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Additive Manufacturing Cost Minimization Techniques: Successes, Challenges and Future Growth in Supply Chain Management

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ABSTRACT: The competiveness in manufacturing, coupled with the need to reduce cost and manufacture of smaller or fewer, sometimes complex components has accelerated the growth of additive manufacturing in recent years. However,there is need to determine how the cost in additive manufacturing can be brought down. This research provides an updated estimate of the value of goods produced. It then provides the instances where this technology is effective through economies of scale. The research further provides approaches for examining and testing the cost models and benefits of the technology from monetary view and resource consumption view point. It therefore shows that additive manufacturing can be cost effective system in supply chain management.

KEYWORDS: Additive, manufacturing, cost, supply chain, management, minimisation.

1 INTRODUCTION

Traditional manufacturing (TM) processes falls into two main categories namely formative (injection moulding, die casting etc.) and subtractive (milling, grinding, CNC machining etc.) have dominated manufacturing activities in supply chain for decades. Manufacturers deploying these processes rely on scale economies because of the use of expensive dedicated production tools for the fabrication of identical parts, which constrains them to large batches to amortize the cost of tooling investment. This usually results in high physical and market mediating costs along the supply chain, especially in instances of uncertain demand such as gears. Further, scale-economies inhibit the mobility of production facilities because of capacity utilization constraints [1].

The complexity of products in terms of number of parts and modules increases the layers of production in the supply chain presenting co-ordination challenges for assembly operations. Altogether these factors increase the geographical dispersion of production activities and ultimately, the distance from market locations, resulting in extended delivery lead-times and inefficiencies related to demand forecasting and capacity scheduling. This creates a major problem for manufacturers dealing with a large variety of products. In essence the structural characteristics of traditional manufacturing supply chains namely economies of scale, dispersed nature of multiple manufacturing stages and distance from market locations poses a challenge for supply chain management especially in terms of cost efficiency and responsiveness [2]. These are problems that additive manufacturing offers solutions to. In 2013, the world produced approximately $11.8 trillion in manufacturing value added, according to United Nations Statistics Division (UNSD) data, however implementation levels are significantly lower than traditional manufacturing (TM) counterparts due to factors such as The associated starting costs and slow print [2].

Speed of additive manufacturing systems often hinder this technology from being used for mass production [3], however, as these issues improve this technology may change the way that consumers interact with producers. Additive manufacturing (AM) allows the manufacture of customized and increasingly complex parts. This customization of products will require increased data collection from the end user to determine their preferences, resulting in a new relationship between manufacturer and consumer. Previous research work has predicted significant impacts to supply chain (SC) structures, however implications are far from being understood. This research conceptualizes the potential impacts of cost management of additive manufacturing on the supply chain structure.

The introduction of Robots, Artificial Intelligence (AI) Machines, Computer Numerical Control (CNC) Machines, and other flexible machines were aimed at achieving cost minimization on a traditional supply chain structure. Sadly, these machines alone did not achieve the desired results, but with the introduction of Three Dimension (3D) printing or additive manufacturing, the manufacturing landscape in terms of cost minimization has drastically changed for the better, though this technology also has its own inherent problems which this study seeks to find solutions to, especially when integrated into the already existing supply chain structure. The problems encountered by this technology are:

(i) Associated costs and slow print speed of additive manufacturing systems which often hinder this technology from being used for mass production; however, as these issues improve, the technology may change the way that consumers interact with producers.

(ii) Additive manufacturing allows the manufacture of customized and increasingly complex parts. This customization of products creates a serious problem of increasing data collection from the end user to determine their preferences, resulting in a new relationship between manufacturer and consumer [4].

All over the world, there is an estimated $667 million in value added manufactured using additive manufacturing, which is equivalent to 0.01 % of total global manufacturing value added. US alone, the value added is estimated as $241 million. Present research on additive manufacturing costs reveals that it is cost effective for producing small batches with continued centralized production; however, with increased automation distributed production may become cost effective [2]. Because of complexities of quantifying additive manufacturing costs and data limitations, present studies are limited in their scope. Many of the present studies examine the production of single parts and those that examine assemblies tend not to examine supply chain effects such as inventory and transportation costs along with decreased risk to supply disruption. The additive manufacturing system and the material costs constitute a significant portion of an additive manufactured product; however, these costs are reducing over time. The current trends in costs and benefits have resulted in this technology representing 0.02 % of the relevant manufacturing industries in the US[2]. However, as the costs of additive manufacturing systems reduce, this technology may become widely accepted and change the supplier, manufacturer, and consumer interactions [2]. An examination in the application of additive manufacturing reveals that for this technology to surpass $16.0 billion in 2025, and $196.8 billion in 2035 it would need to deviate from its current trends of application [5].

Therefore, there is need to seek and review an additive manufacturing costs and identifies those instances in the literature where this technology is more cost effective, develop a cost minimization model for additive manufacturing, develop a structure that will optimize it application for mass production, design, produce and test a product by applying cost minimization model and structures which will optimize mass production and show the trends on the adoption of additive manufacturing to enhance efficiency in supply chain structure.

The presence of expensive dedicated tools constrains manufacturers to large batches to amortize the cost of tooling investment[3]. Furthermore, the complicated nature of traditional manufacturing machine tools creates challenges for non-specialists [6]. By making fabrication of small batches of parts economical and removing the complications of operating traditional manufacturing machines, additive manufacturing potentially enables the participation of supply chain entities further downstream, which do not possess the scale of low-cost suppliers, to vertically integrate the production of parts in-house, albeit with the potential for lower capacity utilization. That said, capacity utilization can be enhanced with additive manufacturing's capability known as "Fungibility", which enables part substitution whereby identical and non-identical parts can beproduced in one build[7]. Further, non-specialized part suppliers can boost additive manufacturing capacity utilization by providing commoditized services to external customers[8]. In the spare parts supply chain, low demand volumes may weaken the bargaining power of the products, serving as an additional incentive to deploy additive manufacturing capacity in-house, especially where supply options are limited. On the other hand, additive manufacturing could also decrease the dependence of small specialized suppliers on particular customers, due to elimination of large-scale investments in costly production runs tailored to one buyer, for traditional manufacturing processes. With all these considerations, the producers must also consider when to switch back to traditional manufacturing to leverage the economies of scale of specialized suppliers at higher volumes, however the feasibility of part redesign also has to be considered [9]. For specialized suppliers heavily invested in traditional manufacturing, established markets may control its resources against investments in additive manufacturing, especially when demand for additive manufacturing parts is not significant . Capacity utilization is highly dependent on the number of parts that can be digitally manufactured [10]. Further, additive manufacturing capacity utilization decreases with decreasing distances of production facilities to market locations in the order of centralized configuration with the highest capacity utilization potential, hub configuration with an intermediate level and distributed with the lowest level and least economical[4]. Additionally, the distributed configuration for additive manufacturing has been criticized as being infeasible because of dependence on scale economies from skilled operators and sophisticated equipment to produce durable parts. Localization of additive manufacturing capacity depends on an established customer base and a sound understanding of market demand and near net-shape production quality of parts. Requirements of post processing (e.g. heat treatment, support removal) and supporting traditional manufacturing technology, such as CNC, restrict the scope to localize additive manufacturing capacity because they operate with economies of scale [11].

1.1 Material Flow Within and Between Key Unit Operations

For specialized traditional manufacturing part suppliers, additive manufacturing could be deployed to improve process efficiency in that parts with low and sporadic volume can be allocated to additive manufacturing, thereby reducing setup and changeover on traditional manufacturing production lines [1]. This type of process configuration is reported by [12]. This will be particularly suitable to firms using jobbing or batching processes where additive manufacturing is expected to be effective in reducing the number of traditional manufacturing steps, eliminating scrap, material movement, work-in-process inventories and defects – process savings [13]. For example process-savings have been achieved for a filter manufacturer[14].

