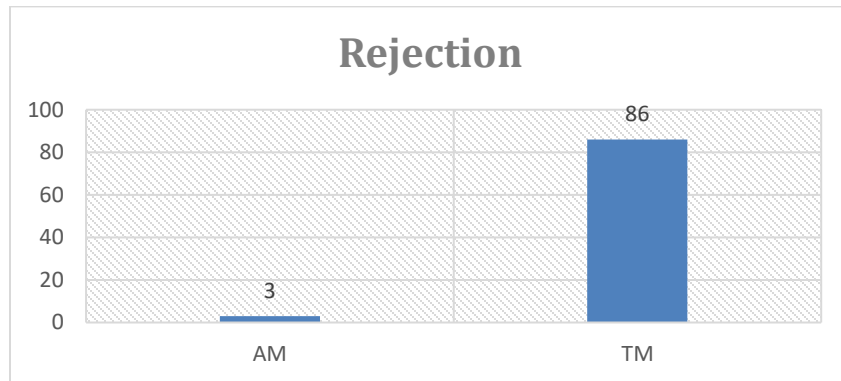


Figure 4.5: Number of parts rejected in a shift

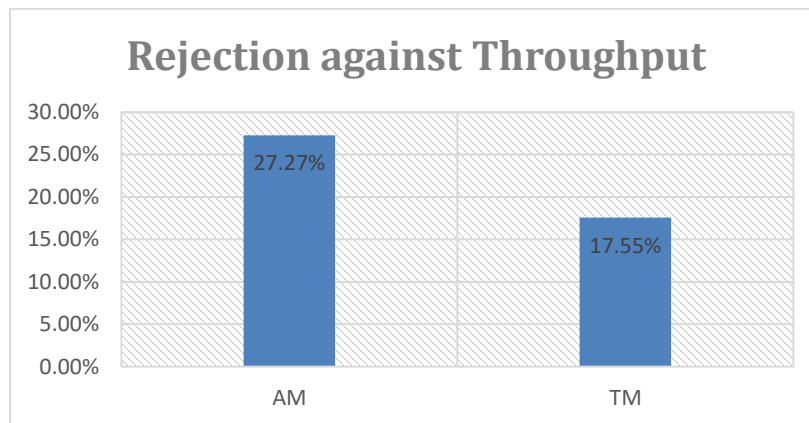


Figure 4.6: Rejection against throughput

4.2 Survey 1

As discussed in the methodology, this survey was constructed to work with the most important factors. Thirteen out of twenty Additive Manufacturing experts answered the survey with an overall response rate of 65%; this is justifiable as per the various available

literature on AHP. From the responses, the factors with 70% or more response rate were selected for the study which resulted in a total of 23 out of the 99 factors as listed in Figure 4.7. Four factors from cost, four factors from quality, six factors from time, six factors from flexibility and three factors from environment had a response rate of more than 70%. These twenty-two factors were used to construct the AHP survey that was sent to the same audience chosen for the first survey. Eight respondents completed the AHP questionnaire with a response rate of 40%. Figure 4.8 shows the network constructed using five factors, twenty-two sub factors and two alternatives as required in the AHP model.

