Analysis of AM Hub Locations for Hybrid Manufacturing in the United States

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Danielle B. Strong

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Danielle Strong

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Approvals:

Dr. Guha Manogharan, Thesis Advisor Date

Dr. Brett Conner, Committee Member Date

Dr. Thomas Wakefield, Committee Member Date

Dr. Salvatore A. Sanders, Dean of Graduate Studies Date

ABSTRACT

Additive Manufacturing (AM) combined with subtractive methods such as machining, referred to as Hybrid-Manufacturing, has the ability to provide the discrete advantages belonging to each manufacturing process. Although metal AM parts are highly complex and customizable they often do not meet required dimensions and tolerances, and subtractive machining is required in order to post-process these parts by eliminating surface roughness. Subtractive machining alone is limited in regards to design, complexity and weight. Research shows that traditional shops have both interest in and excess capacity utilization to adopt AM to form an integrated hybrid-manufacturing supply chain. The hypothesis of this research is that, if strategically located, AM technology can integrate and streamline supply chains, connecting the AM supply chain with traditional machine shops and heat treatment centers for hybrid-manufacturing processes in both manufacturing and reverse logistics applications.

In this research, the following investigations are presented, 1) Strategically locating AM hub centers based on existing machine shops in the United States in order to improve small and medium OEM accessibility to AM technology, 2) Strategically locating AM hub centers based upon both existing machine shops and heat treatment centers in the United States given that the majority of metal parts must go through some surface enhancement process, 3) Strategically locating AM repair technology based upon existing machine shops and aircraft engine maintenance and repair shops in order to utilize the benefits of AM to improve the reverse logistics process, and 4) Analyzing the competition and economic implications of traditional shops adopting AM technology to offer hybrid-manufacturing through a production economics approach. A series of facility location models and an economic duopoly model are developed in this research. The implications of integrating AM with traditional supply chain by strategically locating AM technology across the United States are derived with regards to geography, demand, fixed cost and transportation cost. Similarly, the economic model provides implications on being the first to adopt AM technology among competing firms with regards to product prices, quantities and profits. The results from each model are studied to support the widespread adoption of AM in the United States and to advance future applications of AM.

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LIST OF ABBREVIATIONS

3D	Three Dimensional
3PL	Third Party Logistics Providers
AISI	American Iron and Steel Institute
ALA	Alternate Location Analysis
AM	Additive Manufacturing
ASTM	American Society of Testing & Materials
CAD	Computer Aided Drafting
CAM-IT	Consortium for Advanced Hybrid Manufacturing-Integrated Technologies
CATA	Center for Additive Technology Advancement
CFLP	Capacitated Facility Location Problem
CMM	Coordinate Measuring Machine
CNC	Computer Numeric Control
CRC	Centralized Returns Centers
CT/MRI	Computerized Tomography/Magnetic Resonance Imaging
DDM	Direct Digital Manufacturing
DED	Directed Energy Deposition
DM	Digital Manufacturing
DMLS	Directed Metal Laser Sintering
EBM	Electron Beam Melting
EF	Existing Facility
FAA	Federal Aviation Administration
HIP	Hot Isostatic Pressing
ISO	International Standards Organization
LENS	Laser Engineered Net Shaping
LMD	Laser Melting Deposition
MRO	Maintenance Repair and Overhaul
NAICS	North American Industry Classification System
NASA	National Aeronautics and Space Administration
NDT	Non Destructive Testing
NF	New Facility
NIST	National Institute of Standards Technology
OEM	Original Equipment Manufacturer
PBF	Powder Bed Fusion
PSS	Product Service System
R&D	Research & Development
REF	Rapid Equipping Force
SIC	Standard Industrial Classification
SLM	Selective Laser Melting
SME	Small and Medium Sized Enterprises
TC	Total Cost
TDC	Total Distribution Costs

TLC	Total Logistics Cost
TPC	Total Production and Procurement Costs
UFL	Uncapacitated Facility Location
UFLP	Uncapacitated Fixed Charge Location Problem
US	United States
USD	United States Dollars

CHAPTER 1: INTRODUCTION

Additive Manufacturing (AM), a rapidly emerging manufacturing technology, enables the production of parts-on-demand while offering the potential to reduce cost (Frazier, 2014). ASTM has defined additive manufacturing as ‘‘a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies” (ASTM, 2012). The initial application of AM was limited to rapid prototyping but, due to continuous advancements, is now being used for part production. However, its impact in industry is still small (Mellor et al., 2014). This is due to several challenges that industry has identified with the adoption of AM, including access to AM technology due to high machine costs (Strong et al., 2016). In this chapter, metal AM is introduced along with the concept for hybrid-AM.

While AM is applicable to all classes of materials including ceramics, polymers, composites, and biological systems (Frazier, 2014), the focus of the rest of this work will be on metals. Most AM processed metal alloys are often difficult to fabricate through conventional manufacturing methods such as casting, forging, and machining. Due to this advantage, AM processing could be preferred over traditional ‘bulk’ shaping and subtractive methods when it comes to difficult-to-machine alloys such as titanium. The one disadvantage to metal AM processing is that current AM methods produce parts with poorer surface finish and part accuracy (Manogharan et al., 2015). A solution to this issue is to successfully integrate AM and machining through a hybrid approach which would combine the discrete advantages of both approaches (Karunakaran et al., 2010).

The hybrid approach, referred to in this work as hybrid-additive manufacturing; hybrid manufacturing; hybrid-AM, is defined as "An integrated set of dissimilar manufacturing processes such as an additive manufacturing (AM) process (e.g. powder-bed fusion, binder jetting, directed energy deposition, sheet lamination) linked to one or more manufacturing processes including, but not limited to, machining (subtractive manufacturing), material property enhancement, grinding, polishing and other non-AM manufacturing processes" (Strong et al., 2016). In this work, hybrid-AM is hypothesized to impact production economics and supply chains of traditional manufacturing through adoption of AM and optimal facility location.

The most difficult challenge identified by traditional shops is gaining access to AM technology. Small traditional manufacturers are struggling because they face more challenges in adopting new technologies and processes compared to large manufacturers, such as barriers in capital and expertise to adopt the new technologies (The Executive Office of the President and Department of Commerce, March 2015). With regards to production economics, small manufacturers are struggling to keep up with technology in order to stay competitive (The Executive Office of the President and Department of Commerce, March 2015). The issue here is that small manufacturing lacks the money and research and development present in large manufacturers and the cost to commercialize findings is expensive (The Executive Office of the President and Department of Commerce, March 2015). In fact, less than 60% of small manufacturers have even experimented with 3D printing (The Executive Office of the President and Department of Commerce, March 2015). The ultimate decision to invest in AM should be linked to the market and product characteristics. Usually this includes products with customization, design optimization and low volume. Implementation must be preceded by strategic alignment of business, manufacturing and R&D (Mellor et al., 2014). Competitive position, markets and technology also need considered prior to adoption (Chen et al., 2014).

AM also has the potential to significantly disrupt the current traditional manufacturing supply chain with regards to location and supply chain configuration. The importance of optimizing AM facility locations has been highlighted but not supported by real data (Kim, 2013). Melo et al. (2009) elaborates on this, discussing how facility location affects the overall supply chain strategy. Khajavi et al. (2014) discussed how AM could improve supply chains suggesting a centralized supply chain. One primary benefit of AM is distributed manufacturing in which parts can be manufactured at multiple geographic locations to shorten transportation distances (Reeves, 2009). Bhat et al. (2014) proposed models to predict new business locations at the county level in order to strengthen supply chains. It is hypothesized that facility location models can similarly predict new AM hub locations to support traditional manufacturing firms in the US.

SUMMARY

In this chapter, preliminary research is presented which includes survey results from OEMs on the challenges, acceptance and potential implementation of hybrid manufacturing. From these results, the motivation to expand investigation on integration of additive manufacturing along with traditional manufacturing supply chains is recognized. The remainder of this thesis is organized as: Chapter 2 aims to use machine shop data at the county level in the US and an uncapacitated facility location approach to optimally locate AM hub centers to integrate with machine shops. This hub and spoke system would allow machine shops to experience the benefits offered by AM while addressing the need for metal part post-processing. Chapter 3 expands on Chapter 2 by introducing a second stage uncapacitated facility location approach, in which heat treatment facility data at the county level in the US is added into the machine shops and AM hubs supply chain. Chapter 4 investigates the scenario in which AM technology is installed in hub facilities specifically for metal AM part repair. An uncapacitated facility location approach is used to determine the locations of remanufacturing hubs relative to machine shops and aircraft engine maintenance and repair facilities that could strategically host AM repair technology and offer AM repair as a service. Chapter 5 uses an economic model to analyze the game-theory behavior of traditional shops' decision making to adopt hybrid-AM. This includes an analysis with regards to competition and risk of being "first to adopt". A summary of the research and future work is provided in Chapter 6.

PRELIMINARY RESEARCH

The following work presented consists of the preliminary research done for this study. Before proceeding with the intended investigations of AM adoption through a hybrid-AM approach, it was appropriate to first gauge the interest and capabilities of current traditional machine shops. This thesis in its entirety follows the theme of benefiting traditional shops by gaining access to AM technology. For this integration to be successful and for the rest of this work to be relevant and applicable, traditional shops must have the appropriate part production volume and machine utilization to be a potential fit for a hybrid-AM supply chain system. Given the following results and implications, it is concluded that the majority of traditional shops are in fact machining low volume, complex metal parts, interested in the benefits of hybrid-AM such as part customization and shorter lead times, and have the excess machine utilization available to devote to post-processing metal AM parts while still utilizing their current capacity. All of these indications imply that hybrid-AM would be successful if access to AM technology was less expensive. These results have motivated the rest of this work in order to propose solutions for ways that AM technology can be easily accessed within the current traditional manufacturing supply chain, considering various factors such as post-processing, heat treatment, part repair and market competition.

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CURRENT STATE AND POTENTIAL OF ADDITIVE - HYBRID MANUFACTURING FOR METAL PARTS

1. Introduction

Evolving from Rapid Prototyping in the late 1980s, Additive Manufacturing (AM) has emerged as a powerful facet of advanced manufacturing (Gibson et al., 2010). The American Society of Testing and Materials (ASTM) defines Additive Manufacturing (AM) as “The process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies; Synonyms: 3D printing, additive fabrication, additive process, additive techniques, additive layer manufacturing, layer manufacturing, and freeform fabrication” (ASTM, 2012). With the contribution of the digital revolution to ever-growing computing and communication capabilities, there is synthesis of cloud-based technology and reverse engineering of complex part designs such as legacy replacement parts and implants through CT/MRI and AM capabilities (Pereira and Carro, 2007). Collectively, this has resulted in Direct Digital Manufacturing (DDM) for “an interconnection of additive manufacturing equipment, computers through a network (e.g. internet and servers) and computer software” which benefits the entire manufacturing community (Chen et al., 2015). In particular, developments in material processing capabilities from plastics for prototyping during product development stage to metals have led to fully functional part production (Mellor et al., 2014; Morgan et al., 2014). The range of materials that can be processed has grown steadily and now includes elastomers, biomaterials, and alloys ranging from aluminum to high-temperature nickel-based super alloys such as Inconel, and ceramics (Horn and Harrysson, 2012).

Since most AM processed alloys are often difficult to fabricate through conventional manufacturing methods such as casting, forging, and machining, there is a unique advantage for AM processing over traditional 'bulk' shaping and material removal manufacturing methods. For instance, challenges in metallurgical homogeneity in casting (Auburtin et al., 2000) and machinability of super alloys (Pramanik, 2014) do not exist in AM processing. In addition, AM offers an unparalleled advantage in design freedom because of the 'freeform fabrication' approach which does not require custom fixtures and jigs for every part design (Seppälä and Hupfer, 2014). However, when compared to conventional subtractive methods such as machining, current AM methods produce parts with poorer surface finish and part accuracy (Groover, 2007; Zhu et al., 2013; Manogharan et al., 2015). In the case of biomedical applications, these aspects are not critical, but rather preferred to accelerate bone ingrowth (Bartolo et al., 2012). However, in the case of load-bearing functional parts for mechanical and aerospace applications, poorer surface finish and part accuracy need to be addressed through integration with the traditional manufacturing approach. Such applications that require AM post-processing are of interest in this study. Successful integration of AM and machining processes through a hybrid approach combines the discrete advantages of both approaches (Manogharan et al. (2), 2015; Karunakaran et al., 2010).

Within the scope of this paper, Hybrid-AM is defined as “An integrated set of dissimilar manufacturing processes such as an additive manufacturing (AM) process (e.g. powder-bed fusion, binder jetting, directed energy deposition, sheet lamination) linked to one or more manufacturing processes including, but not limited to, machining (subtractive manufacturing), material property enhancement, grinding, polishing and other non-AM manufacturing processes. The attributes of each process (e.g. part accuracy or internal grain structure) are planned together (preferably concurrently) so that the required product engineering specifications can be met. This is different than sequential production in that the decisions are coordinated so that intermediate part specifications are determined in the hybrid process”. It should be noted other manufacturing processes such as sand casting also require post-processing. In the context of Hybrid-AM, post-processing of ‘near-net’ processes such as design-independent and fixture-less AM are considered as opposed to casting which requires custom molds and cores for each part design. The objective of this paper is to investigate the potential impact of combining these two varied approaches on local traditional manufacturing providers. In this context, it is asserted that added post-processing services by traditional metal manufacturers to enhance functionality to low volume, high performance AM metal parts (i.e. complex part design and/or super alloys) along with their traditional product offerings would be viable (Lewis et al., 2004). The literature review reveals a gap between the potential implementation of AM and hybrid-AM systems and the participation of local traditional manufacturers who are assumed to have the capabilities and machine utilization for integration. It is critical to understand the traditional manufacturers’ level of awareness and ability to support hybrid manufacturing activities and other related factors that are critical to successfully developing a hybrid-AM supply chain.

2. Literature Review

Manufacturing of metal parts is the ideal target for the initial implementation of additive and hybrid manufacturing systems since plastics and other AM materials mostly do not require the extensive post-processing needed to address part tolerance and surface finish. Specifically, metal parts that favor low volume production and critical part accuracy include those required in the defense, aerospace, automotive and medical industry sectors. In the last decade, traditional manufacturing has experienced slower growth and a stagnant market, and companies have realized the need to re-evaluate their use of capacity and allocation of costs to remain globally competitive (Lavopa and Szirmai, 2012). Traditional metal parts manufacturers referenced in this research are facilities pursuing metal manufacturing processes such as machining, grinding and heat treatment. These traditional shops are struggling to satisfy an increased demand for customized, low volume parts at competitive prices (Visnjic and Van Looy, 2012). Although there are major benefits in AM due to lower production volume and increased part design complexity, the risks associated with higher initial costs and lack of best practices hinder the transformation and implementation of AM (Munguía et al., 2008). In order to design an appropriate survey method relevant to traditional manufacturers, the following background information on AM and hybrid-AM was identified.

AM Growth/Challenges/Economics

AM not only offers the capability to process a wide and growing range of materials, but also the ability to produce customized parts with complex designs in smaller batch size without the additional cost and time associated with fabricating fixtures, dies and tools as in conventional manufacturing. This paper focuses on additive manufacturing with metal parts, specifically low volume high performance parts (e.g. aerospace components). For instance, automobile and aerospace industries use AM for product development and highly specialized part production, while the medical industry utilizes AM for models and orthopedic implants (Wohlers Report, 2015).

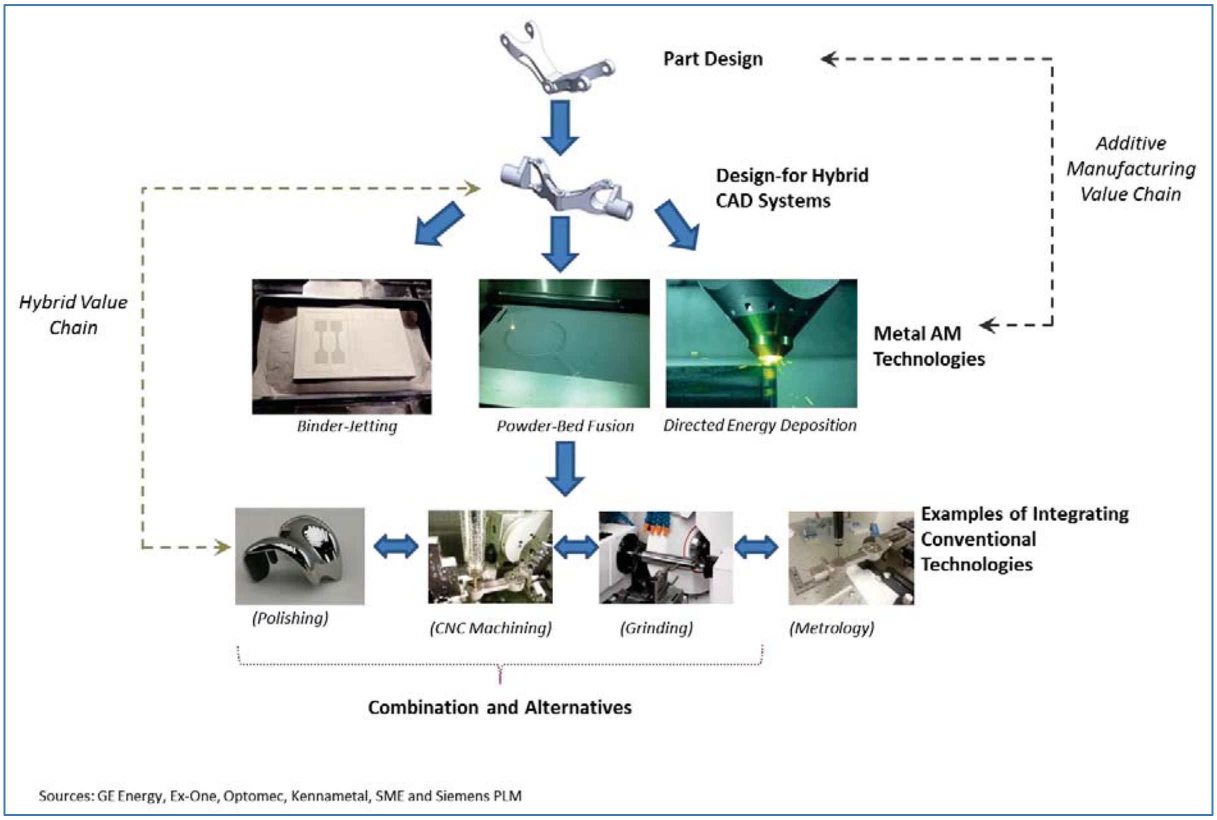
Over the past 26 years, the compound annual growth rate for AM industries is 27.3% (Wohlers Report, 2015). This growth rate has been accelerating over the past five years. From 2012-2014, the growth rate is an impressive 33.8%. In 2014, the additive manufacturing industry grew 35.2% to $4.103 billion (Wohlers Report, 2015). Worldwide revenues from AM products were an estimated $1.997 billion in 2014, an increase of 31.6% from 2013 and continuing a series of years of impressive growth rates, including 41.3% in 2013, 28.8% in 2012, and 28.0% in 2011 (Wohlers Report, 2015). Revenue from additive manufacturing of metal products grew 49.4% in 2014 to an estimated $48.7 million, up from $32.6 million in 2013 (Wohlers Report, 2015). The use of AM for part production also continues to grow. Since 2003, revenues from additive manufacturing have drastically increased to 42.6% of the total product and service revenues (Wohlers Report, 2015).

Many researchers have discussed the key impacts of AM on traditional supply chain, particularly on how AM would simplify the complexity of the supply chains. For example, Petrick and Simpson (2013) contended that AM will localize both production and sourcing activities, but noted that there is a need for finishing and post-processing (e.g. heat treatment) to achieve functional tolerances and part performance for widespread adoption. Manners-Bell and Lyon (2012) also argued that AM would shift manufacturing facilities closer to the customer, resulting in fewer opportunities for logistics suppliers to be involved in companies' upstream supply chains. The authors further posited that a major new sector of the logistics industry would emerge dealing with the storage and movement of the raw materials which 'feed' the 3D printers and the home delivery market of these materials would increase. Walter et al. (2014) asserted that AM has the potential to become a base for new solutions in supply chain management through centralized and decentralized applications of AM using a decision-support model to help supply chain managers better capture emergent business opportunities arising from AM technology. However, there are challenges to adopting AM including the significant investment costs, cost of materials, challenges to scale up to mass production, and the lack of awareness of the advantages of AM (Wohlers Report, 2015).

In summary, AM provides many value-added capabilities. However, AM methods alone produce parts with poorer surface finish and part accuracy compared to traditional methods such as machining (Gibson et al., 2010). For most mechanical and aerospace applications parts with superior surface finish and part accuracies are desired. Hence, there is a tremendous need to solve major challenges in AM: (1) Increasing part accuracy,

(2) Improving surface finish and (3) Improving material property (e.g. heat treatment and hot isostatic pressing). The fundamental approaches in addressing these challenges could be to: (1) Improve the performance of each AM process and/or (2) Develop a hybrid approach that incorporates AM methods as a pre-cursor where near-net AM-made parts can be coupled with traditional processes such as machining, grinding and heat treatment. The former is relatively challenging and time-consuming since there are multiple AM processes with unique processing techniques and characteristics such as energy source (laser, electron beam), processing nature (binder jetting, material powder bed fusion), etc. In order to improve the process performance of each AM method, discrete research efforts targeted at specific AM technologies are required. The second approach would employ AM to produce near-net parts and incorporate a hybrid approach with secondary processing to improve part accuracy, surface finish and material properties. Several researchers have identified the need for secondary operations and the advantages in integrating AM and machining processes (Hur and Lee, 2002; Xiong et al., 2009). Hybrid strategies have been developed for specific AM methods where additive and subtractive operations are repeated in a cycle until the final part is created (Xiong et al., 2009; Karunakaran et al., 2010) but limited to the nature of each individual AM process. For instance, in AM processes categorized as powder bed fusion processes where the material is spread across in each layer, such hybrid strategies have limited design freedom. Hence, it is more efficient and rational to develop a hybrid strategy which is versatile and independent of “up-stream” AM process. Such a hybrid process would be consolidated yet adaptable to combine any near-net AM process with traditional processes. Successful development and implementation of hybrid processing will accelerate the applications of

AM-made parts and efficiently incorporate functionality such as part accuracy and surface finish (e.g. assembly sub-parts) as shown in Figure 1.1. Detailed reviews of single platform workstations for hybrid additive and subtractive processes identify CAD, process planning and need for varied inspection capabilities as immediate challenges (Flynn et al., 2016; Oyelola et al., 2016).



Sources: GE Energy, Ex-One, Optomec, Kennametal, SME and Siemens PLM

Figure 1.1: Value-Adding Hybrid-AM Processes

PSS Implications

Additive manufacturing has recently been referred to as a disruption in traditional manufacturing, posing a threat due to the opening of new markets (Durugbo and Beltagui, 2015). Traditional manufacturing firms are affected by these disruptions and may explore adoption of AM and transition to PSS (Product Service-System). PSS is defined as "a system of products, services, supporting networks and infrastructure that is designed to be: competitive, satisfy customer needs and have a lower environmental impact than traditional business models" (Mont, 2002). Through PSS, Original Equipment Manufacturers (OEMs) will move beyond manufacturing and offer services and solutions through their products (Neely, 2007). The main drivers for PSS are economic motives, changing user needs, competitive motives, and environmental rationales (Tukker, 2004; Raddats and Easingwood, 2010). OEMs report the need for service growth to be about 5-10% a year in order to differentiate their products (Avlonitis et al., 2014). The underlying common principle among all the definitions is the concept of a manufacturer to expand from offering traditional products (goods) into a combination of products and services. As highlighted in a prior study, PSS has been proven to provide integrated solutions (Tukker and Tischner, 2006). There are several examples that highlight the benefits of this approach in manufacturing, including aerospace (Johnstone et al., 2008). Mont (2002) describes these benefits as accelerations towards a more sustainable practice and higher consumption.

An additional PSS goal is extending product life. Ford et al. (2015) explored two major ways that AM can extend product life: a 'make-to-order' model which can be applied to the production of spare parts in order to eliminate inventory and energy wastes and AM for worn, broken or damaged parts. Both approaches lead to improved revenue due to faster procurement of parts when compared to the traditional approach. This was illustrated during the redesign of Siemens PGS for AM in a windmill burner application where production time was reduced to one tenth that of traditional approach (Avlonitis et al., 2014).

Another study done by Durugbo and Beltagui (2015) explored the prospects of implementing services among a number of AM firms consisting of ExOne, Stratasys, and 3D Systems. Some of the servicing techniques provided by the AM firms are leasing 3D scanners and printers, scheduled maintenance and replacement of parts, upgrades for equipment and software, field support, machine diagnostics via internet connection, and testing and installation. For example, Voxeljet reported that 60% of its revenue in 2012 came from its services division. Increased revenue is just one benefit that PSS provided in the case of AM firms which can also be explored for hybrid manufacturing. Khajavi et al. (2014) explored how AM, referred to as digital manufacturing (DM), affects service providers, users and OEMs. In spare part production for the F-18 Super Hornet, the direct benefits of AM-based supply chain for a complex product, through extended lifecycle and availability of parts in challenging locations, was presented. It was also shown that integrating AM offers an opportunity to better control demand and capacity, with one method including re-engineering to increase capacity (Ford et al., 2015). For instance, varying demand from multiple customers is favorable for AM service providers due to production flexibility (Nopparat et al., 2012). In certain scenarios, higher capacity utilization in AM can be achieved through collaboration among OEMs since one AM machine (or few) might have sufficient capacity to support multiple OEMs. AM could play the role of near-net material provider as part of an upstream supply chain whereas distribution between support locations and maintenance locations would follow traditional manufacturing logistics. Overall, PSS can potentially increase profit margins, deliver high quality products, and remanufacture parts of equal quality (Ford et al., 2015).

From existing literature, we can capture the importance of PSS in manufacturing, specifically the possibility of combining traditional processes with AM methods. In particular, manufacturing resources and capabilities of AM to produce highly customized parts are of great interest (Tao et al., 2015). Outsourcing of AM services was recommended by Ford et al. (2015) in order to gain access to AM without significant initial high investment. Durugbo and Beltagui (2015) suggested that further study on the utilization of traditional manufacturing is required in order to adopt AM and AM services. Some of the major obstacles identified were high cost, slower speeds of AM processing, added complexity for re-engineering and willingness of OEMs to re-engineer their products (Khajavi et al., 2014). The need for AM certification associated with material, processing conditions and designs was acknowledged by Ford et al. (2015).

Although the current literature focuses on AM technologies, little attention has been placed on the readiness and willingness of traditional manufacturers to participate in hybrid manufacturing. The investigation presented in this paper aims to bridge the literature gap between AM and implementation of hybrid-AM manufacturing systems by investigating the feasibility of integrating traditional manufacturers in hybrid manufacturing by offering the post-processing services as a PSS.

3. Methodology

In order to assess the current state of traditional manufacturers and their capabilities for integration with AM, we obtained data involving the underlying factors that will promote – as well as hinder – the adoption of hybrid manufacturing: (a) profitability of low-volume products, (b) excess capacity available and (c) resource constraints. The first two factors are critical for traditional manufacturers to be willing to participate in a hybrid system, as they must have excess capacity in order to offer post-processing as a PSS, as well as ensuring that it would be profitable. The resource constraints highlight the concerns of traditional manufacturers on integration with AM processes.

Using these factors, an online survey utilizing the SurveyMonkey® web-based tool was developed and distributed to traditional OEMs who responded anonymously and voluntarily. The online survey was distributed to Consortium for Advanced Hybrid Manufacturing-Integrating Technologies (CAM-IT) (NIST, 2015) members and also America Makes (formerly the National Additive Manufacturing Innovation Institution) (America Makes, 2015) which facilitated the distribution of the survey through weekly emails to their membership database. This database consists of various qualified OEMs and stakeholders in the hybrid-AM value chain which is of particular importance due to the rapid advancement in AM and the recent trend in reshoring (Gray et al., 2013; Fratocchi et al., 2014; Ellram et al., 2013). A similar study was done by Pirraglia et al. (2009) which utilized SurveyMonkey® and distributed an online survey amongst an industry membership list to provide insight on the implementation of lean manufacturing in the wood manufacturing industry.

The survey questionnaire consisting of multiple-selection questions (Pirraglia et al., 2009; Bruns et al., 2015) was designed to examine the current state of traditional manufacturers, assumed to seamlessly adopt potential hybrid-AM systems, and investigate their actual readiness and capabilities to support hybrid-AM. The structure for the survey questions was based on the factors for investigation and were grouped into categories (Piccinno et al., 2012) including: (1) production of low volume metal parts (Frazier, 2014), (2) associated profit margin when compared to mass manufacturing (Weller et al., 2015), (3) lead time associated with such products (Eberhart, 2016), (4) current machining utilization and additional machine availability for hybrid services of AM parts (Ford et al., 2015) and (5) challenges associated with traditional manufacturers engaging in the AM supply chain through the hybrid approach.

The survey was accompanied with an optional supplemental background presentation on current AM and traditional processing capabilities to inform the respondents of current state of technologies. Research surveys in literature have included related information (e.g. objectives and procedures) for review prior to responding to the survey (Fenner et al., 2012). The background information consisted of: (1) the current state of additive manufacturing capabilities and materials, (2) traditional manufacturing methods and (3) hybrid manufacturing principles and applications. This was provided to ensure that all OEMs were knowledgeable of the current state of AM and hybrid-AM processes and the capabilities required before taking the survey. Over the course of two months 17 replies were received, which was a positive outcome considering that the survey was anonymous and dispersed through e-mail. The responses were monitored as they were received and checked for consistency, ensuring that the survey was clear and unbiased. The detailed survey questions, optional answer selections and rationale for each question are presented in Table 1.1. It should be noted that the rationales were not presented in the survey. The predefined numerical scales, similar to those used by Piccinno et al. (2012), for several of the questions were designed based on a conservative estimate and allowed the OEMs to dictate their responses as a range as opposed to exact numbers that may reveal their identity.

Table 1.1: Survey Questions, Available Answer Selections and Question Rationales

Q1. What is the total number of unique metal parts you produce/repair/service in a year? For example, different parts with unique part design and/or material.
< 50
50-100
100-200
> 200
Other:

Q2. What percentage of those products are considered low volume production?
< 5%
5-25%
25-50%
> 50%
Other:

Rationale: Q1and Q2 capture low volume production which could be supported through integration with AM services.

Q3. What is the average additional profit margin on average in such low volume products when compared to other high volume products?
< 5%
5-10%
10-20%
20-30%
30-40%
40-50%
>50%
Other:

Q3b. If profit margin is lower in low volume products, it is what percentage less than high volume products?
Answers…

Rationale: Higher profitability of low volume product adds appeal to adopting hybrid AM.

Q4. What is the typical lead time for the low volume products?
< 2 Weeks
2-4 Weeks
4-6 Weeks
>6 Weeks
Other:

Q5. Is changeover time between different part productions a concern for low volume production?
Yes
No
Other:
Rationale: Q4 and Q5 assess the lead-time and challenges in low-volume production lead time which can be alleviated via hybrid AM.

Q6. What is the average utilization rate of machine tools related to metal parts in your facility?
< 50%
50-60%
60-70%
70-80%
80-90%
90-100%
Other:

Rationale: Excess capacity presents an opportunity to support hybrid AM activity.

Q7. Can the current utilization rate of machine tools to process metal parts in your facility accommodate hybrid?
Yes
No
Other:

Q8. If yes, how much utilization is available for hybrid manufacturing?
<5%
5-10%
10-15%
15-20%
>20%
Other:

Rationale: Q7 and Q8 assess if and amount of existing capability that can be assigned to hybrid processes.

Q9. In your opinion, what are the other potential challenges for your organization to consider hybrid manufacturing processing?
Access to Metal Printers
Time for Process Engineering for Low-Volume or Custom Products
Tooling Requirement
Quality Control
Other:

Rationale: Understanding practical challenges from traditional manufacturer's perspective in adopting hybrid AM.