The traditional manufacturing process involved two machining operations, before finishing, testing and packaging and parts were made-to-stock. With additive manufacturing, barring design activities with the customer, the actual production process was the printing operation and parts were made to order, effectively reducing work in progress (WIP) and finished goods inventory.

Economic fabrication of smaller batches could potentially enable postponement and localization of production and creation of variety at the point of use effectively shifting the order decoupling point to the customer's location, thereby enabling responsiveness [7]. This is an added incentive for supply chain entities, without the scale of specialized suppliers, to deploy the technology for the fabrication of a variety of parts for their production lines. For original equipment manufacturers (OEMs), fabrication of parts formerly handled by external suppliers can be localized within assembly plants and spare parts production can be redistributed closer to customer, material handling and transportation costs. Further these assemblers deploying additive manufacturing on the shop floor could also eliminate just-in-time co-ordination efforts from suppliers, significantly reducing transportation costs in the long run [9]. However, the speed and throughput of the additive manufacturing processes must be assessed in relation to demand rates as studies show that the throughput of additive manufacturing systems are significantly lower than traditional manufacturing[13].

1.2 Information Flow and Relationship between Key Partners

By shrinking the supply chain distance and fabricating parts at the point of use, additive manufacturing could potentially reduce the errors associated with demand planning and forecasting as the number of supply chain entities involved is reduced. This also leads to increased levels of collaboration between supply chain entities, especially in terms of knowledge dependency for design activities between producers and additive manufacturing suppliers [15]Further, the removal of intermediaries in the supply chain with electronic commerce solutions for additive manufacturing is also expected to create better demand visibility, which in turn aids capacity optimization and production planning. The customer also increasingly becomes a stronger member of the supply chain in relation to its suppliers through co-creation, as such the relationship link becomes stronger. Also, shifting production closer to point of use also enables improved decision making based on more accurate information from local conditions [16].

1.3 Value Structure of Product

The success of implementing additive manufacturing for postponement in manufacturing and service supply chains depends on reengineering existing traditional manufacturing parts, new products for additive manufacturing and alignment with supply chain design. Traditional manufacturing is governed by design for manufacturing (DFM) rules which places constraints on designs because of manufacturability requirements determined by the degrees-of-freedom in the manufacturing process. Increasing complexities of part design also causes corresponding increases inproduction process costs for traditional manufacturing (e.g. CNC machines) as more axes in machines must be built in to accommodate complex design patterns. Products are usually divided up into modules, with a trade-off on performance, forming the basis of supplier selections based on parts and modules with similar materials. These parts and modules, produced by different suppliers, are assembled in the manufacturing plant, requiring a high degree of supply chain integration so that products are delivered in the right quantities at the right times. Product structures with a large number of materials tend to have complicated supply chain structures with many tiers that cross organizational and national boundaries, increasing co-ordination requirements such as just in time, lean manufacturing and advance shipment notices [17].

Further, various stages of the supply chains of multinational corporations have been outsourced to more cost effective locations in emerging and developing economies, effectively increasing the dispersion of key operations and requirements for co-ordination and transportation. Additive manufacturing breaks barriers between integral and modular architectures to enhance production efficiency, however coupled with post-processing issues [18] Parts consolidation is recognized as one of the most significant capabilities of additive manufacturing [19]. It reduces the part count, which essentially reduces the number of value adding activities within and between unit operations in a supply chain, effectively shortening process chains, reducing lead time [20]**.** A notable example in the aerospace industry is that of the fuel nozzle produced by General Electric (GE) aviation where the part count was reduced from 18 to 1. The impact of parts consolidation on the structure of the supply chain is expected to be significant, however the extent depends on the

level of the product at which consolidation is achieved in the overall product structure (i.e. component, subassembly, final assembly) and also the supply chain entity that deploys the additive manufacturing technology.

At the level of part consisting of smaller components within the boundaries of a module, possibly of the same material and fabricated in the same processing plant, the effect of parts consolidation is confined to a process saving, reducing the number of manufacturing and assembly operations to fabricate a part. For hearing aid shell fabrication, manual traditional manufacturing production steps namely sculpting, molding, and curing are compressed into two steps with additive manufacturing namely printing and grinding [4]. For the specialized supplier, who deploys additive manufacturing in-house, the impact of this process-saving is likely to be evident and more significant as they perform job-shop operations in-house [13]. For the component assembler, vertically integrating the production of a part with additive manufacturing in-house, it is likely to be a supply chain saving in terms of reducing coordination efforts with specialized suppliers and transportation costs. At the level of the module, containing a number of parts (with similar or different materials) from different suppliers, additive manufacturing is likely to bring a process saving for the component assembler in that a lot of steps associated with traditional assembly operations will be eliminated. There will also be a supply chain saving from elimination of the co- ordination efforts and transportation costs from sourcing parts from external specialized suppliers, a similar benefit for the final assembler. At the level of the final assembly, involving several modules, additive manufacturing is likely to bring a process saving for the final assembler in that hitherto traditional manufacturing assembly operations involving several steps can be reduced with additive manufacturing fabricating complex products with different types of materials. Similar to the benefits from the module assembler, a supply chain saving is also expected. The level of sophistication of the additive manufacturing process must be on a higher level in terms of its ability to process a higher number of materials than the level of the module. This will effectively collapse the tier structure of traditional supply chains reducing the production of complex products to significantly fewer stages. This has also been referred to as the supercenter capable of producing an array of low-volume products, containing no asset specificity and, in theory, zero change-over costs [1].

1.4 Traditional Manufacturing Supply Chain Configurations

Some studies have investigated the structural characteristics of traditional manufacturing supply chains, with respect to competitive priorities such as efficiency and responsiveness. Such studies are rooted in the theory of configuration with the thesis of alignment between elements of market strategy and elements of organizational structure, postulated by Alfred Chandler [3]. Research in this area focuses on developing typologies and taxonomies that map elements of organizational strategy to elements of organizational structure. This is based on the fundamental assumption that elements of strategy, structure and environment often converge into a tractable number of common, predictively useful archetypes that describe a significant proportion of high-performing firms [21]. From an operations perspective, the elements of strategy correspond to the competitive priorities recognized as critical to a firm’s success in the market place; the elements of environment correspond to the characteristics of the markets that a firm operates in and the elements of structure correspond to the operations resources, within and beyond the boundaries of a firm in a supply chain.

Fisher’s seminal work created a strategy-structure typology for traditional manufacturing supply chains based on the demand characteristics of functional and innovative products. For example, Innovative product supply chains focus on responsiveness because of unpredictable demand, short lifecycles and high profit margins, by deploying inventory and capacity buffers in the supply chain [22]. A typology combining, lean and agile philosophies were developed, employing lean principles such as waste elimination upstream of the supply chain, and agile strategies downstream by decouplinginventories [23]**.**Fisher’s work was extended to include supply-side uncertainties, creating four typologies with similar objectives. The level of stock holding centralization and transportation modes required for products based on Product-Value-Density (PVD) and throughput [21]. Fisher’s model was also extended to include Replenishment Lead Time (RLT), creating four typologies [24]. Collectively, these studies highlight the critical structural supply chain dimensions with respect to the most cited competitive priorities, efficiency and responsiveness, accounting for contextual elements such as product demand and supply characteristics. These structural dimensions have been consolidated by researchers under five headings namely: Supply chain structure, Material and information flow between and within key unit operations, the role, inter-relationships and governance between key network partners and value structure of product or service. These structural supply chain dimensions are expected to be significantly affected by the deployment of additive manufacturing in manufacturing and service operations, however the nature of this impact is not yet fully understood [25].