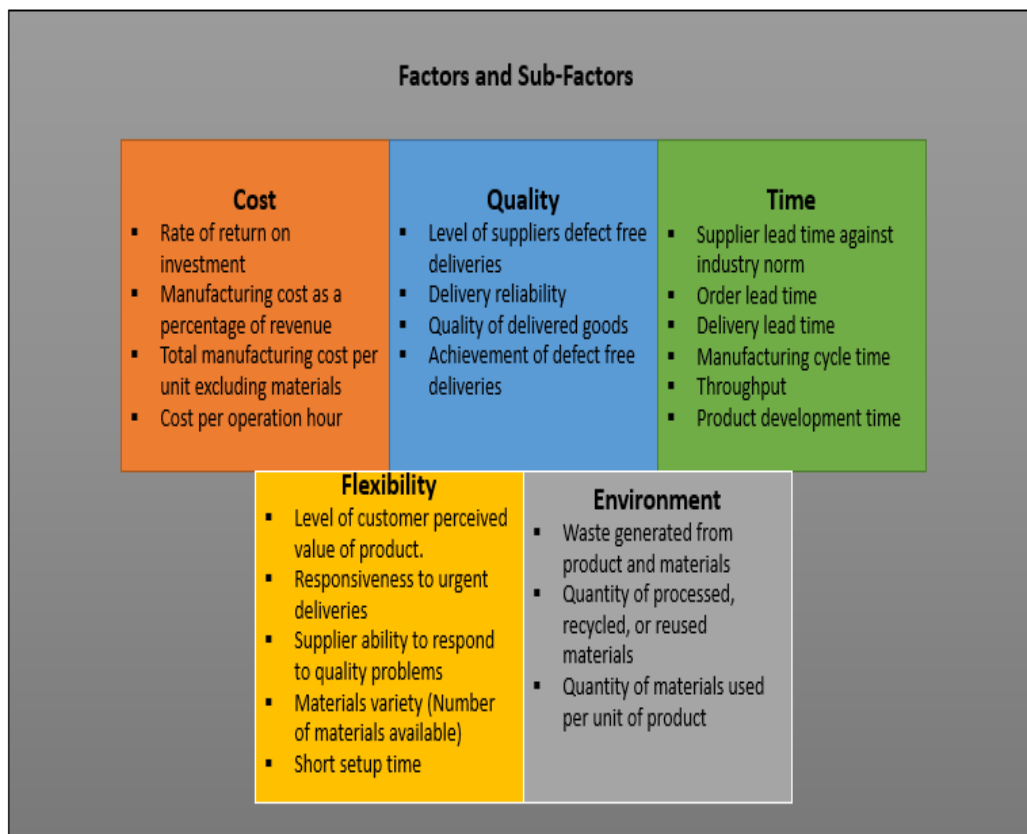


Figure 4.7: Image showing factors and sub factors

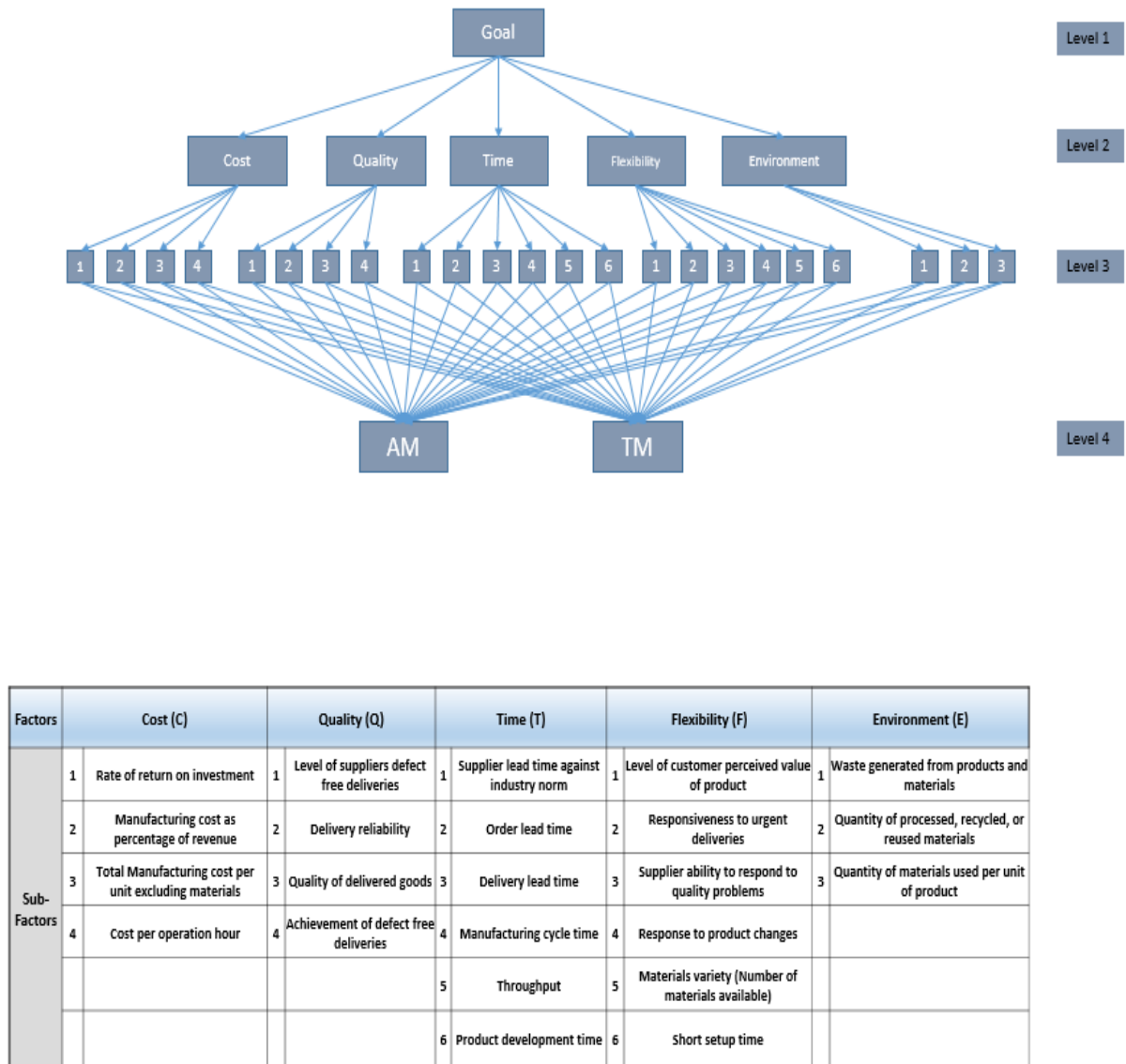


Figure 4.8: Hierarchical structure constructed to five factors and twenty-three sub factors

4.3 AHP analysis

Step1: The analysis on the software was run, each expert was asked to rate cost, quality, time, flexibility and environment on the basis of their importance to a supply chain. According to the results, quality is the most important variable that would influence the performance of a supply chain followed by cost, flexibility, time and environment. According to the experts, quality is the most vital element of a supply chain manufacturing setup with a weighted average of 0.25014; followed by cost with a weighted average of 0.22048; flexibility ranked third with a weighted average of 0.21078; finally, time and environment ranked fourth and fifth with a weighted average of 0.17628 and 0.14232 respectively, as shown in Figure 4.9.

Table 4.1: Factor weight

Factor	Weight
Cost	0.22048
Quality	0.25014
Time	0.17628
Flexibility	0.21078
Environment	0.14232

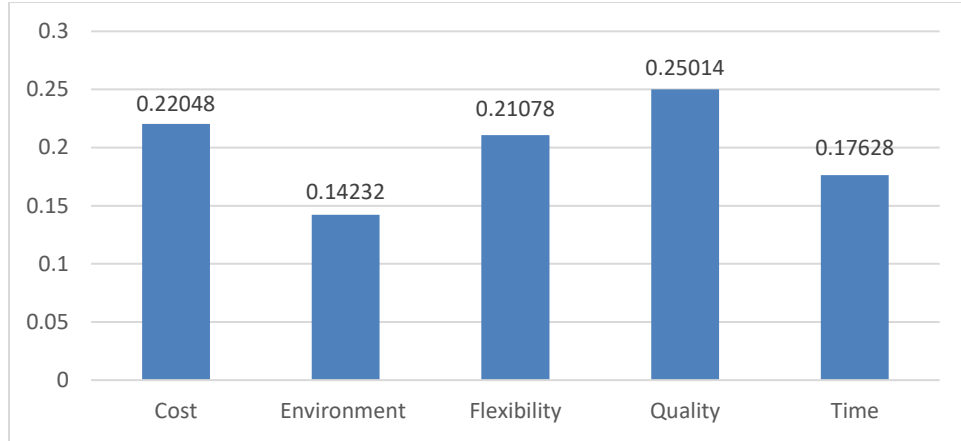


Figure 4.9: Graphical representation of criteria weights

Step 2: Experts from the questionnaire were asked to choose alternatives based on each sub criteria. From this, we can understand which system is preferred and individually rated. Out of the 23 sub criteria taken from various literature [21] [22] [29] [30] [33] [31], expert's opinion resulted in the majority of the sub criteria favoring AM. Shown in Table 4.2, are the sub criteria, representation, and the weight of the alternatives AM and TM. Looking at the data, most of the criteria favors AM except Q1 level of defect free deliveries which has a weight of 0.632911 for TM against AM weight of 0.367089; Q2 delivery reliability where the weight of TM is 0.552486 against the weight of AM at 0.447514; Q3 quality of delivered goods where the weight of TM is 0.531915 and AM was weighed at 0.468085. The data from the table is exported to a graph as shown in Figure 4.10. The data suggests that a supply chain manufacturing of a traditional set up has better quality than an additive manufacturing setup. One of the reasons for the outcome could be because there is no standard in place for a "Quality Management" system for additive manufacturing processes or materials as of today [53]. Data also suggests that cost, time, flexibility and environment

has a better weightage overall for AM. To understand this, we look at various practical reasons. Additive Manufacturing does not need tooling unlike traditional manufacturing methods as also shown in the experiment above as this reduces the production ramp up time and also decreases the cost of tooling. Industries spend a considerable amount of money and time on tooling, its maintenance and warehousing. AM has shorter lead times, due to little or no requirement of these tools. The possibility of quick changeovers results in shorter lead times and decreases inventory. AM, unlike traditional methods, has an advantage of quick design changes, due to the same reason of no tooling, quick engineering changes to the product reduces the time and makes the system very flexible. Design customization of AM also has the edge over the traditional methods, due to its ability to meet complex tolerances with quick changeovers, the lead time for the supply of customized products is greater. Finally, waste and energy management in AM is highly efficient; there is no need for cutting tools and long manufacturing lines, which reduce the generation of wastes, wastes generated from materials in production and consumption of energy to run the machines [54]. The reasons justify the results that AM has a distinct advantage over TM for certain criteria. However, TM manufacturing will continue to dominate the mass manufacturing market.

