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Additive manufacturing in the spare parts supply chain: hub configuration and technology maturity

Abstract

Purpose - Innovative startups have begun a trend using laser sintering (LS) technology patents expiration, namely by introducing LS additive manufacturing (AM) machines that can overcome utilization barriers, such as the costliness of machines and productivity limitation. The recent rise of this trend has led us to investigate this new class of machines in novel settings, including hub configuration. There are various supply chain configurations to supply spare parts in industrial operations. This research explores the promise of a production configuration that combines the benefits of centralized production with the flexibility of local manufacturing without the huge costs related to it.

Design/methodology/approach – This study quantitatively examines the feasibility of different AM-enabled spare parts supply chain configurations. Utilizing cost data extracted from a case study, three scenarios per AM machine technology are modeled and compared.

Findings - Results suggest that hub production configuration depending on the utilized AM machines can provide the economic efficiency as well as effectiveness to reduce equipment downtime. While previous studies have suggested the need for AM machines with efficiency for single part production for a distributed supply chain, the findings in this research illustrate the positive relationship between multi-part production capability and the feasibility of a hub manufacturing configuration establishment.

Originality/value - This study explores the promise of a production configuration that combines the benefits of centralized production with the flexibility of local manufacturing without the huge costs related to it. Although the existing body of knowledge contains research on production decentralization, research on various levels of decentralization is lacking. Using a real-world case study, this study aims to compare the feasibility of different levels of decentralization for AM-enabled spare parts supply chains.

Keywords Additive manufacturing, direct digital manufacturing, spare parts supply chain, AM hub configuration, aerospace industry

Paper type Case study

1. Introduction

The additive manufacturing (AM) industry has been growing due to two main reasons—an increasing number of companies are utilizing this technique for the commercial end-use components production, and newer cost-efficient production machines are emerging at greater quantities (Wohlers Report, 2017). Aerospace and medical industries are on the leading edge of AM developments as their production batch sizes, parts complexity, and customization requirements allow the economic implementation of AM (Gibson et al., 2006; Hopkinson et al., 2006; Atzeni & Salmi, 2012; Campbell et al., 2012). This point can be seen with a number of companies and organizations. General Electric Aviation—a subsidiary of General Electric Company (GE)—is now producing fuel injection nozzles by AM for their Leading Edge Aviation Propulsion (LEAP) jet engines (Kellner, 2013). Airbus has used 1000 additively manufactured components in their A350 XWB commercial jetliner (Stratasys, 2015). SpaceX has utilized three-dimensional (3D) printed main oxidizer valve body for their Merlin 1D rocket engines and is printing the whole engine chamber of its upcoming SuperDraco engines for the crewed Dragon space capsule (SpaceX, 2014). The main reasons behind these implementations are time and cost savings in addition to the product design improvements, including improvements for less weight, better durability, and a longer life span. For instance, in the case of fuel injection nozzle, GE succeeded with parts consolidation by reducing the number of parts from 20 to one, thereby saving 25% on a component's weight (GE aviation, 2015). Moreover, part strength improved substantially by a factor of five in comparison to its traditionally manufactured predecessor (Cotteleer & Joyce, 2014). All in all, the new additively manufactured fuel injection nozzles yield sizable savings for the operating airlines up to $3 million per aircraft per year (Rao, 2016). These examples are based on the immediate operating and production supply chain benefits. In addition, it is crucial to consider the potential benefits of AM for aftersales.

Spare parts supply chain operations are of great importance for original equipment manufacturers (OEMs), third party maintenance repair and operations (MRO) service providers (Pearce, 2013), and customers for different reasons. Firstly, the operations provide a high profit margin for the OEMs (Cohen et al., 2006). This explains the existence of third parties providing a reliable spare parts supply chain at a high service level. Such providers help to minimize equipment downtime and ultimately contribute to the customers. In factories, the lack of spare parts may halt multi-million-dollar production lines and push back the entire production schedule. In the aviation industry, spare parts shortage causes Aircraft On Ground (AOG) situations which can impose up to thousands of dollars of losses per hour (DHL, 2018). According to ICF International Inc., which is among the largest aviation and aerospace consulting firms, the cost of commercial aircraft MRO in 2015 was $64.3 billion, and it is expected to grow to $96 billion by 2025 (Berger, 2016). This point illustrates the seriousness of efficiency and effectiveness in spare parts provision, which is a major component of every MRO. Other main components include a skilled workforce and having the required tools and equipment.

In a number of settings, the cost of equipment downtime can lead to the fatalities of individuals. In a battlefield, non-functional equipment may be a decisive factor between victory and defeat. In a recent report by the United States Government Accountability Office (GAO), the problem of inadequate parts can be seen:

> “Parts were not always available to perform the work because the DOD [Department of Defense] supply system did not maintain sufficient parts in the right mix to meet demand. Without the DOD supply system maintaining the right mix and sufficient quantities of spare parts, industrial operations activities cannot complete their funded workload timely and efficiently. Supply chain management has been a long-standing problem for DOD” (GAO, 2016)

Moreover, this report further explains how the "army had accumulated billions of dollars in excess spare parts inventory against current requirements for some items and substantial inventory deficiencies in other items" (GAO, 2016). AM can provide a solution to part of these problems (Sasson & Johnson, 2016), and since the scale of the issues are in billions of dollars, even the smallest improvement leads to massive operational savings.

AM has the potential to address the most challenging aspects of a spare parts supply chain, namely the aspects of capital investment in inventories, inventory carrying cost, obsolescence, and transshipment. After the expiration of major laser sintering (LS) technology patents in 2014 (Deckard, 1989; Schoffer, 2016), this opportunity seems to be closer to reality. AM patents' expiration of LS has led to the emergence of new AM machines with specific characteristics, namely professional grade machines with low cost and high throughput; this in turn can affect the AM implementation for the spare parts supply chains. However, the current body of knowledge in this field is still in its infancy (Holmström et al., 2016) and thus requires further development. In this study, we aim to contribute to the earlier works by incorporating the actual data of the state-of-the-art machines and utilize previously published scenario modeling (Khajavi et al., 2014) to AM-enabled manufacturing hubs. In this way, we can examine the feasibility of the AM hubs configuration for the spare parts supply chain in a real-world setting.

The remainder of this paper is organized as follows. Chapter 2 presents a literature review, while Chapter 3 explains the research methodology; Chapter 4 presents the findings and results of our analysis. Finally, this paper closes with discussion of results, conclusions summarizing the research outcomes and suggestions for future studies.

2. Literature review

2.1. Additive manufacturing

AM is commonly known as three-dimensional printing (3DP), and it is a method of producing an object directly from a three-dimensional computer-aided design (CAD) file (Frazier, 2014). It can be referred to as a bridge between the digital and physical worlds (see Chapter 14 of Gibson et al., 2010). This method works contrary to the conventional production methods that subtract excess material from a raw shape to achieve the intended geometry. AM produces parts by adding thin cross sections of the part's three-dimensional geometry to construct the intended design with one cross section on top of the other (see Figure 1). These thin two-dimensional cross sections are extracted by computer software from the design and then sent to an AM machine to be laid out of raw material. In a number of major AM methods, a laser is utilized as the source of heat; the idea is to melt and fuse each layer accurately and reliably onto the previous layers (Gibson et al. 2010, Hopkinson et al. 2006).

AM processes emerged in 1980s as prototyping tools, and these processes were called rapid prototyping (Gibson et al., 2010). However, development of various technologies and expansion in a range of available materials brings AM to its current state where the largest share global applications are in the production of final parts (Wohlers & Caffrey, 2015). AM has a number of promising characteristics to improve manufacturing and aftersales supply chains (Holmström et al., 2010; Markillie, 2012; Pérès & Noyes, 2006). There are a number of significant advantages of this technique, including toollessness, lower raw material waste (for metal AM), and the possibility to produce extremely complex geometries (Holmström et al., 2016; Holmström et al., 2010). This production technique has captured the attention of the aerospace industry because of its invaluable features—it allows part components consolidation, reliability improvement, weight reduction, and waste alleviation throughout a life-cycle (Mellor et al., 2014; GE, 2015; Rao, 2016).