1.5 Capabilities of Additive Manufacturing

The technical capabilities of additive manufacturing for the fabrication of end-use parts are well known in literature with empirical examples. For instance, production of complex geometries for lattice and honeycomb structures, internal cooling channels, overall serving to produce lightweight components that are critical in sectors such as aerospace and automotive. Consolidation of several parts in an assembly into one also reduces part failure rate because of fewer number of potential failure points in joints. On the other hand, there are non-technical or operational capabilities of additive manufacturing that have mostly been captured by the conceptual literature. The most fundamental of such capabilities is tool elimination, which makes it possible for the economical production of parts in smaller batches, potentially enabling the distribution of production capacity close to customer locations, reducing lead-time. Secondly, the additive layer process reduces waste in comparison to subtractive traditional manufacturing processes and raw materials are recyclable, which improves the efficiency of materials management. Thirdly, the on-demand capability of additive manufacturing means that less capital is tied up in inventory, thereby freeing up workingcapital for other aspects of the operation [26]. Also, inventory obsolescence and part shortages could potentially be reduced [27]. Lastly, the capability of additive manufacturing to combine multiple assembly components into one build operation, known as functional integration or parts consolidation, reduces the burden of changeovers and setups, number of machinists, part count and handling, potentially creating shorter production lead times. These capabilities and benefits are being exploited, to varying degrees, in manufacturing and service supply chains and have reawakened the old question of manufacturing process choice, in this case traditional manufacturing or additive manufacturing, for the production of parts and modules

The manufacturing process represents a primary structural element that determines the characteristics of other secondary elements in a supply chain. Recent approaches to the manufacturing process choice problem have adopted a narrow perspective, focusing solely on costs and ignoring implications for structural dimensions, a similar problem in past approaches to the make-or-buy question[28]. There have been recent calls for more holistic approaches to evaluate the question of whether to use traditional manufacturing or additive manufacturing and the impact of that decision on supply chain management.

1.6 Additive Manufacturing Cost

There are two major important categories for examining additive manufacturing costs.The first is to compare additive manufacturing processes to other traditional processes such as injection molding and machining [2]. The purpose of these types of examinations is to determine under what circumstances additive manufacturing is cost effective. The second category involves identifying resource use at various steps in the additive manufacturing process. The purpose of this type of analysis is to identify when and where resources are being consumed and whether there can be a reduction in resources use [2].

1.7 Additive Manufacturing Processes and Materials

There are a number of additive manufacturing processes; however, at first glance it may appear that there are more types than in actuality. Many companies have created unique system and material names in order to differentiate themselves, which has created some confusion. Fortunately, there has been some effort to categorize the processes and materials using standard methods. The categorization and descriptions of processes and materials below relies heavily on [29] and ASTM International Standards.

The total global revenue from additive manufacturing system sales was $502.5 million with U.S. revenue estimated at $323.6 million. These systems are categorized into various different processes. ASTM International Committee F42.91 on Additive Manufacturing Technologies has developed standard terminologies. Provided below arethe categories and adapted definitions from the ASTM F2792 standard[29]:

(i) Binder Jetting: This process uses liquid bonding agent deposited using an inkjet-printhead to join powder materials in a powder bed.

(ii) Directed Energy Deposition: This process utilizes thermal energy, typically from a laser,to fuse materials by melting them as they are deposited.

(iii) Material Extrusion: These machines push material, typically a thermoplastic filament,through a nozzle onto a platform that moves in horizontal and vertical directions.

(iv) Material Jetting: This process, typically, utilizes a moving inkjet-print head to depositmaterial across a build area.

(v) Powder Bed Fusion: This process uses thermal energy from a laser or electron beam to
selectively fuse powder in a powder bed.

(vi) Sheet Lamination: This process uses sheets of material bonded to form a 3D
object.

(vii) Vat Photopolymerization: These machines cure a liquid photopolymer in a vatusing
light

Approximately $327.1 million was spent globally on materials for additive manufacturing in 2011 [30]. There are two primary types of materials: plastics and metals. There are also ceramics, composites, and other materials that are used as well, but are not as common. Wohlers groups the materials into eight categories:

a) Polymers and polymer blends Composites b) Metals Graded/hybrid metals Ceramics

c) Investment casting patterns Sand molds and cores Paper

Certain processes lend themselves to certain materials. Table 2.4 presents the combinations of additive manufacturing processes and their corresponding materials. Thecombinations that are left blank are material/process combinations that are not currently utilizing [30].

1.8 Existing Cost Model on Traditional Supply Chain Structures

As discussed by[8], the costs of production can be categorized in two ways.The first involves those costs that are "well-structured" such as labour, material, and machine costs. The second involves "ill-structured costs" such as those associated with build failure, machine setup, and inventory, however, some of the more significant benefits and cost savings in additive manufacturing may be hidden in the ill-structured costs, and that is where this research work will place more attention to, moreover, considering additive manufacturing in the context of lean production might be useful

Many costs are hidden in the supply chain, which is a system that moves products from supplier to customer. Additive manufacturing may, potentially, have significant impactson the design and size of this system, reducing its associated costs.

Inventory: At the beginning of 2011, there were $537 billion in inventories in the manufacturing industry, which was equal to 10 % of that year's revenue [15].. At Transcorp power limited in Ughelli, Gas Turbine parts are infrequently ordered during maintenance procedure; however, when a part is ordered, it is needed quite rapidly, as idle Turbine waiting for parts is quite costly. Being able to produce these parts on demand using additive manufacturing reduces the need for maintaining large inventory and eliminates the associated costs. . The parts are shipped to a facility where they are assembled into a product.

Three alternatives have been proposed for the diffusion of additive manufacturing.The first is where the consumer use it for 3D printing.The second is a copy shop scenario, where individuals submit their designs to a service provider that produces goods. The thirdscenario involves additive manufacturing being adopted by the commercial manufacturing industry, changing the technology of design and production [15].

But in this research, we consider a fourth scenario. Because additive manufacturing can produce a final product in one build, there is limited exposure to hazardous conditions, and there is little hazardous waste, there is the potential to bring production closer to the consumer. For example, currently, at GT 18 in Delta IV combustion inspection was postponed due to delay in shipment of combustion chamber inner liner which may take multiple days to be delivered .The supply chain includes purchasing, operations, distribution and integration. Reducing the need for these activities can result in a reduction in costs. Transcorp Power Limited, for example, cut links in the supply chain, making the link between their stores and the manufacturers more direct. Additive manufacturing may reduce the need for supply chain management by bringing manufacturers closer to consumers, reducing the links in the supply If additive manufacturing reduces the number of links in the supply chain and brings production closer to consumers, it will result in a reduction in the vulnerability to disasters and disruptions. if production is brought closer to consumer sit will result in more decentralized production where many facilities are producing a few products rather than a few facilities producing many products.

Figure 1 shows an example of Traditional Manufacturing flow. Figure 2 provides an example that compares traditional manufacturing to additive manufacturing supply chains. Under traditional manufacturing, material resource providers deliver to the manufacturers of parts and components, who might deliver parts and components to each other and then to an assembly plant. From there the assembled product is delivered to a retailer or distributer**.** Additive manufacturing with localized production does not have the same vulnerability. First, there may not be any assembly of parts or components.Secondly, a disruption to manufacturing does not impact all of the retailers and distributors [31].