Table 4.2: Alternative selection weights

Sub criteria	Representation	AM weight	TM weight
Rate of return on investment	C1	0.817518	0.182482
Manufacturing cost as percentage of revenue	C2	0.57265	0.42735
Cost per operation hour	C3	0.827883	0.172117
Total Manufacturing cost per unit excluding materials	C4	0.539171	0.460829
Level of defect free deliveries	Q1	0.367089	0.632911
Delivery reliability	Q2	0.447514	0.552486
Quality of delivered goods	Q3	0.468085	0.531915
Achievement of defect free deliveries	Q4	0.62963	0.37037
Supplier lead time against industry norm	T1	0.752475	0.247525
Order lead time	T2	0.770115	0.229885
Delivery lead time	T3	0.778271	0.221729
Throughput	T4	0.754902	0.245098
Manufacturing cycle time	T5	0.790795	0.209205
Product development time	T6	0.837925	0.162075
Response to product changes	F1	0.740933	0.259067
Materials variety(Number of materials available)	F2	0.872123	0.127877
Short setup time	F3	0.641577	0.358423
Supplier ability to respond to quality problems	F4	0.862448	0.137522
Responsiveness to urgent deliveries	F5	0.601594	0.398406
Level of customer perceived value of product	F6	0.833055	0.166945
Waste generated from product and materials	E1	0.790795	0.209205
Quantity of processed, recycled or reused materials	E2	0.77221	0.22779
Quantity of materials used per unit production	E3	0.710145	0.289855

Table 4.3: Weight of criteria and sub criteria

Criteria	Weight	Sub Criteria	Representation	Weight
Cost	0.22048	Rate of return on investment	C1	0.56068
		Manufacturing cost as percentage of revenue	C2	0.18185
		Cost per operation hour	C3	0.13838
		Total Manufacturing cost per unit excluding materials	C4	0.11909
Quality	0.14232	Level of defect free deliveries	Q1	0.17393
		Delivery reliability	Q2	0.20249
		Quality of delivered goods	Q3	0.42061
		Achievement of defect free deliveries	Q4	0.20297
Time	0.21078	Supplier lead time against industry norm	T1	0.27587
		Order lead time	T2	0.20794
		Delivery lead time	T3	0.10843
		Throughput	T4	0.18516
		Manufacturing cycle time	T5	0.0953
		Product development time	T6	0.12729
Flexibility	0.25014	Response to product changes	F1	0.1623
		Materials variety(Number of materials available)	F2	0.11968
		Short setup time	F3	0.21399
		Supplier ability to respond to quality problems	F4	0.24951
		Responsiveness to urgent deliveries	F5	0.15529
		Level of customer perceived value of product	F6	0.09923
Environment	0.17628	Waste generated from product and materials	E1	0.55082
		Quantity of processed, recycled or reused materials	E2	0.27239
		Quantity of materials used per unit production	E3	0.1768

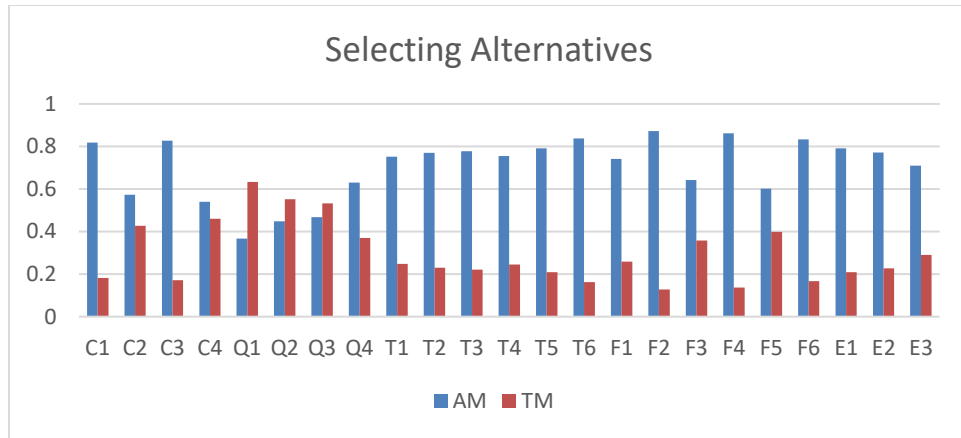


Figure 4.10: Graphical representation of alternative selection

Step 3: Pair wise comparison is comparing variables or sub criteria among each other by calculating the weights of each of the sub criteria. By doing this, we were able to understand the relative importance of each of the criteria. Weights of the criteria and sub criteria are shown in table 4.3. The data was exported to a graph shown in Figure 4.11, to understand the distribution of each of the weights on the whole.

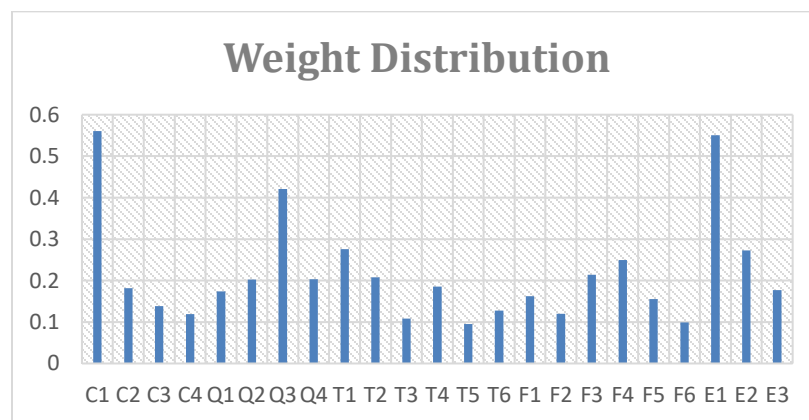


Figure 4.11: Graphical representation of weight distribution

- **Cost:** This factor is very important in a global competition, “Efficient utilization of labor, material, and equipment is essential to keeping costs competitive” [23]. The following are sub-criteria that are considered under the main factor of cost. Expert opinion suggests that in cost, the rate of return on investment has the highest weightage (0.56068), suggesting cost sub criteria is very critical in a manufacturing supply chain industry. Manufacturing cost, as a percentage of revenue, has a second highest weightage at (0.18185), followed by cost per operation hour (0.13838) and total manufacturing cost excluding materials (0.11909) shown in Figure 4.12.