Q10. Are there additional comments regarding Hybrid manufacturing that you would like to share?
Answers…

4. Results and Analysis

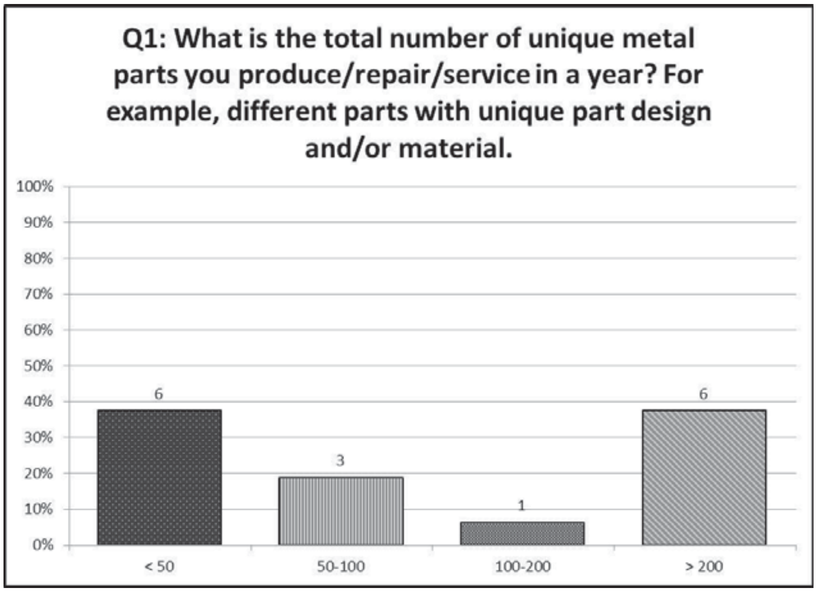
This section presents the survey results and evaluates the potential capabilities of traditional manufacturers in a hybrid manufacturing system for metal parts. The investigation includes the current state of the traditional manufacturers, the metrics used to determine feasibility for adoption and current challenges and barriers identified by the OEMs.

Survey Results

The survey results are presented as bar graphs and are categorized according to the major metrics determined from literature: (1) production volume, (2) profit margin, (3) lead time, (4) capacity utilization and (5) challenges/barriers. The final survey question, requesting comments about hybrid AM adoption from OEMs, is also discussed.

As shown in Figures 1.2 and 1.3, the first metric associated with production volume includes (1) total number of unique metal parts produced/repaired/serviced per year and (2) percentage of low volume production. The results indicate that most manufacturers were either focused on production of low quantities or high quantities: 38% of OEMs with less than 50 total parts and 38% with over 200 parts annually. It should also be noted that products that were considered low volume production were of importance: 82% of OEMs indicate that more than 50% of the total parts are low volume production. These results show that in the current state of the OEMs surveyed, independent of total production volume, more than 50% of products are considered low volume production.

This makes hybrid manufacturing an attractive proposition for the majority of OEMs for low volume metal production since, as discussed in Frazier, 2014, hybrid and additive manufacturing favor low volume production such as metal parts (e.g. defense and aerospace).



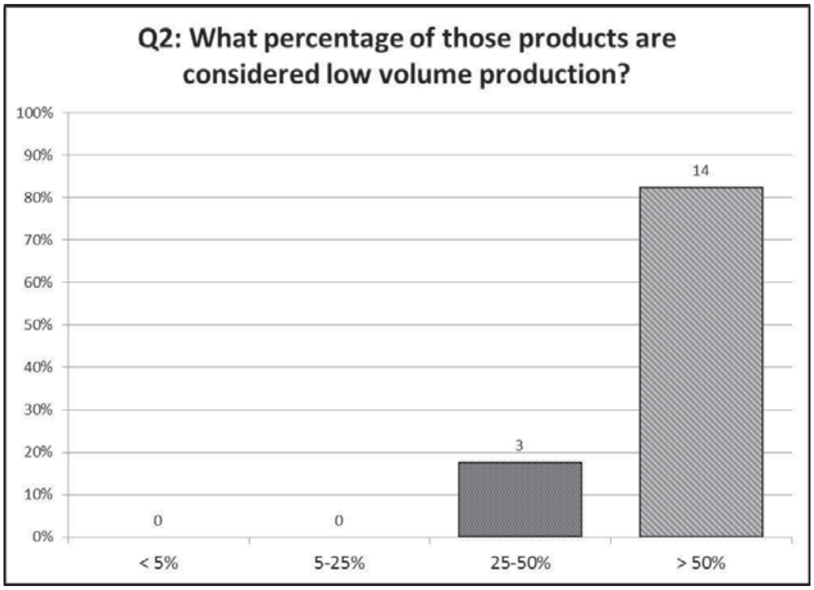


Figure 1.2 and Figure 1.3: Production Volume Survey Responses

The second metric on additional profitability of low volume metal parts presented in Figure 1.4 shows that almost 69% of survey respondents have at least 10-20% additional profit margin for low volume products and 23% of participants with at least 5-10% additional profit margin. Only one OEM noted in a comment that their “low volume products’ profit margin was about 5% lower than high volume products due to higher production cost”.

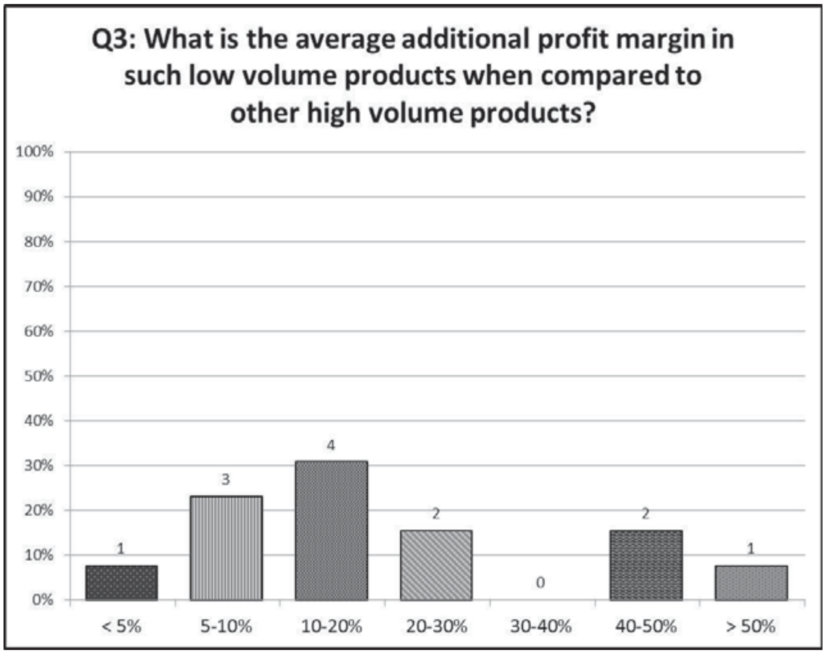


Figure 1.4: Profit Margin Survey Responses

It is important to note that, currently, AM parts are also employed for low volume products and the second metric results indicate low volume products are more profitable. The results of this survey metric support the notion that hybrid manufacturing can help in providing additional profitable services for traditional manufacturers through post processing of AM parts (Ford et al., 2015). Hybrid-AM is proposed as a solution for: (1)

low volume customized products that are more expensive than high volume products and (2) since the demand for low volume products is greater, traditional manufacturers can benefit from reduced production cost component, i.e. only secondary processing. Hybrid-AM has the potential to reduce production costs due to lack of tooling requirement and increase profits in the traditional manufacturing setting (Wimmer, 2015). Manufacturing firms can increase profitability by offering customization at a lower cost (Weller et al., 2015).

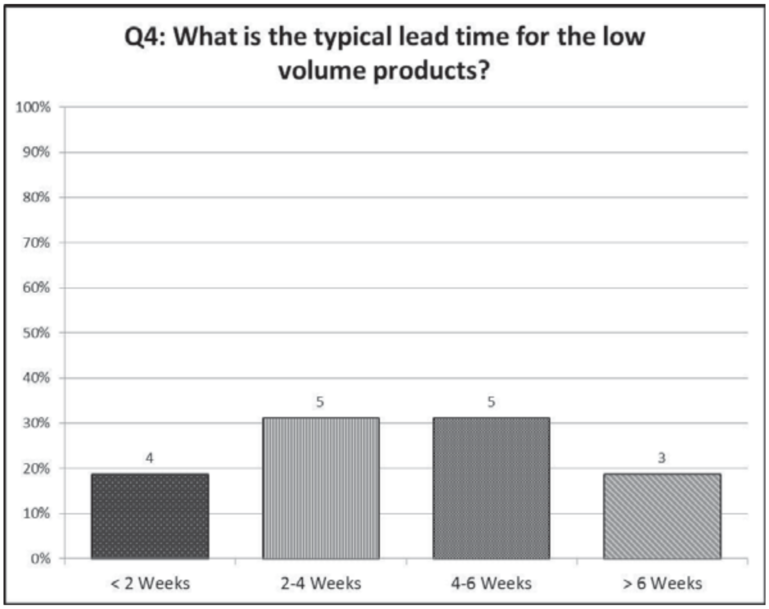
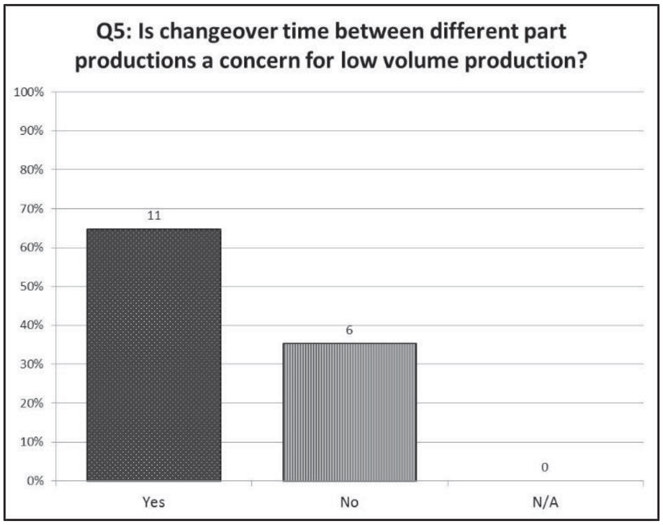
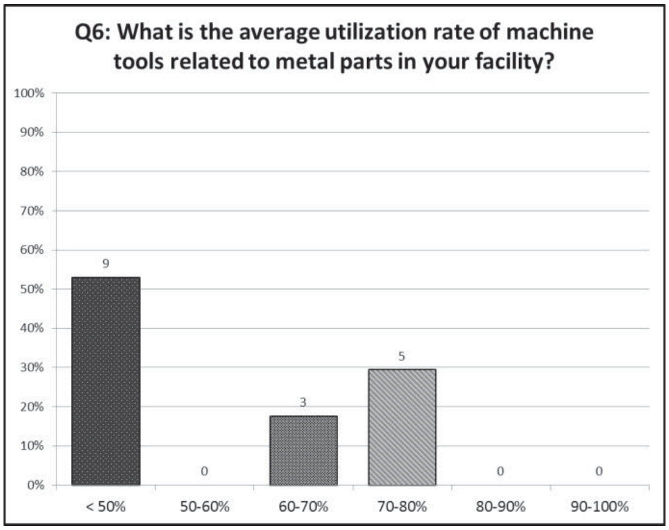
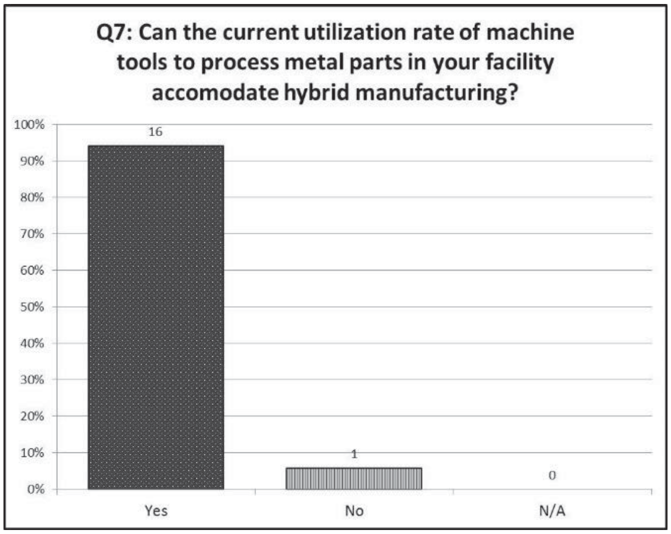


Figure 1.5: Lead Time Survey Responses

The third metric analyzed was the lead time of producing low volume products as shown in Figure 1.5. Results indicate OEMs currently have long lead times of either 2-4 weeks (31%) or 4-6 weeks (31%). There is an opportunity to improve lead time through near-net AM, as only 19% of responses reported typical lead time of less than 2 weeks. Through discrete AM processing and traditional post-processing, hybrid manufacturing could reduce lead time by eliminating or minimizing the need for custom fixtures or tooling when compared to current traditional processes (Manogharan et al. (2), 2015).







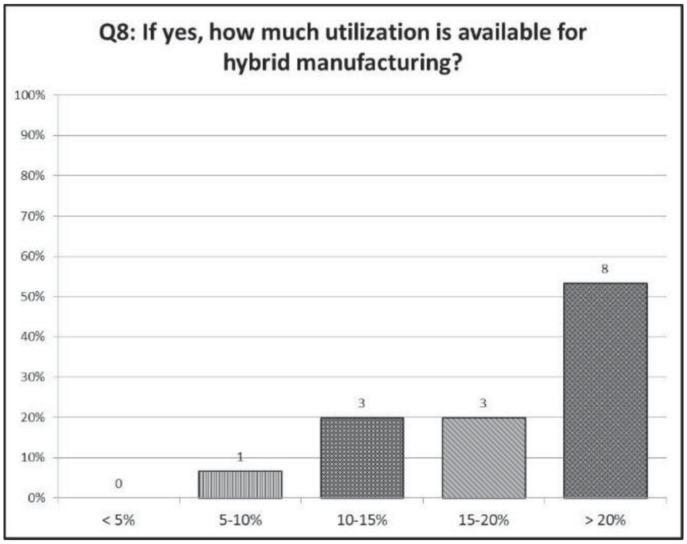


Figure 1.6, Figure 1.7, Figure 1.8 and Figure 1.9: Utilization Survey Responses

The fourth metric was based on current operational state of OEMs such as changeover time between parts which is a concern for low volume production, and is presented in Figures 1.6-1.9. With 65% of respondents having identified that changeover time is important when producing low volume parts, there is a need for a hybrid manufacturing system that would mitigate this issue since changeover time could be streamlined. If process-planning consideration to “post-processing” of AM parts is standardized, AM can eliminate/minimize additional tooling requirements.

The average utilization rate of machine tools for traditional metal manufacturers as shown in Figure 1.6 indicates that 53% of OEMs have less than 50% machine tool utilization that can be otherwise used for hybrid-AM. Currently, traditional manufacturers are not quite capable of capturing the additional revenue stream associated with post-processing of AM parts in spite of additional capacity as shown in Figure 1.8 (e.g. 94% respondents want to accommodate hybrid-AM).

This shows that for the near future (e.g. 5 years) the core system characteristics of traditional manufacturing industry are generally suitable for the implementation of hybrid manufacturing. Overall, the surveyed traditional shops are currently operating at a very low utilization rate and could also benefit from high performance AM-based applications as suggested by Durugbo and Beltagui (2015). Hybrid manufacturing can help to shift available capacity and costs allocations specifically for the traditional post processing needed to finish the printed metal parts.

The final questions inquire about the current challenges preventing the OEMs from adopting hybrid processing (Figure 1.10) and four of the most common barriers mentioned in AM research were provided: (1) access to metal printers, (2) time for process engineering for customization, (3) tooling requirement, and (4) quality control. Additional optional comments on challenges to hybrid-AM were also collected.

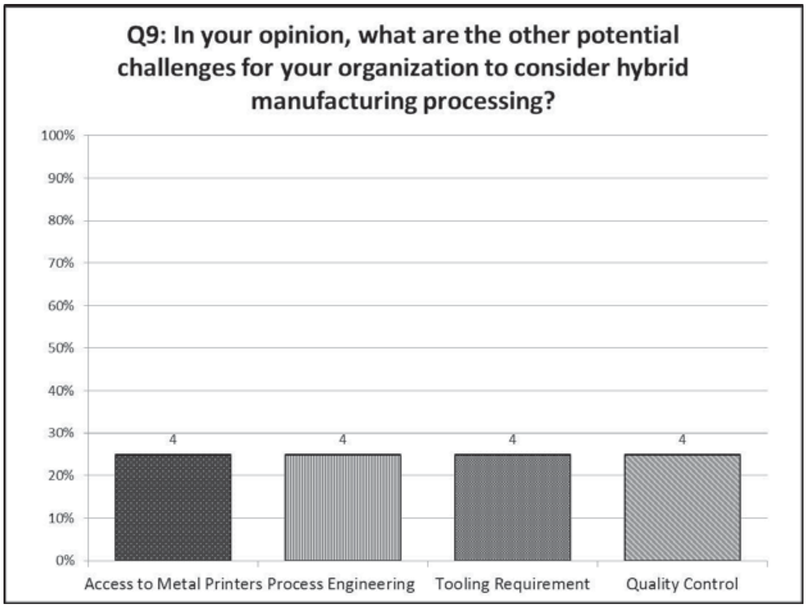


Figure 1.10: Challenges to Hybrid AM Survey Responses

These responses describe the additional challenges that OEMs believe hinder the adoption of technologies such as AM and hybrid-AM. For instance: (1) "Tooling cost and programming time/cost are the most important activities in most low volume activities.", (2) "Emerging technology, very slow market adoption; need to educate customers about the process and technology potential." and (3) "Defense customers require qualified parts that meet design specifications." were reported. Other challenges that were noted included the need for design specifications and process planning. Overall, these analyses indicate that there is an interest in adopting hybrid manufacturing in the metal parts industry upon addressing the identified challenges.

5. Discussion

As identified from the survey, high-value (profit) low volume metal AM parts (e.g. tooling) are of great interest to OEMs. The results also showed that current lead time is generally high due to traditional manufacturing constraints. Through integration with AM, this drawback can be mitigated in a hybrid approach. Most importantly, current machine utilization of traditional manufacturers is sub optimal and hybrid-AM post-processing as a 'service' to metal AM providers can facilitate a transformation to a PSS structure. The challenges associated with adopting hybrid-AM can be categorized into: (1) Access to metal AM, (2) Knowledge-based process planning and (3) Current state of metal AM.

Based on the survey results, a feasible hybrid-AM supply chain is presented to fill the literature gap and to address the challenges. The integrated process-planning for hybrid-AM, i.e. re-design of part for hybrid-AM such as incorporation of standardized fixtures in the part prior to AM processing and process planning for down-stream post-processing (e.g. machining allowance, tool path generation) will address challenges related to tooling and process engineering. Another major challenge in the immediate adoption of hybrid metal AM processing is the qualification and certification needs that are currently being developed by the industry and standards organization such as NIST (National Institute of Standards and Technology) and ASTM (American Society for Testing and Materials). For example, the use of hybrid-AM to fabricate aerospace parts would require qualification by the manufacturer and certification by the Federal Aviation

Administration (FAA), National Aeronautics and Space Administration (NASA), Air Force or Navy depending on the application. Since hybrid-AM for metal parts is a relatively new technology where materials, design, processes and post-processes are so intertwined, the costs and resources required for qualification and certification could be significant barriers to technology transition. Similar challenges exist for automotive applications where in-situ monitoring for quality control, non-destructive testing (NDT), physics based performance modeling, and many other issues need to be resolved.

The access to metal AM is the challenge that can be addressed by developing hybrid-AM supply chain. This will also accelerate knowledge-based process planning challenges. The simplified supply chain of metal parts illustrated in Figure 1.11(A) where customers order products directly from the manufacturer represents the status quo of many current traditional supply chains in which manufacturers compete for a wide variety of products. Manufacturers invest in tooling, equipment, labor, and technology in order to maintain their competitiveness in the industry. While low volume, complex design, highly customized products can be a highly profitable product segment (survey Q1-Q3), it is often challenging for traditional manufacturers with limited human and capital resources to achieve the anticipated quality. From the manufacturers' viewpoint, such circumstance may also increase competition for standardized products and under-utilization of resources. In addition, there are currently fewer alternatives for complex products.

The manufacturing capability can be enhanced by integrating AM into the supply chain system as shown in Figure **1.**11(B). In this scenario, customers can order standardized products directly from the manufacturer. If the product design and/or level of complexity favor the hybrid route, it can be first fabricated to near-net shape using AM and post-processed to its final specification. This would also help absorb the excess capacity in traditional shops (survey Q4-Q8). The main challenge involves the high upfront investment associated with the AM processing center which is widely identified as key barrier to the proliferation of AM (survey Q9-Q10).

The hybrid supply chain shown in Figure 1.11(C) depicts a system where low-volume products with complex design can be fulfilled directly by an AM center and/or initially fabricated to near-net shape in an AM center and post-processed at a traditional manufacturing facility to achieve final part specification. The centralization of AM equipment limits the upfront investment required for the supply chain to implement hybrid-AM and researchers have shown that such an approach would be the most feasible route with the current state of AM technology (Holmstrom and Partanen, 2014). The centralization of AM also negates the need for conventional machine shops to adopt new technology, but only use their excess capacity to provide post-processing as a service thus increasing their overall utilization rate. This hybrid supply chain is proposed as the desired structure to link AM and traditional processes as it mutually benefits both AM service centers (broader use of AM due to post processing) and small and medium traditional manufacturers (access to existing AM supply chain without direct AM resources). It should be noted that the final option of introducing machine tools into existing AM facilities also exists. It could be argued that this reflects the current state of production of metal AM parts in vertically integrated companies (Smith, 2013).

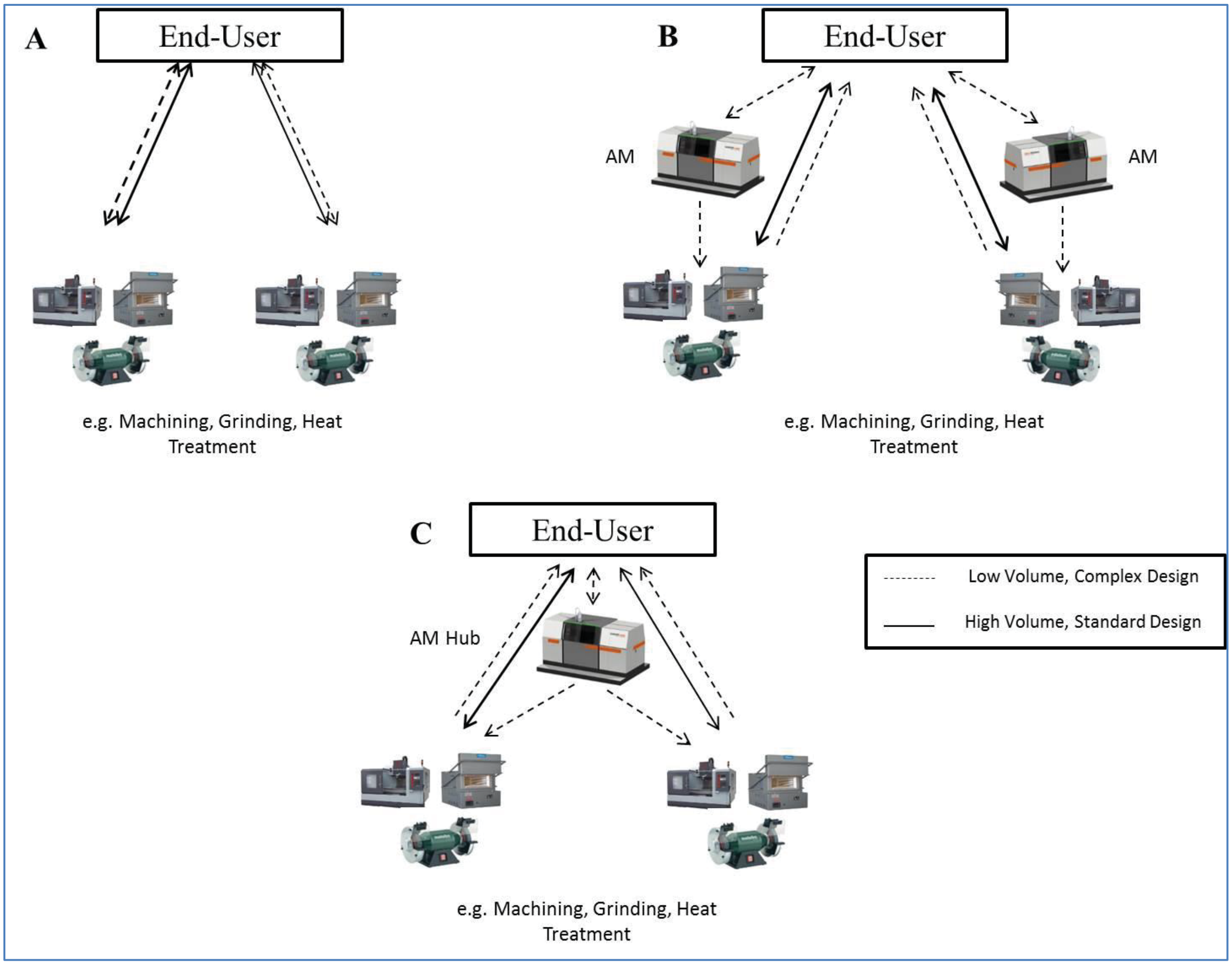


Figure 1.11: (A) Traditional, (B) Hybrid and (C) Hybrid Ecosystem Supply Chain

6. Conclusions

With growing demand for low volume, highly customized mechanical parts (e.g. aerospace and defense), this research analyzes OEM data to determine if hybrid manufacturing could be feasibly adopted into the traditional manufacturing of the metal parts industry. The implication of this study is that the majority of OEMs surveyed exhibit operational characteristics that would support hybrid manufacturing, and challenges involving the implementation are identified. The results of this survey can be used as a guide to measure the capability for hybrid manufacturing which is the critical first step for successful implementation.

Further, it is asserted that hybrid manufacturing has the potential to improve the capabilities of traditional manufacturing by integrating additive manufacturing given the following conditions:

1. Hybrid manufacturing in industry would not replace traditional manufacturing shops. Rather, a hybrid-AM supply chain ecosystem could be utilized to allocate fabrication of metal parts to additive manufacturing hubs (centralized or decentralized) and allocate the post-processing (machining, grinding, heat treat, etc.) to traditional manufacturers in order to decrease the effects of supply chain disruption. Near-net metal AM parts would flow from multiple additive manufacturing hubs for production into the traditional facilities for secondary processing.

2. Under this supply chain ecosystem, the traditional shops should operate based on PSS methods (i.e. along with core manufacturing). The PSS methods include post-processing, but could also include repairs, replacement parts, and maintenance. These PSS methods are capable of additionally increasing profit margins, customer loyalty and

extending product life cycle. In order to adopt this method successfully, OEMs need to consider their specific data related to production volume, profit margin, lead time, utilization and current challenges. Based on our study, the majority of OEMs surveyed met the criteria in which hybrid manufacturing would successfully benefit their operations. By focusing on low volume AM parts with higher profit margins, OEMs can improve their current lead times and utilization rates through hybrid manufacturing. Challenges to traditional manufacturers mentioned such as access to AM, time for process engineering for customization, tooling requirement, quality control, high upfront costs, and post processing costs can be alleviated through the proposed hybrid-AM supply chain ecosystem.

The hybrid approach is not applicable to all industries, as noted in a survey comment: “We make primarily large steel parts that aren’t the best fit for today’s 3D printing technology.” Until technology advances even further, some industries may be restricted by the size of their metal parts and/or other product considerations. However, hybrid manufacturing structured through the proposed supply chain ecosystem has the potential to help metal parts manufacturers advance and evolve through the elevating demands of low volume and customized parts. In order to adapt to the disruption due to AM in the traditional supply chain and manufacturing system, OEMs should consider the benefits that hybrid manufacturing has to offer, including both production and PSS services. This research is limited to only small and medium metal parts manufacturers, and the survey was distributed explicitly to OEMs on the CAM-IT and America Makes database. Future work includes expansion to support larger metal parts manufacturers and exploration of the proper hybrid supply chain ecosystem and location of the additive manufacturing hubs upon analyzing the current locations of traditional manufacturers.

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CHAPTER 2: HYBRID MANUFACTURING: INTEGRATING TRADITIONAL MANUFACTURERS WITH ADDITIVE MANUFACTURING (AM) HUBS

1. Introduction

Additive manufacturing (AM) has emerged as a solution to streamline supply chains through both centralized and decentralized applications (Walter et al., 2004). As defined by ASTM (2012), AM is the process of adding material layer by layer based on 3D model data. AM applies to a wide range of materials from polymers and ceramics to metals. There is a growing interest in processing metallic super-alloys for low-volume aerospace, medical, industrial, and transportation applications using AM due to complex design freedom, higher degree of customization and better material utilization when compared to traditional manufacturing (Conner et al., 2014). Although there are many benefits to AM such as the wide range of materials (Guo and Leu, 2013), significant part weight reduction, freeform fabrication and lack of fixtures and tooling (Seppala and Hupfer, 2014), there are also many challenges to readily adopt metal AM. Inadequate surface finish (i.e. uneven and rough surface profile) and inaccurate dimensional tolerances in printed metal parts, along with high investment costs for AM machinery and materials are identified as the primary challenges in furthering the adoption of AM (Wohlers Report, 2016).

Traditional manufacturers such as machine shops have reported that despite the realization of AM benefits to their industries, access to metal AM capabilities remain the primary barrier and challenge for their adoption of AM (Strong et al., 2017). Currently, costs of gaining direct access to AM capabilities in-house is too expensive for small and medium sized manufacturers. Due to this challenge, Original Equipment Manufacturers (OEMs) surveyed expressed their interest in supply chain strategies where AM processes can be accessed externally (Strong et al., 2017). Petrick and Simpson (2013) have noted that there is a need for finishing and post processing in AM production. This is the premise behind hybrid-AM, in which a metal part is first 3D-printed, i.e. Additively Manufactured and subsequently, post-processed using traditional processes such as machining, grinding, etc. to achieve the desired surface finish, dimensional tolerances and material properties. In this paper, hybrid-AM refers to two or more sequential discrete processes (e.g. AM + Machining) employed to achieve the final part specifications. Several studies have highlighted the economic benefits (Manogharan et al., 2016) and detailed the current state of hybrid manufacturing (Zhu et al., 2013 and Manogharan, 2014). Almost 94% of the OEMs surveyed in a recent study have reported an interest in offering post-processing of AM parts as a service through hybrid-AM (Strong et al., 2017). More than 53% of OEMs have a minimum of 20% excess machine capacity to offer post-processing services for AM parts. In the context of this paper, hybrid-AM is defined as the integration of dissimilar metal manufacturing processes, i.e. AM linked to traditional manufacturing processes, which are planned together such that the final required engineering specifications is fully realized through AM.

This study explores a hybrid-AM based DDM supply chain in which AM hubs would act as suppliers to traditional manufacturers with capabilities and demand for hybrid AM. In this system, OEMs would send demand that qualifies for hybrid AM to a regional AM hub (e.g. service bureau) which would control all aspects of AM fabrication and operations. Subsequently, the AM hub would ship the 3D-printed (AM) metal part to the OEMs who would perform post-processing, i.e. hybrid manufacturing using traditional processes to achieve the desired surface finish and dimensional tolerances (e.g. machining, grinding, polishing).

The overall goal of this work is to determine the optimal locations for metal AM hubs in the U.S. based on estimated demand, production metrics (e.g. total cost of establishing and operating AM hubs), logistics (shipping cost) and their assignment as suppliers to existing machine shops based on county-level NAICS data. This work employs both uncapacitated facility location and p-median models based on facility and transportation costs, location and density of current traditional manufactures, and hybrid-AM demand estimated by current annual sales. This paper intends to present a decision-making model for both: (1) AM service companies who can use these models to locate their next AM facility to operate as a hub and (2) OEMs who can evaluate participating in the DDM supply chain through hybrid post processing services to fully harness the benefits of AM. Finally, a detailed sensitivity analysis is conducted for growing AM demand, number of AM machines at each hub and AM machine utilization (i.e. AM processing that would not require post-processing).

In Section 2, a detailed background on facility location, hybrid AM and supply chain implications is presented. The methodology applied for the uncapacitated facility location and p-median models is detailed in Section 3, followed by results on AM hub location and supply chain costs in Section 4. Discussions and key insights obtained from this study are presented in Section 5. Finally, Section 6 summarizes the conclusions, limitations and future direction for the hybrid-AM based DDM supply chain.

2. Literature Review

2.1 Facility Location

The AM hub problem in this study will be treated as a single allocation problem because each county is only assigned to one AM hub. Since optimal allocations are affected by hub locations and optimal hub locations are affected by allocation decisions, location and allocation problems must be simultaneously modeled to design cost effective AM hub networks. Alumur and Kara (2008) presented a review of prior studies on hub locations and allocation of demand nodes to hubs for traffic routing between origin–destination pairs using both single allocation and multiple allocations. Daskin and Dean (2005) highlighted the importance of facility location models. In industry, poorly located facilities or the use of too many or too few facilities will result in increased expenses and/or degraded customer service. If too many facilities are deployed, capital costs and inventory carrying costs are likely to exceed the desirable value. If too few facilities are used, customer service can be severely degraded. Even if the optimal number of facilities is established, poorly sited facilities will result in unnecessarily poor customer service and expensive transportation costs. Optimally located sites can help a company gain competitive advantages and improve operational performance not only in the short term but also in the long term (Chen et al., 2014). The ability of a firm to market and produce its products effectively and/or to deliver high-quality services is dependent in part on the location of the facilities in relation to other facilities and its customers (Daskin, 2011). Daskin (2008) also presented a comprehensive list of taxonomy for multiple location model problems in contrast to vehicle routing problems which are often limited to fewer locations (i.e. nodes).