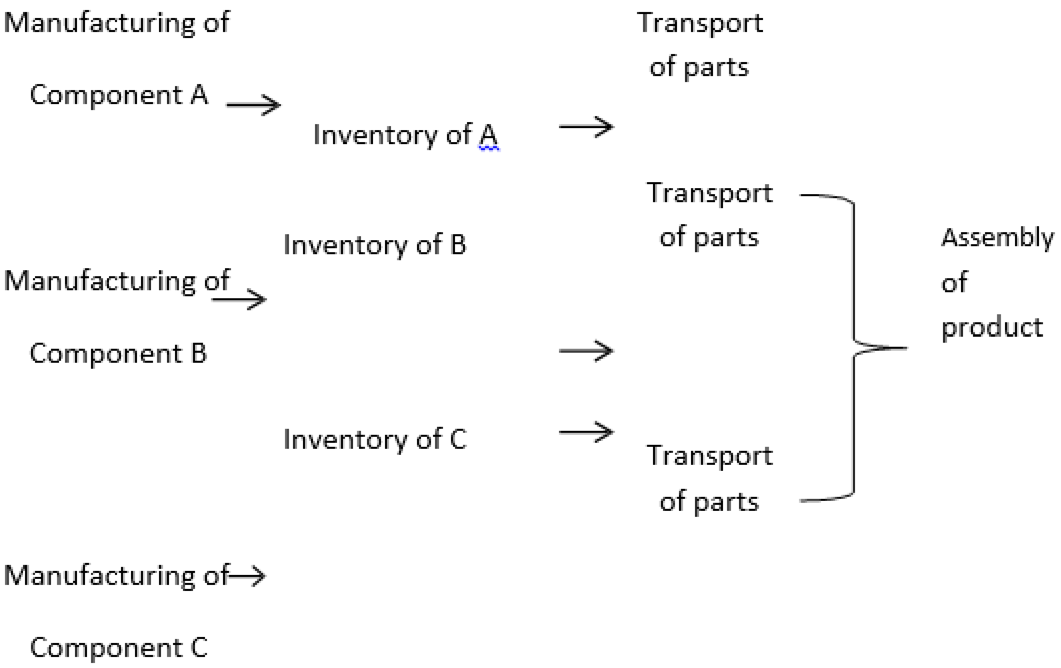


Figure 2 shows the traditional supply chain compared to the supply chain of additive manufacturing with localized production.

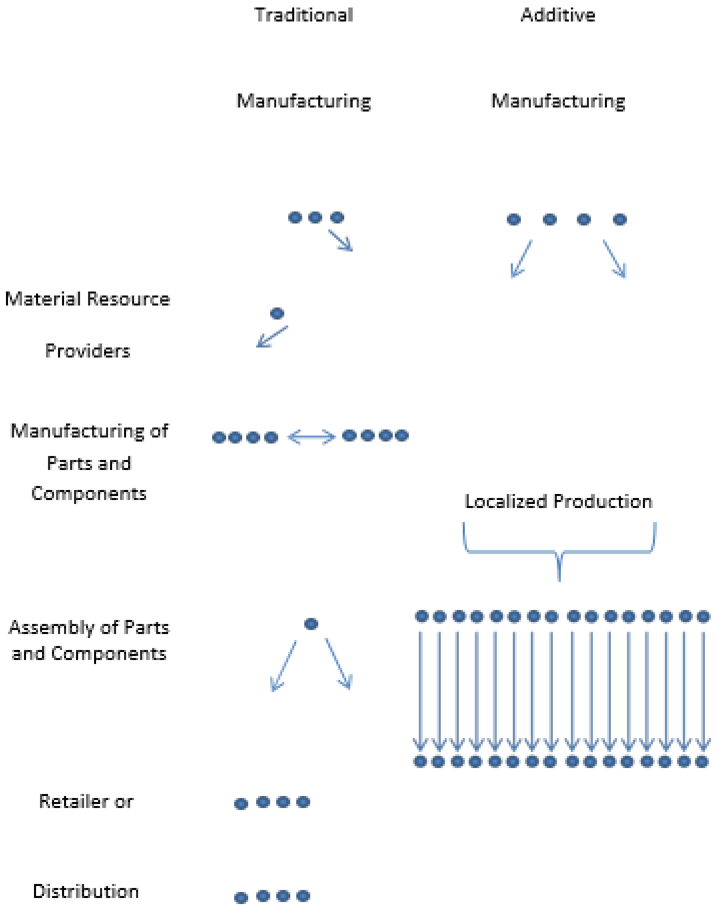


Figure2 : Traditional supply chain compared to the supply chain of additive manufacturing with localized production [31]

Well-structured costs as earlier mention comprises the cost of materials (plastics, metals and composites) [32], build time, energy consumption (the price of gas consumption/hr), build envelope and envelope utilization and labour and manpower [33]. These well-structured costs are embedded in traditional manufacturing method, but if additive manufacturing into the supply chain structure, it will cut down significantly or eliminate some of this avoidable costs especially the cost of labour**.**

In addition to material costs, machine cost is one of the most significant costs involved inadditive manufacturing. The average selling price of an industrial additive manufacturingsystem was $73 220 in 2011. Although the price is up from $62 570 in 2010, the price has fallen for most years prior to this point. Between 2001 and 2011, the price decreased 51 % after adjusting for inflation [34].

For metal material cost studies by[34], showed that machine costs ranged from 23 % to 75 % of a metal part. The cost difference between the different types of additive manufacturing machinery was quite significant ranging between $0.1 million typically for polymer systems and $1.0 million typically for metal system

1.9 Product Enhancements and Quality

Although the focus of this report is the costs of additive manufacturing, it is important to note that there are product enhancements and quality differences due to using this technology. There is more geometric freedom with additive manufacturing and it creates more flexibility; however, there are limitations, as some designs require support structures and means for dissipating heat in production. Complexity does not increase the cost of production as it does with traditional methods. However, there is a need for standard methods to evaluate and ensure accuracy, surface finish, and feature detail to achieve desired part quality [35].

The objective of this research is to investigate the efficiency of additive manufacturing as a cost minimization technique in supply chain management

This research seeks to improve on the use of this technology by examining the costs and benefits of additive manufacturing. It identifies areas where it maintains a cost advantage over traditional manufacturing techniques in a supply chain structure using spur gear as a case study. It further identifies trends and models of implementing and adopting additive manufacturing technology to enhance efficiency in supply chain structures

2.0 MATERIALS AND METHODS

To address the criticism associated with the narrow cost perspective on manufacturing process, this research adopts the holistic framework, developed for the make-or-buy decision for the traditional manufacturing vs additive manufacturing decisions. The interaction of external and internal elements (elements of environment) activates performance-related triggers for the traditional manufacturing vs additive manufacturing decision. For example, supply risk of legacy parts like gears and batch manufacturing constraints with traditional manufacturing results in high- inventory holding costs thereby increasing inefficiencies in the supply chains. This increased inefficiency triggers the comparison between traditional manufacturing and additive manufacturing decision because of the capabilities of additive manufacturing to reduce inventory holding via tool elimination

2.1 Research Materials and Methods

The methods used for this research work are as follows;

(i) Designing of a spur gear product to illustrate a simple product manufacturing

(ii) Applying a cost reduction model on the designed gear product from additive manufacturing process.

(iii) Applying a structure for mass production of the product using additive manufacturing

2.2 Design Analysis of Spur Gear

The analysis was done using spur gear as a case study and compared with the cost of manufacturing the product for both the traditional manufacturing processes and additive manufacturing processes on existing supply chain structure. Figure 3 is the a diagrammatic representation of a spur gear.

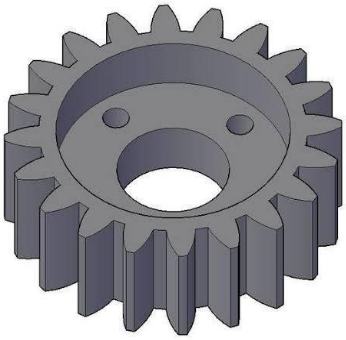


Figure 3: A Diagrammatic representation of a spur gear

2.2.1 Design of the spur gear

For the gears to mesh together, there is a need for the wheels to have the same circular pitch which is denoted on the Equation 1.

$$P_c = \frac{\pi D}{T}$$ Equation 1

where

D is the diameter of the pitch circle

T is the number of teeth on the gear

Figure 4 shows the parameters of the spur gear pair having normal straight teeth.