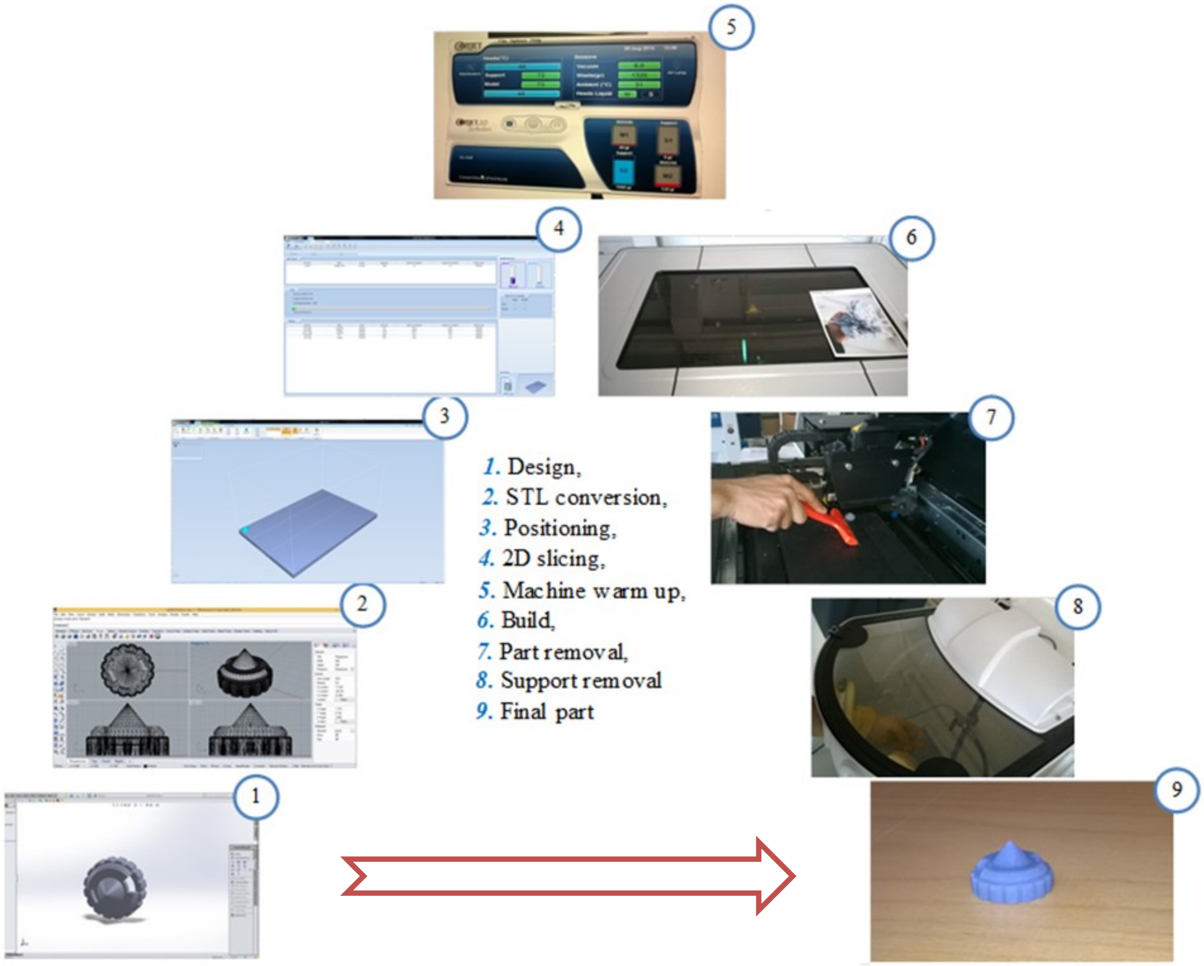

Figure 1: Additive manufacturing process from CAD design to final part (courtesy of Khajavi et al., 2015)

It should be noted also that there are some limitations of AM. These limitations are related to the availability of materials, production finish quality, production rate, production chamber size, repeatability of production, and the cost of machines and material (Khajavi et al., 2014; Flores Ituarte et al., 2015; Lyly-Yrjänäinen et al., 2016).

2.2. Hub configuration

In logistics, the concept of a hub for supply is well defined in conventional production (Lee, 2002). In multi-echelon supply chains, a consolidation hub enables the smooth and reliable supply of components or subassemblies to the production facility (Bowling et al., 2011). This in turn facilitates the required production postponement in a just-in-time (JIT) setting (MacCormack et al., 1994; Naylor et al., 1999). In other words, a supplier hub provides an inventory buffer for the production plant. Filling in the downstream demand in a timely manner is the internal function of a consolidation (supplier) hub (see Figure 2); this is done by producing either the kits or the subassemblies using the acquired parts from the upstream suppliers, or even both (Creazza et al., 2010). In principle, utilization of a reliable supplier hub reduces the complexity of operations for the production plant compared to a direct delivery of components by the suppliers to the plant; it also eliminates unnecessary capital investment in equipment and labor. Moreover, a supplier hub that serves multiple customers can take advantage of a bulk purchase discount and focus on its core competences. The location and number of hubs depend on the production strategy emphasis on any of the following areas: cost, quality, time to market and flexibility (Beamon, 1998).

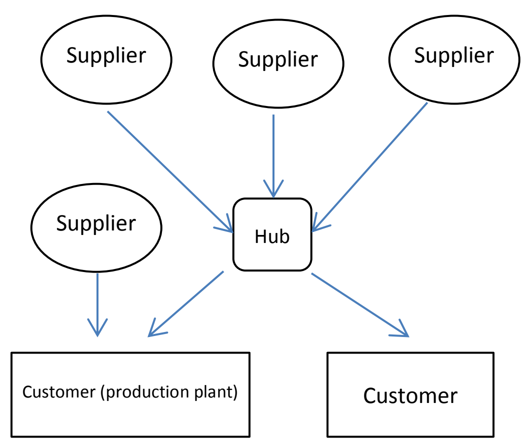

Figure 2: The illustration of a supplier hub in a conventional multi-tier supply chain setting

In this study, we use the term *hub configuration* for AM production facilities. A hub configuration refers to a supply chain configuration between the fully centralized and fully distributed configurations. The machines are located near the regional demand centers comprising of multiple client locations. It has some of the main advantages of a centralized production supply chain configuration, namely that there are less personnel and machines involve due to better capacity utilization. It also benefits from the positive aspects of decentralized production supply chain; these aspects include less transshipment as well as a faster and cheaper delivery.

2.3. Literature gaps

The current body of knowledge regarding AM is highly focused on process, material, and design research (Gao et al., 2017; Shamsaei et al., 2015; a large portion of the article published in Elsevier's Additive Manufacturing journals and Emerald's Rapid Prototyping Journal). This is understandable since AM still struggles in these technical aspects—specifically the limitations in process cost, throughput, repeatability, multi-material AM, raw material range, raw material cost, and design and topological optimization for performance (Ituarte et al., 2015; Chekurov & Salmi, 2017; Spalt & Bauernhansl, 2016). This field of research is still limited in the application inquiry of AM supply chain settings (Khorram Niaki & Nonino, 2017). However, a number of studies have been conducted in the area of spare parts supply chains. Liu et al. (2014) investigated the utilization of AM by MRO agents in the aerospace industry for three scenarios of conventional (without AM), fully centralized and fully distributed. Their analysis measured the level of safety stock in each scenario, and they concluded that a centralized AM supply chain is beneficial for parts with low average demand, long lead times, and high demand fluctuation. On the other hand, their study found that distributed scenarios need lower safety stock for certain components, namely (a) parts with high average demand, (b) items with very stable demand, and (c) parts with very short production lead-time (Liu et al., 2014). Holmström et al. (2010) conceptually compared a fully decentralized AM spare parts supply chain with another supply chain that replaces the inventory in the regional distribution centers with AM capacity. They pointed out the possibility to implement the former configuration while capacity utilization of AM machines is high, as well as for specific settings such as battlefields and aviation. However, they did not use a case study to illustrate which alternatives are feasible and which factors affect the feasibility of each configuration. In another study, Holmström & Partanen (2014) examined the impact of direct digital manufacturing technologies on the logistics operations. Their findings indicate that there are some benefits to be gained, including the life-cycle extension of products and improvement of parts availability in challenging locations.