Different models employed for facility location include the p-hub median problem, p-hub center problem, uncapacitated hub problem, capacitated hub problem and hub covering problem. Methodologies employed include mixed integer (Ebery, 2001), branch and bound (Mayer and Wagner, 2002), genetic algorithms (Topcuoglu et al., 2005), heuristics (Chen, 2007), and Lagrangian relaxation (Elhedhli and Hu, 2005; Alumar and Kara, 2008). Snyder and Daskin (2005) studied classical facility location models like the p-median problem (PMP) and the uncapacitated fixed-charge location problem (UFLP) that implicitly assume that once constructed, the facilities chosen will always be fixed in location and capacity. The uncapacitated fixed-charge location problem (UFLP) is a classical facility location problem that chooses facility locations and assignments of customers to facilities to minimize the sum of fixed and transportation costs. In Melkote and Daskin (2001), plant and warehouse location problems are referred to as UFLP with consideration to routing and geography. The distinguishing feature of the UFLP is the decision maker’s ability to determine the size of each facility without any budgetary, technological, or physical restrictions and is closely related to the p-median problem. In many cases, it is more realistic to incorporate the capacity limitations on the facilities to be established called the capacitated facility location problem (CFLP) (Eiselt and

Marianov, 2011). The p-median problem is framed to locate *p* facilities to minimize the demand-weighted average distance between demand nodes and the nearest of the selected facilities (Daskin and Maas, 2015). Using sensitivity analysis on p-median based on number of hubs, it was shown that branch-and-bound approach is optimal for large amount demand and supplier locations (nodes in the order of 1000s). In a supply chain that comprises of multiple suppliers, production plants, distribution centers, warehouses and customers, these basic formulations are relevant for making location decisions (Eiselt and Marianov, 2011). The uncertainty is typically in the input conditions including the costs and demands which require sensitivity analysis to capture the effects of the inherent variability (Daskin and Dean, 2005).

Prior studies on hub locations have been applied to industries such as airlines (Lin et al., 2012), postal service (Cetiner et al., 2010), warehouse and supply chain logistics (Wang and Cheng 2010), emergency services, delivery services, logistics services, and transportation (Farahani et al., 2013). In the case of tiered supply chain, hierarchical hub network has been shown as an effective method to locate hub facilities (Yaman, 2009; Lin, 2010). Figueiredo et al. (2013) also used p-median models in two stages to locate regional hubs for commercial aviation in regional market sectors. However, there is a knowledge gap in the literature on AM hub locations that can be integrated with existing facilities in traditional manufacturers for hybrid-AM. Also, it is important to note that lack of real data for facility location models often limits its applications to real world problems (Farahani et al., 2013).

2.2 Additive - Hybrid Manufacturing

According to ISO/ASTM 52900:2015, additive manufacturing (AM) describes manufacturing processes where material is deposited or fused together layer-by-layer until a net-shape or near net-space is achieved (ASTM, 2012). This is contrasted with subtractive manufacturing (i.e. milling, grinding, cutting, drilling, etc.) where material is removed to obtain the final part shape. Additive manufacturing is often called 3D printing in the popular media. A variety of materials can be processed additively including polymers, metals, ceramics, electronic materials, and biological materials (Gibson, 2014). Of interest to this research is metal additive manufacturing (AM). Metals produced using AM include but are not limited to titanium, stainless steel, tool steels, nickel based alloys, aluminum, and cobalt chrome (Frazier, 2014; Murr, 2012). ISO/ASTM 52900:2015 also standardizes terminologies for AM equipment technologies into seven categories. Four of these are currently used for metals production: powder bed fusion, binder jetting, directed energy deposition, and sheet lamination. This research will focus on the most widely used technology for metals AM production: powder bed fusion (Wohlers, 2016). In this AM technology, feedstock in the form of metal powder is spread on a build plate layer-by-layer. Based on the 3D part information from a CAD (Computer Aided Drafting) model, an energy source in the form of either a laser or an electron beam selectively melts the powder in each layer. This process is repeated until the final part is produced. The most common form of powder bed fusion is a laser based system invented by Deckard and Beaman (1990). Currently, all metal AM methods require some form of post-processing to obtain the final part geometric dimensions, surface finish, and material properties. Additive and subtractive machining can occur in the same machine envelope with the directed energy deposition AM process (Jones, 2012). However, the vast majority of AM metal processing occurs in a dedicated additive manufacturing build envelope (Wohlers, 2016). Recent studies have presented details on near-net AM and post-processing through traditional machining (Zhu et al., 2013), non-traditional cryogenic machining (Bordin et al., 2017), laser polishing (Rosa et al., 2016) and thermal processes such as Hot Isostatic Pressing – HIP (Qian et al., 2016).

The 3D digital solid model is often created using CAD although reverse engineering methods like 3D laser scanning or MRI/CT techniques can be used to digitally produce an existing part geometry. The solid model will be converted into a standard format suitable for AM processing. Standard formats include .STL, .AMF and .3MF. The processing software will slice the CAD model based on the thickness of the powder layers to create tool path for the laser/e-beam to selectively fuse material in the AM machine envelope. The digital thread associated with AM and corresponding hybrid AM steps is critical in connecting AM processing (CAD) through traditional CNC (Computer Numeric Control) machining and quality control using CMM (Coordinate Measuring Machine). In today’s world of digital manufacturing (Wu et al., 2015), it has been acknowledged that AM is well positioned to drastically impact conventional operations (Birtchnell and Urry, 2016) and time-sensitive production scenarios such as defense (Scheck et al., 2016) and part replenishment in the automotive service sectors (Savastano et al., 2016). Hence, there is a critical need to expand the existing DDM supply chain to incorporate hybrid AM processing which would include traditional manufacturers.

2.3 AM Supply Chain

Since AM emerged as one of the most important disruptive technologies, there has been a continuous stream of research that evaluates its potential benefits to supply chain, logistics management and operation strategies (e.g. location decisions). For instance, Thomas (2015) used operational cost data for a representative mechanical product to identify avenues when AM can potentially improve overall efficiency and reduce total cost. Scott and Harrison (2015) developed a stochastic cost model that determines when AM is an optimal choice (over traditional manufacturing) to the supply chain as a whole and identified raw material cost and demand as the key decision criteria. In the domain of spare parts supply chain, the characterization of cost factors that favor or hinder the adoption of AM are presented in Knofius et al. (2016), Li et al. (2016), Sirichakwal and Conner (2016), Savastano et al. (2016) and Khajavi et al. (2014), among others.

Nyman and Sarlin (2014) summarized the four key principles of AM in the context of supply chain strategies with emphasis on improving the sustainability aspect of an operation through efficient material utilization in AM. Other studies have outlined scenarios where relatively lower fixed costs and small batch sizes production capability will move AM production towards the point of wider adoption (Weller et al., 2015; Berman, 2012; Kleer and Piller, 2013). This transformation to localization of production and sourcing activities is a notion shared among many researchers, including Manners-Bell et al. (2012) who noted that shifting of manufacturing facilities closer to the customer as a result of AM adoption would lead to fewer opportunities for logistics suppliers to be involved in companies' upstream supply chains. They further posited that a major new sector of the logistics industry would emerge to facilitate the storage and movement of raw materials which ‘feed’ the AM equipment and that the home delivery market of these materials would increase.

Petrick and Simpson (2013) addressed how the trend of localization is empowered by direct interactions between consumers and producers. The projected transformation is also discussed in Frazier (2014) who developed a business case for AM and noted that the reduction in logistical footprint, cost, and energy associated with packaging, transportation and storage of spare parts could be significant for large organizations. Walter et al. (2004) contended that AM production through both centralized and decentralized applications will become the basis for new solutions in supply chain management and developed a decision-support model to capture emergent business opportunities arising from AM technology. Reeves (2008) argued that the traditional production-distribution-retail model would shift toward DDM based model where electronic retail will initiate AM manufacturing and distribution activities for the end customer (Achillas et al., 2015).

Despite the promising future and endless potential to simplify supply chain, an adoption of AM to the existing supply chain remains a big challenge (Kieviet and Alexander, 2015). In addition, the literature review reveals a critical gap regarding hybrid AM supply chain, particularly in the lack of studies that use real data to predict demand and location of AM hubs. To the best of our knowledge, this paper is one of the early studies that would incorporate data on the current state of manufacturing cost, transportation, and logistics in the U.S. to develop a quantitative model that identifies potential locations of AM hubs for a DDM supply chain via hybrid-AM.

3. Methodology

This investigation aims to initially develop an uncapacitated facility location model based on demand, location, fixed cost, production cost and transportation cost to identify candidate counties in the United States that could serve as AM hubs for existing machine shops. A schematic representation of the hybrid-AM based DDM supply chain is shown in Figure 2.1. These AM hubs would offer AM services to OEMs, which would provide the post-processing services for the 3D-printed parts.

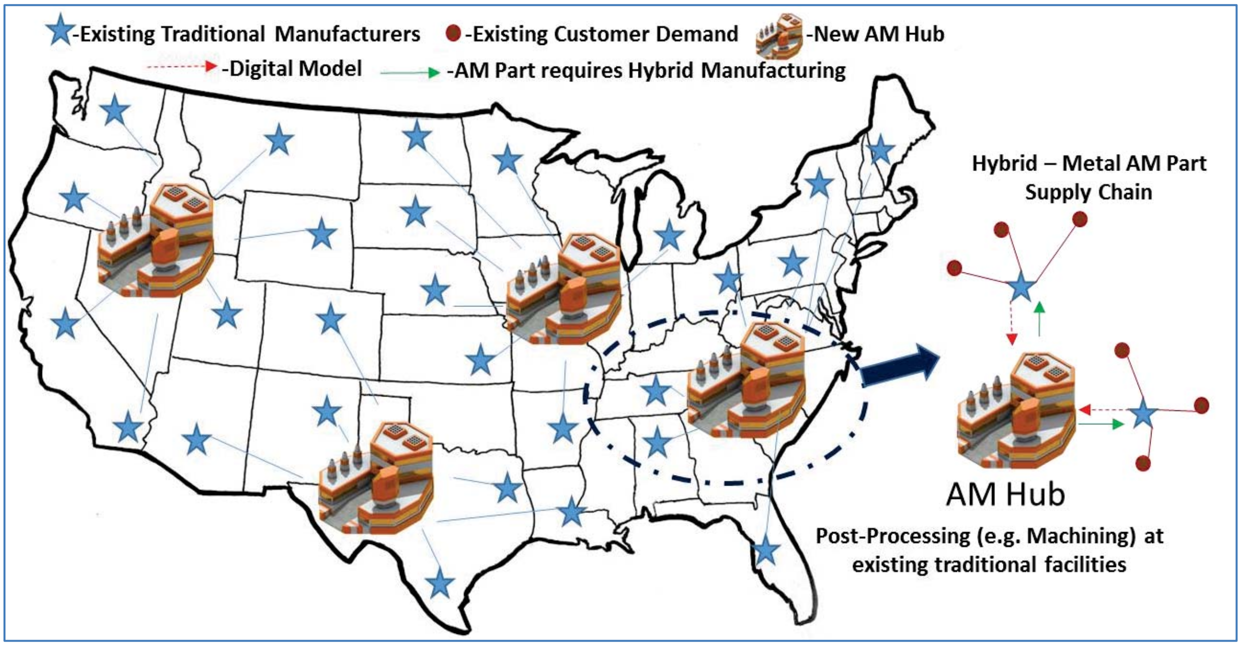


Figure 2.1: Hybrid metal-AM Supply Chain in the U.S.

3.1 Model Parameters

The primary data set used for this analysis was obtained from the North American Industry Classification System (NAICS) Association for NAICS code 332710 (Machine Shops) in 3109 U.S counties. It included the following information for each county: (1) region of U.S., (2) state, (3) number of machine shops, (4) annual sales volume ($M/yr) and (5) number of employees per county. In order to estimate metal AM costs, price quotes for five CAD models of metal AM parts representative of mechanical/aerospace applications, varying complexities, batch sizes and metals were obtained from multiple AM service bureaus in the U.S. The parts and their specifications are presented in Table 2.1. The part design included a part overgrowth of 0.255mm (0.01in) for machining during hybrid processing which resulted in geometric mean unit price of $1,303 per metal AM part based on batch size (1-10 parts/batch), weight (2-5 lbs. per part) and volume (15-30 in^3).

Table 2.2 presents the input and output parameters employed in this study. It is evident that metal hybrid-metal AM is suitable only for low volume, highly complex and customized production runs and is a subset of the current annual demand for metal production (NAICS, 2013). While 82% of metal manufacturers in the U.S estimate that 50% of their products are low volume production (Strong et al., 2017), this study conservatively assumes two scenarios of 5% and 10% of current metal parts as candidates for hybrid-AM. Annual demand for hybrid-AM parts for each county is estimated based on respective annual sales volume and average AM unit price.

Table 2.1: Hybrid metal AM parts surveyed among existing AM service bureaus in the U.S.

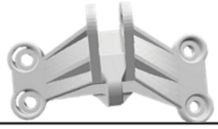
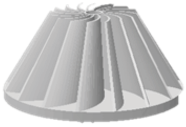
Part Name	Figure	Materials Quoted	Bound Volume (in)	Weight (lbs)	Batch Size
Alcoa Bearing Bracket		Ti64, Inconel 718 Inconel 625, Stainless Steel (316), Direct Metal Titanium (6Al-4V ELI) , and Aluminum (AlSi10Mg)	4.99 x 1.3 x 3.25	3.42	1, 5, 20
GE Bracket			7.15 x 4.22 x 2.61	23.47	
Mounting Bracket			4.28 x 3.87 x 2.24	6.03	
Trip Bracket			4.03 x 2.52 x 2.45	7.42	
Turbine Blade			1.48 x 1.48 x 1	0.3	

Table 2.2: Model parameters for AM hub location problem

	Category	Name	Units	Comments
Inputs	Current Demand	Sales Volume	\$/yr/county	NAICS, 2013
	Existing Facilities	Locations	-	
	AM Parts	Avg. Unit Price	\$/unit	Metal AM service bureaus, see Table 1
		Avg. Weight/part	lb/unit	
		Avg. Batch Size	#/order	
		Avg. Volume/part	in^3/unit	
	Transportation	Shipping Rate	\$/lb/mile or \$/in^3/mile	FedEx (FedEx, 2016)
	Cost Component	Total Fixed Cost	\$M/year	Literature (Baumers, 2012), see Table 3
Outputs		Production Cost		Metal AM production per year at each hub
		Transportation cost		Cost of shipping AM parts from hub to assigned regional manufacturers
		No. of Hubs	-	Required AM hubs in the U.S. based on demand and machine capacity-utilization
	AM Hubs	Location	Cities-County-State	Largest city within the county and nearest metropolitan for AM hub locations in the U.S (U.S. Census Bureau, 2017)
		Allocations	-	Allocations of AM hubs to serve regional manufacturers

Annual operating costs for the hubs were also estimated using data from literature. The fixed cost for a new hub facility with one AM machine at 57% utilization or 5000 hrs/yr (Baumers, 2012) is presented in Table 2.3. Fixed costs for facilities with 1, 2, 5 and 10 AM machines at 90% utilization or 7884 hours a year for both 57% and 90% utilization are presented in Table 2.3 and 2.4 (Baumers, 2012). These differences in machine numbers and utilization rates will be analyzed to account for variations in fixed costs and utilization given that AM hubs could process non-critical prototypes and/or parts that do not require post-processing as part of their product mix. The transportation costs for shipping metal AM parts to traditional manufacturers are based on FedEx ground shipping rates, detailed in Section 3.3.

Table 2.3: Annual fixed cost per AM hub: 1 AM machine at 57% utilization (5,000 hrs/yr)

Fixed Cost	Cost/Year (USD)	Source	Category
Machine Depreciation	$97,702	Baumers 2012; Lindemann et al., 2012; Niklas 2015	Production Overhead
Rent	$34,170	Thomas and Gilbert, 2014	
Utilities	$12,562	Baumers 2012	
Technician Salary	$26,732		Labor Overhead
Indirect Cost/Machine hr	$223,104		Administrative Overhead
Indirect Consumables	$1,540	Thomas and Gilbert, 2014	
Indirect Software Cost	$462	Thomas and Gilbert, 2014; Baumers 2012	
Indirect Hardware Cost	$462	Thomas and Gilbert, 2014; Baumers 2012	
Machine Software Cost	$3,081		Machine Costs
Machine Hardware Cost	$924		
Machine Maintenance	$23,104	Thomas and Gilbert, 2014; Niklas 2015	
Direct Machine Consumables	$2,700	Baumers 2012	
Total Fixed Cost	$340,335		

Table 2.4: Annual fixed cost per AM hub based on AM capacity

Number of AM Machines	Fixed Cost in $M at 90% utilization (7884 hrs/yr)
1	$0.43
2	$0.82
5	$1.99
10	$3.96

As illustrated in Table 2.3, two major categories of results are deducted from this study: Cost (production, shipping) and logistics for AM hubs. Based on longitude and latitude of AM hub locations from the models, city within the county with the highest population and the closest metropolitan city are identified (U.S. Census Bureau, 2017). Locating AM hubs in such cities could facilitate economies of agglomeration in terms of sourcing material, skilled designers, AM operators and other ancillary services.

3.2 Model Assumptions

In order to address this evolving hybrid metal AM supply chain, major assumptions employed in the UFL model are presented in Table 2.5. Other aspects such as time sensitivity of production, skilled AM technician availability, cost of land, state and local taxes, AM investor market and reverse engineering of part designs into CAD models are not considered in this study.

Table 2.5: Assumptions for hybrid metal AM supply chain in the U.S

	Justification
Locations	Existing traditional manufacturers will remain fixed in their current locations and capacities
Demand	A small percentage of recent sales volume is an indicator of the demand for AM metal parts for each county (e.g. 5 and 10 %)
Contagious U.S.	Since FedEx ground shipping rate is applied, District of Columbia (D.C) is included in the study and states of Hawaii and Alaska are not considered along with the U.S. territories
Supply Chain Integration	Hybrid-AM operates in sequence with in-built costs for potential part failure/scrap: Traditional manufacturers receive orders for low production run from customers → CAD models sent to AM hub → AM hub produces 'near net' metal parts → AM hub ships metal parts to traditional facilities who perform hybrid post-processing the part → fulfill orders to customers using existing delivery methods. See Figure 1.

3.3 Uncapacitated Facility Location Model

The logistics based uncapacitated facility location (UFL) model was developed in Matlab using the Matlog Logistics Toolbox (Kay, 2017). With reference to the Equation 2.1 and Figure 2.2, the UFL problem determines the number of new facilities (n) that need to be established to minimize the relevant total logistics costs (TLC), which is the sum of transport costs from each new facility to its allocated existing facilities (TDC) along with the sum of the fixed cost (k) associated with establishing each new facility (nk). While it is usually straightforward to estimate the transport costs from each new facility to each existing facility (c_{ij}), it is difficult to estimate the fixed cost of each new facility because this cost must not include any cost related to the quantity of product produced at the facility. One means of estimating the fixed cost is to perform linear regression on the total production and procurement costs (TPC) of a representative set of existing facilities (N') and then the y-intercept of the line (k) can be used as the fixed cost for the UFL problem since variable production cost (c_p) is not used in UFL model. Thus,

$$TPC = \textstyle\sum_{ieN'} TPC_i = \sum_{ieN'} (k + c_p f_i) \qquad \text{Equation (2.1)}$$

$$TLC = TDC + nk$$
$$= \sum_{ieN} \sum_{jeMi} c_{ij} + nk$$

where *TPC*= total production and procurement cost

N' = set of representative existing plants
k = fixed portion of TPC_i
c_p = variable portion of TPC_i per unit of f
f = annual plant production
TLC = total logistics cost of UFL
TDC = total outbound distribution costs from each NF
n = number of NFs
c_{ij} = distribution cost from NFi to EFj
N = set of NFs
M_i = EFs allocated to NFi

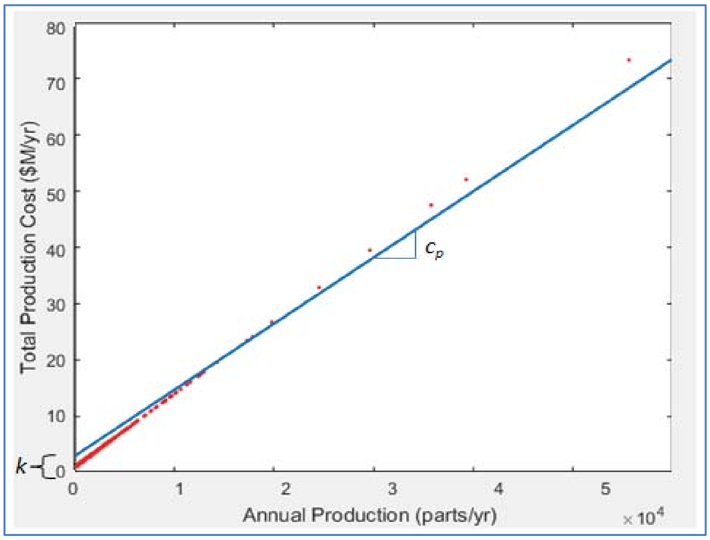


Figure 2.2: Linear Regression Analysis for Fixed Cost

Since the facility being located is a new facility, county data for all of the counties in the U.S. is imported into the model from Matlog. The imported data includes latitude and longitude, population and land area of each county. Population and land area are used to adjust the latitudes and longitudes based on population centroids and land barriers. Based on model parameters noted in Section 3.1, we assume that the standard FedEx large box of dimensions 8.75” x 7.75” x 11.3125” will be used. The transportation costs are then determined using distances based on population centroids and land area, 2016 FedEx ground rates, order weight, order size and order cost. Undiscounted 2016 FedEx Ground rates (FedEx, 2015, 2016) were used to estimate transportation costs. The ground rates cover shipments between 1 and 150 lbs. occurring within the contiguous U.S. The rate is determined by the chargeable weight and distance of the shipment, with the distance falling into one of seven different zones. The chargeable weight is the maximum of a shipment’s actual and dimensional weight. Dimensional weight is the product of a package’s cubic dimensions in inches divided by 166 and is meant to account for the fact that the actual weight of a low-density package would underestimate its utilization of the cubic capacity of a transportation vehicle. The rate includes additional charges for excessive linear dimensions, weight beyond 70 pounds, and declared value in excess of $300 (as in this study). One notable feature of the rate with respect to its use in location procedures is that distance-based zones result in transport charges that remain flat for extensive changes in shipment distance; for example, the first zone (Zone 2) covers all distances up to 150 miles and the other zones have distance ranges from 300 to 400 miles. An uncapacitated facility location heuristic (Daskin, 2011) is then used to choose the hub locations based on the fixed facility costs and transportation costs. The results include the variable y which represents the hub locations, the variable x which represents the hub allocations, and the variable TC which represents total costs of the hubs.

Similar to earlier studies (Yaman, 2009, Lin, 2010, Figueiredo et al., 2013, Daskin 2008), multiple location stages are applied to this problem. Initially, the model will employ uncapacitated AM hubs to determine required capacity and corresponding annual fixed costs for AM hubs. Subsequently, a p-median heuristic (Daskin, 2011) will be applied to account for capacity needs of the AM hubs based on respective regional demand and transportation cost (TPC+TLC). Using metal AM powder bed fusion machine specifications and average metal part volume (Table 1), it is found that one AM machine can print up to about 400 parts per year at 57% utilization and about 630 parts per year at 90% utilization. Since AM hubs under UFL scenario will be dedicated systems, only 90% utilization will be considered. These capacities are used to determine the number of hubs needed from the UFL results based on an average upper bound of $40M to establish a new AM hub. The rationale for this assumption is based on the total investment cost reported for a dedicated AM hub by General Electric - Center for Additive Technology Advancement (CATA) which has been actively pursuing metal AM in 2016 (GE Reports, 2016).

3.4 Sensitivity Analysis

In order to account for demand in metal AM and uncertainty in capacity utilization solely for hybrid-AM, sensitivity analyses are included in this study. Specifically, UFL model was applied for 5 and 10 % hybrid-AM demand rate and at 90% AM utilization rate. In addition, based on the estimated fixed costs from UFL model, varying numbers of AM machines per hub (1, 2, 5, and 10) is considered in the p-median analysis. Additionally, as demand for metal AM grows an Alternative Location Analysis (ALA) heuristic based on Cooper (1963) is applied to compare the effects of adding more capacity at an existing hub when compared to creating a new additional AM hub. Based on historical data on metal AM machines, reduction in AM machine costs of 3.5% (Wohlers, 2016) and 6.7% (IsBisWorld, 2016) is expected in 2017-2018. We also consider a more optimistic scenario of 10% reduction in AM machine costs in the future to study the effects of lower annual fixed hub costs in establishing the hybrid-AM supply chain.

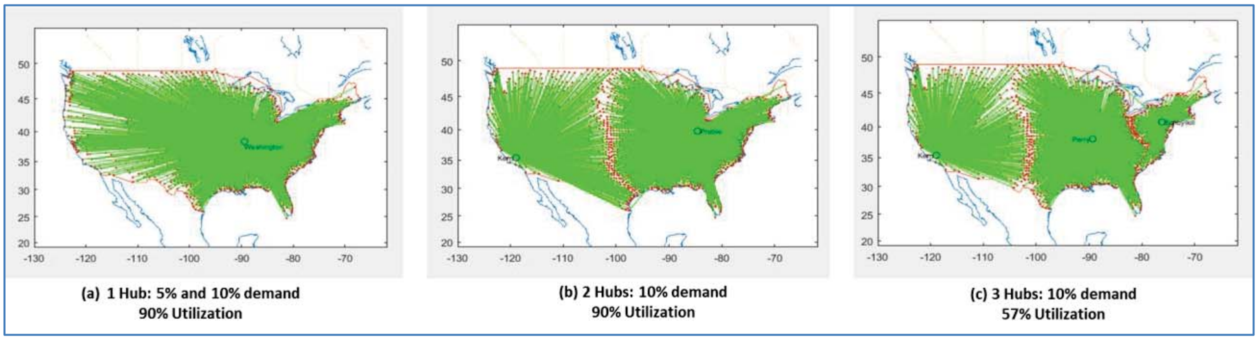
In summary, this study applies recent data on existing traditional machining facilities and cost of metal AM production at varying utilization rates to determine the location and total annual costs for metal AM hubs. Sensitivity analyses are performed to account for the capacity of AM hubs, continued growth in demand for hybrid metal AM and reduced cost of metal AM machines.

4. Results and Analysis

4.1 Uncapacitated Facility Location

A representation of AM hub locations based on UFL model is presented in Figure 3. Additional information on all AM hub locations are included in the Appendix A1-A5 with the following information: county, state, city within the county with the highest population, closest metropolitan city, production and transportation costs, annual number of orders and annual metal AM part production. As shown in Figure 2.3(a), it was found that Washington County in the state of Illinois is the optimal location for establishing an AM hub at 90% utilization rates and AM demands of 5% and 10% which would require

2245 and 4490 AM machines at enormous fixed costs of $0.88B and $1.76B respectively. The city within the county with highest population is Nashville, Illinois and is near St. Louis, Missouri. It was interesting to observe that this county was about 200 miles northwest of Plato, Missouri which is the current population centroid of the U.S (U.S. Census Bureau, 2010).



(a) 1 Hub: 5% and 10% demand
90% Utilization

(b) 2 Hubs: 10% demand
90% Utilization

(c) 3 Hubs: 10% demand
57% Utilization

Figure 2.3: UFL results for Optimal AM hub locations at: (a) Washington County, IL (b) Preble County, OH and Kern County, CA and (c) Schuylkill County, PA, Perry County, IL and Kern County, CA

In the case of reduced AM machine costs (see Table A2), the UFL model showed that Washington County, IL was still the optimal location for AM hubs at both 5 and 10% demand. This indicates that reduction in AM machine cost and increased demand does not affect optimal hub locations when the fixed cost is unconstrained. In addition, when the model is forced to pick more than one hub as shown in Figure 2.3 (b), the optimal locations were identified as: (1) Kern County, CA and Preble County, IL (See Table A3). Similar to a single UFL facility (Table A1 and A2), the fixed cost required was $0.44 B and $1.32B respectively. It was also found that in the unlikely event of 57% utilization rate of dedicated AM hubs (see Table A4), 3 AM hubs across CA, IL and PA were found as optimal locations with a minimum fixed cost of $0.36B, which is still 9 times the upper limit of $40M for fixed costs (Figure 2.3 (c)). It is evident that fixed cost is the main driver behind the location of hubs.

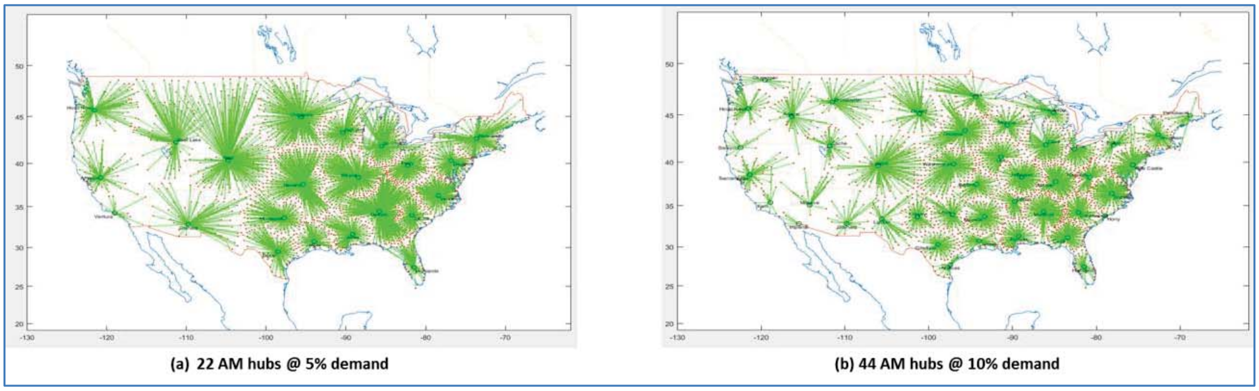
4.2 P-Median

Based on the average part volume per AM metal part (see Table 1) and average metal AM powder bed fusion production rate based on part volume (23-35 cubic centimeters per hour) (Bhavar et al., 2014) it was determined that capacity of 1 AM machine is 630 parts per year at 90% utilization. As shown in Table 2.6, the number of AM hubs was determined when AM hub fixed cost is limited at $40M this resulted in 22 and 44 hubs for 5% and 10% demand for hybrid AM.

Table 2.6: Using UFL results to identify p-Median parameters

Demand	**Utilization**	**# Parts**	**# Machines Needed (Parts/630)**	**Total Fixed Cost ($B)**	**Fixed Cost - Upper Bound ($M)**	**# Hubs**
5%	90%	1,414,400	2245	$0.88	$40	22
10%		2,828,800	4490	$1.76		44

The resulting 22 and 44 number of AM hubs identified using p-median approach are shown in Figure 2.4. Although it is formulated to find AM hubs based on an average of $40M fixed investment per hub, the results are not expected to be exactly $40M since demand allocation to each hub will vary based on location. Hence, the actual fixed cost per hub would vary below or above $40 million per hub; however the $40 million should still remain as the average investment per AM hub for the total supply chain.



(a) 22 AM hubs @ 5% demand

(b) 44 AM hubs @ 10% demand

Figure 2.4: p-Median results for AM hubs based on: (a) 5% demand and (b) 10% demand

Additional information on fixed costs, counties allocated, transportation costs, number of AM machines required and annual production rate at 90% utilization for all AM hubs are included in Appendix A6-A7. The hub counties along with their largest population cities and metropolitan cities are outlined in Tables 2.7-2.8 below and Figure 2.5.

