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Additive manufacturing in the spare parts supply chain

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ABSTRACT

As additive manufacturing (AM) evolves to become a common method of producing final parts, further study of this computer integrated technology is necessary. The purpose of this research is to evaluate the potential impact of additive manufacturing improvements on the configuration of spare parts supply chains. This goal has been accomplished through scenario modeling of a real-life spare parts supply chain in the aeronautics industry. The spare parts supply chain of the F-18 Super Hornet fighter jet was selected as the case study because the air-cooling ducts of the environmental control system are produced using AM technology. In total, four scenarios are investigated that vary the supply chain configurations and additive manufacturing machine specifications. The reference scenario is based on the spare parts supplier's current practice and the possible future decentralization of production and likely improvements in AM technology. Total operating cost, including downtime cost, is used to compare the scenarios. We found that using current AM technology, centralized production is clearly the preferable supply chain configuration in the case example. However, distributed spare parts production becomes practical as AM machines become less capital intensive, more autonomous and offer shorter production cycles. This investigation provides guidance for the development of additive manufacturing machines and their possible deployment in spare parts supply chains. This study contributes to the emerging literature on AM deployment in supply chains with a real-world case setting and scenario model illustrating the cost trade-offs and critical requirements for technology development.

1. Introduction

The digitalization of after-sales, particularly spare parts sales, is both a strategic opportunity [1] and a threat [2] for many original equipment manufacturers, as the focus of the competition increasingly shifts away from the price and quality of the offerings toward the delivery of value to customers [3]. Customer value is related to keeping the products in operational condition with high reliability. Maintenance, repair and operations (MRO) are closely tied to the accessibility of proper parts and skills whenever a demand occurs to satisfy the needs of customers and reduce downtime costs. However, the ability to provide the necessary parts with high fulfillment rates at low costs is a major challenge to overcome [4] and one that digital manufacturing technologies promise to resolve [5].

Conventionally, firms must invest heavily in their spare parts supply chain operations to reach high fulfillment rates and reliability [6]. The need to hold a relatively large inventory of parts close to the consumption locations leads to issues such as high warehousing and inventory obsolescence costs and capital costs related to slow-moving parts. Throughout recent decades, ICT-enabled technologies such as enterprise resource planning (ERP) have effectively addressed some of these problems. Now the question is if this trend can continue as technologies based on digital manufacturing mature. This study investigates the effects of utilizing additive manufacturing (AM) to produce spare parts within the structure of the spare parts supply chain. The scenario analysis indicates how developments of AM machines enable novel configurations of the spare parts supply chain for simultaneously improved efficiency and increased customer value.

The remainder of this paper is organized as follows. Section 2 presents a literature review. Section 3 explains the research methodology. Section 4 presents the findings and results of our analysis. This paper ends with conclusions summarizing the research outcomes, and suggestions for future investigation are provided.

2. Literature review

In the following section, our aim is to introduce the reader to concepts that have been utilized in this research and to construct a theoretical foundation based on prior published literature. The challenges to spare parts provision, the additive manufacturing production method and distributed production are reviewed.

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2.1. Challenges of managing spare parts supply chains

According to the provided description by the International Institute of Management, the main characteristics of an excellent supply chain are the following [7]: delivering high quality customer responses, efficiently converting inputs into outputs and improving asset utilization. These characteristics also play a crucial role in the excellence of spare parts supply chains. Spare parts supply chain management attempts to reduce operating costs while keeping the customers' satisfaction level at an acceptable level [8]. To accomplish this, the company needs to overcome a number of challenging issues. A major issue is the unpredictability of demand, especially for new product launches for which the data on parts failure rates are unavailable [9]. In uncertain demand situations, delivering customer satisfaction (low downtime costs) leads to higher inventory levels in more locations. Another important challenge is that companies need to support the previous generation of their product as well as their new products. This obligation magnifies the number of stock-keeping units in after-sales inventories. Moreover, the management of the after-sales supply chain addresses a combination of workforce, parts and equipment issues [6]; thus, to be effective and efficient, a proper combination must be employed. The correct parts without the right technician are useless and vice versa. These challenges make it difficult for the supply chain managers to deliver a high level of service with a low cost with regard to spare parts.