In Sasson and Johnson's (2016) conceptual study, they built upon the previous research and pointed out the potential future regional AM supercenters, which allow manufacturers to replace inventory of low volume finished goods with AM raw material inventory. Moreover, Khajavi et al. (2014) utilized a detailed case study to shed light on actual feasibility of AM implementation in aerospace spare parts supply chain in centralized and distributed configurations. They concluded that with the available state-of-the-art selective laser sintering AM machines in 2013, a centralized configuration is economically superior. Based on their hypotheses, they proposed a machine that can make a distributed supply chain feasible. However, their paper fell short of analyzing an AM hub configuration where machines are located close to the demand centers but not in a fully decentralized configuration to offset the excess cost of labor and initial investment in production equipment. With the above gaps in mind, this present study builds upon the F-18 Super Hornet case presented by Khajavi et al. (2014). These airplanes carry roughly 100 three-dimensional printed parts in their environmental control system and are among the first real-world applications of AM technology to produce final parts. The feasibility of AM spare parts production in a hub configuration is investigated. Moreover, we consider the latest AM trends and LS machines developments.

3. Methodology

The methodology used is a scenario analysis based on real-world case data and a complementary expert analysis. Following Börjeson et al. (2006), this study constructs strategic explorative scenarios that deal with managers' decisions on the implementation of AM machine type in various supply chain configurations. The objective is to understand the economic result of such decisions.

Liu et al. (2014) utilized a scenario analysis method to measure the impact of different centralized and decentralized AM configurations on aircraft spare parts safety stock. However, their focus was solely on spare parts safety stock. In this study, we adopted a more comprehensive mathematical cost model for scenario analysis in the context of aircraft spare parts supply chain, and the model used was developed by

Khajavi et al. (2014). The scenario analysis model by Khajavi et al. (2014) allows for the supply chain cost evaluation of the impact of AM in different configuration.

The supply chain cost model utilized by Khajavi et al. (2014) takes into account a number of cost components to compare different AM-enabled spare parts supply chain configurations. These components include "personnel, material, transportation, inventory carrying, aircraft downtime, inventory obsolescence, initial investment in AM machine depreciation and annualized cost of initial inventory production" (Khajavi et al., 2014). In the first step, calculations are made for the probability of stock-outs for different supply chain configurations and with distinct inventory levels and replenishment intervals. In the second step, the stock-out probabilities are utilized to find the optimum settings in terms of inventory levels and replenishment intervals. Finally, these optimum settings are then used in conjunction with a number of facts and assumptions related to the F-18 Super Hornet case in order to calculate the cost components and the total cost of each scenario. Appendix A presents modeling-related facts and assumptions and formulas.

As mentioned, this study builds upon work by Khajavi et al. (2014)—particularly the scenario analysis used in their case study—and complements their work using significant modifications to incorporate the AM-hub supply chain configuration. This study also contributes to their results by utilizing the current state-of-the-art technology. For this purpose, we selected two selective laser sintering AM machines that are introduced by Norge Systems, a startup company which was later acquired by Gorgé Group (see Molitch, 2015); this company has utilized the opportunities emerged from the expiration of key patents in the field of selective laser sintering additive manufacturing. In addition, we also analyzed other machines from other startups before disqualifying them due to their small production chamber size. The following section describes the selection criteria and machine specifications in detail.

3.1. The state-of-the-art AM technology

In this section, the actual specification of AM machines is presented, and this information helps with the analysis of their compatibility for our spare parts provision case study—that is, the F-18 Super Hornet environmental control system. For the study, the average assumed volume for each environmental control system (ECS) part is 9.56 L; however, not all the new machines have the required production chamber capacity (i.e., 9 L), and thus they are left out of the analysis. Only two machines satisfy the size requirements, which are Norge Ice 9 and Ice 1 (see Appendix B).

After the selection of suitable machines, the relevant data regarding each machine was extracted from the reliable news websites. Table 1 shows a summary of this data, along with a side-by-side comparison of the utilized machines in the study by Khajavi et al. (2014).

Table 1: The summary of the Khajavi et al. (2014), and newly emerging LS AM machines (Krassenstein, 2014)

AM Machine Name / Improvement Criteria	State of the Art 2013 (SoA-2013) (Khajavi et al. 2014)	Required Technology for Distributed Manufacturing (ReqTecDM) (Khajavi et al. 2014)	SoA-MP (Norge Ice 9)	SoA-SP (Norge Ice 1)
Laser power (W)	70	70	40	10
Speed (mm/h)	-	-	10-30	8-25
Speed (lit/h)	1.8	1.8	0.9 -1.8- 2.7	0.32 -0.66- 1
Automation level (operator: machine)	2:5	1:15	2:5	2:5
Production chamber size (mm)	381x330x457	190x165x305	300x300x450	200x200x250
Producible parts per run in this case	6	1	4	1
Production speed (h)	50	8.33	66.66- 33.33 – 22.22	46.87 – 22.72 - 15
Procurement price (k$)	350	58.33	34	13
Production rate (parts per year)	1050	1051	525 – 1048 - 1576	186 – 385 - 584

For the sake of simplicity, we refer to Khajavi et al.'s (2014) "state of the art 2013" and "required technology for distributed manufacturing" machines, as SoA-2013 and ReqTecDM respectively. Similarly, Norge Ice 1 and Ice 9 are referred to as "state of the art single part" (SoA-SP) and "state of the art multi-part" (SoA-MP) respectively. In Table 1, production rates of the SoA-SP and SoA-MP machines are given as a range; however, we analyzed the scenarios using the maximum rates.

There were two main assumptions in the study by Khajavi et al. (2014) regarding the future AM (ReqTecDM) machine scenarios. The first assumption is that a ReqTecDM machine is more automated, although this has not yet materialized in reality with new AM machines. The second assumption is that a ReqTecDM machine has higher productivity by being cheaper, faster, and more suitable for single part manufacturing; this assumption has taken place partly as new machines are cheaper and smaller. In addition to these points, SoA-MP has another advantage regarding the build rate, which is even faster than the future AM machine assumptions in the work by Khajavi et al. (2014). Moreover, the SoA-MP and SoA-SP both have the option of using third-party raw material, which might be cheaper than the polyamide powder supplied by the vendor. However, for the sake of simplicity, we assume $100/kg for the Nylon 11 powder in all scenarios.

3.2. AM hub supply chain configuration

Figure 3 illustrates the AM hubs supply chain configuration in this research. The location of the hubs are based on several factors, namely (a) the position of naval air stations; (b) the position of the master jet bases, which are both the spare parts demand locations; and (c) the high density of these places in four regions of the United States, as indicated by red rectangles. Based on these factors, we assumed the establishment of four hubs in total, with one AM hub in each region. Each AM hub is assumed to be located in one of the naval air stations (NAS). In this way, the hub can supply the parts to the NAS with no transportation needed, and it can provide service to the other four demand locations in that same region with lower transshipment cost and time.

In this study, we made a minor modification to the actual location of the two naval air stations—one station is not included, thus reducing the number of service locations to 20, and another station is relocated to the East Coast. These changes do not have any impact on the results of the Khajavi et al. (2014) analysis, given that the researchers assumed the number of service centers to be 20 and their transshipment policy for centralized scenarios utilized average transportation time and cost from the United Parcel Service (UPS) company.