2.7: Locations for 22 AM hubs for 5% demand at 90% utilization

Hub County	State	Largest City	In Proximity To
DeKalb	AL	Fort Payne, AL	Chattanooga, TN
Graham	AZ	Safford, AZ	Phoenix, AZ
Amador	CA	Ione, CA	Sacramento, CA
Ventura	CA	Oxnard, CA	Los Angeles, CA
Weld	CO	Greeley, CO	Denver, CO
Highlands	FL	Sebring, FL	Sebring, FL
Bear Lake	ID	Montpelier, ID	Salt Lake City, UT
Wayne	IL	Fairfield, IL	St. Louis, MO
Neosho	KS	Chanute, KS	Springfield, MO
St. Joseph	MI	Sturgis, MI	South Bend, IN
Chippewa	MN	Montevideo, MN	Minneapolis, MN
Jones	MS	Laurel, MS	Jackson, MS
Rensselaer	NY	Troy, NY	Albany, NY
Vance	NC	Henderson, NC	Raleigh, NC
Perry	OH	New Lexington, OH	Columbus, OH
Hood River	OR	Hood River, OR	Portland, OR
Dauphin	PA	Harrisburg, PA	Philadelphia, PA
Saluda	SC	Saluda, SC	Columbia, SC
Bexar	TX	San Antonio, TX	San Antonio, TX
Jasper	TX	Jasper, TX	Houston, TX
Montague	TX	Bowie, TX	Dallas, TX
Richland	WI	Richland Center, WI	Madison, WI

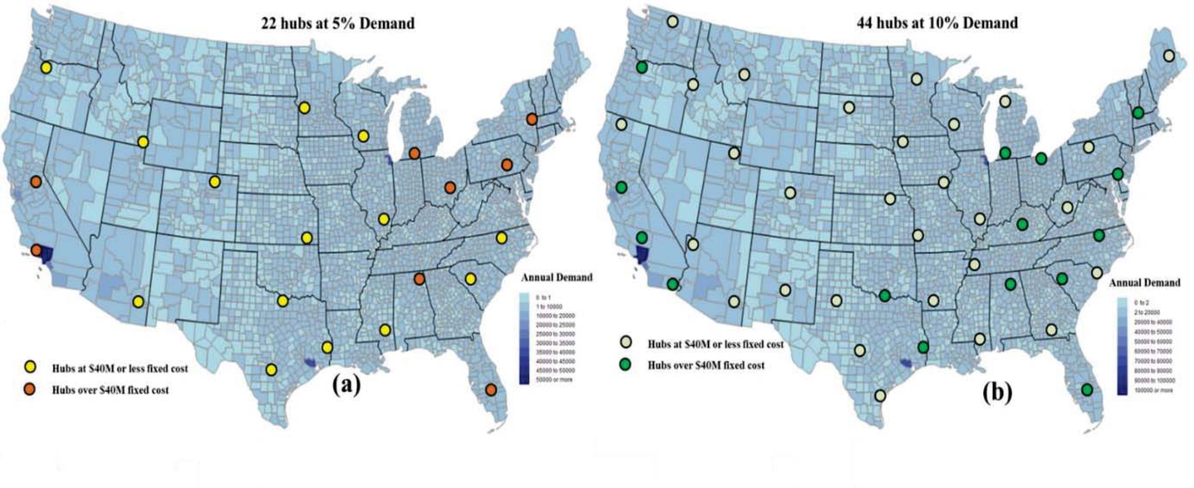


Figure 2.5: Demand density and AM hub locations at: (a) 5% demand and (b) 10% demand

Table 2.8: Locations for 44 AM hubs for 10% demand at 90% utilization

Hub County	State	Largest City	In Proximity To
Marshall	AL	Guntersville, AL	Chattanooga, TN
Graham	AZ	Safford, AZ	Phoenix, AZ
Mohave	AZ	Lake Havasu City, AZ	Las Vegas, NV
Nevada	AR	Prescott, AR	Shreveport, LA
Imperial	CA	El Centro, CA	San Diego, CA
Kern	CA	Bakersfield, CA	Los Angeles, CA
Sacramento	CA	Sacramento, CA	Sacramento, CA
Siskiyou	CA	Yreka, CA	Medford, OR
Summit	CO	Breckenridge, CO	Denver, CO
New Castle	DE	Wilmington, DE	Philadelphia, PA
Highlands	FL	Sebring, FL	Sebring, FL
Cook	GA	Adel, GA	Tallahassee, FL
Adams	ID	Council, ID	Boise, ID
Jefferson	IL	Mount Vernon, IL	St. Louis, MO
Lee	IA	Fort Madison, IA	Iowa City, IA
Osceola	IA	Clarke, IA	Sioux Falls, SD
Washington	KS	Washington, KS	Kansas City, KS
Mercer	KY	Harrodsburg, KY	Lexington, KY
Penobscot	ME	Bangor, ME	Augusta, ME
Cass	MI	Dowagiac, MI	South Bend, IN
Charlevoix	MI	Boyne City MI	Traverse City, MI
Cass	MN	Lake Shore, MN	Minneapolis, MN
Forrest	MS	Hattiesburg, MS	Jackson, MS
Barton	MO	Lamar, MO	Springfield, MO
Broadwater	MT	Townsend, MT	Helena, MT
Lincoln	NM	Ruidoso, NM	Albuquerque, NM
Warren	NC	Norlina, NC	Raleigh, NC
Erie	OH	Sandusky, OH	Sandusky, OH
Love	OK	Marietta, OK	Dallas, TX
Hood River	OR	Hood River, OR	Portland, OR
Potter	PA	Coudersport, PA	Williamsport, PA
Greenwood	SC	Greenwood, SC	Columbia, SC
Horry	SC	Myrtle Beach, SC	Charleston, SC
Dewey	SD	North Eagle Butte, SD	Rapid City, SD
Tipton	TN	Covington, TN	Memphis, TN
Crosby	TX	Crosbyton, TX	Amarillo, TX
Gillespie	TX	Fredericksburg, TX	San Antonio, TX
Jasper	TX	Jasper, TX	Houston, TX
Nueces	TX	Corpus Christi, TX	Corpus Christi, TX
Cache	UT	Logan, UT	Salt Lake City, UT
Windham	VT	Brattleboro, VT	Albany, NY
Okanogan	WA	Omak, Washington	Seattle, WA
Nicholas	WV	Summersville, WV	Charleston, WV
Monroe	WI	Sparta, WI	Madison, WI

Counties and corresponding largest metropolitan cities that were identified for both 5% and 10% demand are highlighted in Table 2.8. The only city to appear in the 5% demand result that did not appear in the 10% demand result was Columbus, Ohio. In the 10% demand result, the closest chosen hub was at Sandusky, Ohio which is 115 miles north of Columbus, Ohio. The results for both demands show that it could be beneficial to initially locate the AM hubs that appear in both scenarios and to continue adding additional AM hubs as demand increases. Figure 2.6 shows that 19 states were chosen multiple times throughout both the 5% and 10% demand rates. Since the tax incentives of investing in manufacturing are determined at the state level, it may be of interest for AM companies or investors seeking to open AM hubs to examine the most chosen hub locations by state.

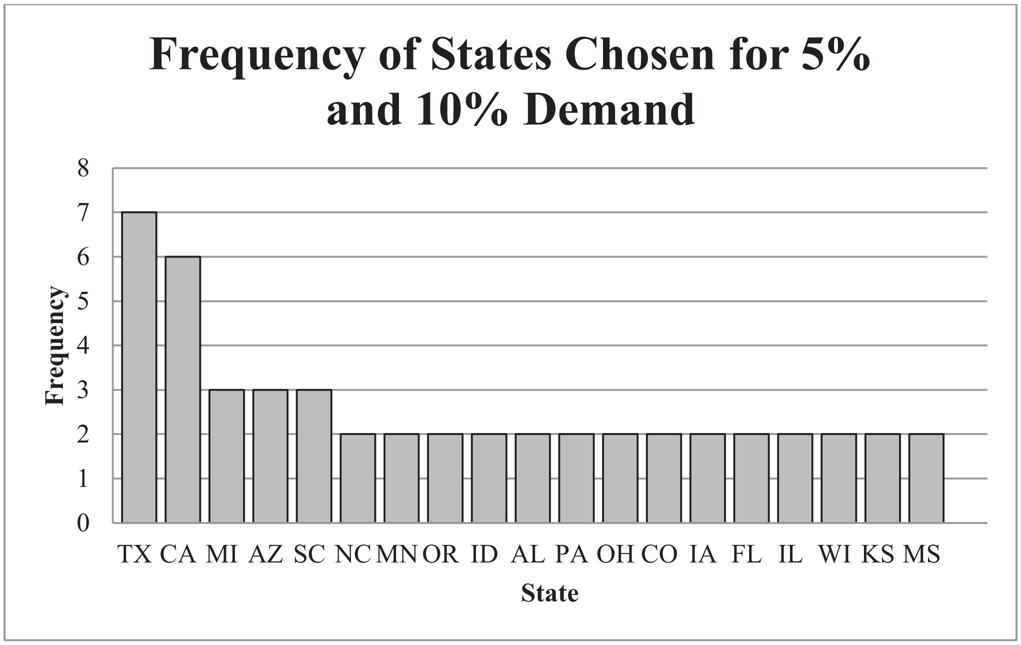


Figure 2.6: Frequency of States Chosen for 5% and 10% Demand

The p-median results for 22 hubs and 44 hubs are employed to develop decision criterion between adding an additional AM hub versus adding more capacity into the existing AM hubs. An alternate location analysis heuristic (Cooper, 1963) was used to locate the 23rd and 45th hub respectively as shown in Table 2.9 and Figure 2.7.

Table 2.9: Sensitivity analysis for adding AM hubs

	5% Demand- 23rd Hub	**10% Demand- 45th Hub**
Hub Location	Catron County, NM	Pima County, AZ
Largest City Within	Reserve	Tucson
In Proximity To	113.11 mi SW of Albuquerque, NM	6.75 mi NW of Tucson, AZ
# of Orders Allocated	6732	12628
Additional Transportation Cost ($M)	$1.49	$1.34
Additional Fixed Cost ($M)	$40.00	$40.00
Total Cost of New Hub ($M)	$41.49	$41.34

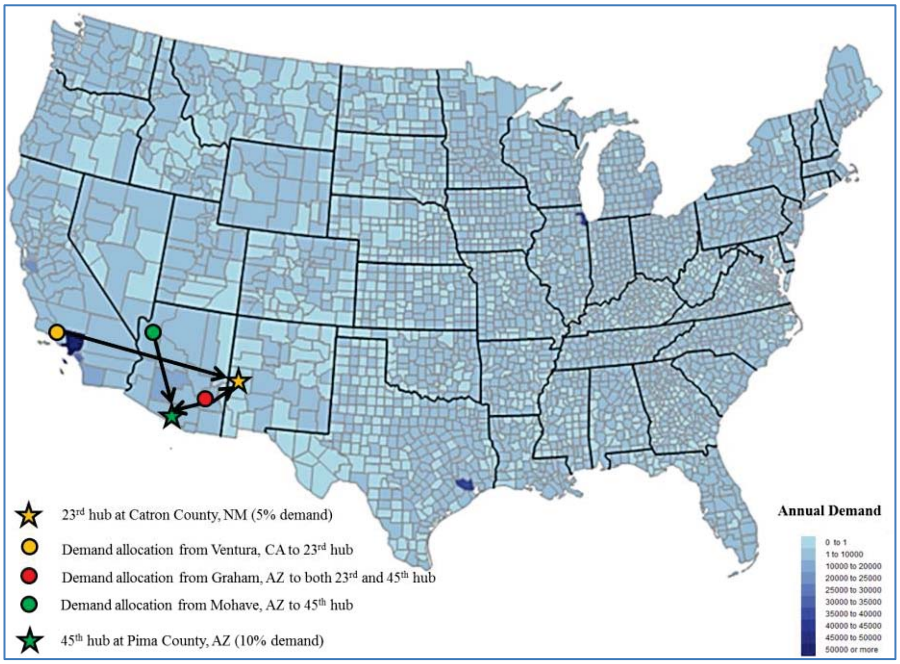


Figure 2.7: Addition of 23rd and 45th AM hubs

Table 2.10: Sensitivity analysis for adding capacity in existing AM hubs

	5% demand	**10% demand**
# of Orders	408,296	816,510
# of New Orders	415,028	829,225
# of Parts	1,414,371	2,828,769
# of New Parts	1437703	2872520
Transportation Cost Total ($M)	$28.39	$44.76
New Transportation Cost Total ($M)	$28.39	$45.46
Production Cost Total ($M)	$1,842.95	$3,685.88
New Production Cost Total ($M)	$1,873.32	$3,742.88
Fixed Cost Total ($M)	$880.00	$1,760.00
New Fixed Cost Total ($M)		
Total ($M)	$2,751.34	$5,490.64
New Total ($M)	$2,781.71	$5,548.34
Difference ($M)	$30.37	$57.70

In order to simulate additional capacity to the existing system, the p-median heuristic was applied by increasing the number of orders in the system. The number of orders allocated in Table 2.10 represents the additional capacity. It was found that it is cheaper to add additional capacity to an existing hub ($30.37 million vs. $41.49 million) for 5% demand, and that as demand grows (10% demand), the opposite would be true ($57.70 million to add additional capacity vs $41.34 to add an additional hub).

5. Discussion

From this study, it is proposed that a widespread adoption of direct digital manufacturing (DDM) through Hybrid-AM could be achieved by strategically locating AM hubs. Such a logistical approach would facilitate consolidation of AM resources in AM hubs which would support existing machine shops and demand for complex metal parts. This would enable easier access to AM technology and related technical support for traditional manufacturers who might not require metal AM for all of their current needs. From an operations and supply chain management perspective, adding AM hubs into the current traditional supply chain could benefit both the advancement of AM and performance of machine shops by improving capacity utilization and product offerings. The integration of AM into traditional manufacturing processes could accelerate the current adoption of metal AM, which have been predominantly within product development and research. For current AM service bureaus seeking to expand locations or an investor looking to establish new AM hub centers, the results provide insights into both locations and associated costs (fixed, annual transportation and production costs). From the UFL results, it is evident that considering one uncapacitated hub is not feasible, i.e. an AM machine with infinite capacity results in exuberant fixed costs in the order of billions of USD and the location is representative of demand centroid as shown in Figure 3. It was also observed that reduction in AM machine costs (10%) does not affect AM hub locations and UFL results are only impacted by lower AM utilization rate (57%). This shows that establishing AM hubs dedicated only for hybrid-AM supply chain is beneficial. Alternatively, based on this study it can be interpreted as an opportunity for existing AM service bureaus that have existing AM capacity to seek traditional manufacturers as potential customers.

As observed in Figure 2.8, both UFL and p-median resulted in annual production cost of 67%, fixed cost of 32% and transportation costs of only 0-1% of the total the average AM hub costs (UFL -1, 2, 3 and p-Median at 22 and 44). It should be noted that initial investment of \$0.8B and \$40M respectively is a critical decision criterion. In addition, this study did not quantify the time-sensitive pricing, i.e. delivery deadlines and "agglomerative" benefits (Audretsch, 1998) due to proximity of AM hubs to traditional manufacturers.

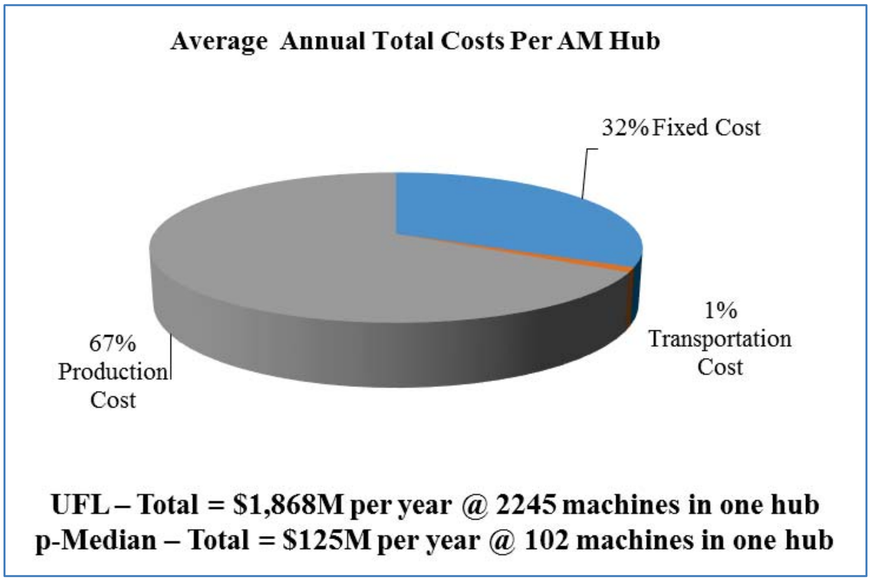


Figure 2.8: Average costs per AM hub (a) UFL and (b) p-median

However, the commonality between UFL and p-median would show prospective AM hub investors to estimate cost components involved in establishing and operating an AM hub. In addition, as noted in Figure 2.9, increase in demand increases required number of AM hubs based on p-median results for each demand and sensitivity analysis based on adding capacity vs. new AM hub (Table 9 and 10). It is observed that about 4-5 hubs should be added for every 1% increase in demand. However, as observed in the first sensitivity analysis, if demand stays closer to 5%, it may be more beneficial to allocate extra capacity to existing hubs.

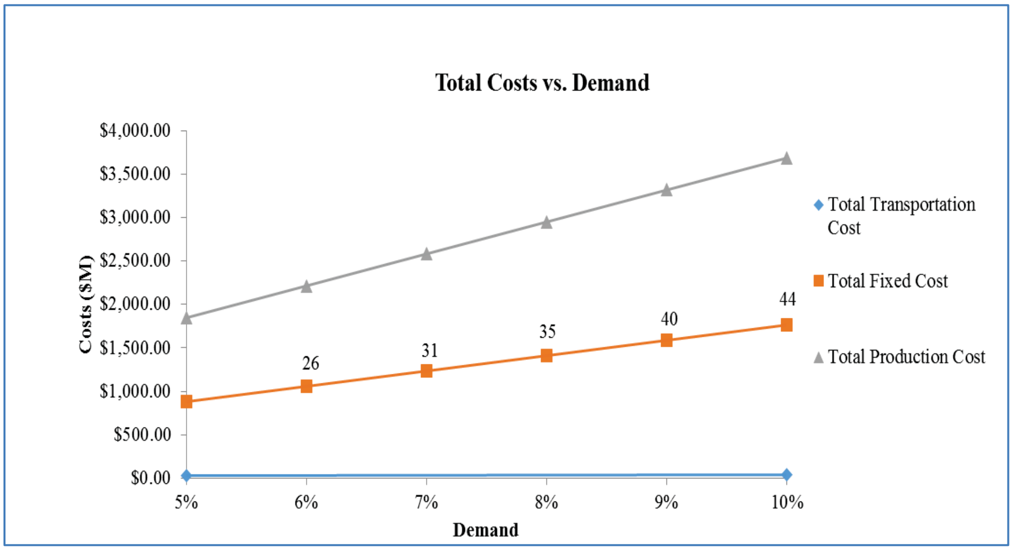


Figure 2.9: Total AM hub costs vs. demand

It should be noted that the transportation costs based on p-median results (FedEx 2016 rates) which varies based on county allocations and production volume is not significantly affected by increase in demand. This shows that both fixed cost and production cost are the main drivers of cost in the AM hub system. It should be noted that although the upper bound for average fixed cost was set at $40M per hub, p-median analysis resulted in 35% of AM hubs over $40M. As shown in Figure 2.5 and Tables A6-A7 in appendix, hubs with over $40M fixed cost were observed to represent regional demand density. Although 35% of AM hubs are over the $40M fixed cost and likewise some are under $40M, the average fixed cost for all the hubs chosen is still $40M.

Existing traditional manufacturers can employ these results based on expected demand to utilize excess machine capacity and identify potential AM hub locations for near-net AM parts. For instance, based on this study manufacturers in regions with higher demand density (e.g. Mid-western and Atlantic states) can explore establishing a shared-user model for an AM hub (e.g. consortium model).

6. Conclusions

This study specifically links existing traditional manufacturers with evolving AM technologies through a classical facility location problem. The location decisions represent the theoretical optimal locations for AM hubs which would offer near-net AM production services for hybrid manufacturing, i.e. post-processing at local machine shops. Establishing such AM infrastructures amongst existing machine shops will mutually benefit both traditional and AM supply chains. Previous research has shown that there is a strong interest among machine shops to take advantage of AM and available excess capacity through hybrid-AM. AM has the ability to alter current traditional manufacturing logistics. Proposed integration of metal AM is beneficial to them by post-processing highly complex parts which have a higher unit margin without the need for special tooling. By centralizing AM resources, every machine shop in the U.S does not have to directly invest in expensive AM systems and associated training, maintenance and R&D efforts.

In summary, increasing demand for complex metal parts could be realized by establishing AM capabilities closer to the existing traditional manufacturing supply chains. This study uses multiple facility location approaches to strategically locate AM hubs that would integrate with traditional machine shops using NAICS data for existing machine shops in the U.S. The major findings from this study are highlighted below:

- Uncapacitated Facility Location (UFL) model results in AM hubs closer to density centroid with extremely high fixed cost irrespective of expected demand
- UFL model is affected only by lower AM utilization rates which indicate opportunities for existing AM hubs to seek regional traditional manufacturers as additional customers
- Reduction in current AM machine costs (10%) does not affect AM hub locations
- Based on p-median results, 22 and 44 AM hubs are recommended for 5 and 10% demand for hybrid AM parts
- Adding capacity to existing hubs is preferred over establishing new AM hubs at current demand levels, i.e. based on current hybrid-AM costs, 22 AM hubs is initially recommended
- Transportation costs do not affect AM hub locations, since the FedEx ground rate was employed in the study. Although it would likely over-represent the actual negotiated transport rates, transportation costs did not play a major role in locating the AM hubs.

Future direction for this research includes: incorporating product-mix models with varying post-processing needs (machining, grinding, polishing, heat treatment, etc.) and time-sensitivity (e.g. aerospace and defense suppliers). In addition, this study did not include local factors such as availability of AM supplies, operators and policies that could affect the proposed AM hubs.

Appendix A.

Table A1: AM hub in Washington County, IL based on UFL model and existing AM machine costs

	5% Demand	10% Demand
	90% Utilization	90% Utilization
AM Machines required	2,245	4,490
Orders per hub:	408,300	816,590
Parts per hub:	1,414,400	2,828,770
Fixed Cost ($B):	$0.88	$1.76
Transportation Cost ($M):	$25.08	$50.16
Production Cost ($M):	$1,842.90	$3,865.90

Table A2: AM hubs based on UFL model and lowered AM machine costs at 90% utilization

	5% Demand			10% Demand		
Reduction in AM Machine Costs	3.5%	6.4%	10%	3.5%	6.4%	10%
AM Machines required	2,245			4,490		
Orders per hub:	408,300			816,590		
Parts per hub:	1,414,400			2,828,770		
Fixed Cost ($B):	$0.87	$0.86	$0.85	$1.75	$1.73	$1.72
Transportation Cost ($M):	$25.08			$50.16		
Production Cost ($M):	$1,842.90			$3,865.90		

Table A3: AM hub in Kern County CA and Preble County OH based on UFL model and existing AM machine costs

	10% Demand	
	90% Utilization	
	Kern, CA	Preble, OH
AM Machines required	1,127	3,363
Orders per hub:	205,020	611,570
Parts per hub:	710,220	2,118,500
Fixed Cost ($B):	$0.44	$1.32
Transportation Cost ($M):	$12.37	$37.01
Production Cost ($M):	$925.42	$2,760.50

Table A4: AM hubs in Kern County CA, Perry County IL and Schuylkill County PA based on UFL model and existing AM machine costs

	10% Demand		
	57% Utilization		
	Kern, CA	Perry, IL	Schuylkill, PA
AM Machines required	1,660	3,577	1,835
Orders per hub:	191,670	413,070	211,860
Parts per hub:	663,960	1,430,900	733,910
Fixed Cost ($B):	$0.36	$1.09	$0.56
Transportation Cost ($M):	$11.53	$24.97	$12.61
Production Cost ($M):	$865.14	$1,864.50	$956.28

Table A5: UFL results hubs and related cities for 5% and 10% demand

Hub County	State	Largest City	In Proximity To
Kern	CA	Bakersfield, CA	Los Angeles, CA
Perry	IL	Du Quoin, IL	St. Louis, MO
Schuylkill	PA	Pottsville, IL	Philadelphia, PA
Preble	OH	Eaton, OH	Dayton, OH
Washington	IL	Nashville, IL	St. Louis, MO

Table A6: P-median results for 5% demand, 22 hubs

Hub County	State	Counties allocated	Transportation Cost ($M)	# Orders	# Parts	Production Cost ($M)	AM Machines Required	Fixed Cost ($M)
DeKalb	AL	377	$1.76	29,616	102,590	$133.68	163	$63.92
Graham	AZ	61	$0.75	12,560	43,510	$56.69	69	$27.13
Amador	CA	62	$1.18	19,892	68,909	$89.79	109	$42.95
Ventura	CA	13	$1.94	33,586	116,340	$151.60	185	$72.49
Weld	CO	208	$0.77	8,688	30,096	$39.22	48	$18.78
Highlands	FL	60	$1.30	23,529	81,505	$106.20	129	$50.79
Bear Lake	ID	95	$1.89	6,310	21,858	$28.48	35	$13.65
Wayne	IL	265	$0.78	15,266	52,883	$68.91	84	$32.97
Neosho	KS	258	$1.27	15,032	52,074	$67.85	83	$32.47
St. Joseph	MI	159	$1.79	34,798	120,540	$157.07	191	$75.11
Chippewa	MN	232	$0.78	9,712	33,642	$43.84	53	$20.99
Jones	MS	124	$1.30	8,647	29,953	$39.03	48	$18.69
Rensselaer	NY	141	$1.82	50,984	176,620	$230.13	280	$110.03
Vance	NC	188	$0.82	16,429	56,912	$74.16	90	$35.48
Perry	OH	142	$1.30	19,582	67,835	$88.39	108	$42.28
Hood River	OR	84	$1.20	14,141	48,987	$63.83	78	$30.54
Dauphin	PA	116	$1.81	32,223	111,620	$145.45	177	$69.55
Saluda	SC	107	$0.81	11,332	39,254	$51.15	62	$24.48
Bexar	TX	103	$1.27	10,369	35,918	$46.80	57	$22.40
Jasper	TX	75	$1.80	12,732	44,105	$57.47	70	$27.50
Montague	TX	129	$0.77	14,150	49,018	$63.87	78	$30.56
Richland	WI	110	$1.28	8,719	30,202	$39.35	48	$18.84
	Total	3109	$28.39	408,296	1,414,371	$1,842.95	2245	$881.60

Table A7: P-median results for 10% demand, 44 Hubs

Hub County	State	Counties allocated	Transportation Cost ($M)	# Orders	# Parts	Production Cost ($M)	AM Machines Required	Fixed Cost ($M)
Marshall	AL	154	$2.15	36,300	125,580	$163.64	199	$78.25
Graham	AZ	21	$0.98	16,600	57,471	$74.89	91	$35.83
Mohave	AZ	16	$0.42	7,110	24,641	$32.11	39	$15.38
Nevada	AR	101	$2.19	10,700	37,153	$48.41	59	$23.17
Imperial	CA	6	$0.99	28,500	98,703	$128.61	157	$61.50
Kern	CA	11	$0.43	37,000	128,170	$167.00	203	$79.86
Sacramento	CA	48	$2.38	35,300	122,340	$159.40	194	$76.23
Siskiyou	CA	13	$1.02	2,110	7,308	$9.52	12	$4.56
Summit	CO	124	$0.43	15,300	52,881	$68.90	84	$32.97
New Castle	DE	125	$2.22	104,000	360,910	$470.26	573	$224.81
Highlands	FL	34	$1.08	41,400	143,430	$186.89	228	$89.36
Cook	GA	122	$0.46	14,000	48,370	$63.03	77	$30.16
Adams	ID	45	$2.36	3,730	12,931	$16.85	21	$8.09
Jefferson	IL	143	$1.03	18,100	62,709	$81.71	100	$39.09
Lee	IA	100	$0.44	10,400	35,916	$46.80	57	$22.40
Osceola	IA	145	$0.44	8,420	29,168	$38.01	46	$18.20
Washington	KS	145	$2.22	12,800	44,461	$57.93	71	$27.73
Mercer	KY	163	$1.06	23,900	82,621	$107.65	131	$51.49
Penobscot	ME	20	$0.47	3,800	13,151	$17.14	21	$8.22
Cass	MI	119	$2.20	64,300	222,650	$290.12	353	$138.70
Charlevoix	MI	48	$1.06	3,200	11,094	$14.46	18	$6.94
Cass	MN	70	$0.44	11,000	38,188	$49.76	61	$23.82
Forrest	MS	86	$0.88	14,800	51,303	$66.85	81	$31.99
Barton	MO	74	$0.56	9,460	32,755	$42.68	52	$20.43
Broadwater	MT	49	$0.14	2,360	8,172	$10.65	13	$5.12
Lincoln	NM	35	$0.37	6,310	21,865	$28.49	35	$13.65
Warren	NC	156	$1.69	28,600	99,102	$129.13	157	$61.76
Erie	OH	69	$1.55	26,100	90,414	$117.81	144	$56.35
Love	OK	80	$1.47	24,800	86,032	$112.10	137	$53.62
Hood River	OR	46	$1.26	21,300	73,819	$96.19	117	$46.01
Potter	PA	46	$1.06	17,800	61,747	$80.46	98	$38.49
Greenwood	SC	99	$1.27	21,500	74,328	$96.85	118	$46.33
Horry	SC	9	$0.20	3,400	11,763	$15.33	19	$7.36
Dewey	SD	73	$0.12	1,930	6,682	$8.71	11	$4.19

Tipton	TN	62	$0.42	7,080	24,515	$31.94	39	$15.30
Crosby	TX	59	$0.23	3,840	13,292	$17.32	21	$8.31
Gillespie	TX	65	$0.85	14,300	49,488	$64.48	79	$30.86
Jasper	TX	49	$1.30	22,000	76,203	$99.29	121	$47.49
Nueces	TX	21	$0.36	6,020	20,863	$27.19	33	$13.03
Cache	UT	36	$0.48	8,130	28,160	$36.69	45	$17.57
Windham	VT	70	$2.67	45,000	155,860	$203.09	247	$97.11
Okanogan	WA	12	$0.30	5,000	17,306	$22.55	27	$10.81
Nicholas	WV	70	$0.39	6,610	22,909	$29.85	36	$14.30
Monroe	WI	70	$0.72	12,200	42,344	$55.17	67	$26.41
	Total	3109	$44.76	816,510	2,828,769	$3,685.88	4490	$1,763.25

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CHAPTER 3: LOCATING AM HUBS USING A TWO-STAGE FACILITY LOCATION APPROACH

1. Introduction

The heat treatment process is defined as "to subject a metal or alloy to controlled heating and cooling to improve hardness or other properties; a controlled process used to alter the microstructure of metals and alloys such as steel and aluminum to impart properties which benefit the working life of a component, for example increased surface hardness, temperature resistance, ductility and strength" (Bodycote, 2017). Heat treatment is an essential step in the traditional manufacturing process, most often following procedures such as welding, known as post-weld heat treatment (Chen et al., 2006). However, the applications for heat treatment are growing as new metal technologies emerge, such as additive manufacturing (AM). In additive manufacturing, the process of joining materials to make objects from 3D model data, usually layer upon layer (ASTM, 2012), metal parts must be heat treated after they are built (Wohlers, 2015). Metal AM parts are heat treated to remove internal stresses and after the parts are cleaned and excess material is removed, the post-thermal processes impart better mechanical properties in the parts (Wohlers, 2016). In other studies, the need for finishing and post-processing including heat treatment for metal AM parts has been noted (Petrick and Simpson, 2013). Since heat treatment is often required in both traditional machining and metal additive manufacturing processes, it is important to consider it when planning integrated manufacturing, such as combining AM with traditional manufacturing, otherwise known as hybrid-AM.

According to previous research, a hybrid-AM supply chain ecosystem could be utilized to allocate fabrication of metal parts to additive manufacturing hubs and allocate the post-processing (machining, grinding, heat treat, etc.) to traditional manufacturers in order to decrease the effects of supply chain disruption (Strong et al., 2016). Near-net metal AM parts would flow from multiple additive manufacturing hubs for production into the traditional facilities for secondary processing. Since most mechanical and aerospace applications require superior surface finish and part accuracies, improving material property via heat treatment and other thermal processes such as hot isostatic pressing is necessary (Strong et al., 2016). Previous research has also been done to strategically locate the proposed additive manufacturing hubs with respect to the locations of existing machine shops in the US, but the analysis did not consider heat treatment (Strong et al., 2017).

This study expands on previous research to study the effects of adding locations of existing heat treatment facilities in the US as a third step in the hybrid-AM supply chain. Since traditional shops usually outsource the heat treatment step to specialized heat treatment facilities, the same approach can be considered for this study. Two stages of p-median models will be applied to strategically place AM hubs to connect both existing machine shops and heat treatment facilities in the US. The results of this two-stage facility location model will be compared to previous results that do not include heat treatment. The results are also analyzed to realize the impacts and barriers of locating the AM hubs, with respect to demand, fixed costs and transportation costs. This paper proposes several implications such as allowing prospective AM service companies to consider future locations with respect to multiple variables (machine shops and heat treatment facilities). The model can help with decision making and allow both machine shops and heat treatment centers to develop a better understanding of the potential role they can play in the hybrid-AM supply chain. The costs are further analyzed with regards to sensitivity in demand.

The work in this paper is organized as follows. In Section 2, the current literature review on facility location, hybrid AM and heat treatment are presented. The methodology for the model is outlined in Section 3, followed by the results obtained from the model in Section 4, a discussion based on the results and insights in Section 5, and conclusions in Section 6.