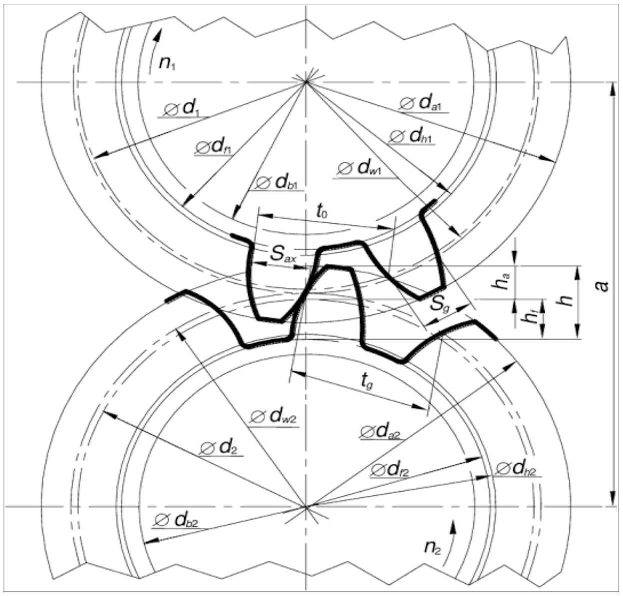


Figure 4: **The parameters of the spur gear pair having normal straight teeth**

2.2.2 Diametral Pitch Analysis

The diametrical pitch is given by:

$$P = \frac{T}{D}$$ Equation 2

T is the number of teeth, and, D is the pitch circle diameter.

2.2.3 Module Design

Here, the pitch circle diameter ratio against the number of teeth denoted by m is:

Module, $m = \frac{T}{D}$ Equation 3

Therefore the number of teeth on the gear, T is given in Equation 4

$$T = \frac{D}{m}$$ Equation 4

2.2.4 Design Considerations for a Gear Drive

In the design of a gear drive, the following data were considered:
(i) The power to be transmitted.
(ii)The speed of the driving gear,
(iii) The speed of the driven gear or the velocity ratio, and
(iv) The centre distance.

2.2.5 Design Procedure for Spur Gears

Figure 5 shows the load and stress analysis on spur gear.

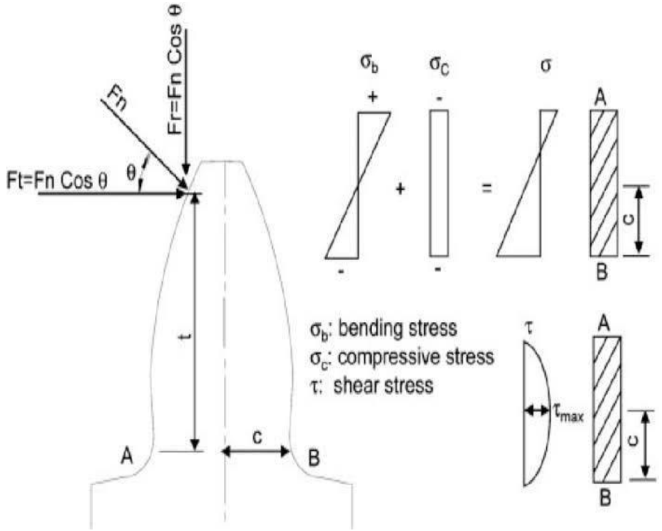


Figure 5: Load and stress analysis on spur gear

(i) Design tangential tooth load: This is obtained from the power transmitted and the pitch line velocity by using the following relation.

$$W_T = \frac{P}{v} C_s$$ Equation 5

where

W_T is the Permissible tangential tooth load in Newtons,

P is the Power transmitted in watts,
*v is the Pitch line velocity in m / s

Pitch line velocity, $v = \frac{\pi D N}{60}$

Figure 6 shows the Maximum tooth loading

Equation 6

D is the Pitch circle diameter in metres, N is the Speed in r.p.m

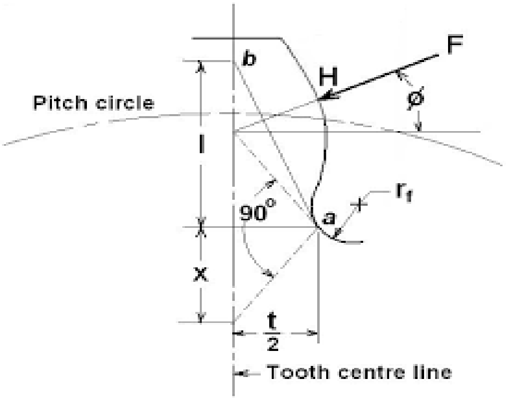


Figure 6: Maximum tooth loading

2. Apply the Lewis Equationfor the weaker wheel (the pinion) since the pinion and the gear are made of the same material.

$$W_T = \sigma_w b p_c y = \sigma_w b \pi m y$$ Equation 7

But $\sigma_w = \sigma_\circ C_v$

Therefore $W_T = \sigma_y C_v b \pi m y$ Equation 8

Figure 7 shows the tooth of a gear.

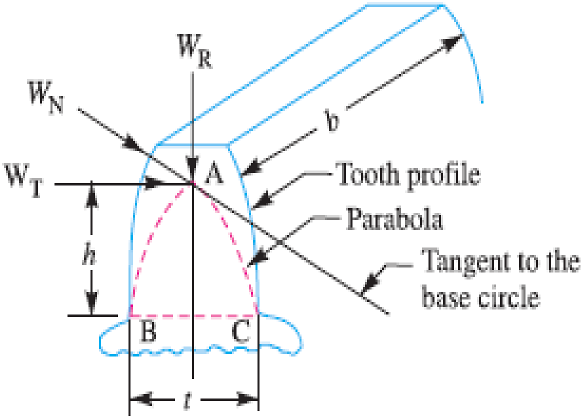


Figure 7: Tooth of a gear

where;

M is the max bending moment at section BC = Wt. l

W_T is the Tangential force acting on gear tooth

l is the Length of tooth

y is the Half the thickness of the tooth t is the Thickness of tooth ,section at b is the Face width of the gear tooth

I is the moment of inertia about the centre line of the tooth,

$I = bt^3 / 12$ Equation 9

Max. bending stress at pt. B

3. Calculating the dynamic load W_D on the tooth by using Buckingham Equation.

$$W_D = W_T + W_t \quad \text{Equation 10}$$

$$W_D = W_T + W_t = W_T + \frac{21v(bC + W_T)}{21v + \sqrt{bC + W_T}} \quad \text{Equation 11}$$

In calculating the dynamic load , the value of tangential load may be calculated by neglecting the service factor

i.e. W_D = P / v Equation 12

where

P is in watts and v in m / s.

4. Calculating for the static tooth load
using the Equation below;

$$W_T = \sigma_e b p_c y = \sigma_e b \pi m y \quad \text{Equation 13}$$

To prevent breakage, W_s should be greater than W_D.

5. The wear tooth load was calculated using the Equation below;

$$W_w = D_p b Q K \quad \text{Equation 14}$$

where

W_w is the maximum or limiting load for wear in Newtons

D_p is pitch circle diameter of the pinion in mm

b is the face width of the pinion in mm

Q is ratio factor

The wear load W_w should not be less than the dynamic load W_D

2.2.6 Systems of Gear Teeth

The 14 1/2° Composite system of gear teeth was used in practice.

Table 1descibes the gear proportion.

Table 1: Standard proportions of gear systems.