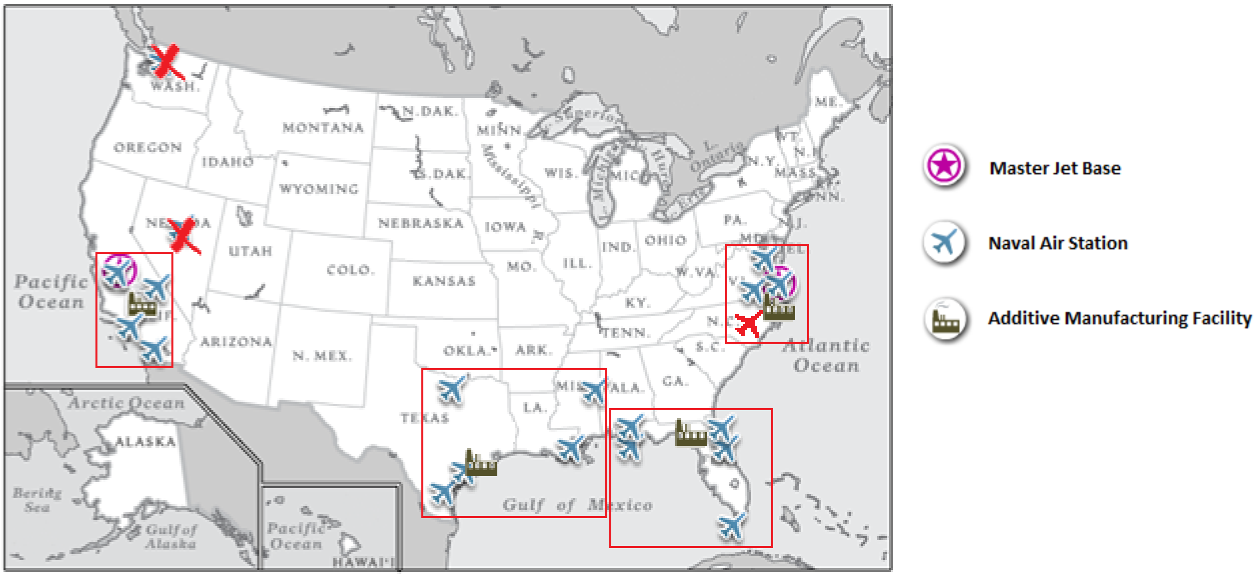

Figure 3: Hub production supply chain configuration

4. Results: Impact on spare parts supply chain

Khajavi et al. (2014) presented their results in a matrix of two by two with two variables of supply chain configuration and AM machine technology. We contribute to their results by adding two real-life machines (i.e., SoA-SP and SoA-MP) as well as one additional supply chain configuration (i.e., a hub) as follows:

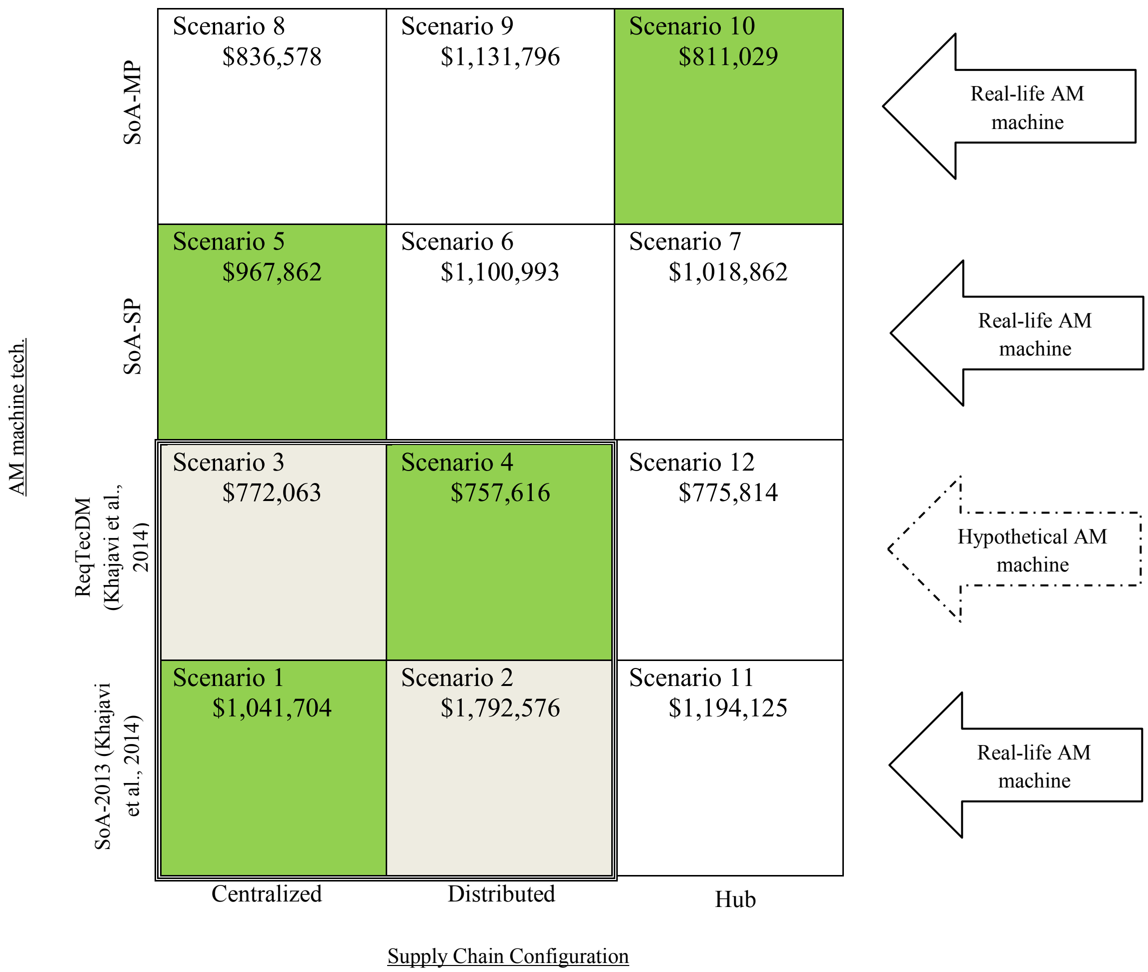

Figure 4: Differences among the investigated scenarios and their associated total costs

As shown in Figure 4, results of the analysis are rather diverse. The ReqTecDM AM machine used in Scenarios 3, 4, and 12 is not real and is based on Khajavi et al., (2014) assumptions. While analyzing the total operation cost of these supply chain configurations with different real-life AM machines, Scenario 10 offers the lowest cost. Scenario 10 utilizes the SoA-MP LS machines in an AM hub spare parts supply chain configuration. This is significant, and it indicates that utilizing AM machines in a hub setting can compete with the centralized implementation with the current state-of-the-art technology. Moreover, Scenario 10 only costs about 7% more than the Scenario 4 (see Table 3). While Scenario 4 has the lowest overall cost, it is based on a hypothetical machine that is used for enabling distributed production.

4.1. Prevalence of AM hubs

As Figure 5 illustrates, the largest differentiating cost for distributed production is the personnel cost and initial investment depreciation cost for AM machines. On the other hand, due to the annual production capacity of SoA-SP, AM hub configuration optimally suits this specific hub scenario with four regional locations and therefore requires the same number of machines as the centralized scenario. Compared to the centralized scenario, Scenario 10 has a marginally higher inventory obsolescence, inventory carrying, and annualized initial inventory cost. However, the aircraft downtime cost for Scenario 10 is roughly half of Scenario 8, which nearly offsets all these additional costs. Finally, Scenario 10 offers around a $25,000 saving in spare parts transportation cost over Scenario 8, which makes it overall the most feasible real AM option.