2. Literature Review

2.1 Heat Treatment Processes

Defined by Bodycote (2017), heat treatment is "a process used to subject a metal or alloy to controlled heating and cooling to improve hardness or other properties". It is considered a controlled process and is "used to alter the microstructure of metals and alloys such as steel and aluminum". This helps to improve the material and structural properties of the part which benefit the overall life cycle of a component. Metal alloys undergo heat treatment to increase hardness (Kempen et al., 2012), strength and ductility (Brandl et al., 2009).

Heat treatment also includes stress relieving, defined by Bodycote (2017) as "a process used on metal products in order to minimize residual stresses in the structure". This helps to eliminate any risk of change to material shape and part dimensions for final use. Machining and cutting can cause a buildup of material which can cause these undesirable changes. Stress relieving will minimize these stresses and risk of dimension changes. Parts with tight tolerances, and are going to be further processed are most often stress-relived. The process usually occurs after machining and before final finishing. (Bodycote, 2017).

Another form of heat treatment is known as hot isostatic pressing (HIP). HIP has been used to improve material properties significantly and increase mechanical properties (Lindemann et al., 2012). Bodycote (2017) describes Hot isostatic pressing (HIP) as a form of heat treatment that uses high pressure to improve material properties. Pressure is applied by a gas such as argon. In industry, castings for critical applications use HIP to eliminate internal micro porosity. This improves mechanical properties by removing defects. Hot isostatic pressing also helps to bind multiple materials together and even convert powder to solid and dense components resulting in superior physical properties than traditional manufacturing technologies. Carroll et al., (2015) found that researchers have mainly used hot isostatic pressing to homogenize microstructural features. It was noted that "improvements in ductility are generally only obtained with post-fabrication heat treatments" (Carroll et al., 2015).

2.2 Heat Treatment in AM

Wohlers Report (2016) states that metal parts must be heat treated after they are built to remove internal stresses. After the parts are cleaned and excess material is removed, post-thermal processes are often used to relive stress and impart better mechanical properties in the parts. A number of thermal processing solutions can be used, and a variety of factors determine which method is best depending on part material, size, geometric features, the mechanical properties required, and the AM process that was used to create the parts. The first step is usually a stress relief, followed by hot isostatic pressing. Finally, the part is precipitation hardened and solution heat treated to strengthen, harden or provide homogeneity to the material. Thermal processing will almost always change the grain structure of the material and thus provide different mechanical properties from as-built parts. Once parts have been through the necessary heat treat cycles, then the supports can be removed. For parts that require tighter tolerances or a superior surface finish, post-machining may be necessary (Wohler's Report, 2016).

To improve the strength of parts produced by AM, post processing such as machining, heat treatment and hot isostatic pressing is applied (Osakada and Shiomi, 2006). In Spierings et al., (2012), metal specimens printed by a selective laser melting (SLM) laser were heat treated. Heat treatment and stress relief is necessary after additive manufacturing fabrication, especially for parts with large solid sections and for critical components used in applications under a dynamic load (Wathle et al., 2014). Wathle et al., (2014) discusses how AM microstructures can be changed or optimized by applying heat treatments. Since AM is a layer by layer process, a crystallographic texture may be present in a certain direction if no heat treatment is applied. Heat treatments such as HIP and stress reliving have resulted in larger strut density, ductility yield stress, stiffness and a decrease in strain fracture (Wautle et al., 2014). Post heat treatment is regarded as a must do process to transform microstructures while reducing thermal stresses at the same time. During AM, the previously deposited layers are always affected by the thermal effect from the heating, melting and solidification of the successive layers (Xu et al., 2014).

The work presented in Vrancken et al., (2012) shows that optimization of mechanical properties via heat treatment of parts produced by AM is profoundly different compared to conventionally processed parts. Furthermore, these treatments allow the reduction of thermal stresses that have been built up during the process. In Gasser at al., (2010) tensile testing samples of Inconel 718 were manufactured, heat treated and tested. It was demonstrated that the static mechanical properties of SLM manufactured Inconel 718 are equal or even better than those of conventionally processed Inconel 718. The surface roughness of SLM-manufactured parts was also improved. There are a few cases in which parts do not require heat treatment. In directed metal laser sintering (DMLS) parts, it has been found that parts in the as-built state, i.e. non heat treated condition, are already at their maximum hardness and strength (Manfredi et al., 2013). In this work, we assume that all of the metal AM parts require heat treatment and machining operations to achieve functionality. Work by Petrick and Simpson (2013) states that “metallic parts produced with 3D printing methods frequently require additional heat treatment or other finishing and post-processing steps to achieve specified tolerances”. A major challenge in industry is how AM parts will be qualified. There is currently no AM technology capable of creating net shape parts. The integration of AM within a supportive production system, such as current traditional manufacturing production systems, is needed for implementation success. Heat treatment, finishing and measuring processes are required for quality production parts (Mellor et al., 2014). It is especially important for mechanical and critical components. Biamino et al., (2011) states that specimens are heat treated in order to reach the mechanical properties that make alloys appropriate for aerospace application. In industry, the landing gear for aircraft is heat treated to strengths up to 1800–1900 MPa (Williams and Starke, 2003).

3. Methodology

This investigation aims to define a supply chain system that links AM hubs with both machine shops and heat treatment centers in the U.S. using a two-stage p-median approach. The AM hubs would offer additive manufacturing services for machine shops and heat treatment centers would provide the appropriate material treatment for machine shops, which would then provide the post-processing services. A schematic representation of the hybrid-AM supply chain with heat treatment is shown in Figure 3.1.

Figure 3.1: Hybrid metal-AM Supply Chain in the U.S.

3.1 Model Parameters

The primary data set used for this analysis was provided by the North American Industry Classification System (NAICS) Association for NACIS codes 332710 (Machine Shops) and 332811 (Heat Treatment Facilities) in 3109 U.S counties. The data set included the following information for each county: (1) region of U.S., (2) state, (3) number of machine shops and heat treatment facilities in each county, (4) annual sales volume ($M/yr) and (5) number of employees per county. Since only the machine shops interact with the end-use customer, the demand will be generated at the machine shop level of the supply chain. The same method used in Strong et al., (2017) was applied to estimate demand using the quotes of the five sample CAD drawings of AM metal parts for mechanical/aerospace applications of various complexities and metal materials. The average unit price of $1,303 per metal AM part was quoted for batch sizes with batch size (1-10 parts/batch), weight of 2-5 lbs. per part and volume of 15-30 in^3. In this analysis, it is also assumed that the build plate stays attached to the metal AM part throughout heat treatment, and will eventually get machined off at the machine shops. This increases part weight by an additional 15 lbs. assuming that the build plate is made of Ti64 and is 250 x 250 x 25 mm. Table 3.1 presents the inputs and outputs for the study.

Table 3.1: Model parameters for AM hub location problem

	Category	Name	Units	Comments
Inputs	Current Demand	Sales Volume	\$/yr/county	NAICS, 2013
	Existing Facilities	Locations	-	
	AM Parts	Avg. Unit Price	\$/unit	Metal AM service bureaus, see Table 1
		Avg. Weight/part	lb/unit	
		Avg. Batch Size	#/order	
		Avg. Volume/part	in^3/unit	
	Transportation	Shipping Rate	\$/lb/mile or \$/in^3/mile	FedEx (FedEx, 2016)
	Cost Component	Total Fixed Cost	\$M/year	Literature (Baumers, 2012), see Table 3
Outputs		Production Cost		Metal AM production per year at each hub
		Transportation cost		Cost of shipping AM parts from hub to assigned regional manufacturers
		No. of Hubs	-	Required AM hubs in the U.S based on demand and machine capacity-utilization
	AM Hubs	Location	Cities-County-State	Closest city with minimum 50,000 populations for AM hub locations in the U.S (U.S. Census Bureau, 2017)
		Allocations	-	Allocations of AM hubs to serve regional manufacturers

3.2 Model Assumptions

The model includes the following assumptions as found in Table 3.2.

Table 3.2: Assumptions for hybrid metal AM supply chain in the U.S with heat treatment

	Justification
Locations	Existing traditional manufacturers will remain fixed in their current locations and capacities
Demand	Recent sales volume is an indicator of the demand for AM metal parts for each county
Contagious U.S.	Since FedEx ground shipping rate is applied, District of Columbia (D.C) is included in the study and states of Hawaii and Alaska are not considered along with the U.S. territories
Supply Chain Integration	Hybrid-AM operates in sequence with in-built costs for potential part failure/scrap: Traditional manufacturers receive orders for low production run from customers → CAD models sent to AM hub → AM hub produces 'near net' metal parts → AM hub ships metal parts to heat treatment facilities → Heat treatment facilities ship part to traditional facilities who perform hybrid post-processing the part → fulfill orders to customers using existing delivery methods.

This study will also follow the assumed average fixed cost of $40 million per hub and that all metal AM parts require heat treatment and machining operations to achieve functionality (Strong et al., 2017).

3.3 Two-Stage P-Median

A two-stage p-median model (Daskin, 2011) is used to solve the facility location problem. The first stage involves allocating machine shops to heat treatment shops in order to aggregate demand at the heat treatment level, since demand is currently known at the machine shop level. To do this, a cost matrix *jk* is formed based off the FedEx transportation costs for a 263 x 2,162 matrix given 263 heat treatment counties and 2,162 machine shop counties exist in the continental US. To allocate demand from machine shops to heat treatment, we set P equal to all 263 heat treat counties as seen in Equation 3.1.

$$\text{Min} \sum_{j=1}^{n} \sum_{k=1}^{n} x_{jk} \ c_{jk} \qquad \text{Equation 3.1}$$

Such that

$\sum_{j=1}^{n} Y_j = 263$

$\sum_{k=1}^{n} X_{jk} = 1$

$X_{jk} - Y_j \leq 0$

$X_{jk} \in \{0,1\}$

$Y_j \in \{0,1\}$

After demand is aggregated at the heat treatment level, another p-median model is run to solve the second half of the facility location problem. To do this, another cost matrix ij is formed based off the FedEx transportation costs for a 3,109 x 263 matrix given that there are 3,109 counties in the continental US and 263 heat treatment counties. We set P equal to 22 at the 5% demand rate and 44 at the 10% demand rate based off of Strong et al., (2017). Since the demand and fixed costs remain the same, the same numbers of hubs needed are assumed. The model is presented in Equation 3.2

$$\text{Min} \sum_{i=1}^{n} \sum_{j=1}^{n} x_{ij} \ c_{ij} \qquad \text{Equation 3.2}$$

Such that

$\sum_{i=1}^{n} Y_i = 22$ or 44

$\sum_{j=1}^{n} X_{ij} = 1$

$X_{ij} - Y_i \leq 0$

$X_{ij} \in \{0,1\}$

$Y_i \in \{0,1\}$

4. Results and Analysis

The p-median model was run in the Matlog toolbox for Matlab (Kay, 2017) for the 5% and 10% demand scenarios. The results are shown in Figure 2.3.

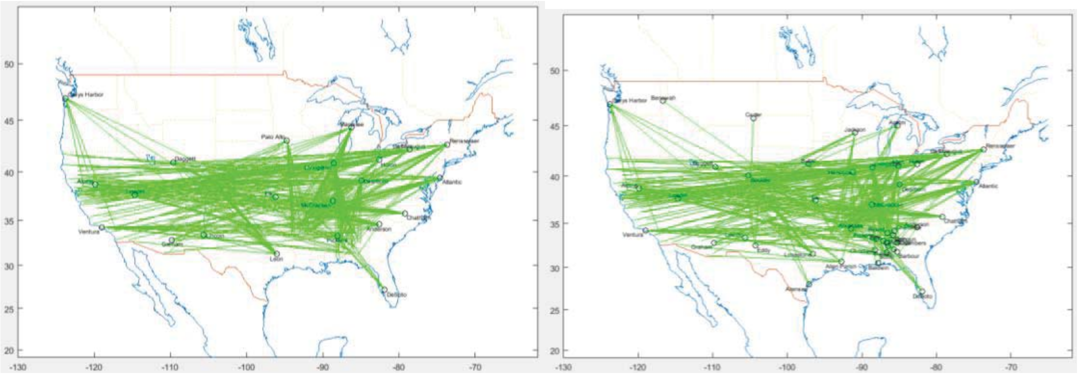

Figure 3.2: p-Median results for AM hubs based on: (a) 5% demand and (b) 10% demand

It is observed that the hub locations chosen are more concentrated in location than in Strong et al., (2017) without the heat treatment step. This is because there are less heat treatment shop counties (263) in the US than machine shop counties (2,162). The model chooses hubs that minimize the distances and costs to fewer numbers of counties while still satisfying the demand. Another effect observed occurred in the 10% demand model. Only 38 out of 44 hubs chosen were allocated heat treatment counties, and 35 were allocated demand. However, the allocations of the 38 hubs added up to the 263 heat treatment counties and the demand allocated to the 35 hubs added up to the total number of orders required. Due to the model satisfying the demand with less hubs than required according to fixed cost constraints, adding the heat treatment step into the supply chain could be considered a cost savings for total annual fixed cost given that the investment that would be planned for those 9 hubs could be reallocated into the remaining 35 hubs.

The hub counties chosen along with their state, largest city and closest metropolitan city are shown in Tables 3.3-3.4 for 5% and 10% demand.

Table 3.3: Locations for AM hubs for 5% demand

Hub County	State	Largest City Within	In Proximity To
Pickens	AL	Aliceville, AL	Tuscaloosa, AL
Graham	AZ	Safford, AZ	Phoenix, AZ
Alpine	CA	Markleeville, CA	Sacramento, CA
Ventura	CA	Oxnard, CA	Los Angeles, CA
DeSoto	FL	Arcadia, FL	Sebring, FL
Livingston	IL	Streator, IL	Chicago, IL
Dearborn	IN	Lawrenceburg, IN	Cincinnati, OH
Palo Alto	IA	Emmetsburg, IA	Sioux Falls, SD
Elk	KS	Howard, KS	Wichita, KS
McCracken	KY	Paducah, KY	Nashville, TN
Manistee	MI	Manistee, MI	Traverse City, MI
Lincoln	NV	Caliente, NV	Las Vegas, NV
Atlantic	NJ	Egg Harbor, NJ	Philadelphia, PA
Lincoln	NM	Ruidoso, NM	Albuquerque, NM
Cattaraugus	NY	Olean, NY	Buffalo, NY
Rensselaer	NY	Troy, NY	Albany, NY
Chatham	NC	Siler City, NC	Raleigh, NC
Huron	OH	Norwalk, OH	Sandusky, OH
Anderson	SC	Anderson, SC	Greenville, SC
Leon	TX	Buffalo, TX	Houston, TX
Daggett	UT	Manila, UT	Salt Lake City, UT
Grays Harbor	WA	Aberdeen, WA	Seattle, WA

Table 3.4: Locations for AM hubs for 10% demand

Hub County	**State**	**Largest City Within**	**In Proximity To**
Autauga	AL	Prattville, AL	Montgomery, AL
Barbour	AL	Eufaula, AL	Columbus, GA
Bibb	AL	Brent, AL	Tuscaloosa, AL
Choctaw	AL	Butler, AL	Jackson, MS
Graham	AZ	Safford, AZ	Phoenix, AZ
Arkansas	AR	Stuttgart, AR	Little Rock, AR
Alpine	CA	Markleeville, CA	Sacramento, CA
Ventura	CA	Oxnard, CA	Los Angeles, CA
Boulder	CO	Boulder, CO	Denver, CO
DeSoto	FL	Arcadia, FL	Sebring, FL
Benewah	ID	St. Maries, ID	Spokane, WA
Hancock	IL	Hamilton, IL	St. Louis, MO
Livingston	IL	Streator, IL	Chicago, IL
Allen	IN	Fort Wayne, IN	Fort Wayne, IN
Dearborn	IN	Lawrenceburg, IN	Cincinnati, OH
Elk	KS	Howard, KS	Wichita, KS
McCracken	KY	Paducah, KY	Nashville, TN
Allen Parish	LA	Oakdale, LA	Lafayette, LA
Antrim	MI	Elk Rapids, MI	Traverse City, MI
Carter	MT	Ekalaka, MT	Rapid City, SD
Butler	NE	David City, NE	Omaha, NE
Lincoln	NV	Caliente, NV	Las Vegas, NV
Atlantic	NJ	Egg Harbor, NJ	Philadelphia, PA
Eddy	NM	Carlsbad, NM	El Paso, TX
Lincoln	NM	Ruidoso, NM	Albuquerque, NM
Cattaraugus	NY	Olean, NY	Buffalo, NY
Rensselaer	NY	Troy, NY	Albany, NY
Chatham	NC	Siler City, NC	Raleigh, NC
Huron	OH	Norwalk, OH	Sandusky, OH
Anderson	SC	Anderson, SC	Greenville, SC
Aransas	TX	Rockport, TX	Corpus Christi, TX
Limestone	TX	Mexia, TX	Dallas, TX
Daggett	UT	Manila, UT	Salt Lake City, UT
Grays Harbor	WA	Aberdeen, WA	Seattle, WA
Jackson	WI	Black River Falls, WI	Minneapolis, MN

The counties and major cities chosen for both 5% and 10% demand are highlighted. It is observed that there are more counties chosen twice when heat treatment is added into the supply chain when compared to the results in Chapter 2 without heat treatment. This is also because there are 263 heat treatment counties and thus there is a greater opportunity for the optimal locations to be consistent for different levels of demand. The chosen hub locations are also presented in Figure 3.3 respective to the demand at the machine shop level, since these hub locations are optimizing both stages of the model.

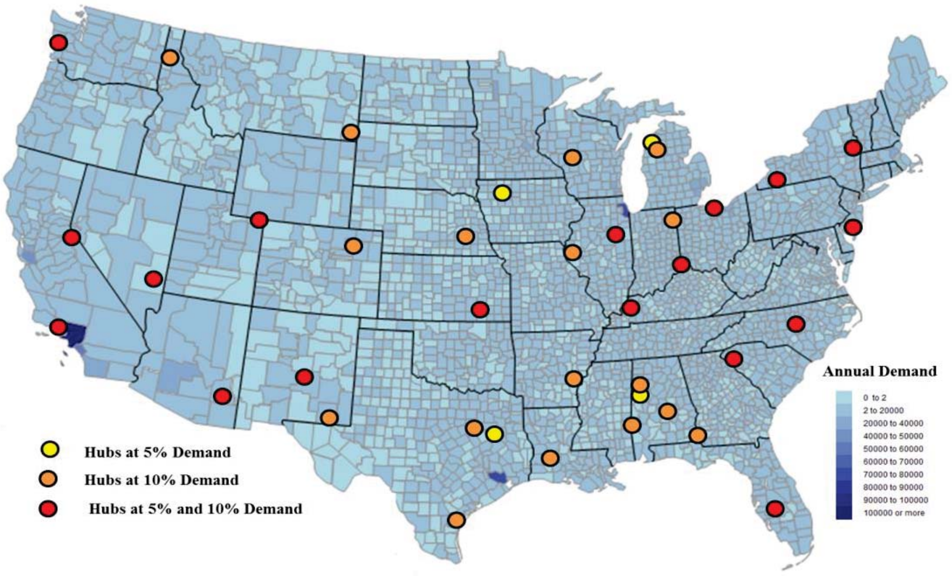

Figure 3.3: Chosen hub locations respective to machine shop demand

As highlighted in Strong et al., (2017) AM investors or AM companies wishing to invest into AM hub centers may also want to consider hubs chosen at the state level. Since investment incentives, taxes and policies are put in place by the state, Figure 3.4 lists the frequencies of states chosen at both 5% and 10% demand. It would be of interest for those AM investors to contact the states including the optimal counties chosen to develop a plan for expanding AM in those respective states.

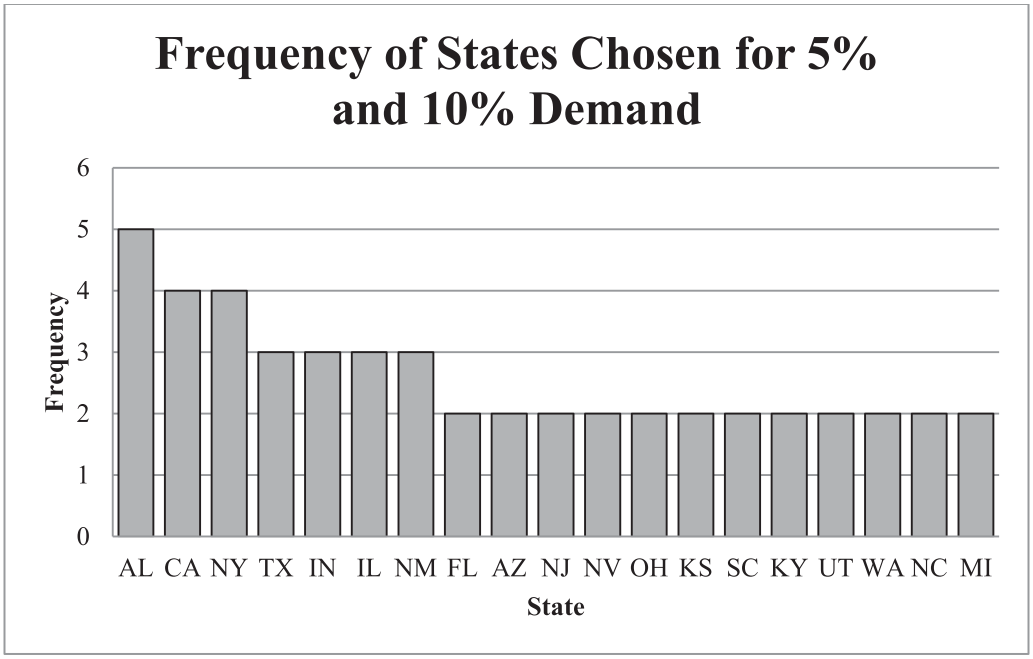

Figure 3.4: Frequency of states chosen for 5% and 10% demand

5. Discussion

From this study, it is evident that including the heat treatment step into the hybrid-AM supply chain has several effects on the locations of AM hubs chosen for the hybrid-AM supply chain without heat treatment studied in Chapter 2. When heat treatment is included, 22 hubs were chosen for 5% demand and 35 hubs were chosen for 10% demand. Fewer hubs were chosen for 10% demand than what was required (44 hubs from Chapter 2) due to the small number of counties with heat treatment (263) and their concentrated locations. It was found that demand could be satisfactorily allocated amongst 35 hubs, which results in a cost savings associated with fixed cost when compared to the 44 hubs chosen without heat treatment. Also, there were more counties chosen twice for 5% and 10% demand due to the more concentrated locations. Without heat treatment, only 4 counties and 19 states were chosen for both demand levels. With heat treatment included, 17 counties and 19 states were chosen for both demand levels.

When compared further, both models with and without heat treatment shared the county Graham in Arizona. Both models also shared the states of Alabama, Arizona, California, Florida, Illinois, Kansas, Michigan, North Carolina, Ohio, South Carolina, and Texas. From these implications, AM investors may want to consider these states first if they are deciding whether or not to incorporate heat treatment into their supply chain.

As seen in Figure 3.5, the average annual costs per AM hub were identified. The cost breakdown was identical to the costs identified without the heat treatment step in Chapter 2.

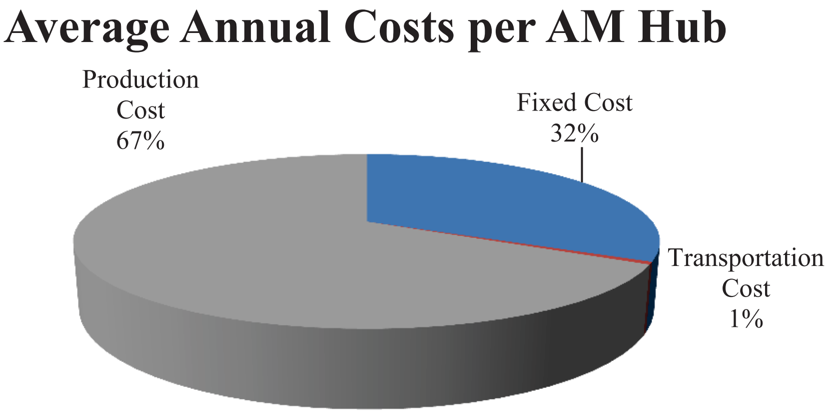

Figure 3.5: Average Annual costs per AM Hub

Since the average annual costs per AM hub are consistent with and without heat treatment, AM hubs can expect to pay 67% annually in production costs, 32% annually in fixed costs, and 1% in transportation costs. Even though the transportation costs per county increased due to the addition of the 15 lb. build plate per part, the overall percentage of annual spend on transportation cost per AM hub did not change.

6. Conclusion

This study expands on the study done in Chapter 2 to link both existing traditional manufacturers and heat treat facilities with the evolving hybrid-AM supply chain. A two-stage p-median model facility location model was used to strategically locate AM manufacturing hubs with respect to both heat treatment counties and machine shop counties. The location decisions represent the optimal locations for AM hubs when printed metal parts must go through a heat treatment process before being sent for post-processing at machine shops. By comparing the results identified from this model with those in Chapter 2, AM companies and investors can determine the effects of adding heat treatment into their supply chain model.

In summary, by adding NAICS heat treatment county data along with the NAICS machine shop county data, a two stage facility location model can be used to determine optimal hub locations when the supply chain includes separate stages (from hub county to heat treatment county and from heat treatment county to machine shop county). The major findings from this study are highlighted below:

- 22 AM hubs were chosen for 5% demand and 35 AM hubs were chosen for 10% demand.
- There are fewer heat treatment counties (263) than machine shop counties (2,162) resulting in more concentrated hub locations.
- Demand at the 10% level is satisfied with 35 AM Hubs when the heat treatment step is included compared to 44AM Hubs required when heat treatment is not included.
- Although transportation costs are increased from county to county when heat treatment is included due to the addition of the 15 lb. build plate attached to each AM part, the annual percentage of transportation cost per hub remains at 1%.
- All annual costs per AM hub are consistent with or without the heat treatment step.

Future direction for this research includes examining the heat treatment counties further to include capacity constraints. Sales volume could be used to determine a constraint on how much demand each heat treatment county can process. This study assumed infinite capacity at each heat treatment county.

Appendix A.

Table A1: P-median results for 5% demand, 22 hubs

Hub County	State	Counties allocated	Transportation Cost ($M)	# Orders	# Parts	Production Cost ($M)	AM Machines Required	Fixed Cost ($M)
Pickens	AL	15	$0.21	21,273	73,692	$96.02	117	$45.94
Graham	AZ	1	$0.35	7,195	24,924	$32.48	40	$15.73
Alpine	CA	5	$0.44	17,866	61,890	$80.64	98	$38.49
Ventura	CA	8	$2.03	34,297	118,808	$154.81	189	$74.19
DeSoto	FL	6	$0.64	6,679	23,137	$30.15	37	$14.55
Livingston	IL	28	$1.08	75,438	261,325	$340.51	415	$162.87
Dearborn	IN	22	$0.45	35,404	122,643	$159.80	195	$76.55
Palo Alto	IA	11	$0.26	25,038	86,734	$113.01	138	$54.18
Elk	KS	8	$0.25	14,549	50,399	$65.67	80	$31.42
McCracken	KY	8	$0.29	2,204	7,635	$9.95	12	$4.74
Manistee	MI	17	$0.33	6,277	21,744	$28.33	35	$13.65
Lincoln	NV	1	$0.18	337	1,167	$1.52	2	$0.82
Atlantic	NJ	20	$1.62	46,243	160,190	$208.73	254	$99.69
Lincoln	NM	5	$0.17	3,227	11,179	$14.57	18	$7.09
Cattaraugus	NY	21	$0.49	17,252	59,763	$77.88	95	$37.31
Rensselaer	NY	14	$0.67	11,689	40,492	$52.77	64	$25.15
Chatham	NC	13	$0.34	7,627	26,421	$34.43	42	$16.51
Huron	OH	19	$0.76	20,136	69,753	$90.89	111	$43.59
Anderson	SC	11	$0.21	8,747	30,300	$39.48	48	$18.69
Leon	TX	18	$1.11	28,951	100,289	$130.68	159	$62.42
Daggett	UT	6	$0.19	9,456	32,757	$42.68	52	$20.44
Grays Harbor	WA	6	$0.38	8,419	29,164	$38.00	46	$18.08
	Total	263	$12.46	408,296	1,414,371	$1,842.95	2245	$881.60

Table A2: P-median results for 10% demand, 38 Hubs

Hub County	State	Counties allocated	Transportation Cost ($M)	# Orders	# Parts	Production Cost ($M)	AM Machines Required	Fixed Cost ($M)
Autauga	AL	8	$0.11	22,790	78,947	$102.87	125	$49.20
Barbour	AL	2	$0.19	754	2,612	$3.40	4	$1.66
Bibb	AL	1	$0.12	1,835	6,357	$8.28	10	$3.99
Blount	AL	2	0	0	0	0	0	0
Cherokee	AL	1	0	0	0	0	0	0

Choctaw	AL	2	$0.30	52	180	$0.23	1	$0.44
Pickens	AL	1	0	0	0	0	0	0
Graham	AZ	1	$0.02	14,389	49,845	$64.95	79	$31.08
Arkansas	AR	3	$0.95	6,470	22,413	$29.20	36	$13.99
Alpine	CA	5	$1.18	35,731	123,776	$161.28	196	$77.12
Ventura	CA	8	$4.13	68,592	237,610	$309.61	377	$148.02
Boulder	CO	2	$0.29	8,080	27,990	$36.47	44	$17.47
DeSoto	FL	6	$1.32	13,359	46,277	$60.29	73	$28.86
Benewah	ID	1	$0.08	3,402	11,785	$15.36	19	$7.37
Hancock	IL	10	$0.36	114,351	396,123	$516.15	629	$246.75
Livingston	IL	20	$1.73	42,250	146,358	$190.70	232	$91.19
Allen	IN	32	$2.04	98,640	341,699	$445.23	542	$212.85
Dearborn	IN	6	$0.13	3,717	12,876	$16.78	20	$8.05
Elk	KS	8	$0.42	29,097	100,795	$131.34	160	$62.81
McCracken	KY	3	$0.04	190	658	$0.86	1	$0.44
Allen Parish	LA	8	$0.24	21,411	74,170	$96.64	118	$46.23
Antrim	MI	7	$0.39	8,215	28,458	$37.08	45	$17.76
Carter	MT	1	$0.06	3,113	10,784	$14.05	17	$6.75
Butler	NE	5	$0.16	4,015	13,908	$18.12	22	$8.70
Lincoln	NV	1	$0.01	672	2,328	$3.03	4	$1.66
Atlantic	NJ	20	$1.80	92,485	20,377	$417.45	509	$199.57
Eddy	NM	4	$0.65	4,543	15,737	$20.51	25	$9.84
Lincoln	NM	1	$0.14	1,910	6,616	$8.62	11	$4.15
Cattaraugus	NY	21	$2.48	34,504	119,525	$155.74	190	$74.48
Rensselaer	NY	14	$1.33	23,377	80,980	$105.52	129	$50.47
Chatham	NC	13	$0.73	15,256	52,848	$68.86	84	$32.95
Huron	OH	10	$0.50	12,869	44,580	$58.08	71	$27.80
Anderson	SC	7	$0.53	16,731	57,958	$75.52	92	$36.13
Aransas	TX	2	$0.30	36,207	125,425	$163.43	199	$78.15
Limestone	TX	11	$1.61	16,095	55,755	$72.65	88	$34.76
Daggett	UT	3	$0.32	7,429	25,735	$33.53	41	$16.06
Grays Harbor	WA	6	$0.80	16,840	58,335	$76.01	93	$36.37
Jackson	WI	7	$0.65	37,221	128,937	$168.01	205	$80.34
	Total	263	$26.11	816,510	2,828,769	$3,685.88	4490	$1,763.25

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CHAPTER 4: RETHINKING REVERSE LOGISTICS: ROLE OF ADDITIVE MANUFACTURING TECHNOLOGY IN REMANUFACTURING

1. Introduction

Until recently, Additive Manufacturing (AM) applications have been limited to prototyping and high-value part fabrication such as biomedical implants (O'Conner, 2014). Continuous improvements in the processing capabilities of AM systems has unfolded broader applications due to benefits of AM such as flexibility in part design and customization, available materials (Pinkerton, 2016), part weight reduction (Seppala and Hupfer, 2014), and improved efficiency, lead times and reduced cost of supply chains (Thomas, 2015). Metal parts that favor AM production include those of low production volumes, high material cost, and high machining cost (Frazier, 2014). One emerging application of AM is maintenance and repair (Frazier, 2014). Repair otherwise known as remanufacturing, aids in recapturing the value added to the materials when a product was first manufactured (Hashemi et al., 2016).