C1: Rate of return on investment

C2: Manufacturing cost as percentage of revenue

C3: Cost per operation hour

C4: Total manufacturing cost per unit excluding materials

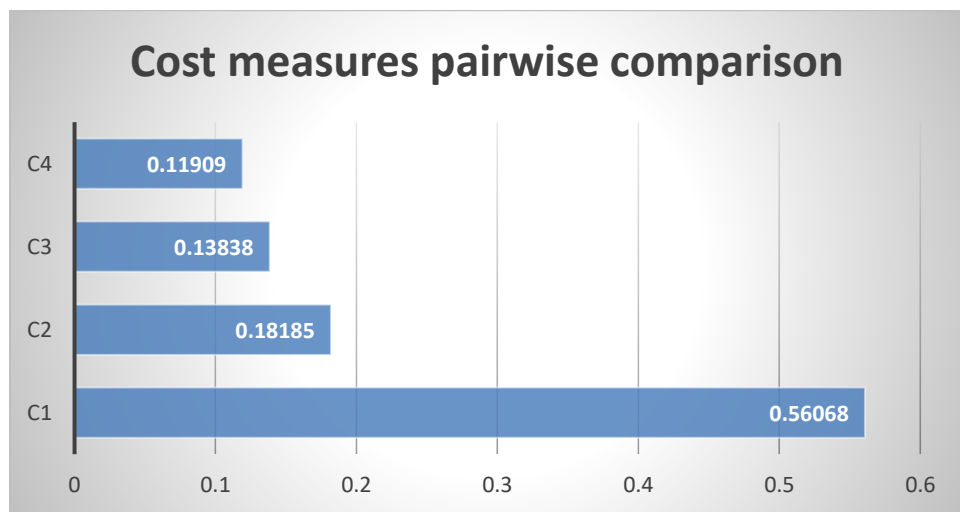


Figure 4.12: Graphical representation of cost weights

- **Quality:** Quality means the fulfillment or meeting the requirement and expectations.

In quality, quality of delivered goods has the highest weightage among the quality sub criteria with a weight of (0.42061), followed by achievement of defect free deliveries (0.20297), delivery reliability (0.20249) and level of supplier defect free deliveries shown in Figure 4.13.

Q1. Level of supplier defect free deliveries

Q2. Delivery reliability

Q3. Quality of delivered goods

Q4. Achievement of defect free deliveries

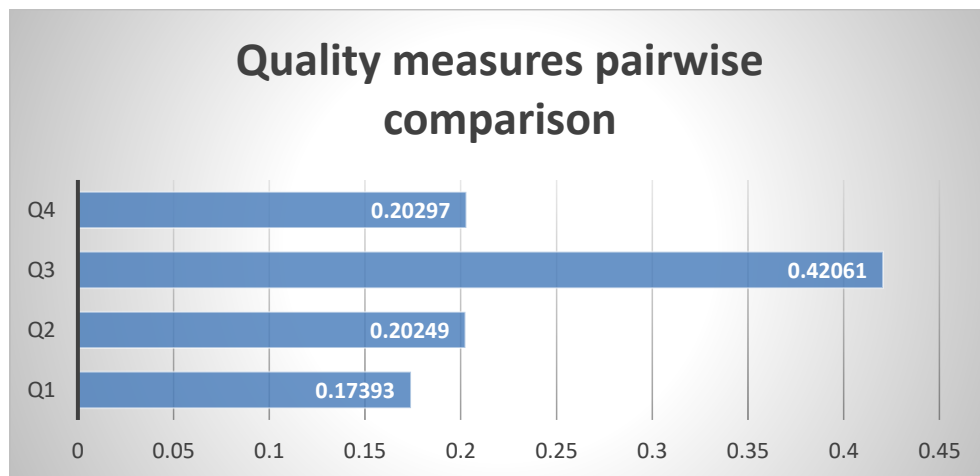


Figure 4.13: Graphical representation of quality weights

- **Time:** Speed or time is next in line behind cost. Customers expect firms to rapidly develop new products coupled with quick delivery of the products. The following are sub-criteria that are considered under the main factor of Time. In time, supplier lead time against industry norm has the highest weightage with a weight of (0.27587), followed by order lead time (0.20794), throughput (0.18516), product development

time (0.12729), delivery lead time (0.10843) and manufacturing cycle time (0.0953) shown in Figure 4.14.

T1. Supplier lead-time against industry norm

T2. Order lead time

T3. Delivery lead time

T4. Throughput

T5. Manufacturing cycle time

T6. Product development time

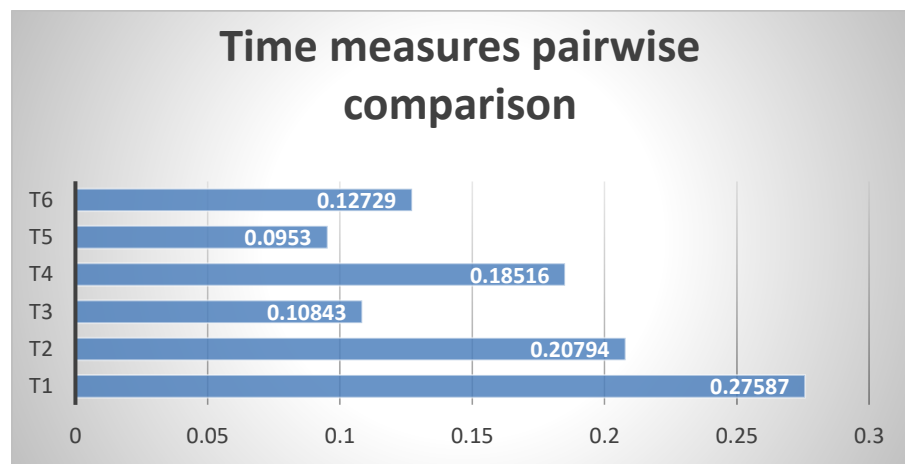


Figure 4.14: Graphical representation of time weights

- **Flexibility:** Flexibility means the system's ability to react in case of changes, whether predicted or unpredicted. The following are sub-criteria that are considered under the main factor of Flexibility. Flexibility sub criteria, supplier ability to respond to quality problems has the highest weight of 0.24951 shown in Figure 4.15.