S/NO	Particulars	Composite System (m)
1	Addendum	14.5
2	Dedendum	1.25
3	Working Depth	2.0
4	Maximum tooth depth	2.25
5	Minimum Total depth	1.5708
6	Minimum clearance	0.25
7	Fillet radius	0.4

2.2.7 Gear Materials

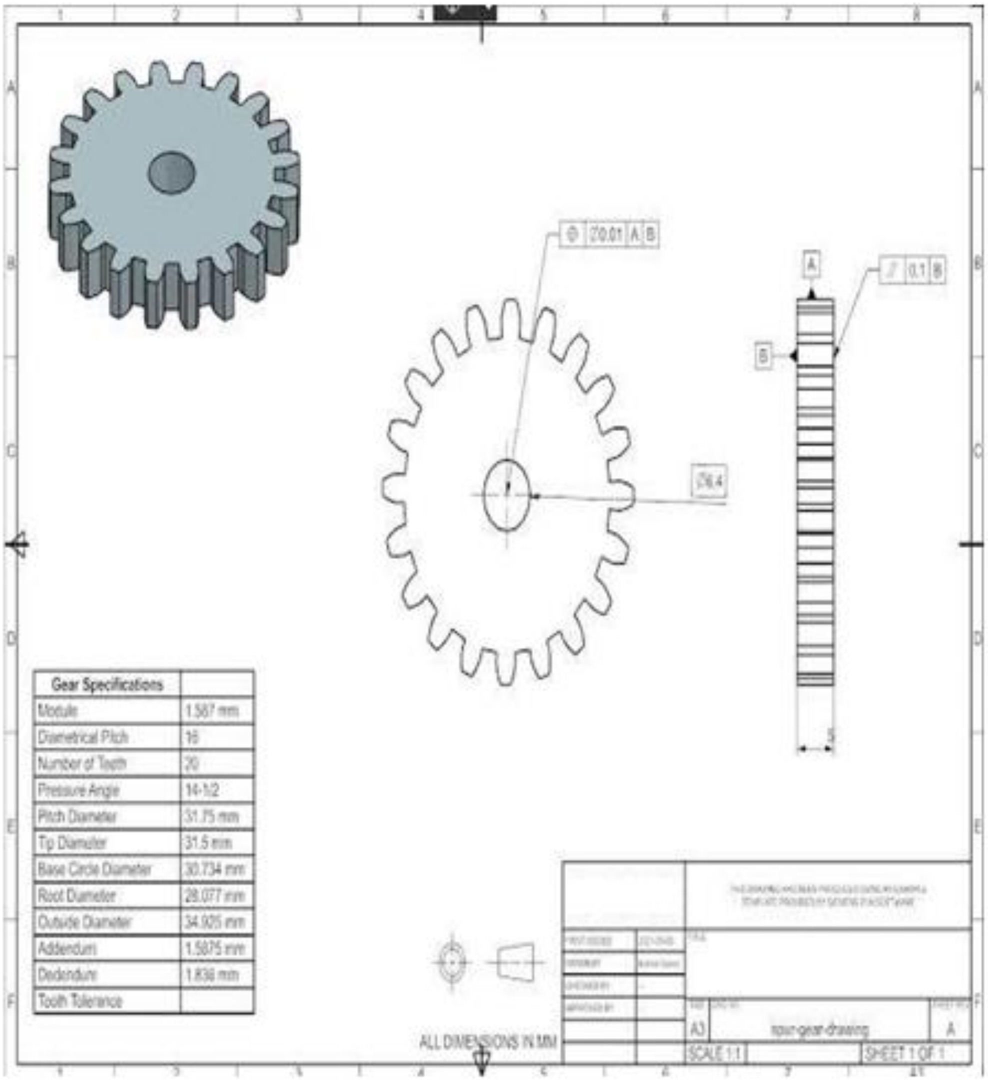
The gears were manufactured from metallic materials. The metallic gears with cut teeth was obtained from cast iron. The cast iron was used due to its good wearing properties, excellent machinability and ease of producing complicated shapes by casting method.Table 2 shows the properties of gear materials

2.2.8 Properties of Materials

Table 2: Properties of the gear materials

Materials	Grade 20
Brinell hardness number	179 minimum
Minimum tensile strength (N/m^2)	200

Figure 8 is the diagram of the designed gear for additive manufacturing.



Gear Specifications	
Module	1.587 mm
Diametrical Pitch	16
Number of Teeth	20
Pressure Angle	14-1/2
Pitch Diameter	31.75 mm
Tip Diameter	31.5 mm
Base Circle Diameter	30.734 mm
Root Diameter	28.077 mm
Outside Diameter	34.925 mm
Addendum	1.5875 mm
Dedendum	1.836 mm
Tooth Tolerance	

Figure 8: Diagrammatical specifications of the designed spur gear

2.2.9 Development of a Cost Reduction Model on the Designed Gear Product from Additive Manufacturing Process

.

In this research work, two major categories for examining additive manufacturing costs were considered:

(i) The first is to compare additive manufacturing process for the gear to other traditional processes such as injection molding and machining. The aim in is to determine the cost implication.

(ii) The second category involves identifying resource use at various steps to produce the gear from additive manufacturing process. The reason is to determine the resources needed and if the resources can be reduced.

The cost of the gear production through additive manufacturing was calculated by [34] based on calculating the average cost per part and three additional assumptions [34] which are:

(i) That the system produces a single type of part for one year

(ii) That It utilizes maximum volumes and

(iii) That the gear is in use for 90 % of the time.

The research analysis include: labour, material, and machine costs, power consumption and space .

The average part cost was calculated by dividing the total cost by the total number of parts manufactured in a year.Calculations were made for spur gear (which is mainly made from cast iron materials) using three different additive manufacturing technologies: stereo-lithography, fused deposition modeling, and laser sintering [34]. A cost breakout for the gear material is provided in Figure 9, which shows that in this analysis laser sintering was adopted as the cheapest additive manufacturing process for spur gear.Figure 9 shows cost of different types of additive manufacturing.

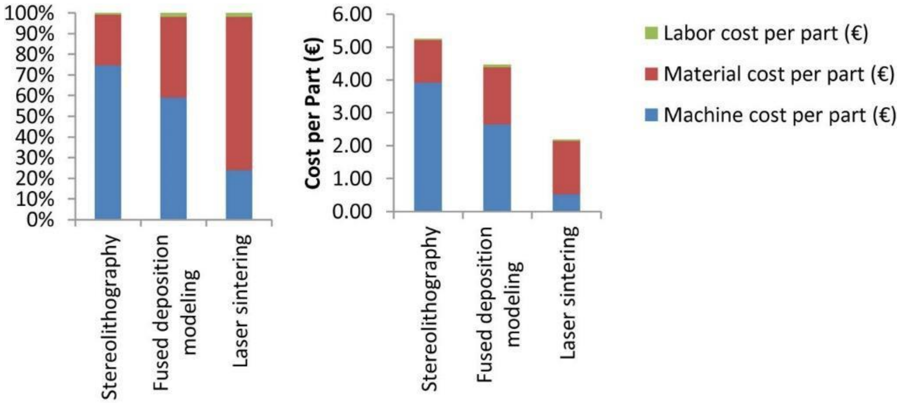


Figure 9: Cost Breakout [34]

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It is important to note that although it is a significant proportion of the total cost, machine costs decreased 42 % between 2001 and 2013, [30] as seen in Figure 10.

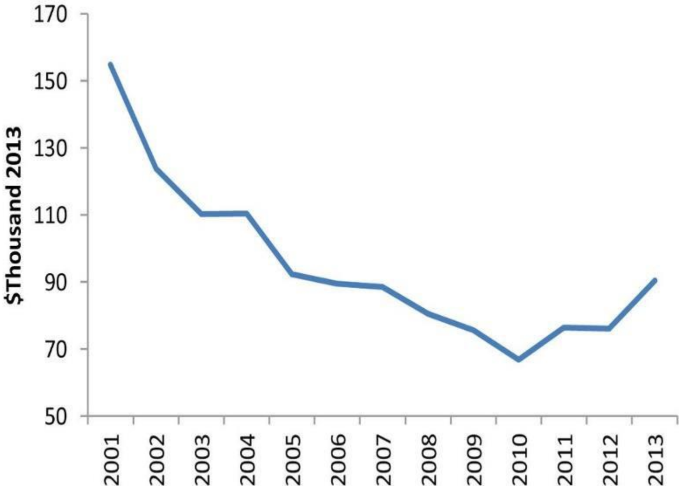

Figure 10:Average Selling Price of a Professional-Grade Industrial Additive Manufacturing System [30]

In the analysis of the gear production, additive manufactured parts cost calculation proposed by [36], using an activity basedcost model was adopted. In this model, the total cost of a build (C), is the sum of raw material costs and indirect costs. The raw materials costs are the price (Pmaterial), measured in naira per kilogram, multiplied by the mass in kg (M). The indirect costs is (T).
The total cost of a build is then represented in Equation 15:

$$C = P_{material} * M + P_{indirect} * T$$ [2] Equation 15

where;
C is the total cost of a gearbuild.