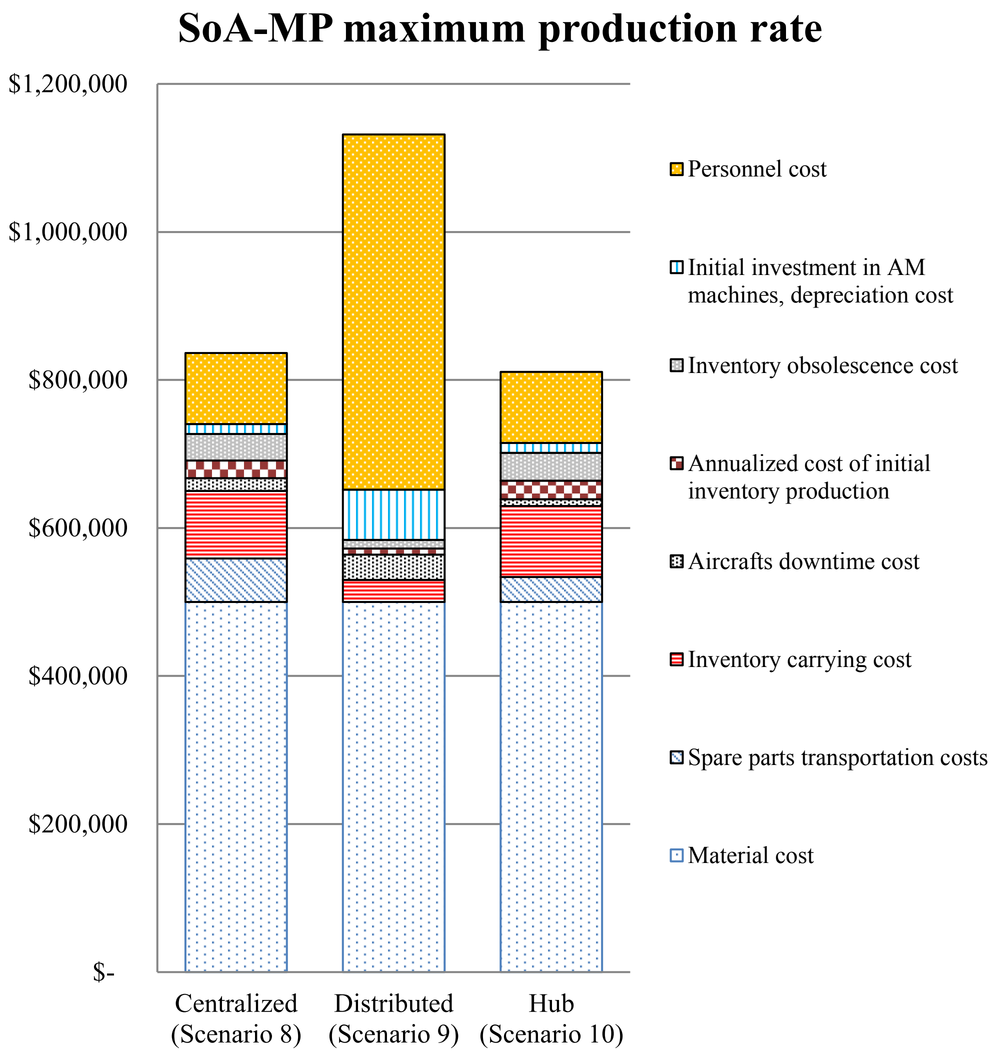

Figure 5: Cost breakdown comparison of the SoA-MP LS AM machine in various supply chain configurations.

4.2. Single part producer

SoA-SP has a chamber size that allows the production of a single spare part for F-18 Super Hornet per run. Therefore, the lower production capacity per machine compared to SoA-MP requires more machines per hub location than SoA-MP, which in turn would mean that 12 machines are required in Scenario 7 compared to the 9 machines in the centralized AM supply chain configuration of Scenario 5. Although the transportation cost for the Scenario 7 is $25,000 lower than Scenario 5, this difference is not enough to compensate for the less than optimal machine and personnel allocation. A possible alternative is seen with Scenario 6, which is the implementation of SoA-SP in a distributed supply chain configuration and is only about $130,000 (or 14% more expensive) than the centralized implementation in Scenario 5. Moreover, Scenario 6 has the lowest total cost for any real-life AM machine in the distributed supply chain configuration of this study (see Figure 6). The reason for this is the elimination of transportation coupled with the very low AM machine initial investment cost and rather quick production cycles, which allows lower inventory levels.

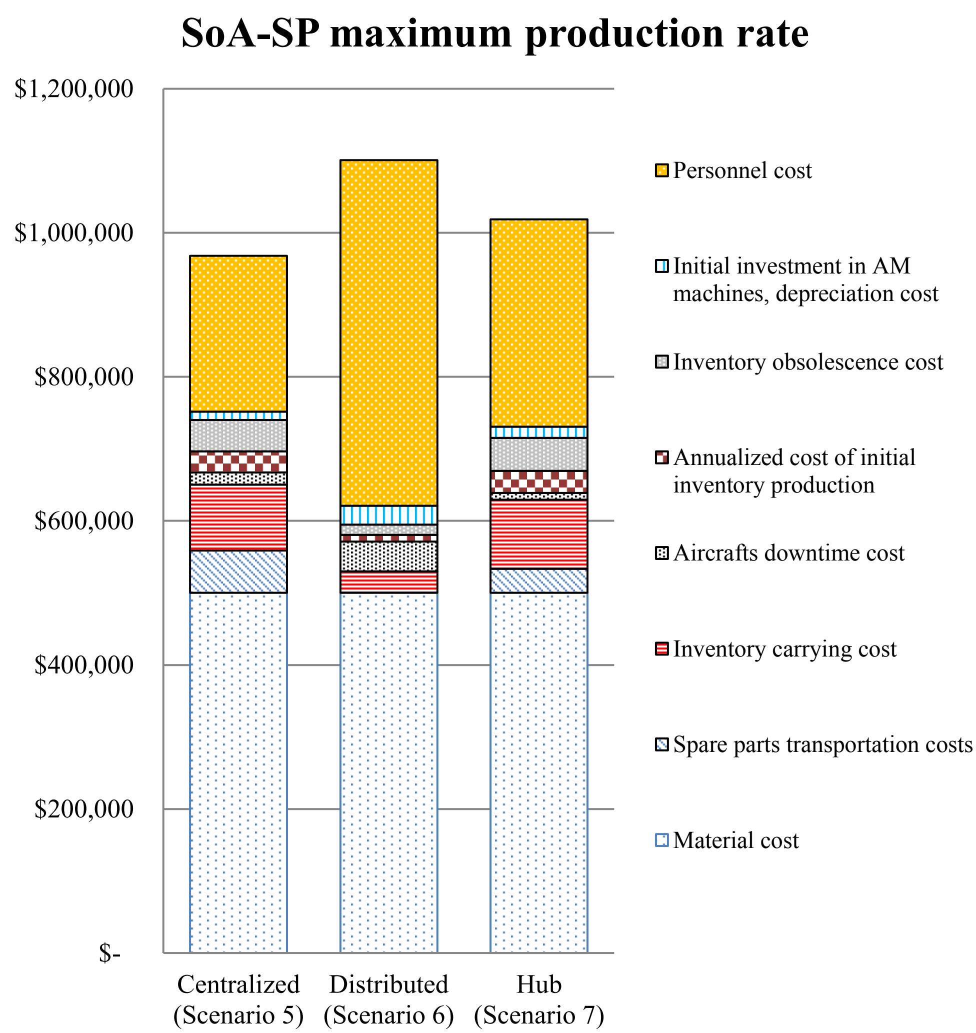

Figure 6: Cost breakdown comparison of the SoA-SP LS AM machine in various supply chain configurations

We also calculated the cost of an AM hub production setting the original cases presented by Khajavi et al. (2014). Figure 7 shows a cost comparison based on the actual machine utilized to produce the F-18 Super Hornet environmental control system parts. The figure also shows the better economics for the AM hubs compared to fully distributed supply chain configuration for spare parts. However, the results are similar to the SoA-SP, namely that a centralized supply chain is the most feasible option between the other two configurations. The main cause is the high initial investment depreciation cost in AM equipment as well as labor intensiveness of the scenarios. Moreover, the annual production capacity of the AM machines does not fit this specific AM hub design—that is, having four hubs with each hub serving five locations.