F1. Response to product changes

F2. Materials variety (Number of materials available)

F3. Short setup time

F4. Supplier ability to respond to quality problems

F5. Responsiveness to urgent deliveries

F6. Level of customer perceived value of product

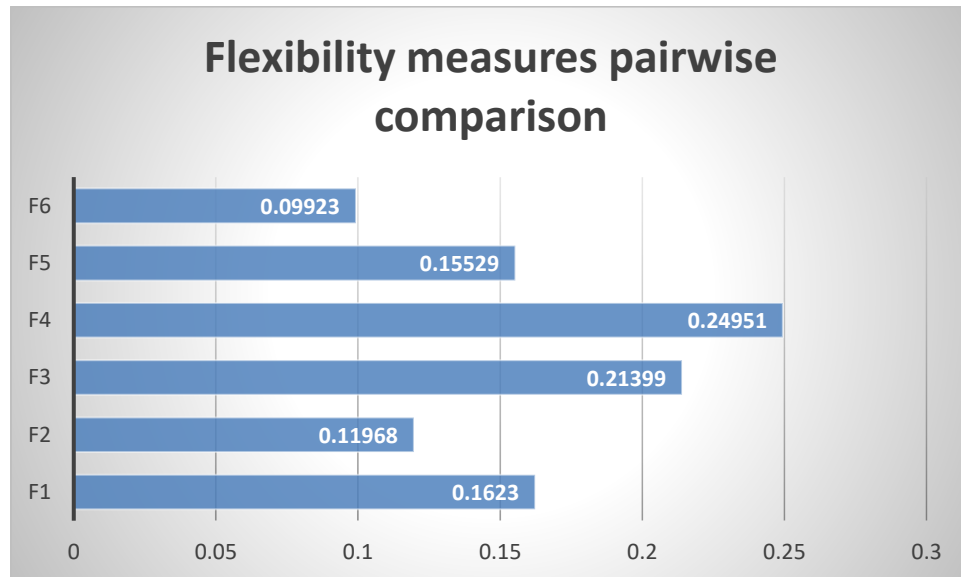


Figure 4.15: Graphical representation of flexibility weights

- **Environment:** Environment metrics help us in optimizing supply chains to a more environmentally friendly and releasing less carbon foot print. The following are sub-criteria that are considered under the main factor of Environment. Finally, the environmental factors, waste generated from products and materials has the highest weightage with 0.55082 followed by a quantity of processed, recycled and reused materials (0.27239) and quantity of materials used per unit of production (0.1768) shown in Figure 4.16.

E1. Waste generated from products and materials

E2. Quantity of processed, recycled, or reused materials

E3. Quantity of materials used per unit of product

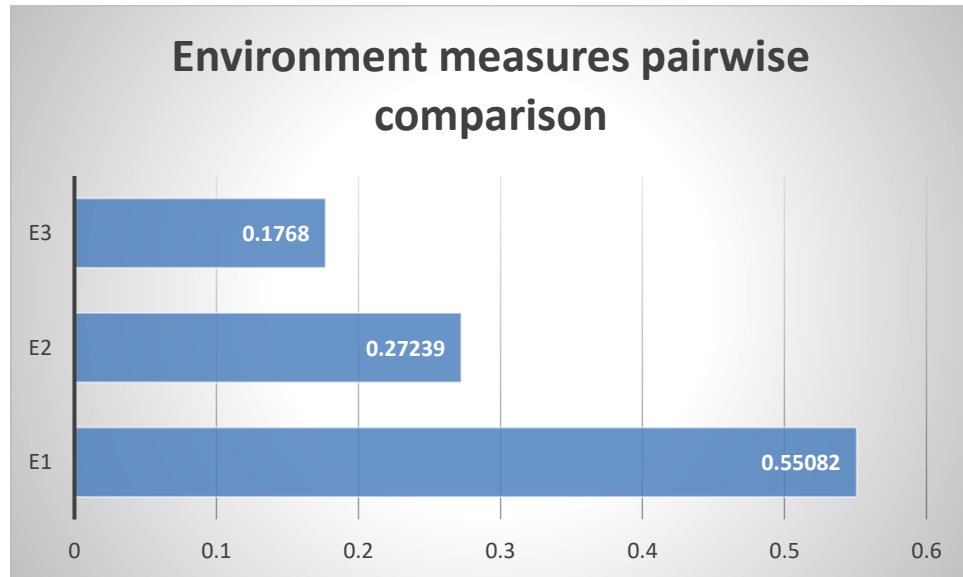


Figure 4.16: Graphical representation of environment weights

4.4 Final Result

The analysis shows that based on expert input, the supply chain of AM performs better than TM for the set of criteria chosen for this study. In a comparison to both the alternatives, the weight of AM is 0.688 against TM with a weight of 0.312 as shown in Figure 4.17 and Table 10. This result could vary based on the type of industry, experts and also the type of criteria chosen for the study.

4.5 Validation

As shown in Table 4.5, 31 different scenarios were created to look into how removing or adding criteria could change the final result. The analysis was run with a different set of combinations derived from the formula of combinations. Each combination shows a

varying result, but on the whole we can understand that AM performs better over TM except for the criteria Quality with a weight of (0.479141) for AM and (0.520859) for TM. This method is not traditionally used in AHP studies.

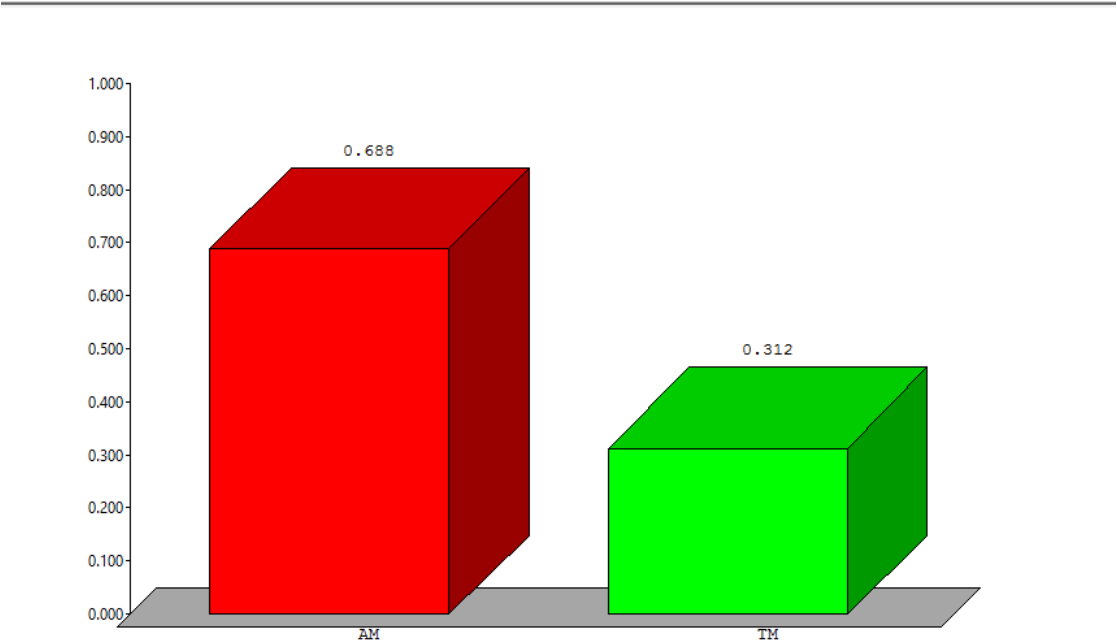


Figure 4.17: Final result graphical representation

Table 4.4: Final result

Graphic	Alternatives	Total	Normal	Ideal	Ranking
	AM	0.3441	0.6883	1.0000	1
	TM	0.1559	0.3117	0.4529	2