The majority of current AM remanufacturing applications are being practiced in the defense industry, such as the US Marine Corps and US Navy (Appleton, 2014; O'Conner, 2014). However, AM remanufacturing is slowly being expanded to include other applications such as mold and die repair (Chen et al., 2013) and aircraft engine repair (Liu et al., 2016). The use of AM for remanufacturing is limited to cases of high-cost parts, where the cost of repair is lower than the cost of replacement. For this reason, most

AM research focuses on the production of end-use parts (Sames et al., 2016). However, AM technology can be utilized for many different types of remanufacturing, including reverse logistics repairs in which the part is sent in from the consumer for repair, line defects in which the part is repaired utilizing AM during the manufacturing process, and the repair of shop tools and machinery components (Kobryn, 2006).

Previous research has investigated locating AM hub facilities for complex metal part fabrication. These facilities act as hubs supporting surrounding machine shops by accepting digital CAD orders, printing the ‘near-net’ metal parts, and sending them to machine shops for post-processing. This allows for machine shops to offer post-processing services to increase their current machine utilization and avoid the upfront costs associated with adopting AM technology internally. However, there may be limitations that exist specific to each machine shop such as the barrier of design for AM of current parts. Machine shops may not be capable yet of re-designing their parts for AM or they may not offer products suitable for AM. For these machine shops that are restricted to traditional manufacturing methods, there is still an opportunity to gain benefits of AM. Machine shops of this nature could use AM to streamline their reverse logistics system. The current method of remanufacturing is traditional manufacturing, which includes machining, welding, and cladding. Although these processes are effective at repairing parts and components, they are very expensive processes, especially when working with materials that are difficult to machine such as titanium. A wide range of potential cost savings have been identified with replacing traditional remanufacturing processes with AM remanufacturing processes (Frazier, 2014). The goal of this paper is to further analyze how AM remanufacturing technology can be utilized in place of these traditional methods to benefit traditional machine shops and how it can be implemented by locating AM remanufacturing hubs.

The literature review reveals a gap in which AM technology is suggested for remanufacturing applications in industry however there is uncertainty with regards to demand and costs. Also, much of current literature does not go into depth about AM for remanufacturing as much is focused on fabricating replacement and spare parts, or make vs buy scenarios that do not include remanufacturing. An uncapacitated facility location model is used in this study to analyze the current locations of machine shops in the US along with repair demand, fixed costs and transportation costs. Counties in the US will be identified where AM remanufacturing technology can be strategically located amongst surrounding machine shops to better manage the growing annual demand for repair.

This paper proposes several practical applications. Machine shops that 1) cannot adopt AM internally and/or 2) cannot take advantage of AM for production can use the model and results to help with decision making on integrating AM remanufacturing technology within their existing reverse logistics system. They can develop a better understanding of the costs and demand associated with AM remanufacturing technology and how it can benefit the current reverse logistics supply chain. Current literature review on remanufacturing, reverse logistics, AM technology, and summary of industry applications is outlined in section 2. The methodology for the uncapacitated facility location model is outlined in section 3, followed by the results obtained and a specific part case study in section 4, a discussion based on results and insights in section 5 and conclusions in section 6.

2. Literature Review

2.1 Metal Remanufacturing

Remanufacturing has been defined as the process of returning a product to its original performance, equivalent or better than the original part (Payne et al., 2016). The scope of remanufacturing is to allow manufacturers to decrease their capital production costs while consumers gain access to "like new" products at a cheaper cost than the actual new products. The latest remanufacturing market report was released in 2012 by the United States International Trade Commission. The report states that the United States is the largest country for remanufacturing in the world. The value of US remanufacturing grew by 15% from 2009 and 2011, bringing in more than $43 billion. The sectors noted that highly utilize remanufacturing include aerospace, electrical apparatus, heavy duty and off road equipment, information technology products, locomotives, machinery, medical devices and motor vehicle parts. The aerospace, heavy duty and off road equipment and motor vehicle parts account for 63% of total US remanufactured products. Most of these remanufactured products are repaired by small and medium-sized enterprises (SMEs). The report describes the remanufacturing demand trend as driven by the prices of new goods. Products with short life cycles face the most concern with competing prices of new products. The report also highlights concerns for SMEs such as transportation costs such that the product to be remanufactured must flow from and back to the point of origin. Manufacturers have stated the importance of regional remanufacturing networks and producing closer to demand points to control transportation costs.

Although remanufacturing demand is smaller than that of manufacturing, the US has increasingly invested in remanufacturing, growing from a \$639 M to a \$1.2 B investment from 2009 to 2011. The report also analyzes the types of firms that send products out to be remanufactured. The firms that are seeking remanufacturing services are mostly those that are currently manufacturers. Original equipment manufacturers (OEMs) are one main driver of demand because they are seeking ways to reduce costs of warranty claims and replace parts for customers. Firms save 30-50% (average of 40%) by choosing remanufactured parts over new ones. In the aerospace sector, maintenance repair and overhaul (MROs) centers are the main suppliers of remanufactured goods.

2.2 Reverse Logistics

Reverse logistics is defined as retrieving used products and components from customers and returning them to a processing facility (Ferrer and Whybark, 2000). The reverse logistics process has the potential to achieve value recovery from used products (Pokharel and Mutha 2009). The decision that most manufacturers face is to choose between recovering products and purchasing new ones. In previous studies, it has been discovered that the cost of remanufactured products can be reduced by assigning optimal locations and allocations of facilities for reverse logistics (Ferrer and Whybark, 2000; Prahinski and Kocabasoglu, 2006). Researchers have also investigated integrating both manufacturing and remanufacturing supply chain systems (Wells and Seitz, 2005). Repair and after-sales services can also be offered to enhance companies' service offerings (Pokharel and Mutha, 2009) and researchers have even suggested locating warranty service centers or warehouses for reverse logistics supply chains (Du and Evans, 2008). The benefit of remanufacturing in reverse logistics is to rebuild products to extend their useful economic life. Also, it presents companies the ability to offer special warranties or service contracts to customers at an additional cost (Ferrer and Whybark, 2000). It has been suggested that OEMs should quickly adopt a reverse logistics system in order to gain first mover advantages over OEMs that do not offer repair, maintenance and overhaul services (Heese et al., 2005). Strong reverse logistics systems also enhance relationships with customers and improve loyalty and customer satisfaction (Meade et al., 2007). Supply chain literature review discusses centralized returns centers (CRCs) where the reverse logistics process is managed at an independent, centralized location (Gooley, 2002). These CRCs help to improve efficiency by enabling managers to focus on reverse logistics at a separate facility rather than within the forward supply chain.

It is also recognized that the reverse logistics system works best when outsourced to a third party (Prahinski and Kocabasoglu, 2006). The third party logistics providers (3PLs) handle product returns at a standardized fee and offer a variety of customization for reverse logistics services. Once major challenge presented to manufacturers is how to effectively balance both the forward and reverse supply chains simultaneously (Rogers and Tibben-Lembke, 2001). For many manufactures, there is a lack of focus on reverse supply chain systems, which negatively influences their operational performance. Reverse supply chain systems do not only repair products, but they also improve them.

Remanufacturing has resulted in repaired products that are superior in both performance and expected life time than the original product (Prahinski and Kocabasoglu, 2006).

Fleischmann et al. (2001) noted that implementation of remanufacturing and repair services require effort in setting up an appropriate reverse logistics infrastructures to manage the flow of used and returned products. Facility/warehouse location models and quantitative models such as mixed integer linear programming models have been suggested in Fleischmann's work. A series of case studies were also analyzed to optimize reverse logistics locations for specific products and industries. Demand was treated as uncertain and was estimated in two ways 1) using a portion respective to population in the regions analyzed and also 2) based on previous year's sales volumes.

2.3 AM Repair Technology

Kobryn (2006) claims that "AM is applicable to various material systems, but is of particular interest for the production and repair of high-cost, long-lead components". Four main applications of AM are recognized: the manufacture of components, the repair of components, the manufacture of tooling, and the repair of tooling. Repair of components usually has a higher pay-off. The application of AM for repair purposes depends on the ability to inspect the repair, to restore the original capability of the part, the ability to repair the part in situ, and the availability other repair techniques. AM for repair is most significant for components which are often repaired or refurbished routinely. AM has the potential to compete with existing repair methods. AM can also tackle "previously impossible repairs" in certain circumstances.

There are a variety of AM processes that could be used for remanufacturing. Liu et al., (2016) looks into metal part repair processes using AM technology. The laser melting deposition (LMD) repair process is studied which is mainly used for surface cladding and laser repair. LMD includes low cost, digital flexibility, small heat affected zone, less distortion, adaptable different machining materials, and it is environment friendly. Currently, LMD is being used for AM of large titanium components. LMD gives parts high quality repair and control defects. Electron beam melting (EBM) also can be used to repair in which power feeding determines repair precision and repair area density.

Appleton (2014) outlines the benefits of using AM for Marine Corps. In traditional manufacturing, material is removed using a Computer Numeric Control (CNC) machine to form the shape of the part. Using these traditional methods, up to 90% of the original material is lost to scrap. When a more expensive material such as Titanium is used, this waste becomes a significant cost driver. AM helps to keep waste minimal at usually less than 5%. The Unites States Army and Navy are already using AM capabilities at their repair facilities called Fleet Repair Centers. The Navy specifically is studying installation of 3D printers aboard ships at sea. The Army's Rapid Equipping Force (REF) has an AM facility integrated with more traditional manufacturing and repair technologies. The ability to manufacture and repair parts nearest to the point of use has the potential to reduce cost. Additional costs and resistance from suppliers might be expected, but the value of the efficiencies would offset the price tag. Other benefits of using AM for part repair include shorter lead times. These are estimated to be about two weeks for AM, and two to five weeks for traditional manufacturing (Morgan and Prentiss, 2014).

O’Conner (2014) discusses the Laser Engineered Net Shaping (LENS) system for repair and maintenance. The tool can be added to existing machine shops and could even replace some of the larger and outdated machines that are currently utilized. Instead of the powder bed fusion (PBF) technologies, “LENS uses an arm with multiple nozzles that deposit powder and fuses the material with a laser in a single step” (OPTOMEC, 2014). LENS can both manufacture new parts and deposit material directly onto a broken part as part of a repair process. This is then followed by a traditional subtractive manufacturing step to return the part to its original shape. Instead of replacing these parts, additive and subtractive processes are combined to bring the part back its original capability. LENS has been tested to very high tolerances, and it is already in use repairing tanks and gas turbine engines (OPTOMEC, 2014).

Chen (2011) expands further on the CNC based AM technology, such as the LENS. Compared to the layer-based AM processes, one challenge associated with the CNC integrated process is that the tool path planning is more complex since it requires considering 3D dimensions compared to the traditional 2D dimensions. This is one benefit to outsourcing the AM repair technology compared to adopting it in house. The AM processes such as laser engineered net shaping (Mudge and Wald, 2007), direct metal deposition (Liou, et al., 2007), and laser cladding (Kerschbaumer, et al., 2004) have been used in repairing metal parts and molds. The CNC integrated process can be beneficial for building around spots that are difficult to machine such as inserts.

The category of AM technology that will be incorporated into this remanufacturing study is directed energy deposition (DED). DED is "the AM process in which focused thermal energy is used to fuse materials by melting as the material is being deposited" (Wohlers, 2016). Zeng et al., (2016) discusses DED being suitable for metal part remanufacturing via layer-by-layer deposition of molten metal powders or filament by utilizing a laser to generate a melt pool on the substrate where the metal material is to be injected. Laser DED is preferred over traditional remanufacturing methods such as weld repair because of the relatively low heat inputs, localized heat affected zone, and greater positional and dimensional control (Scheck et al., 2016). LMD and LENS both belong to the category of DED (Zeng et al., 2016). Specifically, this study incorporates CNC based AM technology as described in Chen (2011). A series of deposition heads and docking systems allows the DED machine to be installed on any CNC machine and changeover between the deposition heads and the traditional CNC tool is automated and done in seconds (Hybrid Manufacturing Technologies, 2016).

CNC integrated DED offers unique process capabilities such as depositing multiple materials simultaneously and using a 4 or 5 axis deposition head for added flexibility to overcome the successive horizontal layers that occur on parallel planes. DED can also process a wider range of metal materials than other technologies (Wohlers, 2016).

2.4 AM Repair Applications and Limitations

Current AM market research presents the growth of AM related services. AM services grew to $2.105 billion in 2014 a 38.9% increase from $1.516 billion in 2013. Secondary

Market (tooling produced from AM such as dies and castings) grew 20.9% to $1.644 billion in 2014 from $1.36 billion in 2013. Market for secondary services such as AM for tooling, dies and castings: growth rate 21% in 2014 and 14% in 2013 (Wohlers Report, 2016). These continued growths imply opportunities for manufacturers to add AM services into their market, for both manufacturing and remanufacturing processes.

Sames (2016) reiterates that "the use for remanufacturing is limited to cases of high-cost parts, where the cost of repair is lower than the cost of replacement". Industrial Laser Solutions (2008) describes in detail an application of AM repair for a gas turbine engine in which housing became out of tolerance and was considered scrap. An AM repair process was utilized to build up the worn area and machined to print tolerances. The housing was repaired successfully. The repair cost about 50% of new unit pricing. Delivery for the repaired housing was a few days compared to several weeks for the purchase of a new housing. Also there is less material and design limitations with AM as similar repairs have been performed on very fine Inconel 718 compressor seals. Working with materials which in some cases is as thin as 0.2 mm is beyond the scope of manual welders and the high-precision positioning of using AM is needed (Deloitte University Press, 2014).

Another application for AM repair is in die and mold repairing. Foundry Management and Technology (2013) has said that the AM approach could save die casters as much as $500 million in annual repair costs. Frazier (2014) discussed that using LENS repair of IN 625 3rd stage turbine blades at the Anniston Army Depot had a cost savings of

$6,297/part or $1,444,416/year. For an AV8B Ti6Al-4V engine blade tip repair, there was an 81% cost saving at a value of $715 k/year.

Ford et al., (2015) explains how Siemens Power Generations Services has also experimented with the benefits of using AM technology for remanufacturing by providing support maintenance and repair services to customers operating rotating power equipment such as turbines, generators and compressors. Burner tips are repaired ten times more quickly with less waste than through traditional manufacturing repairs. Only 18mm of the burner tip requires removal before repair. Siemens is also working on these services being on demand closer to the customers' locations. An additional company described in Ford's work is Caterpillar. They have managed to recover 94% of engine products their end-of-life stage, resulting in increased profit margins and remanufactured engines and parts in equal to superior quality than new parts. Remanufactured engines have been sold in which 60% of components are refurbished or repaired parts.

3. Methodology

In this investigation an uncapacitated facility location model is presented based on SME machine shop remanufacturing demand, location of current machine shops, fixed cost of implementing AM remanufacturing technology, AM repair cost per part and transportation cost. This model will identify candidate counties in the United States in which AM technology, specifically Directed Energy Deposition (DED), could be installed in hubs for AM remanufacturing services. These facilities will specialize in repairing parts and components for surrounding machine shops that do not have the resources to support internal access to AM. Additionally, a case study is presented in which the model is run specifically for a high-value aerospace part for surrounding aircraft maintenance, repair and overhaul (MRO) facilities. A schematic representation of the AM repair supply chain is shown in Figure 4.1.

Figure 4.1: AM Remanufacturing Supply Chain in the U.S.

3.1 Model Parameters

The primary data set used for this analysis was provided by the North American Industry Classification System (NAICS, 2016) Association for NAICS code 332710 (Machine Shops) in 3109 U.S counties. It included the following information for each county: (1) region of U.S., (2) state, (3) number of machine shops, (4) annual sales volume ($M/yr) and (5) number of employees per county.

To assist in estimating demand, the five sample CAD drawings of AM metal parts from Strong et al., (2017) for mechanical applications of various complexities and metal materials were sent to multiple machine shops in the US for quotes on machining. The average quote resulted in a unit price of \$1,373 per part. The sales volumes of each county and this average cost of \$1,373 were used to estimate a maximum demand for metal parts. Two demand factors, 5% and 10% were used to represent the ratio of parts being sent for remanufacturing. This approach was used also in Fleischmann et al. (2001) in which 70% of the sales volume was assumed to be reinvested in the next year and 10% of the 70% represented the targeted parts in need of repair.

For this study, the batch size and weight of the parts from Strong et al., (2017) was altered to represent a machined part in need of remanufacturing, rather than a printed part. The average batch size used is 1 since repairs depend on failure of the part, which is not planned in batches like AM production. Also, the DED and CNC equipment can only work on one part at a time. The average weight used for the parts was 4-10 lbs. assuming that AM (estimated at 2-5 lbs.) reduces weight by about 50% (Additive Manufacturing, 2016). The volume of the parts stays the same at average of 15-30 in^3.

AM repair technology costs were also estimated using data from a U.S. Hybrid-AM company. These are the costs associated with the technology known as directed energy deposition (DED). The breakdown of costs is presented in Table 4.1.

Table 4.1: AM Remanufacturing Hub Costs

Fixed Costs	Dollars/Yr	Source
Tooling Cost	$2,000	Hybrid AM Company
Coolant	$200	Hybrid AM Company
2 Disks	$1,200	Hybrid AM Company
Extraction	$2,200	Hybrid AM Company
Deposition (service/maintenance & consumables)	$2,725	Hybrid AM Company
CNC Machinist	$42,000	Simply Hired, 2017
Machine Software Cost	$2,900	Thomas and Gilbert 2014; Baumers 2012
Machine Hardware Cost	$870	Thomas and Gilbert, 2014; Baumers 2012
CNC Cost per Hour	$630,720	CNC Machinist Training, 2013
CNC Depreciation	$70,000	Cutting Tool Engineering, 2016
Rent	$34,170	Thomas and Gilbert 2014
Total Annual Hub Fixed Cost	$788,985	

The above table represents the fixed cost for a new hub facility with one DED unit and one CEC machine operating at 90% utilization or 7884 hours per year (Baumers, 2012). The actual number of machines required will be analyzed to account for variances in fixed costs. The transportation costs for shipping metal parts are based on FedEx ground shipping rates, detailed in Section 3.3. Table 4.2 presents the input and output parameters employed in this study.

Table 4.2: Model parameters for location problem

	Category	Name	Units	Comments
Inputs	Current Demand	Sales Volume	$/yr/county	NAICS, 2013
	Existing Facilities	Locations	-	
	AM Parts	Avg. Unit Price	$/unit	Metal AM service bureaus
		Avg. Weight/part	lb/unit	
		Avg. Batch Size	#/order	
		Avg. Volume/part	in^3/unit	
	Transportation	Shipping Rate	$/lb/mile or $/in^3/mile	FedEx (FedEx, 2016)
	Cost Component	Total Fixed Cost	$M/year	Thomas and Gilbert, 2014; US AM Company
Outputs		Production Cost		Metal AM remanufacturing per year at each hub
		Transportation cost		Cost of shipping parts from manufacturers to hubs and then returned to manufacturers
		No. of Hubs	-	Required AM Remanufacturing hubs in the U.S based on demand
	AM Remanufacturing Hubs	Location	Cities-County-State	Closest city with minimum 50,000 populations for AM Remanufcturing hub locations in the U.S (U.S. Census Bureau, 2017)
		Allocations	-	Allocations of AM Remanufacturing hubs to serve regional manufacturers

3.2 Model Assumptions

The assumptions involved with creating the uncapacitated facility location model are presented in Table 4.3.

Table 4.3: Model Assumptions

	Justification
Locations	Existing traditional manufacturers will remain fixed in their current locations and capacities
Demand	Recent sales volume is an indicator of the demand for metal part repairs for each county
Contagious U.S.	Since FedEx ground shipping rate is applied, District of Columbia (D.C) is included in the study and states of Hawaii and Alaska are not considered along with the U.S. territories
Supply Chain Integration	Traditional manufacturers receive damaged or end of life parts from customers → Parts are sent to AM remanufacturing hubs → AM remanufacturing hub uses DED to repair or remanufacture the part → AM remanufacturing hub ships metal parts back to the traditional manufacturers using existing delivery methods.

3.3 Uncapacitated Facility Location Model

The logistics based uncapacitated facility location (UFL) model was developed in Matlab using the Matlog Logistics Toolbox (Kay, 2017). The same UFL model used in Strong et al., (2017) was employed, however using different inputs to represent the costs and demand for remanufacturing parts rather than AM printed parts. Undiscounted 2016 FedEx Ground rates (FedEx, 2015, 2016) were used to estimate transportation costs.

4. Results and Analysis

4.1 Uncapacitated Facility Location

The AM remanufacturing hub locations based on the UFL model is presented in Figure 4.2. Additional information on all AM remanufacturing hub locations are included in the Appendix with the following information: county, state, city within the county with the highest population, closest metropolitan city, production and transportation costs, annual number of orders and metal parts repaired.

As shown in Figure 4.2, the following hub locations were chosen: for 5% demand only one hub was chosen in Boone county, Indiana and for 10% demand three hubs were chosen in Kern county, California; Montgomery county, Indiana and Berks county, Pennsylvania. These counties were chosen as the optimal locations for establishing AM remanufacturing hubs.

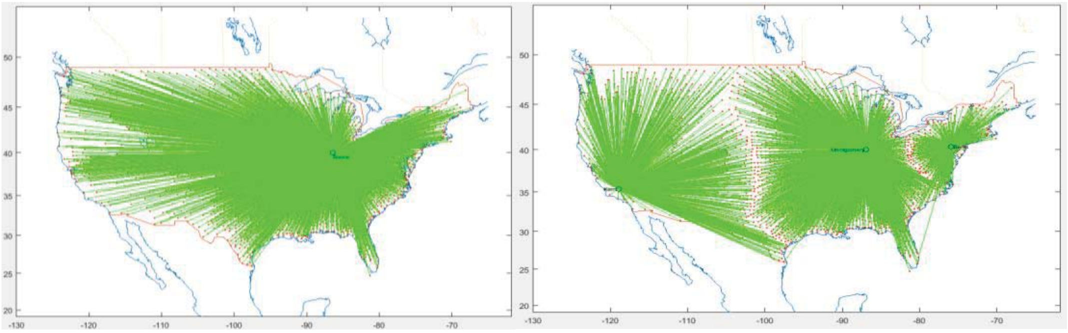

Figure 4.2: UFL results for Optimal AM remanufacturing hub locations

4.2 P-Median

Based on a 60 minute average cycle time for a part repair using the LENS system (EFESTO, 2013) and 7884 machine hours (Baumers, 2012) per year (3 shifts at 90% utilization), 170 and 341 DED and CNC machines were needed for 5% demand and 10% demand respectively. As shown in Table 4.4, the numbers of AM repair hubs needed are 18 and 36 for 5% and 10% demand based on the average investment cost of a CNC machining facility $6.4 M. $6.4 M was the average cost of investment into a CNC machining and remanufacturing facility (Caterpillar (2015).

Table 4.4: Using UFL results to identify p-Median parameters

Demand	**Utilization**	**# Parts**	**# Machines Needed**	**Total Fixed Cost ($M)**	**Fixed Cost Per Hub ($M)**	**# Hubs**
5%	90%	1,342,272	170	$115	$6.4	18
10%		2,684,544	341	$231	$6.4	36

The results of the updated model using p-median approach, 7884 hours per year, and required machines and their fixed costs required are shown in Figure 4.3.

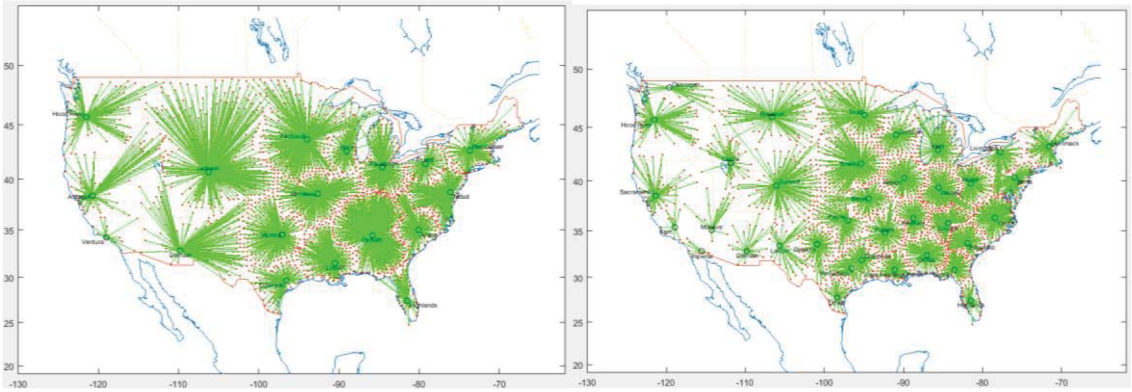

Figure 4.3: p-Median results for AM remanufacturing hubs based on: (a) 5% demand and (b) 10% demand

Additional information on fixed costs, counties allocated, transportation costs, number of DED and CNC machines required and annual repair rate at 90% utilization for all AM remanufacturing hubs are included in the Appendix. The hub counties along with their largest population cities and metropolitan cities are outlined in Tables 4.5-4.6 below.

Table 4.5: Locations for AM remanufacturing hubs for 5% demand

Hub County	State	Largest City Within	In Proximity To
DeKalb	AL	Fort Payne, AL	Chattanooga, TN
Graham	AZ	Safford, AZ	Phoenix, AZ
Amador	CA	Ione, CA	Sacramento, CA
Ventura	CA	Oxnard, CA	Los Angeles, CA
Jackson	CO	Walden, CO	Denver, CO
Highlands	FL	Sebring, FL	Sebring, FL
Talbot	MD	Easton, MD	Washington, DC
Faribault	MN	Blue Earth, MN	Minneapolis, MN
Lincoln	MS	Brookhaven, MS	Jackson, MS
Moniteau	MO	California, MO	St. Louis, MO
Rensselaer	NY	Troy, NY	Albany, NY
Anson	NC	Wadesboro, NC	Charlotte, NC
Paulding	OH	Paulding, OH	Fort Wayne, IN
Murray	OK	Sulphur, OH	Oklahoma City, OK
Hood River	OR	Hood River, OR	Portland, OR
Forest	PA	Marienville, PA	Erie, PA
Colorado	TX	Columbus, TX	Houston, TX
Rock	WI	Janesville, WI	Milwaukee, WI

Table 4.6: Locations for AM remanufacturing hubs for 10% demand

Hub County	State	Largest City Within	In Proximity To
Dallas	AL	Selma, AL	Montgomery, AL
Graham	AZ	Safford, AZ	Phoenix, AZ
Mohave	AZ	Lake Havasu City, AZ	Las Vegas, NV
Pulaski	AR	Little Rock, AR	Little Rock, AR
Imperial	CA	El Centro, CA	San Diego, CA
Kern	CA	Bakersfield, CA	Los Angeles, CA
Sacramento	CA	Sacramento, CA	Sacramento, CA
Summit	CO	Breckenridge, CO	Denver, CO
Highlands	FL	Sebring, FL	Sebring, FL
Brooks	GA	Quitman, GA	Tallahassee, FL
Mason	IL	Havana, IL	Springfield, IL
Decatur	IN	Greensburg, IN	Indianapolis, IN
Shelby	IA	Harlan, IA	Omaha, NE
East Feliciana Parish	LA	Jackson, LA	Baton Rouge, LA
Kent	MI	Grand Rapids, MI	Lansing, MI
Todd	MN	Long Prairie, MN	Minneapolis, MN
Bates	MO	Butler, MO	Kansas City, MO
Rosebud	MT	Colstrip, MT	Billings, MT
Merrimack	NH	Concord, NH	Boston, MA
Lincoln	NM	Ruidoso, NM	Albuquerque, NM
Livingston	NY	Geneseo, NY	Rochester, NY
Vance	NC	Henderson, NC	Raleigh, NC
Noble	OH	Caldwell, OH	Columbus, OH
Payne	OK	Stillwater, OK	Oklahoma City, OK
Hood River	OR	Hood River, OR	Portland, OR
Berks	PA	Reading, PA	Philadelphia, PA
Edgefield	SC	Edgefield, SC	Augusta, GA
Loudon	TN	Lenoir City, TN	Knoxville, TN
Weakley	TN	Martin, TN	Nashville, TN
Cherokee	TX	Jacksonville, TX	Dallas, TX
Dickens	TX	Spur, TX	Amarillo, TX
Duval	TX	San Diego, TX	Corpus Christi, TX
Robertson	TX	Hearne, TX	Austin, TX
Cache	UT	Logan, UT	Salt Lake City, UT
Okanogan	WA	Omak, Washington	Seattle, WA
Jackson	WI	Black River Falls, WI	Madison, WI

The counties and cities chosen twice were highlighted in Tables 4.5-4.6 and the most frequent states chosen are displayed in Figure 4.4.

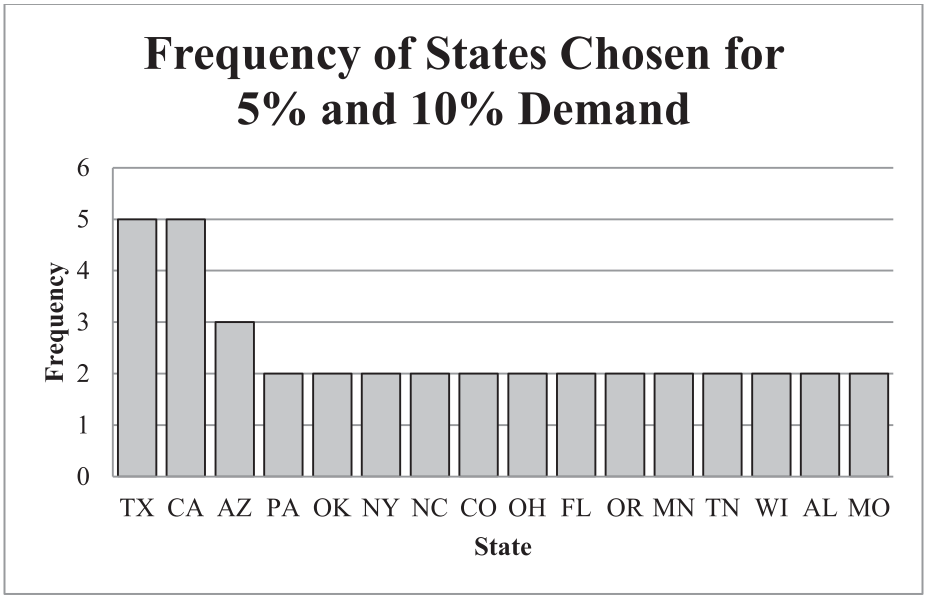

Figure 4.4: States chosen more than once for AM Remanufacturing Hubs for 5% and 10% demand

4.3 Aerospace Case Study

To further investigate AM remanufacturing hub locations, a specific case study was also implemented. It is hypothesized that remanufactured parts that are high-value will have an effect on AM remanufacturing hubs due to an increase in repair cost. An example of a high-valued part that will be investigated is a high pressure turbine outer air seal. This aerospace engine component is valued at $75,000 which is a much larger cost than the machine shop parts valued at $1,373. A U.S. Aerospace company provided details on the specific aerospace part that is frequently sent to MROs for remanufacturing. The cost to traditionally repair the part for the aerospace company is $40,000 and it is estimated that the part can be repaired and even improved using DED for $30,000 (40% of the value to replace the part) which equals a cost savings of $10,000 per part for the company. Since these aerospace parts are about 55 times more expensive than machine shop parts, it would be of interest to see how these critical parts affect the AM remanufacturing hub system and if a set of unique hubs are needed to service specifically aircraft engine MRO facilities.

According to IBisWorld (2016), the aircraft engine repair industry is one of the fastest growing repair industries in the US. Over the past five years, the aircraft engine maintenance, repair and overhaul (MRO) industry has recognized 2.5% annual growth due to increase in air travel and improving economic conditions. Airlines have invested in and increased the use of their fleets, which in turn increase the demand for aircraft maintenance and repair. Lower oil prices may also keep older aircraft flying longer, thus increasing the need for MRO. The United States International Trade Commission (2012) report states that it is not uncommon for MROs to network and send out remanufactured parts to more specialized repair facilities. However, it is important to network strategically to control transportation costs. Remanufacturing of engine parts makes up the majority of aerospace remanufacturing activities.

The same UFL model as above is employed for this specific case. The data set used was provided by the North American Industry Classification System (NAICS) Association for Standard Industrial Classification (SIC) code 458102 (Aircraft Engine Maintenance and Repair Services- MRO) in the United States. The MRO annual sales volume was used to predict repair demand for the part by using the $30,000 repair cost. The weight of the air seal is 0.75 lb.

The MRO hub locations based on the UFL model is presented in Figure 4.5. Additional information on MRO hub locations are included in the Appendix with the following information: county, state, city within the county with the highest population, closest metropolitan city, production and transportation costs, annual number of orders and metal parts repaired.