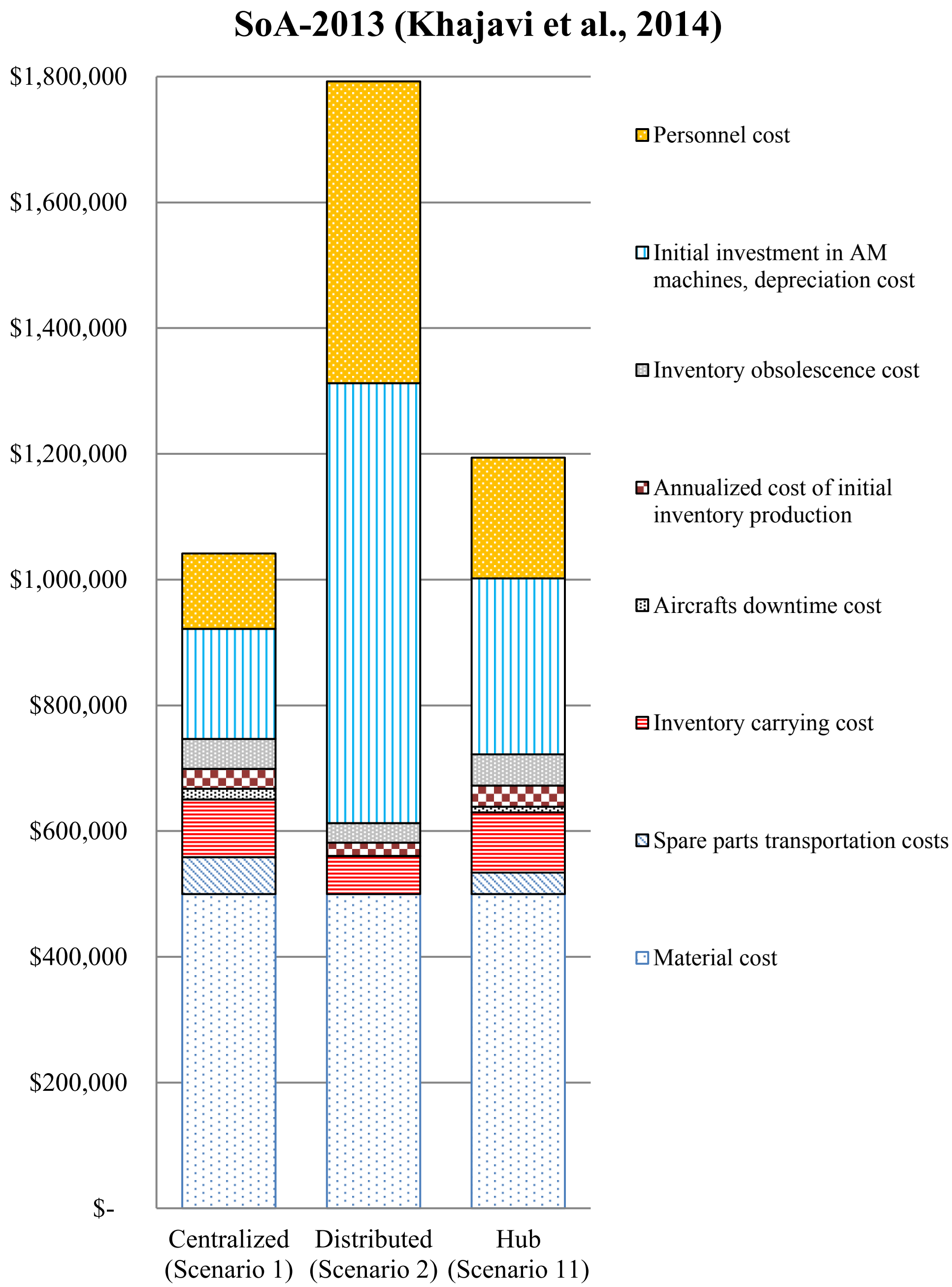

Figure 7: Cost breakdown comparison of SoA-2013 LS AM machine (Khajavi et al., 2014) in various supply chain configurations

For Scenario 2, we made a minor correction in the model as it was originally assumed to have the same time span (i.e., 50 hours) for the production of a single part, which is equal to the amount of time required for the production of six parts on the same machine. However, as the number of stock-outs of the scenario is very low, the correction only reduced the total cost by around $1400.

4.3. Outcome for hypothetical ReqTecDM AM machine

The outcome of the model for the Khajavi et al. (2014) hypothetical (ReqTecDM) AM machine shows the feasibility of distributed production, even when the AM hub scenario is introduced (see Figure 8). For ReqTecDM, Scenario 12 is marginally more expensive to run than both the distributed and centralized supply chain configurations. Scenario 4 has a very high AM machine initial investment depreciation cost and a high personnel cost. However, it does not have transportation cost and the high production speed allows a very low inventory stock at each location which offsets all the other excess costs in comparison to the other supply chain configurations. The main difference that allows this hypothetical machine to produce such a result is the assumption with regard to the high level of automation for AM machines—which in turn reduces personnel cost. This can be observed if the total cost of these scenarios are compared, excluding the personnel cost with the SoA-SP or SoA-MP scenarios: (a) Scenario 4 with ReqTecDM AM machine costs $677,616; (b) Scenario 6 with SoA-SP costs $620,993; and (c) Scenario 9 with SoA-MP costs $651,796. This comparison illustrates that both SoA-SP and SoA-MP AM machines can realize a decentralized configuration if their automation level is increased significantly.

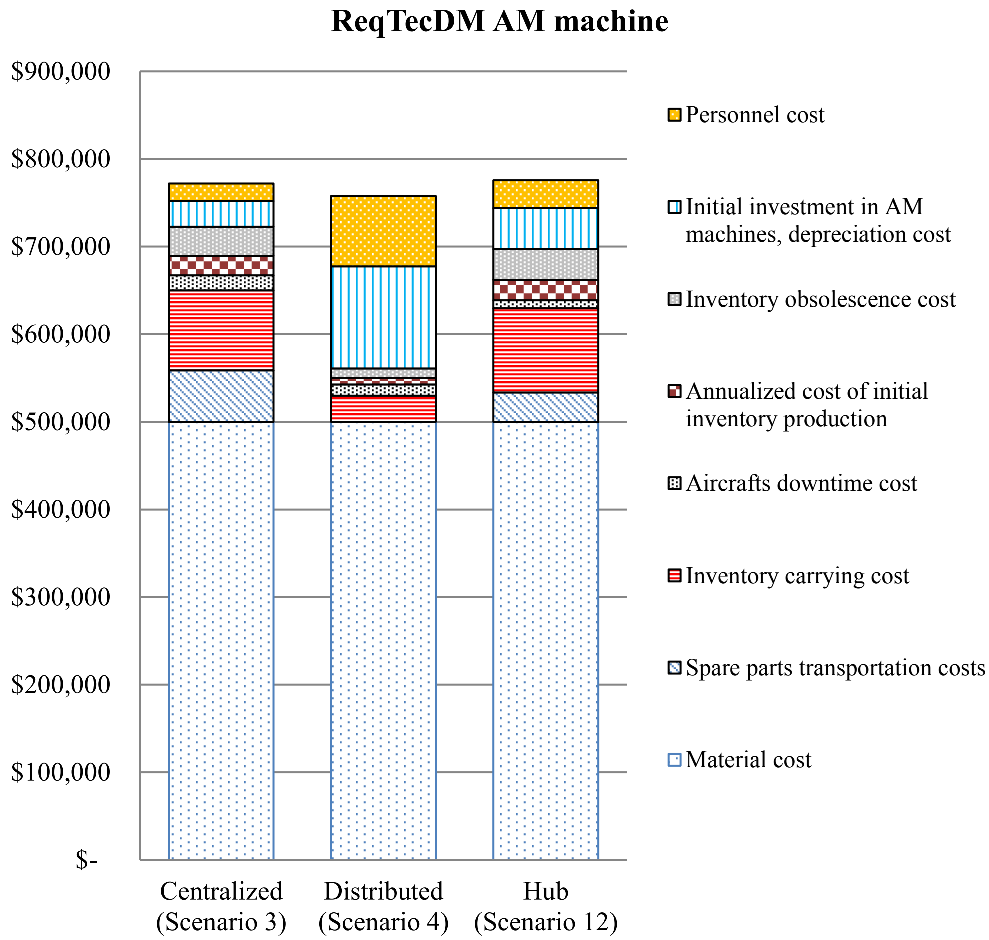

Figure 8: Cost breakdown comparison of the ReqTecDM AM machine (Khajavi et al., 2014) in various supply chain configurations

A comparison of all scenarios with a cost component breakdown is presented in Table 2