Table 4.5: Scenarios weights

Scenario	Combinations	AM	TM
1	C	0.741275	0.258725
2	Q	0.479141	0.520859
3	CQ	0.601947	0.398053
4	T	0.773919	0.226081
5	CT	0.755778	0.244222
6	QT	0.601001	0.398999
7	CQT	0.64881	0.35119
8	F	0.753194	0.246806
9	CF	0.7471	0.2529
10	QF	0.604466	0.395534
11	CQF	0.648733	0.351267
12	TF	0.762633	0.237367
13	CTF	0.754882	0.245118
14	QTF	0.651345	0.348655
15	CQTF	0.674463	0.325537
16	E	0.771474	0.228526
17	CE	0.753121	0.246879
18	QE	0.585151	0.414849
19	CQE	0.64131	0.35869
20	TE	0.772826	0.227174
21	CTE	0.759922	0.240078
22	QTE	0.643659	0.356341
23	CQTE	0.67093	0.32907
24	FE	0.760562	0.239438
25	CFE	0.753148	0.246852
26	QFE	0.643868	0.356132
27	CQFE	0.66994	0.33006
28	TFE	0.76501	0.23499
29	CTFE	0.758031	0.241969
30	QTFE	0.673277	0.326723
31	CQTFE	0.688269	0.311731

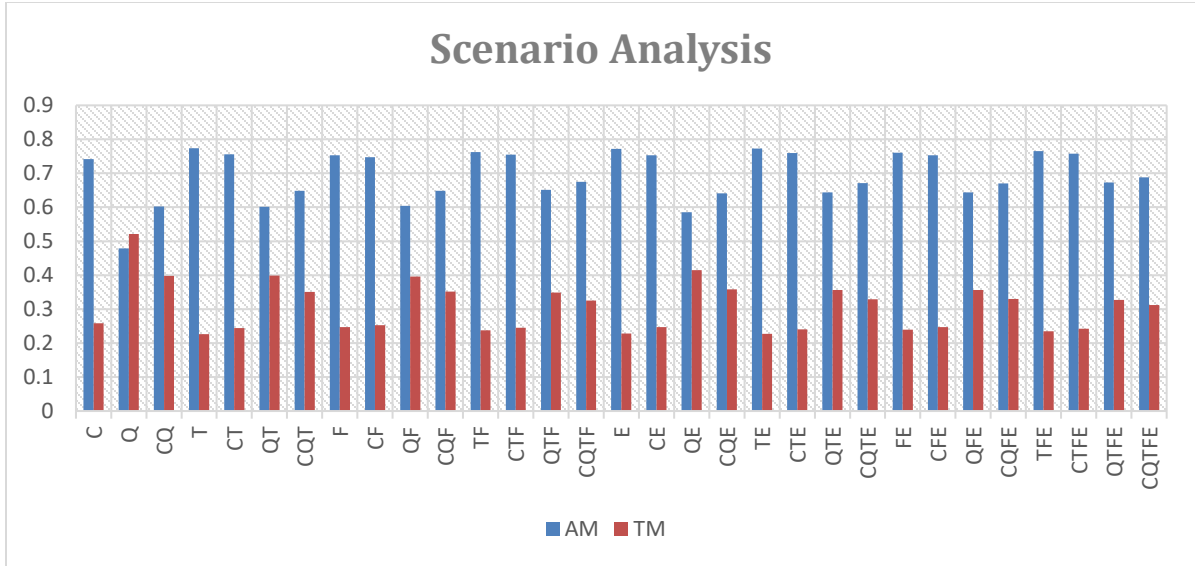


Figure 4.18: Graphical representation of scenario analysis

The graphical representation of the various scenarios is shown in Figure 4.18. Criteria quality has a higher weightage. A combination of cost and quality, quality and time, quality and flexibility, and finally quality and environment have a higher weighted average for TM that is close to the weighted average of the same combinations in AM, although it does not beat them. The results show that criteria, along with quality, perform better for TM since quality has a higher rating for TM over AM.

4.6 Simulation factors vs AHP final result

This section compares the simulation key performance factors to the AHP final result. As seen in Figure 4.19, the simulation results factors, or output results, were converted in decimal points for comparison purposes to the final result. The final output in AHP concluded that AM was 0.688 against 0.312 TM, which means AM performs better under the given conditions and selected performance factors for the study. These two final results

were plotted against the five key performance factors from the simulation results .As stated in the final result that from AHP, AM has a better performance output than TM. The same was not the case in a real-time simulation as Utilization, Rejection rate and Average time are all better in TM. Only WIP showed better output for AM through simulation. The reason for this could be the comparison was between a mass manufacturing setup versus a lab setup and secondly experts, while giving their opinion, would have been biased towards AM under the assumption or belief that AM would be better on all aspects when it can reach the mass manufacturing potential and competing with TM systems of today.

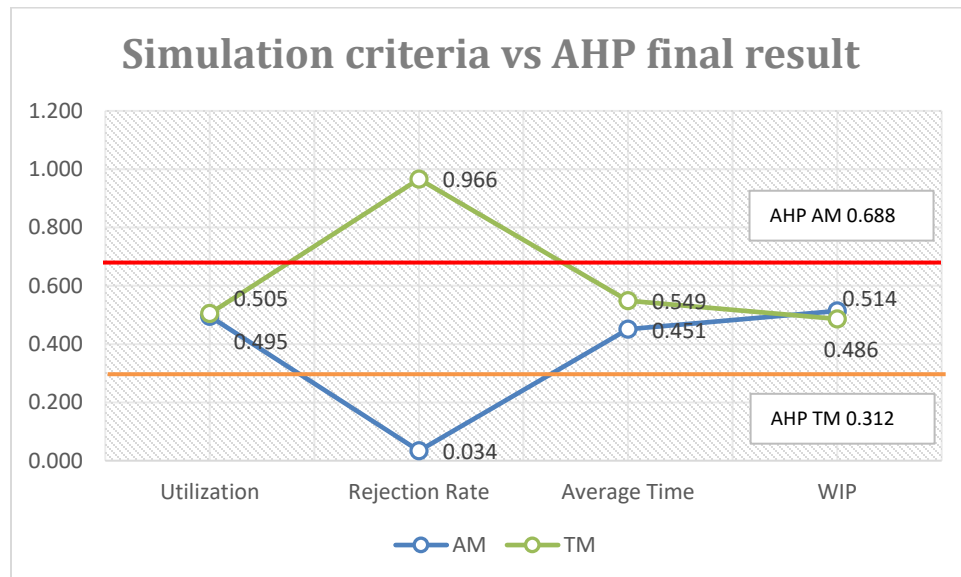


Figure 4.19: Simulation factors VS AHP final result

CHAPTER FIVE

CONCLUSIONS

The previous chapters are briefs about the research work done on this thesis. This chapter summarizes the thesis work and areas for further improvement.