Based on the data from the United States Logistics and Materiel Readiness Office, in 2009 the military spent $194bn on its logistics operations and spare parts supply chain management, consisting of $104bn in supply, $70bn in maintenance and $20bn in transportation. At the end of the same year, the US military held an astonishing 4.6 million stock-keeping units of spare parts inventory, valued at $94 billion [10]. These eye-catching numbers present the opportunity for considerable gains, even with small improvements in the spare parts and logistics operations [11].

2.2. Additive manufacturing

Additive manufacturing (AM), also known as direct manufacturing, is a digital technology for producing physical objects layer by layer from a three-dimensional computer aided design (CAD) file. A simple explanation of this production process is as follows. The process begins with generating a three-dimensional CAD model of the object with all its details and dimensions. Next, the three-dimensional CAD file is sliced into very thin two-dimensional (2D) cross sections (layers) by a computer program. Then, the 2D layers are sent to the three-dimensional printing machine one layer at a time. The machine produces the object by building each layer on top of the previous one, utilizing different solidification methods of raw material in its production chamber [12,13]. The process may take from a few hours to a few days to produce an object, depending on its size and required production precision.

This technology, originally introduced as rapid prototyping (RP) and three-dimensional printing, was invented and put into use throughout the 1980s [14] as a method for producing rough physical prototypes of final products. Since then, it has continued to evolve in different aspects. Currently, increasingly more parts produced with this method are reaching the suitable precision and quality necessary to be used as final functional parts for special applications, such as air-cooling ducts for aircrafts or hearing aid and prosthesis equipment [15]. The technical committee within ASTM (American Society for Testing and Materials) International recently adopted the term additive manufacturing for the technology, as it is no longer solely for prototype production. The advancements that have made AM possible are widening the material range used by the machines, improving precision and final quality and reducing machine acquisition cost [13]. During the last few decades, additive manufacturing equipment has followed the digital technology progress model, aka "Moore's law", in that more capable and cheaper machines have been introduced year after year.

AM technology, with its swift advancements (e.g., precision, speed, affordability, and materials range) and inherent capabilities, has the potential to fundamentally revolutionize manufacturing operations and supply chains [2,16]. Jeff DeGrange, former manager of Boeing Phantom Works' Direct Manufacturing Process, once said, "One day, we'll be building parts on demand in space, on aircraft carriers and at other points of use" [17]. Prior research [5,18] studied this potential for a spare parts supply chain and indicated the feasibility of introducing distributed production by utilizing AM technology. Additionally, Lindemann and his colleagues [19] conducted a study comparing additive manufacturing to conventional manufacturing. Their research focuses on the additive manufacturing of metal parts and indicates the benefits of AM on the lifecycle costs of parts.

What makes this production method a potentially disruptive technology for supply chain management is its characteristics. Holmström et al. [5] highlight the following benefits of AM methods over the conventional manufacturing methods:

- No need for tooling (economies of scale does not exist, which makes customization and design revisions possible).
- Feasibility of producing small production batches economically.
- Possibility for quickly change design.
- Product optimization for function.
- More economical custom product manufacturing (batch of one) plus the capability to produce complex geometries.
- Potential for simpler supply chains with shorter lead times and lower inventories.

In addition, there is the possibility of reducing material waste by as much as 90% according to an Economist special report [2] on additive manufacturing.

These characteristics may enable the supply chain managers to manufacture any part (including customized) at any time in various locations and batch sizes without the need to be concerned about massive tooling costs. The continued evolution of AM will offer original equipment manufacturer companies the opportunity to change their supply chain configurations in the future by introducing distributed production.

2.3. Distributed production

One of the decisions that may lead to significant improvements in spare parts supply chain performance is changing the location of production facilities. There are two basic options to select from. Concentrating production facilities in a centralized location and serving the world market from that location is one option. The other option is decentralizing production in various regional or national locations close to major markets [20].

There are several cases where companies or public organizations in different industries have chosen to decentralize their production activities (goods or services). However, a common theme in all cases has been an organization's ability to balance its customers' value with supply chain costs. Production supply chain configuration decisions may bring essential benefits such as lead-time reduction, which according to De Treville et al. [21] enables significant improvements to the service level and profitability of the firm. Thus, such decisions have the potential to increase the