Table 2: The cost breakdown of all scenarios

Item Description	*Centralized (Scenario 1)*	*Distributed (Scenario 2)*	*Centralized (Scenario 3)*	*Distributed (Scenario 4)*	*Centralized (Scenario 5)*	*Distributed (Scenario 6)*	*Hub (Scenario 7)*	*Centralized (Scenario 8)*	*Distributed (Scenario 9)*	*Hub (Scenario 10)*	*Hub (Scenario 11)*	*Hub (Scenario 12)*
Material cost	$ 500,000	$ 500,000	$ 500,000	$ 500,000	$ 500,000	$ 500,000	$ 500,000	$ 500,000	$ 500,000	$ 500,000	$ 500,000	$ 500,000
Spare parts transportation costs	$ 58,700	$ -	$ 58,700	$ -	$ 58,700	$ -	$ 33,700	$ 58,700	$ -	$ 33,700	$ 33,700	$ 33,700
Inventory carrying cost	$ 91,500	$ 60,000	$ 91,500	$ 30,000	$ 91,500	$ 30,000	$ 96,000	$ 91,500	$ 30,000	$ 96,000	$ 96,000	$ 96,000
Aircrafts downtime cost	$ 17,107	$ 513	$ 17,107	$ 12,723	$ 17,107	$ 41,106	$ 9,124	$ 17,107	$ 34,232	$ 9,124	$ 9,124	$ 9,124
Annualized cost of initial inventory production	$ 31,759	$ 20,825	$ 22,236	$ 7,290	$ 29,142	$ 9,555	$ 30,575	$ 23,868	$ 7,826	$ 25,042	$ 33,321	$ 23,329
Inventory obsolescence cost	$ 47,638	$ 31,238	$ 33,354	$ 10,936	$ 43,713	$ 14,332	$ 45,863	$ 35,803	$ 11,739	$ 37,563	$ 49,981	$ 34,994
Initial investment in AM machines, depreciation cost	$ 175,000	$ 700,000	$ 29,167	$ 116,667	$ 11,700	$ 26,000	$ 15,600	$ 13,600	$ 68,000	$ 13,600	$ 280,000	$ 46,667
Personnel cost	$ 120,000	$ 480,000	$ 20,000	$ 80,000	$ 216,000	$ 480,000	$ 288,000	$ 96,000	$ 480,000	$ 96,000	$ 192,000	$ 32,000
Expected Total Cost of Scenarios per Annum	**$ 1,041,704**	**$ 1,792,576**	**$ 772,063**	**$ 757,616**	**$ 967,862**	**$ 1,100,993**	**$ 1,018,862**	**$ 836,578**	**$ 1,131,796**	**$ 811,029**	**$ 1,194,125**	**$ 775,814**

To calculate the stock-out possibility for each distinct scenario with SoA-MP and SoA-SP AM machines, the Monte-Carlo simulation model was utilized with 400 iterations.

5. Discussion

The main implication of this research is that with the emergence of significantly cheaper LS AM machines—even without improvements in machines automation—centralized production with AM loses its large economic advantage to the extent that it becomes less economical than other configurations. A supply chain arrangement candidate for spare parts AM is hub configuration, which is shown to be more efficient than a fully distributed AM at the current technological setting; this can be seen when the comparison is made using the hypothetical Scenario 4, which has a very high automation level of AM machines.

5.1. AM machine attributes for hub configuration

This study summarized the enabling attributes of AM machines that allow hub configuration in addition to the fully distributed configurations for a spare parts provision supply chain. Table 3 illustrates the differences between an AM hub enabler machine and a distributed supply chain enabler AM machine.

Table 3: Comparison of potential suitable AM machines for hub and distributed spare parts supply chain configurations

		Importance to Enable Each Supply Chain Configuration	
		Hub	**Distributed**
AM Machine Enabler Attributes	**High productivity (large chamber volume)**	High	Low
	Automation of pre-production and post-production activities	Medium	High
	Annual machine cost	Medium	High
	Production speed	Medium	High

5.2. Single-part or multi-part producer

To diminish the equipment downtime cost in a distributed spare part supply chain, the time required to produce each part must be minimal. Therefore, any strategy such as the production of one part at a time (e.g., lower height) or the utilization of AM machines with shorter pre-production and post-production can benefit distributed production more than hubs. The reason is that in a hub setting, parts are often less supplied due to stock-out situations, while in fully decentralized spare parts AM, the frequency of production to fill the stock-out is higher due to having significantly lower inventory. Therefore, a higher importance is placed in having a decentralized setting utilization of AM machines with single-part production capability in order to tightly match the initial investment to application and achieve shorter production cycles.

5.3. AM equipment and personnel cost

The annual cost of equipment and personnel can severely affect the distributed production configuration in a negative way since the number of locations with AM installation outnumbers the AM hub supply chain configuration. Therefore, any small cost reduction in AM equipment can benefit a distributed setting on a larger magnitude. For the AM hub supply chain configuration, the annualized cost of equipment is as important as it can be for a centralized configuration. The reason is that in a hub configuration, the number of AM machines can be minimized through a tight calibration of AM machine production capacity and hub size with regard to demand. Moreover, AM machine autonomy in pre-production and post-production processes is of greater importance for a distributed supply chain configuration than an AM hub configuration. The cause for this is in the higher number of AM machines in the distributed setting.

5.4. Production rate

In a distributed supply chain spare parts provision, no transportation time is required for meeting the demand since the AM machines are located on site. Therefore, the AM machine production rate directly affects the safety stock level and equipment downtime. Having transshipment time in the AM hub supply chain setting reduces the impact of AM production rate on downtime cost. However, in distributed AM supply chain configuration the impact of AM production rate on downtime cost is large. With high value equipment in particular where hourly downtime can be very expensive, a high transshipment period usually neutralizes the benefits of on-demand production. This in turn makes the AM hub spare parts provision configuration less sensitive to AM machine production speed than the fully distributed configuration.

5.5. Different industry

To extend the implication of this research to other industries where the equipment downtime cost is not as high as an aircraft, we changed the equipment acquisition price from $66.9M for the F-18 Super Hornet to $1M. Results are presented in Table 4.

Table 4: The total cost of the scenarios with SoA-MP while the spare parts are manufactured for lower downtime cost equipment

	Revised Scenario 8	**Revised Scenario 9**	**Revised Scenario 10**
Total cost of spare parts supply chain	$767,076	$1,098,076	$763,490.7
Percentage change from original scenarios	-8.31%	-2.98%	-5.86%

As Table 4 illustrates, hub configuration can outcompete centralized production for spare parts AM for less capital-intensive equipment. However, compared to more capital-intensive cases, hub configuration's cost competitiveness is reduced. While the cost of equipment is reduced from $66.9M to $1M, total cost of centralized spare parts supply chain is reduced by 8.31% while hub spare parts provision configuration total cost is reduced by 5.86%. Lower equipment capital intensiveness translates to lower downtime cost and potentially results in tolerability of longer waiting times. This leads to AM being most efficient in the centralized configuration for provision of spare parts for equipment with low downtime cost.

5.6. Other geographical settings

Another interesting point that requires further discussion is the applicability of results in other geographical locations. Providing spare parts to a higher number of service points in the case of F-18 Super Hornet increases economic favorability of centralized AM due to high AM machine initial investment cost and personnel cost. However, it might be different if the service points are located very far apart or in remote locations that require special means of transportation (e.g., a helicopter). The high cost of transportation may lead to decentralized AM where only raw materials are delivered if raw material is not available in the location. A more detailed study of such cases is encouraged for future research.

5.7. Impact of assumptions

Among the limiting assumptions of this study, one of the most crucial ones is the use of constant automation ratio in investigation of new AM machines. If the ratio of operator required to operate an AM machine in pre-production and post-production steps is kept constant for various AM machines with different throughputs and capacities, an AM machine with multi-part capacity is more economical from the perspective of personnel cost. The reason is that a higher throughput machine requires less personnel to produce a constant demand than smaller and slower machines do. This assumption can be adjusted by the reality in future research.

6. Conclusions

This study illustrated the feasibility of AM hubs for the current state-of-the-art AM technology. Moreover, we contributed to the study by Khajavi et al. (2014) with new data from real-life SoA-SP and SoA-MP LS AM machines. Our findings suggest that a AM hub spare parts supply chain may offer the best cost efficiency if AM machine capacity and overall supply chain demand zoning—such as the decision on the hub size—are accurately calibrated. We also discovered that AM machines automation at this point is the most critical factor to enable the cost-efficient decentralization of supply chains. Moreover, findings illustrate the cost impact of a smaller and cheaper AM machine (SoA-SP) on the decentralized supply chains even when the production rate is only moderate.

In this research, we utilized the model developed by Khajavi et al. (2014) to estimate the cost of additive manufacturing utilization in various supply chain settings to meet the spare parts demand of the F-18 Super Hornet fighter jets. This is among the first and most well-known cases in the implementation of AM for final parts production. As the parts were geometrically complex and production volume was not high, it was not possible for Boeing Company to produce these economically utilizing conventional manufacturing methods. Therefore, we followed Khajavi et al. (2014) and studied various supply chain settings enabled by AM. Moreover, the price of raw material was kept unchanged in this analysis, although one of the interesting advantages of SoA-SP and SoA-MP AM machines is the compatibility to operate with third party raw material (i.e., polymer powder). This potentially reduces the cost of raw materials for the parts production as the competition in the market increases, and the operators are no longer confined to the AM machine manufacturers' high margin raw material offerings.