5.1 Summary of research

The main purpose of this work was to develop a methodology to scientifically compare and measure the performance of additive manufacturing and traditional manufacturing. The model developed in this thesis shows a preliminary study of the two manufacturing systems using simulation modeling. An actual manufacturing facility was replicated in the simulation model. The simulation model compares the manufacturing of an automotive part in both the systems. From the simulation results, we were able to see that TM or Traditional Manufacturing has an advantage over AM or Additive Manufacturing. However, the data was not enough to conclude which of the systems is better or performs better. Through literature review, five factors and 108 manufacturing and supply chain sub factors were identified to further expand the research. Due to the complexity in working with 99 factors, an initial survey was conducted to pick the most vital sub-factors for the study. Experts in the field of additive manufacturing, who are also well versed with various traditional manufacturing processes, were selected for the survey. Twenty-two sub factors were chosen and an AHP analysis was conducted. The AHP analysis shows that AM has a better rate or performance with an overall score of 0.688 vs TM with a score of 0.3117.

This proves that for a certain set of factors chosen for the study, AM performs better than TM.

5.2 Recommendations

The result is dependent on the experts who answer the questionnaire. In order to make the model more robust, the recommendation is to take multiple sets of people and send them the same questionnaire. The comparison of the results between the sets of people and by averaging the output should give a more accurate output of the study. For the simulation comparison, the manufacturing system of a forged and machined part was compared with a University lab setup FDM process. The comparison with an industrial metal AM process would have been more optimal for the study.

LIST OF REFERENCES

1. ASTM, *ASTM International F42 committee on Additive Manufacturing Technologies*. 2009.
2. Vayre, B., F. Vignat, and F. Villeneuve, *Designing for Additive Manufacturing*. Procedia CIRP, 2012. **3**: p. 632-637.
3. Terry Wohler, T.G., *History of additive manufacturing*. 2014.
4. Council, C.o.I.E.P.M.N.A.o.E.a.N.R., *Industrial Environmental Performance Metrics: Challenges and Opportunities* (1999). 1999. 264.
5. Iwan Zeina, D.W.H., Kim ChengTan, Swee HinTeoh, *Fused deposition modeling of novel scaffold architectures for tissue engineering applications*. Biomaterials, 2002. **23**(4): p. 1169 - 1185.
6. Pyke, D.F. and M.A. Cohen, *Multiproduct integrated production—distribution systems*. European Journal of Operational Research, 1994. **74**(1): p. 18-49.
7. *Topology Optimization Guide*. 2013; Available from: <http://www.topology-opt.com/2013/03/unmanned-helicopter-optimization/>.
8. Grynol, B., *Disruptive manufacturing The effects of 3D printing*. Deloitte.
9. Thomas, D.S. and S.W. Gilbert, *Costs and Cost Effectiveness of Additive Manufacturing*. 2014.
10. University, L., *ATKINS Project: a low-carbon manufacturing solution*. 2009, Loughborough University.
11. Office, U.S.G.A., *3D printing Opportunities, Challenges, and Policy*. 2015.
12. Wilson, R., *26th Annual "State of Logistics Report®"*. 2015.
13. Huang, S.H., et al., *Additive manufacturing and its societal impact: a literature review*. The International Journal of Advanced Manufacturing Technology, 2012. **67**(5-8): p. 1191-1203.
14. Mokasdar, A.S., *A Quantative Study of Impact of Additive Manufacturing on Aircraft Spare Parts Supply Chain*, in *School of Dynamic Systems of the College of Engineering*. 2012, University of Cincinnati.
15. Khajavi, S.H., J. Partanen, and J. Holmström, *Additive manufacturing in the spare parts supply chain*. Computers in Industry, 2014. **65**(1): p. 50-63.
16. Huang, S.H., et al., *Additive manufacturing and its societal impact: a literature review*. The International Journal of Advanced Manufacturing Technology, 2013: p. 1-13.
17. Mani, M., K.W. Lyons, and S.K. Gupta, *Sustainability Characterization for Additive Manufacturing*. J Res Natl Inst Stand Technol, 2014. **119**: p. 419-28.
18. Chan, F.T.S., *Performance Measurement in a Supply Chain*. 2003.
19. *"3D Printing Market (Technologies, Materials, Applications and Geography) - Global Opportunity Analysis and Forecast-2013-2020"*. 2014 [cited 2016 2/8/2016]; Available from: http://www.researchandmarkets.com/research/9cv6sh/global_3d.
20. Manfred Walter, J.H.a.H.Y., *Rapid manufacturing and its impact on supply chain management*. 2004.