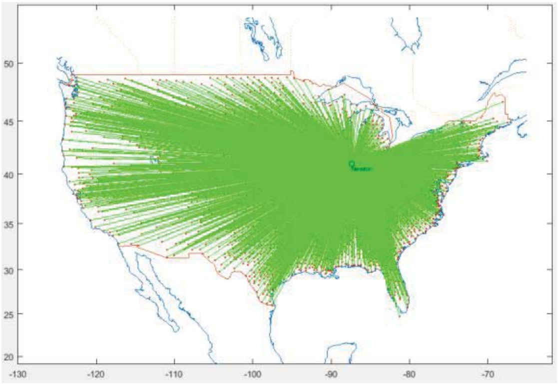

Figure 4.5: UFL results for Optimal MRO hub locations

As shown in Figure 4.5, the following hub location was chosen in Newton County Indiana. This county was chosen as the optimal location for establishing MRO repair hubs. The UFL was only run at the 10% demand rate because the demand rate was known to be 10% provided by the US Aerospace Company. The results would require 8 DED and CNC machines at a fixed cost of $6.0M as shown in Table 4.7.

Table 4.7: Using UFL results to identify p-Median parameters for MRO hubs

Demand	Utilization	# Parts	# Machines Needed	Total Fixed Cost ($M)	Fixed Cost Per Hub ($M)	# Hubs
10%	90%	62,815	8	$6.0	$6.4	1

Since the demand for remanufacturing of high valued parts is lower than that of low-medium valued parts, only 1 hub is required since the total fixed cost required is less than the maximum investment cost.

5. Discussion

It is proposed through this study that optimally locating AM remanufacturing hubs could improve the current reverse logistics process. This would allow traditional shops the opportunity to reap the benefits of AM without upfront investment and gain related remanufacturing support for traditional manufacturers who might not require metal AM for all of their current needs. By strategically locating AM remanufacturing hubs, high costs such as transportation cost can be minimized. Firms can also get remanufactured parts at a lower cost compared to their other options such as traditional remanufacturing or purchasing new replacement parts. The integration of AM remanufacturing within the reverse logistics supply chain is strongly supported by literature review and current applications. For current investors or manufacturing management seeking to outsource remanufacturing services through AM remanufacturing hubs, the results provide insights into both locations and annual fixed, transportation and production costs.

As observed in Figure 4.6, both UFL and p-median models resulted in annual production cost of 79-81%, fixed cost of 14-15% and transportation costs of 4-6% of the total the average AM remanufacturing hub costs (UFL -1 and 3 and p-Median at 18 and 36). This compares with the AM hub costs from Strong et al., (2017) where production cost was 67%, fixed cost was 32% and transportation cost was 0-1%.

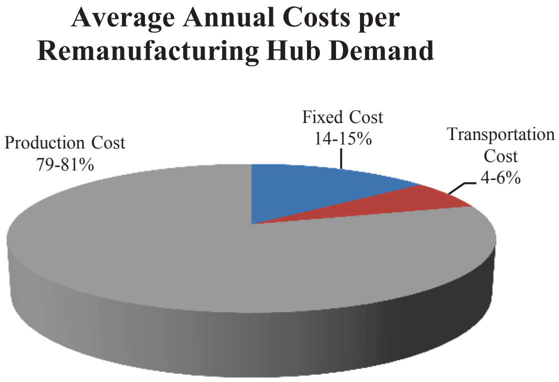

Figure 4.6: Average costs per AM remanufacturing hub

As mentioned, in the reverse logistics process transportation costs are higher due to the fact that parts must travel from the machine shops to the remanufacturing site and then back to the machine shops, compared to AM fabricated parts which would just be fabricated at the AM hub and be delivered to the machine shops. Fixed cost is also lower in the reverse logistics supply chain compared to the hybrid-AM production supply chain such that the depreciation costs for CNC and DED are much lower than that of industrial sized PBF metal printers. Also, the demand is lower for metal remanufacturing than for metal manufacturing. These comparisons also support the less number of hubs needed for remanufacturing than for manufacturing.

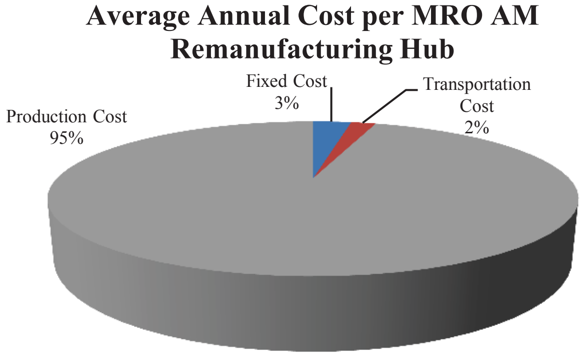

Figure 4.7: Average costs per MRO AM remanufacturing hub

The effect of remanufacturing high-value parts, specifically a high pressure turbine air seal, was also investigated in this study. The aerospace case study was hypothesized to have effects in the reverse logistics supply chain model given that the part was 55 times the value of a machine shop part. Current aircraft engine MRO locations and demand were used instead of machine shops.

As observed in Figure 4.7, the UFL model resulted in annual production cost of 95%, fixed cost of 3% and transportation costs of 2% of the total the average AM remanufacturing hub costs (UFL -1). This compares with the results from the machine shop study such that in the case of MROs and high valued parts, annual production cost is about 15% higher per hub; annual transportation cost is 2-4% lower per hub and fixed cost is about 11-12% lower. Transportation costs are lower due to the lower demand for MRO remanufactured parts compared to machine shop remanufactured parts and also due to the MRO remanufactured parts being lighter in weight. Production costs are higher as expected due to the increase in part value. Fixed cost, the main driver of AM manufacturing, seems to be the less impactful in the overall remanufacturing scenario given the lower fixed costs associated with DED than PBF.

5. Conclusion

This study links traditional manufacturers with AM remanufacturing hub centers through a series of facility location problems. The results represent the optimal locations for AM remanufacturing hubs which would offer AM repair services for metal parts in the reverse logistics system. These remanufacturing facilities will benefit traditional shops through the improvements that AM repair can offer to the current supply chain. Previous research has determined the optimal locations for AM manufacturing hubs and the results are compared with those found in this study for AM remanufacturing. The proposed integration of DED for remanufacturing allows traditional shops access to AM technology for remanufacturing even if they lack the requirements to use AM for production.

The major findings from this study are highlighted below:

- Uncapacitated Facility Location (UFL) model results in 1 and 3 AM remanufacturing hubs
- Based on p-median results, 18 and 36 AM remanufacturing hubs are recommended for 5 and 10% demand for machine shop parts
- Based on UFL results, 1 AM remanufacturing hub is recommended for 10% demand to service aerospace MRO parts

- High value parts results in fewer remanufacturing hubs needed
- Fixed cost for remanufacturing hubs is less than for manufacturing hubs
- Transportation costs double for the reverse supply chain, however there is little increase on average transportation cost per hub annually

Appendix A.

Table A1: AM repair hubs in based on UFL model and existing machine costs

	5% Demand	10% Demand
	90% Utilization	90% Utilization
CNC&DED Machines required	170	341
Parts/Orders per hub:	1,342,270	2,684,550
Fixed Cost ($M):	$115	$231
Transportation Cost ($M):	$55	$106
Production Cost ($B):	$0.7	$1.5

Table A2: UFL results hubs and related cities for 5% and 10% demand

Demand	Hub County	State	Largest City	In Proximity To
5%	Boone	IN	Lebanon, IN	Indianapolis, IN
10%	Kern	CA	Bakersfield, CA	Los Angeles, CA
10%	Montgomery	IN	Crawfordsville, IN	Indianapolis, IN
10%	Berks	PA	Reading, PA	Philadelphia, PA

Table A3: P-median results for 5% demand, 18 Hubs

Hub County	State	Counties allocated	Transportation Cost ($M)	# Orders/Parts	Production Cost ($M)	Machines Required	Fixed Cost ($M)
DeKalb	AL	526	$4.6	122,000	$67.1	16	$12.1
Graham	AZ	101	$1.6	44,200	$24.2	6	$4.6
Amador	CA	86	$2.5	68,300	$37.5	9	$6.8
Ventura	CA	13	$5.5	110,000	$60.6	14	$10.6
Jackson	CO	283	$1.8	43,600	$23.9	6	$4.6
Highlands	FL	60	$3.1	77,400	$42.5	10	$7.6
Talbot	MD	235	$5.0	126,000	$69.3	16	$12.1
Faribault	MN	334	$1.9	49,400	$27.1	7	$5.3
Lincoln	MS	183	$3.0	42,100	$23.1	6	$4.6
Moniteau	MO	241	$4.9	51,800	$28.5	7	$5.3
Rensselaer	NY	127	$2.0	157,000	$85.9	20	$15.1
Anson	NC	150	$3.1	64,100	$35.2	9	$6.8
Paulding	OH	212	$4.9	101,000	$55.5	13	$9.8
Murray	OK	190	$1.8	53,800	$29.6	7	$5.3
Hood River	OR	98	$2.8	50,000	$27.5	7	$5.3
Forest	PA	77	$3.1	48,900	$26.8	7	$5.3
Colorado	TX	97	$5.0	61,800	$33.9	8	$6.0
Rock	WI	96	$1.9	70,400	$38.6	9	$6.8
	Total	3109	$58.5	1,342,270	$0.7 (B)	170	$115

Table A4: P-median results for 10% demand, 36 Hubs

Hub County	State	Counties allocated	Transportation Cost ($M)	# Orders/Parts	Production Cost ($M)	Machines Required	Fixed Cost ($M)
Dallas	AL	116	$2.1	55,235	$30.3	8	$6.0
Graham	AZ	21	$2.0	54,541	$30.0	7	$5.3
Mohave	AZ	16	$0.7	23,385	$12.8	3	$2.3
Pulaski	AR	105	$2.2	40,837	$22.4	6	$4.6
Imperial	CA	6	$2.1	93,671	$51.4	12	$9.1
Kern	CA	11	$0.9	121,630	$66.8	16	$12.1
Sacramento	CA	58	$2.5	121,470	$66.7	16	$12.1
Summit	CO	129	$2.2	50,350	$27.6	7	$5.3
Highlands	FL	34	$1.1	136,120	$74.7	18	$13.6
Brooks	GA	96	$2.1	38,096	$20.9	5	$3.8
Mason	IL	129	$2.3	84,254	$46.3	11	$8.3
Decatur	IN	185	$1.0	116,600	$64.0	15	$11.4
Shelby	IA	217	$2.3	38,999	$21.4	5	$3.8
East Feliciana Parish	LA	81	$2.3	46,923	$25.8	6	$4.6
Kent	MI	106	$1.0	176,480	$96.9	23	$17.4
Todd	MN	129	$0.9	49,829	$27.3	7	$5.3
Bates	MO	101	$2.3	42,886	$23.5	6	$4.6
Rosebud	MT	87	$2.3	10,500	$5.8	2	$1.5
Merrimack	NH	82	$1.1	131,620	$72.2	17	$12.9
Lincoln	NM	37	$2.3	20,963	$11.5	3	$2.3
Livingston	NY	67	$2.4	60,365	$33.2	8	$6.0
Vance	NC	183	$1.1	109,180	$59.9	14	$10.6
Noble	OH	118	$3.4	92,798	$50.9	12	$9.1
Payne	OK	91	$1.4	37,566	$20.6	5	$3.8
Hood River	OR	76	$3.0	81,119	$44.5	11	$8.3
Berks	PA	102	$13.1	353,520	$194.2	45	$34.0
Edgefield	SC	114	$3.8	103,750	$56.9	14	$10.6
Loudon	TN	124	$2.5	66,681	$36.6	9	$6.8
Weakley	TN	108	$1.0	28,011	$15.4	4	$3.1
Cherokee	TX	85	$4.6	125,090	$68.7	16	$12.1
Dickens	TX	80	$0.6	16,209	$8.9	3	$2.3
Duval	TX	41	$1.5	40,075	$22.0	6	$4.6
Robertson	TX	29	$1.2	33,486	$18.4	5	$3.8
Cache	UT	46	$1.0	27,908	$15.3	4	$3.1
Okanogan	WA	20	$0.7	19,186	$10.5	3	$2.3
Jackson	WI	79	$1.3	35,214	$19.3	5	$3.8
	Total	3109	$78.3	2,684,550	$1.5 (B)	341	$231

Table A5: MRO AM Hubs at 10% Demand for UFL Results

	10% Demand
	90% Utilization
CNC&DED Machines required	8
Parts/Orders per hub:	62,815
Fixed Cost ($M):	$6.0
Transportation Cost ($M):	$39.2
Production Cost ($B):	$1.9

Table A6: MRO UFL results hubs and related cities for 5% and 10% demand

Hub County	State	Largest City	In Proximity To
Newton	IN	Kentland, IN	Chicago, IL

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CHAPTER 5: ADOPTING ADDITIVE-HYBRID MANUFACTURING: THE ROLE OF CAPACITY IN IMPLEMENTATION DECISION

1. Introduction:

Additive Manufacturing (AM), the process of adding material layer by layer based on 3D model data (ASTM, 2012), has been referred to as a major disruption to traditional supply chain (Durugbo and Beltagui, 2015). Due to the increasing popularity of this new technology, AM has been gaining interest in various industry sectors. The AM industry grew 35.2% to $4.103 billion in 2014 then another 25.9% to $5.165 billion in 2015 (Wohlers Report, 2016). Revenues from AM have been dramatically increasing and, in metal AM products particularly, revenues grew by almost 50% from $32.6 million in 2013 to $48.7 million in 2014 and then jumped by 80.9% in revenue growth to $88.1 million in 2015 (Wohlers Report, 2016).

With ever increasing demand for highly customized and complex metal parts, traditional manufacturing techniques such as subtractive machining along with processes to improve material properties (i.e. heat treatment, hot isostatic pressing, etc.), grinding and polishing are reported to be too expensive (Kastalli and Van Looy, 2012). On the other hand, the 'freeform fabrication' production freedom offered by AM technology allows for higher degree of part customization and design complexity while also lowering costs due to lack of tooling requirements (Seppälä and Hupfer, 2014). In particular, low production volume runs for metal production are economically restrictive through traditional manufacturing (Manogharan et al., 2016). In addition, expensive superalloys with desired mechanical properties for critical mechanical and aerospace applications are better suited for AM processing when compared to traditional machining (Pramanik, 2014), casting (Auburtin et al., 2000) and forging (Schafrik and Sprague, 2008). However, the current state of metal AM suffers from inherent disadvantages such as non-uniform mechanical properties and poor surface finish and part feature accuracy for most mechanical applications (Zhu et al., 2013). This affects the quality of critical mechanical parts that require specific part tolerances (for assembly) and uniform mechanical properties (in-service). If the desired properties of as-AM parts are acceptable for the designed application, then AM is advantageous when: (1) raw material costs for traditional manufacturing are high such that subtractive methods removing 60-80% of the original material would be expensive, (2) material is difficult to machine resulting in long cycle times, (3) cost of low volume production through traditional methods are prohibitive and (4) part design would benefit from design freedom in complexity and customization (Conner et al., 2014).

Recently, an integrated approach in metal manufacturing has been proposed where AM is employed to produce the ‘near-net’ shaped part followed by traditional manufacturing processes such as machining (Manogharan et al., 2015; Flynn et al., 2016), grinding (Beaucamp et al., 2015) and heat treatment (Wauthle et al., 2015; Brandl and Greitemeier, 2012). In the context of this research, hybrid AM is defined as an integrated set of dissimilar manufacturing processes such as an additive manufacturing (AM) process (e.g. powder-bed fusion, binder jetting, directed energy deposition, sheet lamination) linked to one or more manufacturing processes including, but not limited to, machining (subtractive manufacturing), material property enhancement, grinding, polishing, or other non-AM manufacturing processes (NIST, 2015). The attributes of each process (e.g. part accuracy or material micro-structure) are planned together (preferably concurrently) so that the required product engineering specifications can be met. Although hybrid AM could be considered akin to post-processing of cast metal parts, it should be noted that the lack of tooling requirements and higher part design complexity-customization in metal AM is a critical economical advantage in AM. Since AM is cost-effective in the case of low volume, complex part design and custom production (Conner et al., 2014; Petrick and Simpson, 2013), it has also been found that hybrid metal AM which comprises 'value-adding' post processing is also economically attractive for high performance metal parts (Manogharan et al., 2016).

This study is motivated by a previous research which showed that low volume 'unique' metal products constitutes a significant ratio of the products offered by traditional metal manufacturing firms in the US (Strong et al., 2016). It was also found that available excess resource capacity could be used to adopt hybrid AM processes using traditional manufacturing facilities (Strong et al., 2016) to explore product-service-systems (Neely, 2007; Avlontis et al., 2014). About 94% of firms surveyed are interested in expanding their services to include post processing for hybrid AM and almost 50% of firms have over 20% utilization available to offer these services (Strong et al., 2016). It is inferred that hybrid metal AM would be amenable to existing customers and product offerings since over 50% of production consists of low volume metal parts in 82% of firms. In addition, it was reported that these products are 25% more profitable than high volume parts and it could be assumed that increasing such offerings and lowering their productions costs would be beneficial (Strong et al., 2016).

However, access to metal AM equipment, quality control, process engineering and tooling requirements were identified as key barriers to widespread adoption of hybrid manufacturing. It is important to recognize that production economics that would justify a re-allocation of resources to hybrid AM when a firm has limited resources (e.g. equipment, tooling, labor) has not been investigated. This research gap on the effects of adopting hybrid AM in a resource contention production environment on the firms' profitability needs to be addressed.

The objectives of this paper are to: (1) study the effects of hybrid AM on competing firms in the market and gain insight on conditions that would encourage firms to adopt hybrid manufacturing into their offerings and (2) identify challenges that need to be addressed to make hybrid AM more economical for rapid adoption. In this paper, a price competition model is employed to model the dynamics between two resource-constrained manufacturers in the metal parts industry in the context of hybrid AM. In Section 2, a review of current literature on hybrid AM, the price competition model, and operational implications of AM adoption are presented. The methodology and model developed for this hybrid duopoly scenario are outlined in Section 3, followed by results and numerical analysis in Section 4. Section 5 presents the discussions based on the results and a summary of findings and future directions are outlined in Section 6.

2. Literature Review:

2.1 Hybrid-Additive Manufacturing

As previously defined, hybrid-additive manufacturing refers to the integration of additive (AM) and traditional manufacturing processes, in which the role of traditional manufacturing addresses the limitations of AM in non-uniform material properties, surface finish and dimensional tolerances. Current literature on additive manufacturing has identified the importance of integrating AM with machining processes (Xiong et al., 2009), shot-peening (AlMangour and Yang, 2016), grinding (Beaucamp et al., 2015) heat-treatment (Wauthle et al., 2015), hot isostatic pressing (Qian et al., 2016) and surface treatments (Atzeni er al., 2016). In the case of 'in-envelope' hybrid processing, AM deposition head and CNC tooling are combined in a single machine envelope where both operations are repeated to achieve the final part (Amine et al., 2011). It should be noted that such systems offer a relatively less expensive option to gain hybrid machining capabilities but are severely limited in design freedom (e.g. lack of support structures) and material properties (Wang et al., 2017) when compared to other AM methods such as powder bed fusion (Song et al., 2015). In addition, the majorities (24.5%) of all metal AM systems that are installed across the globe are powder bed fusion systems (Wohlers, 2016); hence, discrete sequential hybrid AM processing, i.e. near-net AM followed by machining, heat treatment, etc. will have a larger impact. Such adaptable hybrid approaches will have little to no change in existing resources in manufacturing firms by maintaining AM and post-processing as separate operations. This allows firms the flexibility to evaluate serving as a post-processing service provider for AM firms or adding AM resources within the firm. With 94% of firms willing to adopt hybrid-AM post-processing as a service and additional resource availability for such services (Strong et al., 2016), there is a major gap in the literature on its effects on not only firms that could offer hybrid AM but also their competing firms.

2.2 Price Competition Model

The Bertrand duopoly model (Bertrand, 1883) is a well-known price competition model in economics. Bertrand duopolies compete on price, and both firms are assumed to be competing on similar products (Khan et al., 2010). While the classic model was introduced more than a century ago, remarkably, it still plays a fundamental role in modern research across multiple disciplines including innovation and technology management. For example, a study by Pal (2010) showed that when technology costs are high, Bertrand competition provides a stronger incentive for firms to adopt the technology. Giovenetti (2001) investigated technological adoption choices by firms through a Bertrand duopoly analysis and discussed how price elasticity of demand as well as asymmetry in cost affects the adoption outcome. For the investigation in this paper, the Bertrand model was chosen because competition in the metal parts industry is predominantly based on price, while quantity is based on low volume production (Strong et al., 2016). It is argued that the Bertrand model based on price is applicable since 'value-adding' aspects such as non-destructive inspection, qualification and certification of manufactured parts will be included in the production cost which directly affects the selling price. In other words, we are assuming that firm 1 and firm 2 are acting in their traditional business models and their business models are not currently changing to take advantage of AM and potential benefits of design freedom offered by AM is not included in this study for conservative analysis.

2.3 Manufacturing Flexibility and AM Operational Implications

Manufacturing flexibility is generally defined as the ability of a firm to manage production resources to meet customer requests, and researchers have proposed numerous dimensions to quantify and classify flexibility (Zhang et al., 2003; Koste et al., 2004; Vokurka and O'Learly-Kelly, 2000). The vast literature on flexibility in manufacturing has been examined through the lens of innovation (Oke, 2013), engineering (Wiendahl et al., 2007), business (Anand and Ward, 2004; Chandra et al., 2005), and strategy (Gerwin, 1993). For comprehensive review of literature on manufacturing flexibility we refer to Jain (2013), Beach et al. (2000), and Sethi and Sethi (1990). The question of how AM enhances flexibility in manufacturing was studied by Weller et al. (2015), particularly on the impacts of adopting AM technology on supply chain and market structures. The authors proposed that AM adoption would allow a monopolist firm to increase its profits by capturing consumer surplus when flexibly producing customized products. In a competitive market, AM could lower barriers, thereby lowering product prices for consumers. Since AM technology in industry is relatively scarce, empirical research on AM implementation is still limited. With AM capability, manufacturers are better equipped for a 'make-to-order' production because, unlike traditional manufacturing, AM does not require tooling to start production. Such production flexibility is discussed extensively in Anupindi and Jang (2008) who asserted that production flexibility helps to keep prices within a desired range, allowing for increases in capacity and higher profits.

Li and Liu (2014) studied two competing supply chains, each consisting of a supplier and manufacturing center and concluded that when new technologies are adopted, market competition which evolve between firms impacts the overall supply chain. Petrick and Simpson (2013) discussed that businesses need to reassess their strategies and operations due to the rise of highly disruptive AM technology.

3. Methodology:

This investigation aims to study the adoption of hybrid manufacturing in a resource contention manufacturing system and its effects on a firm's state of competition and profitability. This study focuses on firms that currently use traditional manufacturing methods to produce low volume metal parts. If hybrid manufacturing is adopted, then traditional shops will add post-processing of metal AM parts as a service to achieve the required surface finish and tolerances desired for part application. In such scenarios, the firm must allocate some of its existing production capacity to the hybrid manufacturing activity.

Three major assumptions are made in this study: (1) Attributes and value of hybrid AM and traditionally manufactured parts are the same (i.e. added benefits of AM such as light-weight structures and lack of tooling requirement are not included), (2) Integration of post-processing of metal AM parts within a firm is seamless (i.e. cost of training and process engineering of AM parts are not included) and (3) Adding resources to incorporate hybrid AM are not included (i.e. reallocation of existing resources such as

CNC machine availability instead of adding a CNC machine solely for hybrid AM). The rationale behind the first assumption is with a wide range of available material selection, design freedom and part size in metal AM, it is extremely difficult to quantify the added value of AM. Consequently, this assumption will lead to a conservative estimate of the benefits of hybrid AM. The second assumption is due to the relatively higher investment costs required to establish metal AM capabilities and, hence, traditional firms will not bring this in-house and will receive near-net metal parts from AM service providers. The final assumption on reallocation of existing resources instead of adding dedicated capabilities to pursue hybrid AM is reflective of a conservative scenario until the firm has thoroughly examined hybrid AM to make the business case for expanding resources and capacity.

It is important to analyze the impact of adopting metal hybrid AM on a firm's production economics based on circumstances where hybrid AM could be beneficial to the implementing firm and factors that may hinder the adoption and effects on a competing firm that chooses not to provide hybrid AM post-processing services. A simple economic model based on the classic Bertrand duopoly model is developed to demonstrate the interactions between two firms and their product offerings.

A general single-stage price competition problem (i.e. Bertrand model) where two manufacturers with similar capabilities compete on product price to maximize their total profits is detailed. The two manufacturing firms simultaneously and non-cooperatively choose the level of product price, and each faces a market demand that is inversely related to its pricing, and positively related to its competitor's price. The total profit consists of two major components: product profit and capacity cost. The function is assumed strictly concave in quantity and takes the following form:

$$\pi_i = \sum_j (p_{ij} - c_{ij}) Q_{ij} - \gamma_i \left(\sum_j Q_{ij}\right)^2 \qquad \text{Equation 5.1}$$

where

Q_{ij}
$= quantity\ demanded\ for\ product\ produced\ with\ technology\ j\ from\ manufacturer\ i$
$p_{ij} = unit\ price\ of\ product\ produced\ with\ technology\ j\ by\ manufacturer\ i$
$c_{ij} = unit\ cost\ of\ product\ produced\ with\ technology\ j\ by\ manufacturer\ i$
$\gamma_i = capacity\ cost\ coefficient\ for\ manufacturer\ i.$

The firm's quantity demanded $Q_{ij} = f(p_{ij}, p_{i'j})$ is treated as a differentiable, non-negative, non-increasing function with its own pricing decision (p_i) and non-decreasing with the competitor's pricing decision ($p_{i'}$). The capacity cost coefficient γ_i is a scaling factor converting capacity used to capacity cost. The notion of price competition for durable products is seen in a broad range of industries including manufacturing (e.g. Yao and Liu, 2005; Kamien et al., 1989; Van Mieghem and Dada, 1999). The convex quadratic function for capacity cost is assumed to represent a resource-contention environment, and is consistent with recent studies in several disciplines (e.g. Kamien et al., 1989; Prokop et al., 2015; Satoh and Tanaka, 2015). It is assumed that these quantities are determined through the function

$$Q_{ij} = K_{ij} - \beta_{ij} p_{ij} + \alpha_{i'j} p_{i'j} \qquad \text{Equation 5.2}$$

where K_{ij}, β_{ij}, α_{ij}, and $\alpha_{i'j}$ are non-negative constants.

Each manufacturer has two production methods *j* to produce the same product: technology 1 represents traditional manufacturing process and technology 2 represents hybrid AM methods. For simplicity, price and quantity demanded for the hybrid-manufactured product are assumed as exogenous parameters rather than decision variables to emphasize their effects in the model. Furthermore, in contrast to typical mass production products where unit cost can be greatly reduced due to the economies of scale, a unit cost for low-volume highly customized product remains relatively constant. If the product's unit cost (c_{ij}) stays constant, the goal of a manufacturer to maximize profit can be expressed as:

$$\max_{p_{i1}} \pi_i = \sum_j p_{ij} Q_{ij} - \gamma_i \left(\sum_j Q_{ij} \right)^2 \quad \text{s.t.} \quad p_{i1} \geq 0 \qquad \text{Equation 5.3}$$

where p_{ij} now represents the unit profit of product produced with technology *j* manufactured by firm *i*.

3.1 Solution Methodology

Since the firm's quantity demanded is a function of both its price and its competitor's price, Equation (1) is modified into:

$$\max_{p_{i1}} \pi_i = \sum_j p_{ij} f(p_{ij}, p_{i'j}) - \gamma_i \left(\sum_j f(p_{ij}, p_{i'j}) \right)^2 \quad \text{s.t.} \quad p_{i1} \geq 0. \qquad \text{Equation 5.4}$$

Since the firm's quantity demand $Q_{ij} = f(p_{ij}, p_{i'j})$ is non-increasing with its own pricing decision ($\partial Q_{ij} / \partial p_{ij} \leq 0$), it is noted that $\frac{\partial^2 \pi_i}{\partial {p_{i1}}^2} < 0$. Hence, this equation is strictly concave as the quantity function is linear. Given the strict concavity property of

Equation (1), closed form solutions for the optimal prices for product produced via traditional manufacturing process p_{i1}^* , $p_{i'1}^*$ are obtained.

In this study, the price and quantity for product fabricated with hybrid AM methods are treated as exogenous parameters, so our profit function for firm *i* becomes

$$\max_{p_{i1}} \pi_i = p_{i1}(K_{i1} - \beta_{i1}p_{i1} + \alpha_{i'1}p_{i'1}) + p_{i2}Q_{i2} - \gamma_i\left(K_{ij} - \beta_{ij}p_{ij} + \alpha_{i'j}p_{i'j} + Q_{i2}\right)^2$$

Equation 5.5

where *i =1,2*.

In order to find the optimal prices p_{11}^* , p_{21}^*, the resulting system of two equations obtained is solved to find the maximum profit for both firms (simultaneously solving $\frac{\partial \pi_1}{\partial p_{11}} = 0$ and $\frac{\partial \pi_2}{\partial p_{21}} = 0$ for p_{11} and p_{21}).

It is evident that the optimal price for product produced via traditional manufacturing is a decreasing function with the quantity for product built via hybrid manufacturing ($\frac{d\, p_{i1}^*}{d\, Q_{i2}} < 0$). Therefore, a price threshold ($\acute{p}_{i2}$) exists beyond which resource allocation to hybrid AM services will increase the profit of both manufacturers even when only one manufacturer adopts hybrid manufacturing.

4. Results and Analysis:

For the numerical analysis, a ‘benchmark’ scenario is first presented, where neither firm adopts hybrid-manufacturing technology. Next, several numerical examples where only one firm adopts hybrid-manufacturing technology are discussed. In each subsequent numerical example, the quantity of hybrid products is increased.

As a benchmark scenario, the following parameters are set (arbitrarily): K_{11}=500, K_{21}=250, $\beta_{11} = 5$, $\beta_{21} = 2$, $\alpha_{11} = 2$, α_{21}=3, $\gamma_1 = 1$ and $\gamma_2 = 1$. Also, Q_{12}=0, Q_{22}=0, p_{12} =0, p_{22}=0, since this scenario assumes neither firm is producing a product via hybrid manufacturing. The results are shown in the first section of Table 5.1.

In the next numerical example, the same set of parameter values is assumed but with Q_{12} = 1 to reflect a scenario where firm 1 produces one unit of product 2. As some manufacturing capacity of firm 1 is shifted from product 1 to product 2, the equilibrium price and quantity for product 1 changes correspondingly. The results from this scenario are presented in the second section of Table 5.1.

Table 5.1: One Firm Produces Hybrid Product

Where p_{ij}=price, Q_{ij}=quantity and π_{ij}=profit

1. Results for Q_{12}=0	**i = 1**	**i = 2**
p_{i1}	275.00	333.33
Q_{i1}	125.00	133.33
π_i	18,750.00	26,667.00
2. Results for Q_{12}=1	**i = 1**	**i = 2**
p_{i1}	275.31	333.59
Q_{i1}	124.23	133.44
π_i	18,519.00 + π_{i2}	26,708.00
3. Results for Q_{12}=5	**i = 1**	**i = 2**
p_{i1}	276.54	334.62
Q_{i1}	121.54	133.84
π_i	17,589.00 + π_{i2}	26,872.00
4. Results for Q_{12}=10	**i = 1**	**i = 2**
p_{i1}	278.08	335.90
Q_{i1}	117.31	134.36
π_i	16,413.00 + π_{i2}	27,079.00
5. Results for Q_{12}=20	**i = 1**	**i = 2**
p_{i1}	281.15	338.46
Q_{i1}	109.62	135.38
π_i	14,019.00 + π_{i2}	27,493

Since Q_{12} = 1, it is straightforward that the unit profit for product produced via hybrid AM (π_{i2}) must be at least $231 (18,750 – 18,519) to incentivize firm 1 to produce it. To further explore this effect, the model is run again three times, only changing the value of Q_{12} (i.e. the number of products that firm 1 will manufacture through hybrid AM). The results are presented in sections 3-5 of Table 5.1.

Using these results, the minimum unit profit for production via hybrid AM for each scenario can be computed. Table 5.2 summarizes the minimum unit profit for all four scenarios. For instance, if firm 1 is producing 20 units of product via hybrid AM, the minimum unit profit must be \$236.55. Otherwise, it will be economically beneficial for firm 1 to produce the product via only traditional manufacturing.

Table 5.2: Minimum Unit Profit for Product Fabricated Using Hybrid-Manufacturing Technology

Q_{12}	Min Profit/Unit
1	\$231.00
5	\$232.20
10	\$233.70
20	\$236.55

When the minimum unit profit can be attained, the adoption of hybrid AM would not decrease the total profit for firm 1. In other words, firm 1 will have economic incentive to adopt hybrid AM as long as the unit profit of hybrid AM product exceeds the values tabulated in Table 5.2 and firm 2 does not adopt. Under this circumstance, we focus on the impact of adopting hybrid AM on the price and quantity demanded for the product produced using traditional manufacturing processes as shown in Figures 5.1-5.2.