Although the producer of SoA-SP and SoA-MP was acquired, and these AM machines are not currently in the market, we believe the emergence of similar AM machines is inevitable in the near future due to the expiration of key patents (Kinstlinger, et al., 2016). A sign of this statement is the introduction of the Fuse 1 LS AM machine by Formlabs Company that is set for launch in the fall of 2018. Therefore, this analysis is relevant in illustrating the implications of upcoming changes (Molitch-Hou, 2016) and the potential of AM hubs, as well as what needs to be added to the machines to make the supply chain of the future fully decentralized.

We suggest that the future studies can focus on the methods that can assist the selection and design of the AM hub supply chains for various demand size and customer locations. Moreover, it is beneficial to study cases where downtime is not as important as for aircrafts in order to examine the feasibility of decentralized supply chain configurations for spare parts provision in those cases.

Appendix A

The specifications of SoA-SP and SoA-MP AM machines used for the cost analysis of spare parts provision are presented in Table 5.

Table 5: Selected machines and speeds for analysis

AM Machine Improvement Criteria	SoA-MP Max Speed	SoA-MP Single Part Per Run	SoA-SP Max Speed
Laser power (W)	40	40	10
Speed (mm/h)	30	>20	25
Speed (lit/h)	2.7	2.027	1
Automation level (operator: machine)	2:5	2:5	2:5
Production chamber size (mm)	300x300x450	300x300x450	200x200x250
Producible parts per run in this case	4	1 at a time	1
Production speed (h)	22.22	13.78	15
Procurement price (k$)	34	34	13
Production rate (parts per year)	1576	635	584

Assumptions used for the calculation of cost components for Scenarios 8, 9, and 10 are presented in Table 6.

Table 6: Information regarding all SoA-MP scenarios

Item	Scenario 8			Scenario 9	Scenario 10	
Expected spare parts demand (number of parts)	5,000					
Total number of locations with AM machines throughout the spare parts supply chain	1			20	4	
Number of AM machines at each production location	4			1	1	
Total number of AM machines	4			20	4	
AM machine automation level (the number of machines one person can operate)	2.5					
AM machine lifetime (in years)	10					
AM machine depreciation rate	10 %					
Spare parts inventory level (number of parts)	6100			2000	6400	
Average inventory carrying cost per part	$15					
Annual inventory obsolescence rate	5 %					
Spare parts transportation costs	$1,000	$200	$100	$100	$200	$100
Number of shipments per annum	21	188	3	0	167	3
Assumed transportation time in hours (Source: UPS company website)	24			-	16	
Required time to produce four parts using AM (also includes pre-production and postproduction time span)	22.22					
Production capability of each AM machine (parts per year)	1576					
Average downtime cost of F-18 Super Hornet fighter jets per hour	$255					
Estimated average length of jet downtime due to lack of parts per airplane per year (in hours)	0.013			0.027	0.007	

Assumptions used for the calculation of cost components for Scenarios 5, 6, and 7 are presented in Table 7.

Table 7: Information regarding all SoA-SP scenarios.

Item	Scenario 5			Scenario 6	Scenario 7	
Expected spare parts demand (number of parts)	5,000					
Total number of locations with AM machines throughout the spare parts supply chain	1			20	4	
Number of AM machines at each production location	9			1	3	
Total number of AM machines	9			20	12	
AM machine automation level (the number of machines one person can operate)	2.5					
AM machine lifetime (in years)	10					
AM machine depreciation rate	10 %					
Spare parts inventory level (number of parts)	6100			2000	6400	
Average inventory carrying cost per part	$15					
Annual inventory obsolescence rate	5 %					
Spare parts transportation costs	$1,000	$200	$100	$100	$200	$100
Number of shipments per annum	21	188	3	0	167	3
Assumed transportation time in hours (Source: UPS company website)	24			-	16	
Required time to produce one part using AM (also includes pre-production and postproduction time span)	15					
Production capability of each AM machine (parts per year)	584					
Average downtime cost of F-18 Super Hornet fighter jets per hour	$255					
Estimated average length of jet downtime due to lack of parts per airplane per year (in hours)	0.013			0.032	0.007	

The replenishment strategy for hub scenarios are similar to fully distributed scenarios. The replenishment of the each NAS is performed by the corresponding hub with five-week intervals, and inventory level in each NAS consists of three full sets of parts while the hub location keeps an additional full set of parts to fill in for the stock-out instances. The cost of planned transshipment is assumed to be $200 for each NAS, while transshipment from hub to fill the stock-out is assumed to cost $100 and to take 16 hours.

All F-18 Super Hornet case facts, assumptions, and formulas are extracted from Khajavi et al., (2014) and are reused in the complementary analysis of this paper (see Tables 8, 9, and 10).

Table 8: Model figures for the reference scenario, Scenario 1.

Item	Quantity
F/A-18E/F Super Hornet flight lifetime (in hours)	9000
Aircraft life span (in years)	~ 30
F/A-18E/F Super Hornet average unit cost (for the year 2012)	M$66.9
Number of F-18 Super Hornets (units)	~ 500
Number of different parts (SKUs) per environmental control system (ECS)	~ 100
Number of aircraft deployment locations inside the US (Naval Air Stations)	~ 20
Average material cost for production of each part (assumption)	$100
Procurement price of each appropriate AM machine (sPro™ 60 HD)	k$350
Average annual salary per employee (assumption)	k$60
Total number of parts at the installed base	~ 50,000
Annual demand for ECS spare parts	5000
Sources: Khajavi et al. (2014)	

Table 9: Comparing the current and future AM machine specifications

AM machine improvement aspects	SoA-2013	ReqTecDM
Automation level (operator: machine)	2:5	1:15
Production chamber size	381 x 330 x 457 mm	190 x 165 x 305 mm
Producible parts per run in this case	6	1
Production speed (hours)	50	8.33
Procurement price	k$350	k$58.33
Production rate (parts per year)	1050	1051
Source: Khajavi et al. (2014)		

Table 10: Formulas for cost component calculation (Khajavi et al., 2014)

Cost component	Formula
Personnel cost	$= \frac{\text{(Number of AM machines utilized in each specific scenario)} \times \text{(average annual salary per employee)}}{\text{Automation level of machine}}$
Material cost	$= \text{Level of expected demand} \times \text{Average material cost for production of each part}$
Spare parts transportation costs*	$= \sum_{1}^{n} \text{Number of type n transportations} \times \text{Cost of type n transportation}$
Inventory carrying cost	$= \text{Level of inventory in hand} \times \text{Average annual cost of carrying each part of inventory}$
Aircraft downtime cost	$= \text{Number of airplane failures (equal to the number of expected demand for the spare parts)}$ $\times \text{Average downtime cost of an airplane per hour (calculated by dividing the cost of each aircraft by th}$ $\times \text{Average number of hours of downtime for every maintenance operation}$
Inventory obsolescence cost	$= \text{Annual part obsolescence rate (assumed to be 5\%)} \times \text{Total production cost of initial inventory for each scenario}$
Initial investment in AM machines, depreciation cost	$= \text{Number of utilized AM machines} \times \text{Price of acquiring each AM machine} \times \text{Depreciation rate of AM machines (which is assumed to be 10\%)}$
Annualized cost of initial inventory production	$= \frac{\text{Material cost} + \text{Personnel salary} + \text{AM machines deprecation cost}}{\text{Project life span}}$

Appendix B

Some of the new cheaper laser sintering machines do not offer large enough production chamber to fit the F-18 Super Hornet environmental control system components for production (see Table 11).

Table 11: Comparison of the new cheaper LS AM machines on the basis of production chamber volume (Krassenstein, 2014; Sharebot, 2016; Sinterit, 2016; Sintratec, 2016)

AM Machine Improvement Criteria	State of the art 2013 (Khajavi et al. 2014)	Required Technology for Distributed Manufacturing (Khajavi et al. 2014)	Norge Ice 9	Norge Ice 1	Sinterit Lisa	Sinteratec S1	Sharebot SnowWhite
Production chamber size (mm)	381x330x457	190x165x305	300x300x450	200x200x250	110x150x130	150x150x200	100x100x130
Producible parts per run in this case	6	1	4	1	0	0	0

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