21. Gunasekaran, A., C. Patel, and R.E. McGaughey, *A framework for supply chain performance measurement*. International journal of production economics, 2004. **87**(3): p. 333-347.
22. Gunasekaran, A., C. Patel, and E. Tirtiroglu, *Performance measures and metrics in a supply chain environment*. International journal of operations & production Management, 2001. **21**(1/2): p. 71-87.
23. Wallace J. Hopp, M.L.S., *FACTORY PHYSICS: FOUNDATIONS OF MANUFACTURING MANAGEMENT Second Edition*. Irwin McGraw-Hill. 726.
24. Tuck, C., R. Hague, and N. Burns, *Rapid manufacturing: impact on supply chain methodologies and practice*. International journal of services and operations management, 2006. **3**(1): p. 1-22.
25. Le Bourhis, F., et al., *Sustainable manufacturing: evaluation and modeling of environmental impacts in additive manufacturing*. The International Journal of Advanced Manufacturing Technology, 2013. **69**(9-12): p. 1927-1939.
26. Stewart, G., *Supply chain performance benchmarking study reveals keys to supply chain excellence*. Logistics Information Management, 1995. **8**(2): p. 38-44.
27. Morris, B., *Operations management-Slack, N, Chambers, S, Harland, C, Harrison, A, Johnston, R*. International Journal of Service Industry Management, 1996. **7**(3): p. 63-64.
28. Bhagwat, R. and M.K. Sharma, *Performance measurement of supply chain management: A balanced scorecard approach*. Computers & Industrial Engineering, 2007. **53**(1): p. 43-62.
29. Boone, T., J. Vaidyanathan, and R. Ganeshan, *Sustainable supply chains: models, methods, and public policy implications*. Vol. 174. 2012: Springer Science & Business Media.
30. DAVIDSON, M. *28 Manufacturing Metrics That Actually Matter*. 2013.
31. Gunasekaran, A., *Agile Manufacturing: The 21st Century Competitive Strategy: The 21st Century Competitive Strategy*. 2001: Elsevier.
32. Metrics, N.R.C.C.o.I.E.P., *Industrial Environmental Performance Metrics: Challenges and Opportunities*. 1999: National Academy Press.
33. Shepherd, C. and H. Günter, *Measuring supply chain performance: current research and future directions*, in *Behavioral Operations in Planning and Scheduling*. 2010, Springer. p. 105-121.
34. Sarkis, J. and S. Talluri, *A model for strategic supplier selection*. Journal of supply chain management, 2002. **38**(4): p. 18-28.
35. C. Lindemann*, U.J., M. Moi*, R. Koch*, *Analyzing Product Lifecycle Costs for a Better Understanding of Cost Drivers in Additive Manufacturing*. 2012.
36. Ardeshtir Raihanian Mashhadi, B.E., Sara Behdad, *IMPACT OF ADDITIVE MANUFACTURING ADOPTION ON FUTURE OF SUPPLY CHAINS*. 2015.
37. Hong, Y. and Y. Zhong-Hua, *Supply chain dynamic performance measurement based on BSC and SVM*. 2013.

38. Triantaphyllou, E. and S.H. Mann, *Using the analytic hierarchy process for decision making in engineering applications: some challenges*. International Journal of Industrial Engineering: Applications and Practice, 1995. **2**(1): p. 35-44.
39. Chan, F.T., *Performance measurement in a supply chain*. The international journal of advanced manufacturing technology, 2003. **21**(7): p. 534-548.
40. Gaudenzi, B. and A. Borghesi, *Managing risks in the supply chain using the AHP method*. The International Journal of Logistics Management, 2006. **17**(1): p. 114-136.
41. Sarkis, J., *A strategic decision framework for green supply chain management*. Journal of cleaner production, 2003. **11**(4): p. 397-409.
42. Wong, J.K. and H. Li, *Application of the analytic hierarchy process (AHP) in multi-criteria analysis of the selection of intelligent building systems*. Building and Environment, 2008. **43**(1): p. 108-125.
43. Joe Hiemenz, S., Inc., *3D PRINTING WITH FDM*.
44. Hauser, J. and G. Katz, *Metrics: you are what you measure!* European Management Journal, 1998. **16**(5): p. 517-528.
45. Saaty, T.L. and M.S. Özdemir, *How Many Judges Should There Be in a Group ?* Annals of Data Science, 2015. **1**(3-4): p. 359-368.
46. Tahriri, F., et al., *AHP approach for supplier evaluation and selection in a steel manufacturing company*. Journal of Industrial Engineering and Management, 2008. **1**(2): p. 54-76.
47. Vaidya, O.S. and S. Kumar, *Analytic hierarchy process: An overview of applications*. European Journal of operational research, 2006. **169**(1): p. 1-29.
48. Saaty, T., *Ahp: The analytic hierarchy process*. 1980, McGraw-Hill.
49. Tramarico, C.L., V.A.P. Salomon, and F.A.S. Marins, *Analytic Hierarchy Process and Supply Chain Management: A Bibliometric Study*. Procedia Computer Science, 2015. **55**: p. 441-450.
50. Dong, Y., et al., *Consensus models for AHP group decision making under row geometric mean prioritization method*. Decision Support Systems, 2010. **49**(3): p. 281-289.
51. Gao, Y., et al., *Solution to gang crime based on Graph Theory and Analytical Hierarchy Process*. Neurocomputing, 2014. **140**: p. 121-127.
52. Amini, M., *TIME ESTIMATION FOR ADDITIVE MANUFACTURING*. 2014.
53. Manfred Schmid*, G.L., *Quality Management and Estimation of Quality Costs for Additive Manufacturing with SLS*. EU project 'DirectSpare'.
54. Holmström, J., et al., *Rapid manufacturing in the spare parts supply chain: alternative approaches to capacity deployment*. Journal of Manufacturing Technology Management, 2010. **21**(6): p. 687-697.

APPENDIX

Which one of the manufacturing systems would have a better "Rate of return on investment" ?

- ☐ Additive Manufacturing
- ☐ Traditional Manufacturing

	Extremely strong	Very Strong	Strong	Moderately	Equally	Moderately	Strong	Very Strong	Extremely strong	
	☐	☐	☐	☐	☐	☐	☐	☐	☐	
Rate of return on investment	☐	☐	☐	☐	☐	☐	☐	☐	☐	Manufacturing cost as percentage of revenue
Rate of return on investment	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total Manufacturing cost per unit excluding materials
Rate of return on investment	☐	☐	☐	☐	☐	☐	☐	☐	☐	Cost per operation hour
Manufacturing cost as percentage of revenue	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total Manufacturing cost per unit excluding materials
Manufacturing cost as percentage of revenue	☐	☐	☐	☐	☐	☐	☐	☐	☐	Cost per operation hour
Total Manufacturing cost per unit excluding materials	☐	☐	☐	☐	☐	☐	☐	☐	☐	Cost per operation hour

**Display This Question:**

If Which one of the manufacturing systems would have a better "Rate of return on investment" ? **Traditional Manufacturing** Is Selected [Edit](#)

Please select the intensity of importance

- ☐ TM would have the same "Rate of return on investment" as AM
- ☐ TM would have a Moderate "Rate of return on investment" over AM
- ☐ TM would have a Strong "Rate of return on investment" over AM
- ☐ TM would have a Very strong "Rate of return on investment" over AM
- ☐ TM would have an Extremely strong "Rate of return on investment" over AM

Recode Values☒ Recode Values☐ Variable Naming

- | | |
|---|--|
| 1 | AM would have the same "Rate of return on investment" as TM |
| 3 | AM would have a Moderate "Rate of return on investment" over TM |
| 5 | AM would have a Strong "Rate of return on investment" over TM |
| 7 | AM would have a Very strong "Rate of return on investment" over TM |
| 9 | AM would have an Extremely strong "Rate of return on investment" over TM |

VITA

Abhishek Chimalapati was born in India. He graduated in 2009 with bachelor's degree in Mechanical Engineering. After working in the automotive industry for 3 years he joined The University of Tennessee as a Graduate Student in Industrial Engineering under Dr. Rupy Sawhney.