$P_{material}$ *is the raw material costs measured in naira per kilogram. M is the gear mass in kg.*

T is the total build time.

$P_{indirect}$ *s the indirect cost rate.*

The cost per item is obtained as the total cost (C) divided by the number of parts in the build. [36] indicated that the time and material used are the main variables in the costing model. [36
] used a machine working 100 hours/week for 50 weeks/year (57 % utilization) [36]. This results is shown in Table 3.

Table 3: Indirect Cost Activities

S/N	Activity	Cost/ hr £
1	Production/Machine hour	7.99
2	Machine Costs	14.78
3	Production overhead	5.90
4	Administrative Overhead	0.41

2.2.10 Additive Manufacturing Cost Methodology for Gear Production

The three costing methodologies for assessing this cost models and comparing them to give a better understanding of which model is most cost effective was proposed by [36]: 1. The first method is based on parts volume given by Equation 16 as given by [2].

$$Cost_{P_i} = \left(\frac{V_{P_i}}{V_B}\right) \sum \frac{indirect\_\ costs}{working\_\ time}\left(t_{xy} + t_z + t_{HC}\right) + \frac{direct\_\ cost}{mass\_\ unit} m_B$$ **Equation 16**

where;
$Cost_{P_i}$ *is the cost of part i*

V_{P_i} *is the volume of part i*

V_B *is the whole volume of the build*

m_B *is the mass of the planned production proportional to the object volumes, and thetime to manufacturing the entire build*
t_{xy}*is the time to laser-scan the section and its border to sinter powder* t_z *is the time to add layers of powder*
t_{HC}*is the time to heat the bed before scanning and to cool down after scanning and adding layers of powder*
i is an index of part

2. The second method is based on cost of building a single part and is given by Equation 17 according to [2].

*

$$Cost_{P_i} = \frac{\frac{Cost^{*}_{P_i} + n_i}{\sum_j \left(Cost^{*}_{P_j} * n_j\right)} \sum \frac{indirect\_costs}{working\_time}\left(t_{xy} + t_z + t_{HC}\right) + \frac{direct\_cost}{mass\_unit} m_B}{n_i} \quad \text{Equation 17}$$

where;

i is the index of the part

j is the index for all parts manufactured in the same bed n_i *is the number of parts identified with i*

$Cost^{*}_{P_i}$ *is the cost of a single part I, C.*

3. The third method is based on the cost of a part built in high-volume.

This is shown in Equation 18 by [2]

*

$$Cost_{P_i} = \frac{\frac{Cost^{\infty}_{P_i} + n_i}{\sum_j \left(Cost^{\infty}_{P_j} * n_j\right)} \sum \frac{indirect\_costs}{working\_time}\left(t_{xy} + t_z + t_{HC}\right) + \frac{direct\_cost}{mass\_unit} m_B}{n_i} \quad \text{Equation 18}$$

where;

$Cost^{\infty}_{P_i}$ *is the hypothetical number, which approaches infinity of manufactured parts i.*

2.2.11 Development and Testing of the Cost Reduction Structure for Mass Production on Existing Supply Chain Structure

Two approaches to implementing additive manufacturing for mass production are: monetary cost view point and resources consumption view point.

2.2.12 Monetary Cost Viewpoint

Additive manufacturing can build an entire assembly in one build, it reduces the need for some of the transportation and inventory costs, resulting in impacts throughout the supply chain. As reported by [38].This is given in Equation 19 according to [2].

$$\begin{aligned} C_{AM} = & \left(MI_{R,AM} + MI_{M,AM}\right) \\ & + \left(P_{E,AM} + P_{R,AM} + P_{M,AM}\right) \\ & + \left(FGI_{E,AM} + FGI_{R,AM} + FGI_{M,AM}\right) \\ & + WT_{AM} + RT_{AM} + T_{AM} \end{aligned} \quad \text{Equation 19}$$

where ;

C_{AM} *defines additive manufacturing cost for the item*

MI is the cost of material inventory for refining raw materials (R) and for manufacturing (M) for additive manufacturing (AM)

P is the cost of the process of material extraction (E), refining raw materials (R), and manufacturing (M), including administrative costs, machine costs, and other relevantcosts for additive manufacturing (AM)

FGI is the cost of finished goods inventory for material extraction (E), refining rawmaterials (R), and manufacturing (M) for additive manufacturing (AM)

WT_{AM} *is the cost of wholesale trade for additive manufacturing (AM)* RT_{AM} *is the cost of retail trade for additive manufacturing (AM)*

T_{AM} *is the transportation cost throughout the supply chain for an additive manufacturedProduct*

(AM).

This could be compared to the cost of traditional manufacturing which is represented in

Equation 20 as given by [2].

$$\begin{aligned} C_{Trad} = & \left(MI_{R,Trad} + MI_{I,Trad} + MI_{A,Trad}\right) \\ & + \left(P_{E,Trad} + P_{R,Trad} + P_{I,Trad} + P_{A,Trad}\right) \\ & + \left(FGI_{E,Trad} + FGI_{R,Trad} + FGI_{I,Trad} + FGI_{A,Trad}\right) \\ & + WT_{Trad} + RT_{Trad} + T_{Trad} \end{aligned}$$

Where ; Equation 20

C_{Trad} is the cost of producing a product using traditional processes (Trad)

MI is the cost of material inventory for refining raw materials (R), producing intermediate goods

(I), and assembly (A) for traditional manufacturing (Trad)

P is the cost of the process of material extraction (E), refining raw materials (R), producing intermediate goods (I), and assembly (A), including administrative costs,machine costs, and other relevant costs for traditional manufacturing (Trad)
FGI is the cost of finished goods inventory for material extraction (E), refining rawmaterials (R), producing intermediate goods (I), and assembly (A) for traditionalmanufacturing (Trad)
WT_{Trad} is the cost of wholesale trade for traditional manufacturing (Trad) RT_{Trad} is the cost of retail trade for traditional manufacturing (Trad)
T_{Trad} is the transportation costs throughout the supply chain for a product made usingtraditional manufacturing (Trad).
From Equations above, it is clearly seen that additive manufacturing has significant cost savings in an assembled product.