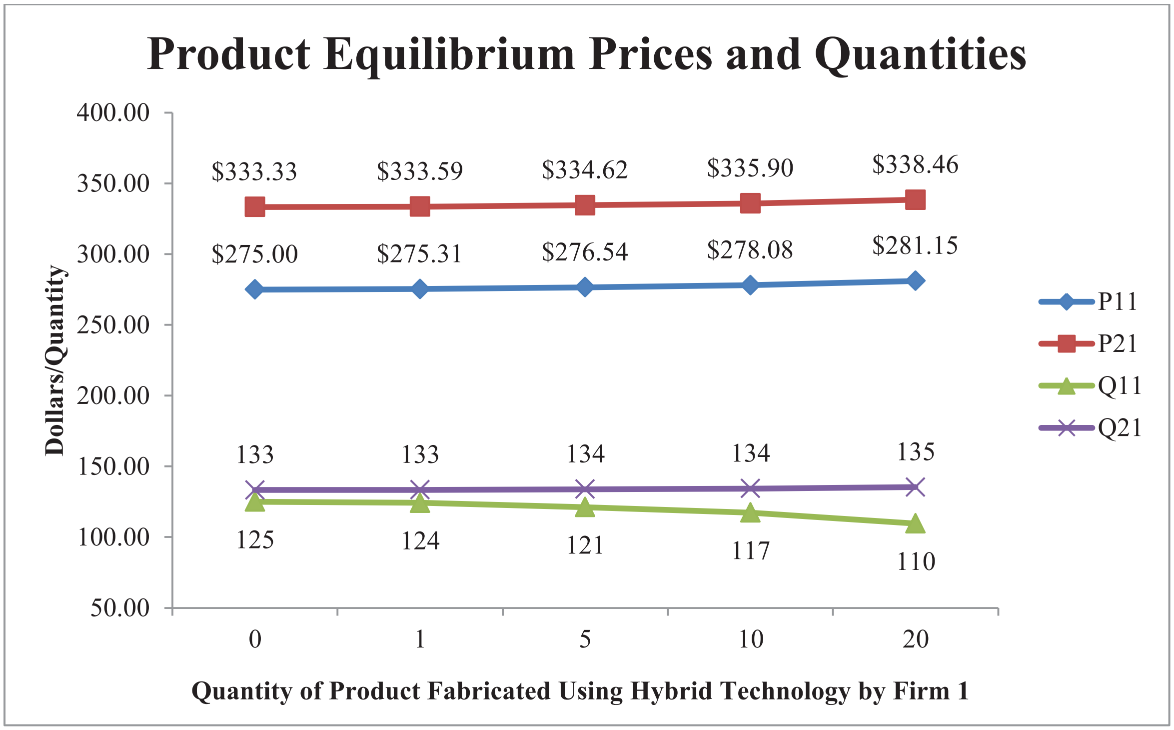

Figure 5.1: Product Equilibrium Prices (P_{ij}) and Quantities (Q_{ij}) when Firm 1 Adopts Hybrid

Where i=Firm 1 or Firm 2 and j=Traditional Product1 or Hybrid Product 2

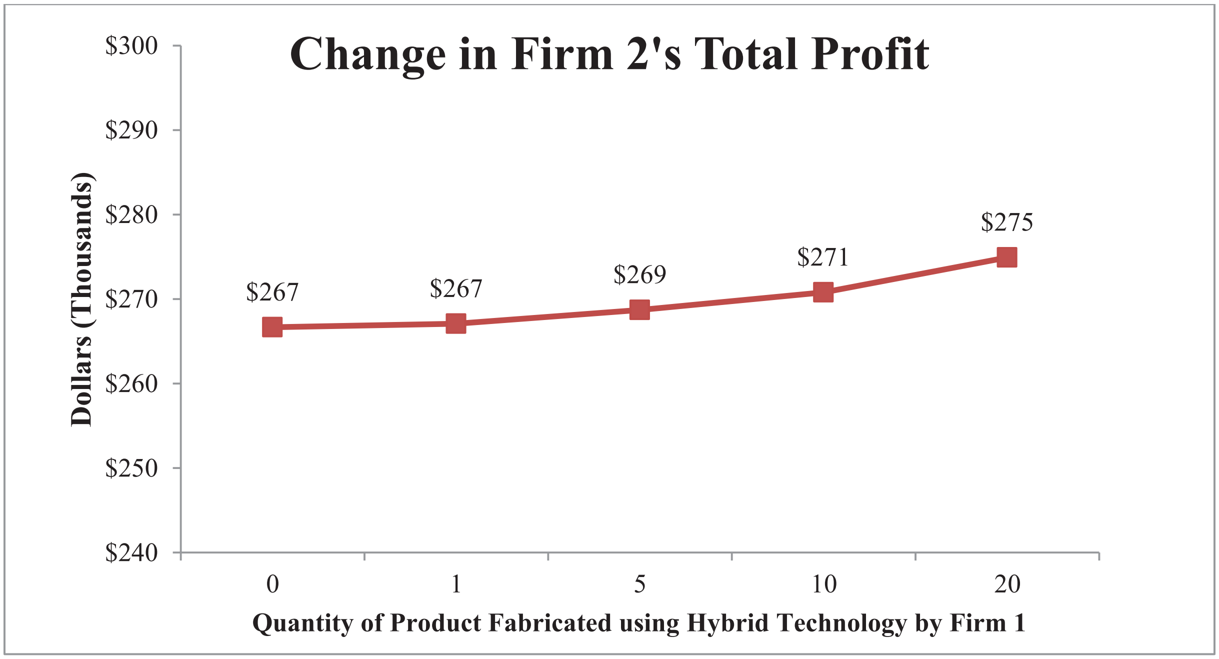

Figure 5.2: Change in Firm 2's Total Profit as Firm 1 Fabricates Hybrid Product

Figures 5.1 and 5.2 provide critical insights into the role of introducing hybrid AM products to the market by one firm and its potential effects on the overall market for traditionally manufactured products. The numerical results suggest that if firm 1 is designated as a risk-taker and offers hybrid AM product to the market, it will unilaterally shift some of its resources to hybrid manufacturing activities. As a result, the equilibrium price of the product produced using traditional manufacturing process will increase due to reduced capacity for products produced using traditional manufacturing. Therefore, both firms will enjoy higher unit profitability in this category.

On the other hand, the equilibrium quantity for products produced with traditional manufacturing for each firm moves in the opposite direction. As shown in Figure 5.2, resource reallocation for hybrid AM by firm 1 could result in higher total profit for firm 2 which employs only traditional manufacturing processes. In other words, firm 2 is designated as risk averse to adopting newer technology but could reap the benefit of capacity reduction of the traditional manufacturing process in the market. It should be noted that this observation holds regardless of profit level generated by hybrid AM as no specific assumption is made about p_{12}.

In this case, ‘value adding’ aspects of metal AM such as light-weight structures for optimal product design and lack of fixture requirements are not incorporated. Based on observations from Figure 5.2, it should not be surprising that many firms might be reluctant to be a pioneer participant in hybrid AM. In other words, the decision to ‘wait-and-see’ how their competitors execute hybrid AM integration may be prudent from both technological and economic standpoints. Such strategy is consistent with the option-value approach that is observed many other industries especially when the adoption of new technology is irreversible (Luque, 2002), and when there is significant learning from adoption experience of others (Hoppe, 2002). Also, in the context of converting traditional manufacturing capacity to flexible automation, Monahan and Smunt (1989) concluded that the optimal decision depends on the timing and current state of the new technology among other factors.

In an alternative scenario, firm 2 could match firm 1 in shifting its existing resources to hybrid manufacturing activities. This may represent a case of industry-wide adoption of the technology which could eventually take place. The numerical study is run again using similar parameters and new equilibrium prices and minimum unit profit for each firm at different quantities of hybrid product 2 and results are shown in Tables 5.3 and 5.4.

Table 5.3: Both Firms Produce Hybrid Product

Where p_{ij}=price, Q_{ij}=quantity and π_{ij}=profit

Results for Q_{i2}=1	**i = 1**	**i = 2**
p_{i1}	275.65	334.21
Q_{i1}	124.38	132.88
π_i	18,565.00	26,485.00
Results for Q_{i2}=5	**i = 1**	**i = 2**
p_{i1}	278.23	337.69
Q_{i1}	121.92	131.08
π_i	17,813.00	25,747.00
Results for Q_{i2}=10	**i = 1**	**i = 2**
p_{i1}	281.46	342.05
Q_{i1}	118.85	128.82
π_i	16,849.00	24,792.00
Results for Q_{i2}=20	**i = 1**	**i = 2**
p_{i1}	287.92	350.77
Q_{i1}	112.69	124.31
π_i	14,839.00	22,779.00

Table 5.4: Minimum Unit Profit of Hybrid to Justify Adoption

Q_{i2}	i = 1	i = 2
1	$185.00	$223.00
5	$187.40	$225.00
10	$190.10	$228.70
20	$195.55	$235.70

As shown in Figure 5.3 and similar to the first scenario where only firm 1 was involved in hybrid AM, both firms will enjoy higher unit profitability for products produced using traditional manufacturing. However, in this scenario, the new equilibrium price and quantity for traditionally manufactured products substantially lowers the minimum unit profit required for hybrid product for firm 1. In other words, firm 1 will indirectly benefit from participation of firm 2 in hybrid AM due to collectively decreased resource availability for traditional manufacturing activities. In addition, the required minimum unit profit for hybrid AM product also decreases which leads to stronger economic justification for adopting metal AM.

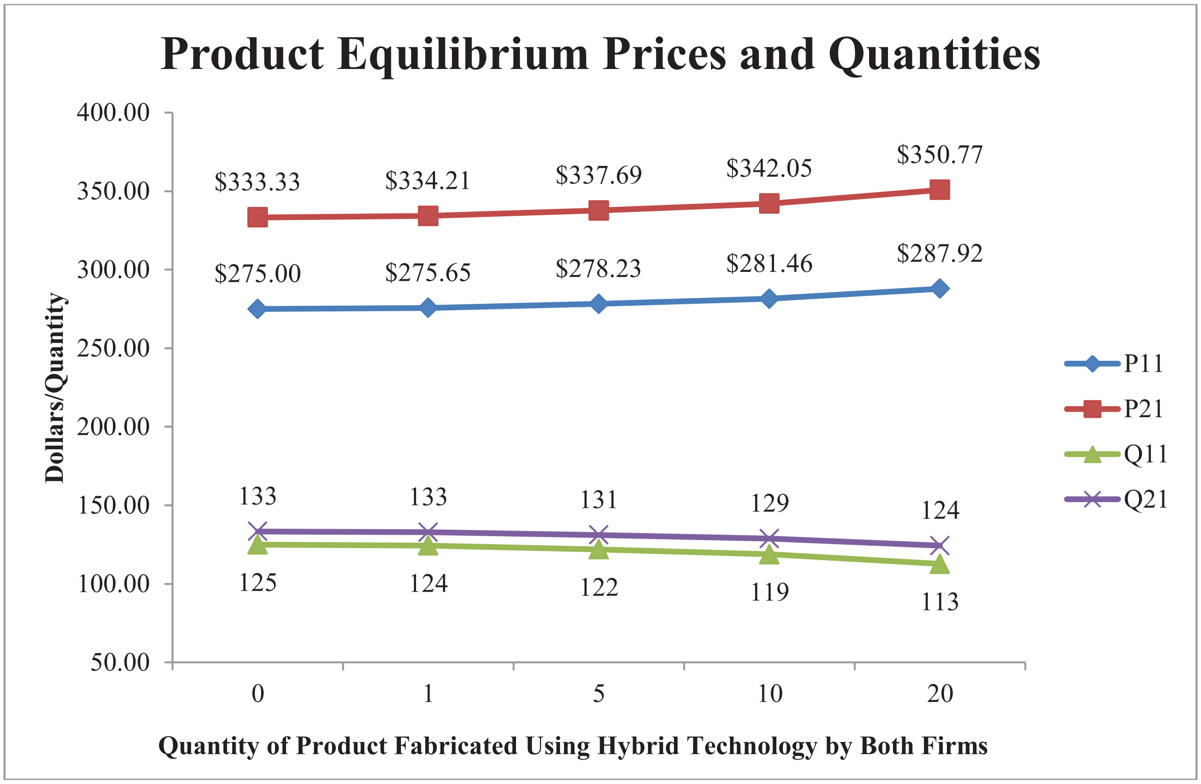

Figure 5.3: Product Equilibrium Prices (P_{ij}) and Quantities (Q_{ij}) when Both Firms Adopt Hybrid

Where i=Firm 1 or Firm 2 and j=Traditional Product1 or Hybrid Product 2

5. Discussion

From this numerical study, it is evident that a complex interplay in price and quantity equilibrium exists that would allow both firms to indirectly benefit from the adoption of hybrid AM even under limited resources. If additional resources are not allocated for hybrid AM by firm 1, firm 2 could enjoy greater profit from traditional product due to shifts in price and quantity equilibrium induced by the resource re-allocation. In such cases, as firm 1 accepts more orders for hybrid AM its capacity for traditional product decreases and firm 2 will reap the benefit of more orders for traditional products. On the other hand, firm 1 would also benefit from participation of firm 2 in hybrid AM. As observed from the numerical experiment, the minimum unit profit required for product 2 in firm 1 drops significantly. This occurs since the collective capacity reduction in product 1 (shifted to product 2) led to an equilibrium in price and quantity that favors firm 1 much more than when firm 1 is alone in the product 2 market. This observation is indicative of the assumption that total product demand for both hybrid AM and traditional metal parts remain constant and under limited capacity, one product category will not cannibalize the other product category.

These results provide insight into the potential and flexibility of AM technologies in production research. The role of capacity plays a huge factor in this decision making process. Before implementation, firms should analyze resource re-allocation from traditional to hybrid AM production and/or addition of resources solely for hybrid AM. Considering this resource contention, if a firm provides hybrid AM service, market behavior and pricing would depend on the current state and response by its competitor (s). The manufacturing strategy debated here is who will ‘go first’ to take the risk of adopting hybrid AM services. The firm to adopt first and meet the minimum profit thresholds will benefit overall at the risk of giving up traditional product capacity, in which its competitors will accept and benefit. In such cases, competing firms face the decision of either continuing to benefit only from traditional production, or also offering hybrid AM services. If the latter occurs, then the minimum profit to justify AM adoption will decrease due to competiveness in the market. Although being the first firm to pioneer hybrid AM could be a risk, it is also a strategy what would allow for more product flexibility. In a recent market report, revenue of metal AM and sales of metal AM systems has grown by 80.9% and 46.9% respectively implying growth for post-processing which is reflective of the argument provided in this numerical study (Wohlers, 2016). When compared to traditional manufacturing, AM parts offer higher design complexity and more customization particularly at lower production volume, hence customers would be willing to pay a price premium. The first firm to offer hybrid-AM services will be able to monetize this market sector, where customers are seeking more sophisticated designs that are only feasible through advanced manufacturing technologies in AM. Therefore, integration of AM technologies through hybrid AM will increase product flexibility leading to increased customer market share, customer retention and economic benefits observed in the model. As observed in the introduction of newer technology, manufacturing firms must realize the importance of quick adaptation. Firms can use this price competition model to help with decision making and strategizing, whether they wish to be the ‘first’ in the market to offer hybrid-AM services or to compete with firms already offering such services.

This analysis assumes that Firm 1 and Firm 2 are tiered suppliers who do not have design authority. Firms 1 and 2 are contracted to make products on behalf of other firms. As such, their business models are largely driven by cost considerations. If Firm 1 and Firm 2 are instead vertically integrated original equipment manufacturers, then each firm would have the ability to leverage the design freedom afforded by AM to create intellectual property through product design and exclude competitors. In that case, the analysis in this paper would not apply. Here it is assumed that both firms are acting in their traditional cost-driven business models and their business models have not changed to take advantage of AM.

6. Conclusion

Due to the popularity and flexibility of AM along with the supporting research on firms' available capacity to offer hybrid AM services, this economic model and numerical analysis provide insight on benefits from adopting hybrid AM into the current traditional supply chain for both competing firms. Even if a firm chooses not to adopt hybrid AM into their manufacturing operations, it may still benefit from other firms adopting the process due to the nature of competition. The economic impacts of hybrid AM on supply chain are demonstrated with regards to quantities, prices, and profits using the Bertrand duopoly model. It is demonstrated that the relationship between competing firms may be impacted by hybrid AM. Competing firms could both benefit even if only one adopts hybrid AM due to the fluctuations in demand and order flow between firms. The risk to adopt first may be outweighed by the benefits of being the first to gain a new customer base seeking hybrid-AM options. Overall, offering hybrid-AM services has the potential to increase profits among both firms and supply chains, increase market share, and offer more flexible production services. Whether in the perspective of the 'go first' firm or a 'following' firm, it is important to consider ways to increase adaptability with regards to capacity, competition and product service systems.

Due to the assumptions required in a duopoly model, this research is limited to two competitive firms that manufacture similar and substitutable products. Future work includes various other supply chain models in which there are multiple firms or a variety of product mix. Scenarios where resource capacity is added rather than re-allocated would also be of great interest based on the findings from this study.

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CHAPTER 6: CONCLUSIONS AND FUTURE WORK

Introduction

This chapter includes an overall summary of the results found in this work along with an outline of the contributions and directions for future research.

6.1 Research Summary

In this thesis, a hybrid-AM supply chain ecosystem is proposed. Based on the preliminary research findings in Chapter 1, the motivation for integrating additive and subtractive manufacturing supply chains was presented through surveying OEMs. It was noted that majority of the OEMs surveyed have machine availability and an interest in adopting hybrid manufacturing to additionally offer post-processing services. Low volume parts which would be suitable for hybrid manufacturing are generally more profitable. Access to metal AM, process engineering time, tooling requirements and the need for quality control tools were equally identified as the major challenges for OEM participation in this evolving supply chain.

Under this supply chain ecosystem, the traditional shops should operate based on PSS methods including post-processing, repairs, replacement parts, and maintenance. These PSS methods are capable of additionally increasing profit margins, customer loyalty and extending product life cycle. By focusing on low volume AM parts with higher profit margins, OEMs can improve their current lead times and utilization rates through hybrid manufacturing.

In Chapter 2, an uncapacitated facility location model and a constrained p-median model are used to investigate where to strategically locate AM hubs in the proposed hybrid-AM supply chain ecosystem. North American Industry Classification System (NAICS) data was used to determine the county-level demand in the United States. By centralizing AM resources, every machine shop in the U.S does not have to directly invest in expensive AM systems and associated training, maintenance and R&D efforts. 22 hub locations were identified for 5% demand levels and 44 hub locations were identified for 10% demand levels. Costs associated with the hybrid-AM supply chain such as fixed cost, transportation cost and production cost were also analyzed. It was found that transportation costs and AM machine costs do not affect AM hub locations, and that fixed cost is the main driver behind the hub locations and demand allocations.

In Chapter 3, the analysis in Chapter 2 was expanded to include NAICS data for heat treatment counties added into the hybrid-AM supply chain since most printed metal parts are required to go through heat treatment. A two-stage p-median facility location model was utilized to identify the locations of AM hubs relative to both heat treatment counties and machine shop counties. 22 hub locations were identified for 5% demand levels and 35 hub locations were identified for 10% demand levels. Costs associated with AM hubs with heat treatment remained consistent compared to without heat treatment. It was found that since there is significantly less number of heat treatment counties (263) compared to heat treatment counties (2,162) that for 10% demand 35 hubs were chosen out of the 44 required. This is due to demand being aggregated at more concentrated locations, and thus adding in heat treatment into the hybrid-AM supply chain could result in cost savings compared to the hybrid-AM supply chain without heat treatment.

Chapter 4 explores the hybrid-AM supply chain in the reverse logistics supply chain. An uncapacitated facility location model and p-median model were used to locate AM remanufacturing hubs respective to remanufacturing costs and demand. 18 AM remanufacturing hubs were chosen for 5% demand and 36 AM remanufacturing hubs were chosen for 10% demand. Annual fixed costs per remanufacturing hub were found to be less than for manufacturing hubs and annual transportation costs were slightly larger for remanufacturing than for manufacturing. A special case study was also done to analyze high value repair parts. 1 AM remanufacturing hub was chosen for an aircraft engine component with 10% annual repair demand. Annual demand and fixed cost were lower for the high value part, however production cost was larger and transportation cost remained consistent.

Chapter 5 explores the role of production resources in a traditional manufacturing facility and economic effects on the adoption of AM via hybrid manufacturing using a price competition model. The effects of introducing hybrid manufacturing on the market structure of a standard product with regard to prices, quantities, and profits are analyzed. The numerical results show that for products manufactured in a resource constrained environment, an adoption of hybrid manufacturing into one firm’s portfolio may potentially improve the profitability of its competitor who chooses not to adopt hybrid manufacturing. An adoption in two firms may indirectly benefit the first firm that adopts hybrid AM due to collectively decreased resource availability. In addition, the required minimum unit profit for hybrid AM product also decreases which leads to stronger economic justification for adopting metal AM.

6.2 Research Contributions

The following presents a summary of the contributions identified from this research:

- By focusing on low volume AM parts with higher profit margins, OEMs can improve their current lead times and utilization rates through hybrid manufacturing. Challenges to traditional manufacturers mentioned such as access to AM, time for process engineering for customization, tooling requirement, quality control, high upfront costs, and post processing costs can be alleviated through the proposed hybrid-AM supply chain ecosystem.
- Uncapacitated Facility Location (UFL) model results in AM hubs closer to density centroid with extremely high fixed cost irrespective of expected demand. UFL model is affected only by lower AM utilization rates which indicate opportunities for existing AM hubs to seek regional manufacturers as additional customers.
- Reduction in current AM machine costs (10%) does not affect AM hub locations

- Based on p-median results, 22 and 44 AM hubs are recommended for 5 and 10% demand for hybrid AM parts.
- Adding capacity to existing hubs is preferred over establishing new AM hubs at the 5% demand level and adding new hubs is preferred at the 10% demand level.
- Transportation costs do not affect AM hub locations, since the FedEx ground rate was employed in the study. Although it would likely over-represent the actual negotiated transport rates, transportation costs did not play a major role in locating the AM hubs.
- When a heat treatment step is added into the AM supply chain, 22 hubs are needed for 5% demand and 35 hubs are needed for 10% demand, thus a cost savings in annual fixed cost may be an incentive to locate hubs respective to heat treatment counties.
- The annual costs associated per AM hub remained consistent with or without the heat treatment step.
- Increasing part weights to include the metal build plates (additional 15 lbs. per part) did not affect the percentage of dollars allocated to annual transportation cost per hub.
- Locating AM remanufacturing hubs result in doubled transportation costs and lower fixed costs compared to AM manufacturing hubs.
- 18 AM remanufacturing hubs were chosen for 5% demand and 36 were chosen for 10% demand.

- For cases with high value part repairs, one centralized AM remanufacturing hub is preferred.
- Figure 6.1 summarizes the states chosen most frequently for hub locations for Chapters 2-4.
- Figure 6.2 summarizes the counties chosen most frequently for hub locations for Chapters 2-4.

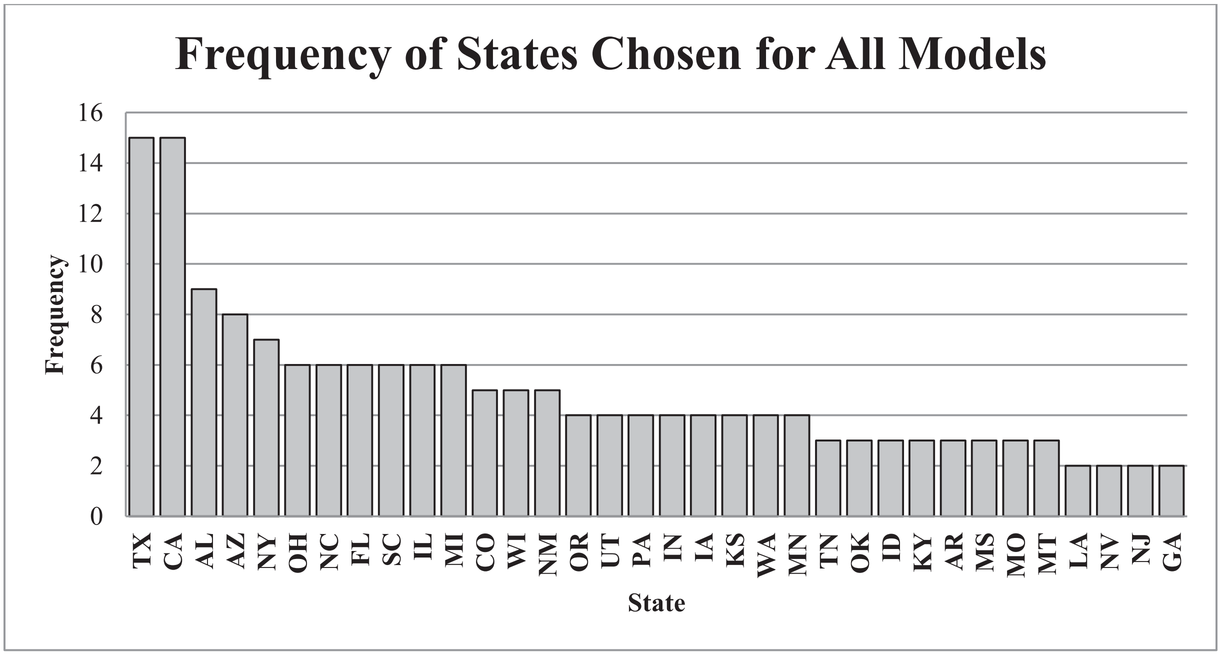

Figure 6.1: Frequency of States Chosen for All Models

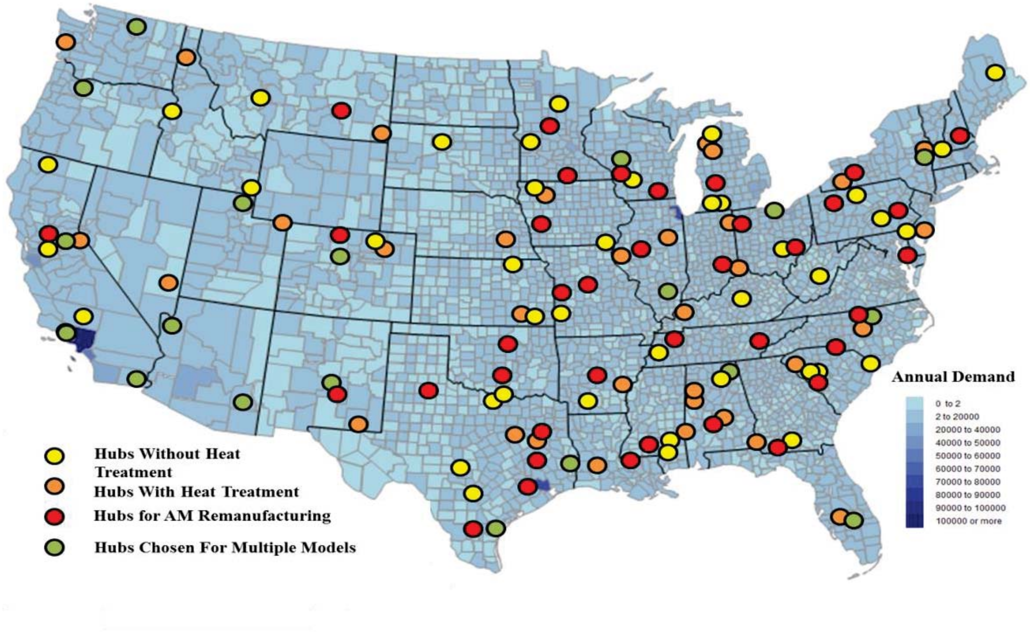

Figure 6.2: Map of All Counties Chosen

- Even if a firm chooses not to adopt hybrid AM into their manufacturing operations, it may still benefit from other firms adopting the process due to the nature of competition. Overall, offering hybrid-AM services has the potential to increase profits among both firms and supply chains, increase market share, and offer more flexible production services.
- It is demonstrated that the relationship between competing firms may be impacted by hybrid AM. Competing firms could both benefit even if only one adopts hybrid AM due to the fluctuations in demand and order flow between firms. The risk to adopt first may be outweighed by the benefits of being the first to gain a new customer base seeking hybrid-AM options.

6.3 Future Research

Future work on the preliminary study done in Chapter 1 includes expansion to support larger metal parts manufacturers as the majority of survey participants were small-medium OEMs distributed explicitly to the CAM-IT and America Makes database. It is also realized that the hybrid approach is not applicable to all industries. Until technology advances even further, some industries may be restricted by the size of their metal parts and/or other product considerations.

In Chapter 2, incorporating product-mix models with varying post-processing needs additional to heat treatment (machining, grinding, polishing, etc.) and time-sensitivity could be an option for research expansion. In addition, this study did not include local factors such as availability of AM supplies, operators and policies that could affect the proposed AM hubs.

In Chapter 3, including additional analysis to consider capacity constraints on the heat treatment facilities is suggested. It is proposed that heat treatment county sales volume could be used to allocate capacity constraints with regards to how much demand each heat treatment county is capable of processing.

In Chapter 4, it would be a great interest to analyze a scenario in which existing machine shops are chosen to adopt AM remanufacturing technology, as opposed to opening a standalone remanufacturing hub. This analysis could involve capacity constraints for each machine shop county with regards to how much demand it is capable of repairing based on sales volume.

In Chapter 5, due to the assumptions required in a duopoly model, this research is limited to two competitive firms that manufacture similar and substitutable products. Future work includes various other supply chain models in which there are multiple firms or a variety of product mix. Scenarios where resource capacity is added rather than re-allocated would also be of great interest based on the findings from this study.

LIST OF RELEVANT PAPERS

PUBLISHED:

1) Strong, D., Sirichakwal, I., Manogharan, G. P., & Wakefield, T. (2017). Current state and potential of additive-hybrid manufacturing for metal parts. *Rapid Prototyping Journal*, *23*(3).

UNDER-REVIEW:

1) Strong, D., Wakefield, T., Sirichakwal, I, Conner & B. Manogharan, G. P.(2017). Adopting Additive-Hybrid Manufacturing: The Role of Capacity in Implementation Decision. International Journal of Production Research

PLANNED SUBMISSIONS:

1) Strong, D., Kay, M., Sirichakwal, I, Wakefield, T., Conner & B. Manogharan, G. P.(2017). Hybrid Manufacturing: Integrating Traditional Manufacturers with Additive Manufacturing (AM) Hubs.

2) Manogharan, G.P., Conner, B. Wysk, R.A., Harrysson, O.L.A & et. al, (2017). A Comprehensive Roadmap for Advanced Hybrid Manufacturing. Journal TBD

3) Strong, D., Kay, M., Sirichakwal, I, Wakefield, T., Conner & B. Manogharan, G. P.(2017). Allocating AM Hubs Using a Two-Stage Facility Location Approach. Journal of Operations Management

4) Strong, D., Kay, M., Sirichakwal, I, Wakefield, T., Conner & B. Manogharan, G. P.(2017). Rethinking Reverse Logistics: Role of Additive Manufacturing Technology in Remanufacturing. International Journal of Production Research

TABLE OF AUTHORS

AUTHOR	DEPARTMENT	UNIVERSITY
Danielle Strong	Mechanical and Industrial Engineering	Youngstown State
Dr. Michael Kay	Industrial and Systems Engineering	North Carolina State
Dr. Issariya Sirichakwal	Information Systems and Operations Management	University of Washington
Dr. Thomas Wakefield	Mathematics and Statistics	Youngstown State
Dr. Brett Conner	Mechanical and Industrial Engineering	Youngstown State
Dr. Guha Manogharan	Mechanical and Nuclear Engineering	The Pennsylvania State

Youngstown
STATE UNIVERSITY

One University Plaza, Youngstown, Ohio 44555
Office of Research
330.941.2377
www.ysu.edu

April 27, 2017

Dr. Brett Conner, Principal Investigator
Ms. Danielle Strong, Co-investigator
Department of Mechanical & Industrial Engineering
UNIVERSITY

RE: HSRC PROTOCOL NUMBER: 187-2017
TITLE: Current State and Potential of Additive-Hybrid Manufacturing for Metal Parts

Dear Dr. Conner and Ms. Strong:

The Institutional Review Board has reviewed the abovementioned protocol and determined that it is exempt from full committee review based on a DHHS Category 3 exemption.

Any changes in your research activity should be promptly reported to the Institutional Review Board and may not be initiated without IRB approval except where necessary to eliminate hazard to human subjects. Any unanticipated problems involving risks to subjects should also be promptly reported to the IRB.

The IRB would like to extend its best wishes to you in the conduct of this study.

Sincerely,

Mr. Michael A. Hripko
Associate Vice President for Research
Authorized Institutional Official

MAH:cc

c: Dr. Hazel Marie, Chair
Department of Mechanical & Industrial Engineering