2.2.13 Consumption of Resources Viewpoint

Additionally, a major element in the production of all goods and services is time, it is important to note that there is a tradeoff between time and labour (measured in labour hours per hour). For example, productivity increase is achieved when machinery consumes natural resources as raw material and energy, thus, productivity increases while sustainability decreases.
From my perspective, the ideal shift would result in a reduction in time, labour, or natural resources without increasing the use of other resources.The use of additive manufacturing brings more gainscompared to that of traditional manufacturing method [17]. The formula for this is given in Equation 21 as developed by [2].

$$\begin{gathered} TA_L = \left(L_{AM,P} + L_{AM,U} + L_{AM,D}\right) - \left(L_{T,P} + L_{T,U} + L_{T,D}\right) \\ TA_{LB} = \left(LB_{AM,P} + LB_{AM,U} + LB_{AM,D}\right) - \left(LB_{T,P} + LB_{T,U} + LB_{T,D}\right) \\ TA_T = \left(T_{AM,P} + T_{AM,U} + T_{AM,D}\right) - \left(T_{T,P} + T_{T,U} + T_{T,D}\right) \\ TA_U = U(P_{AM}) - U(P_T) \end{gathered}$$

Equation 21

where;
TA is the total advantage of additive manufacturing compared to traditional methodsfor land (L), labour (LB), time (T), and utility of the product (U).
L is the land or natural resources needed using additive manufacturing processes (AM) or traditional methods (T) for production (P), utilization (U), and disposal (D)of the product.
LB is the labour hours per hour needed using additive manufacturing processes (AM)or traditional methods (T) for production (P), utilization (U), and disposal (D) of theproduct.
T is the time needed using additive manufacturing processes (AM) or traditionalmethods (T) for production (P), utilization (U), and disposal (D) of the product.
$U(P_{AM})$ is the utility of a product manufactured using additive manufacturing processes, including the utility gained from increased abilities, enhancements, anduseful life.
$U(P_T)$ is the utility of a product manufactured using traditional processes, includingthe utility gained from increased abilities, enhancements, and useful life.

3.0 DISCUSSION AND VALIDATION OF RESULTS

The future of additive manufacturing is great; however, it might be advantageous to conjecture about future adoptions using the trend in past adoptions. Using the number of domestic unit sales, the growth in sales can be fitted using least squares criterion to an exponential curve that represents the traditional logistic S-curve of technology diffusion. The most widely accepted model of technology diffusion is given by [37] in Equation 22.

$$p(t)=\frac{1}{1+e^{\alpha-\beta t}}$$

Equation 22

where;

p(t) is the proportion of potential users who have adopted the new technology by time t

α is the location parameter

β is the shape parameter (β > 0)

From the above Equation, in order to examine additive manufacturing, it is assumed that the proportion of potential units sold by time t follows a similar path as the proportion of potential users who have adopted the new technology by time t.

In order to examine shipments in the industry, it is assumed that an additive manufacturing unit represents a fixed proportion of the total revenue; thus, revenue will grow similarly to unit sales. The proportion used was calculated from by[37]. The variables α and β were estimated using regression on the cumulative annual sales of additive manufacturing systems between 1988 and 2014 [37]. Unfortunately, there is little insight into the total market saturation level for additive manufacturing. In order to address this issue, the modified existing version of [37] model which was adopted from [38] is given in Equation 22.

where;

η is the market saturation level

Because *η* is unknown, it is varied between 0.03 % and 100 % of the relevant manufacturingshipments.

Figure 9, illustrates six of the trend estimates using the model. From the adopted modelfrom [38], it is observed that the R^2 value ranges between 0.95 and 0.97; thus, between 95 % and 97 % of the variation in the growth of additive manufacturing is explained using this existing model [38]. Therefore the value range R^2 indicates that additive manufacturing is to some extent following the S-curve model of diffusion as shown in Figure 11 and for this technology to exceed $16.0 billion in 2025, $57.5 billion in 2030 and $196.8 billion in 2035 it would need to deviate from its current trends of adoption. Figure 11 is the additive manufacturing shipments based on past trends, by varying market saturation levels.

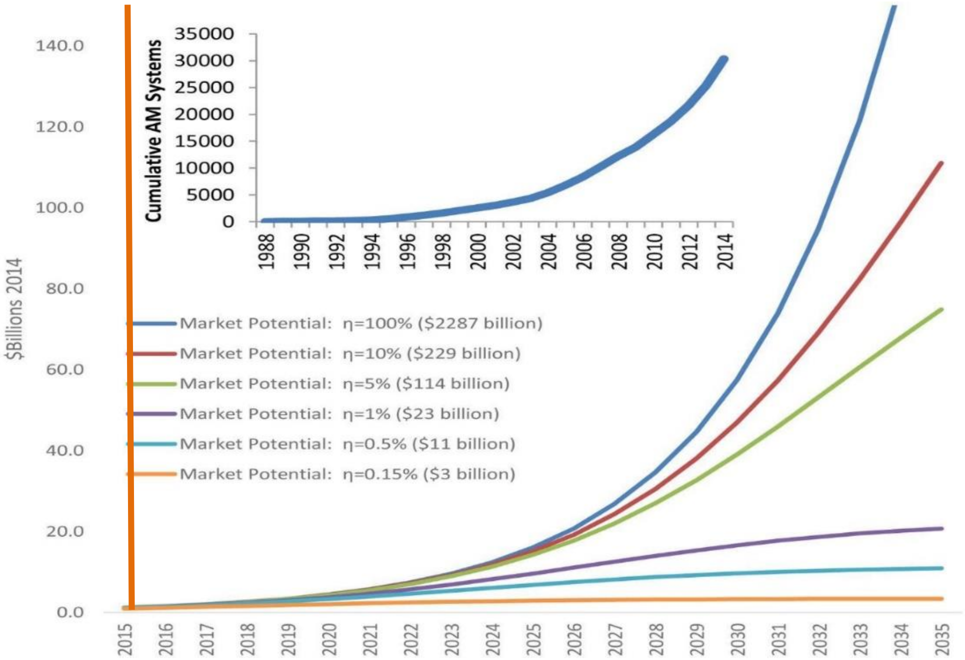

Figure 11: Potential U.S. additive manufacturing shipments based on past trends, by varying markets at

4.0 CONCLUSION

This research has shown clearly that Additive manufacturing has great impact on the costs of production if used extensively. This technology allows for the manufacture of products that might not have been possible using traditional methods. These products may have new abilities, extended useful life, or reduce the time, labour, or natural resources needed to use these products. For example, gas turbine parts might be made lighter to reduce fuel costsor combustionchamber might be designed to reduce cooling needs. For this reason, there is a need to track the land (i.e., natural resources), labour, and time expended on production, utilization, and disposal along with the utility gained from new designs. This research also presented a supply chain approach to examining costs of additive manufacturing from a monetary cost perspective and a resource consumption perspective. The cost perspective examines supply chain costs in monetary values while the resource perspective examines the time, labour, and natural resources used in production, utilization, and disposal of a product.

The adoption of additive manufacturing has increased significantly in recent years; however, in some instances the per unit cost can be higher for additive manufacturing than for traditional methods. The result is that a firm sacrifices controllability for flexibility; thus, it makes sense for those firms that seek a high flexibility position to adopt additive manufacturing. In some instances, however, it is possible for additive manufacturing to positively affect controllability as well, as this technology can reduce costs for products that have complex designs that are costly to manufacture using traditional methods. As the priceof material and systems comes down foradditive manufacturing, the controllability associated with this technology will increase, making it attractive to more firms. Finally, this research has presented an initial framework for interaction between elements of environment, strategy and structure for the manufacturing process choice decision. The application of additive manufacturing in different modes was demonstrated with corresponding performance benefits for the different supply chain entities involved in manufacturing a product. This research contributes to additive manufacturing management by taking a more holistic and qualitative perspective on the manufacturing process choice decision, a departure from narrow cost perspectives prevalent in additive manufacturing management. Further supply chain configuration theory, prevalent in traditional manufacturing supply chains was extended to the realm of additive manufacturing to assess the potential impacts, a seminal contribution to the additive manufacturing management literature. Further, this research contributes to the delineation of additive manufacturing capabilities on different levels of the product structure, a departure from generic approaches. This research is conceptual, and its propositions was empirically tested. Firstly, practicalities and limitations of each of the deployment scenarios must be set out to guide additive manufacturing implementation decisions. This will further serve to provide evidence of successes to enable the diffusion and legitimization of the technology. Secondly, actual performance levels of operations in process and supply chain savings need to be measured empirically in application sectors such as power sector and material handling sector. Case studies, carrying out performance measurement comparisons between additive manufacturing and traditional manufacturing should be carried out to measureperformance gaps in each of the deployment strategies presented.

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