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A Study on the Effects of Additive Manufacturing on the Structure of Supply Networks

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Abstract: With the ongoing development of additive manufacturing (AM) the technology has the potential to increase the efficiency of production processes or to replace classical subtractive production technologies. This will impact the structure of supply networks. In order to quantify this impact, this paper studies to what extend AM may influence a two stage supply network consisting of source nodes, production nodes and customer nodes. Three stylized instances of this model, which differ in the distribution of these nodes as well as the improvement of the resource efficiency through AM have been created. To study the impact of AM on the structure of supply networks, a computational study has been performed. Four indicators are used, i.e. the total costs, tonne-kilometres per customer on the second stage (production site to customer site), number of open production sites, and the proportion of transport costs on the first and the second stage are compared. All indicators improve by using AM and the production sites move closer to the customers.

Keywords: supply network, network structure, 3D printing, facility location problem.

1. INTRODUCTION

With the ongoing development of *additive manufacturing (AM)* the technology has the potential to replace subtractive production technologies. Due to the different approach of producing products this will not only lead to a redesign of production and its processes. The change of the production technology will have numerous implications to other subjects that are on the interface to AM. Among these are *supply networks*. Though, companies and research institutions are aware of the possible implications for logistics they can hardly quantify them. The assessment of the implications of AM remain qualitative many times (Tuck et al., 2007; Fawcett and Waller, 2014; Cottrill, 2011). There are only few quantitative assessments like a case study of Khajavi et al. (2014) on a spare parts supply chain in the aeronautics industry focussing on accounting. In this paper we will present a very first approach for assessing the implications of AM on supply networks. For this a stylized model for a two stage facility location problem is used. In three different supply networks the impact of changing production from subtractive to additive technologies on the network structure will be assessed using performance indicators total costs of transport, average costs per customer on 2^{nd} stage of transport, share of transport costs on 1^{st} and 2^{nd} stage, and required production sites. With our model it will be possible to gain first insights on possible effects of AM on supply networks.

The remainder of this paper is organized as follows. In Section 2 we will define AM and explain two implications on supply networks that form the basis of our computational study. In Section 3 we introduce a model of the studied supply network. Section 4 provides the results and analyses of the computational study. In Section 5 we give some concluding comments and an outlook.

2. IMPLICATIONS OF ADDITIVE MANUFACTURING

To get a basic understanding of AM Section 2.1 will provide a definition of AM. Compared to classical production technologies AM has advantages and disadvantages. Using AM for serial production leads to -among others- two advantages of AM compared to using classical subtractive production technologies (like milling). These two main advantages are functional integration of parts and a higher resource efficiency for production. Apart from these two benefits there could be several other radical effects, e.g. a change of customer demand due to a customized design and production of products. However, we focus on functional integration of parts and a higher resource efficiency for production, because they appear more predictable. Therefore they are essential for setting up the model and the assumptions made within this model. These benefits will be described more in detail in Sections 2.2 and 2.3 respectively.

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2.1 Definition of Additive Manufacturing

AM is a general term for many different technologies and can be divided into rapid manufacturing, rapid prototyping and rapid tooling. Within this set there are several synonyms for AM and the technology respectively. AM is the most often used term in the scientific community. In the non-scientific community the most common synonym is 3D Printing (Wohlers, 2014). Therefore 3D Printing is the more often used term overall. Accordingly to the mainstream-term parts are printed using ink (being equivalent to AM production using raw material). Until now there is no overall-agreed definition on AM. In this paper we use Gebhardts definition, wherein AM is "... a layer-based automated fabrication process for making scaled 3-dimensional physical objects directly from 3D-CAD data without using part-depending tools" (Gebhardt, 2012).

AM is not a new technology in general. A first patent for a technology which could be considered AM at least partly reaches back to 1903 (Peacock, 1903). But its industrial development started mid of the 20th century (Breuninger et al., 2013). In the past, the technology was especially used for producing models or prototypes. In this case it is referred to as rapid prototyping. Today, the technology is not only capable of printing prototypes or models but final products. Due to technological development AM has the potential to replace classical subtractive production technologies (Cottrill, 2011).

Currently companies as well as research institutions work hard on the further development of the technology itself and set up new business models using AM for production. The most popular branches for using AM is the aerospace industry and the medical engineering. For example there is research going on to replace parts like brackets or engine sensors of an air plane, dental implants et cetera (Airbus S.A.S., 2014; General Electric, 2015; Gebhardt, 2012).

2.2 Functional Integration

On the one hand AM enables the functional integration in one production step. Using classical production technologies several production steps have to be performed and several precursors have to be assembled to get the final product. This leads to more production steps and a more complex production planning. Apart from a post-processing of the final part it is possible to print the final product in one production step by using AM (Gibson et al., 2015). Because of that the number of production steps decrease and planning will therefore be simplified.

Furthermore, the effect of the functional integration is not limited to a single company. It could be possible that due to the functional integration Original Equipment Manufacturers (OEMs) would be capable of printing parts by themselves which were originally produced by a supplier. So having the whole supply network in mind this could lead to actors dropping out of the supply network and its structure will change.

2.3 Higher Resource Efficiency

For AM less material is required (Waller and Fawcett, 2014) and therefore AM may increase the resource efficiency during production. Regardless of the printing technology used in the dedicated technical process only the material which is actually needed for the final part is used. The unused raw material can be (re-)used for the later production of other parts. Classical production on the other hand has a rather low resource efficiency. There over 80% of material is removed from the work piece (Gibson et al., 2015).

Especially in the aerospace industry this effect is referred as *buy-to-fly ratio*. It is the weight ratio of the raw material bought for a product and the weight of the final product itself (Gibson et al., 2015). Although our simulations do not address aerospace production but AM-production in general as well as the buy-to-fly ratio is a specific aerospace industry term, we will use it in this paper for addressing a higher resource efficiency.

3. AN OPTIMIZATION MODEL FOR A TWO-STAGE SUPPLY NETWORK

In order to evaluate the effects of a more efficient production by using AM, some core characteristics of supply networks are discussed in Section 3.1. A corresponding network design model is introduced in Section 3.2. Section 3.3 explains the generation of three instances of this model.

3.1 Definition of Supply Network

We assume a stylized two-stage *supply network*. The manufacturing of the products requires only one production step. Therefore, the focus is on a two-stage supply network that consists of only three sets of nodes: source nodes, production sites and customers (see Fig. 1). The *first stage* of such a network includes the transport of raw materials from the source nodes (e.g. a harbour) to the production sites. At a production site, the raw material is transformed into a final product. Afterwards, on the *second stage* of the network, the final products are transported to the customers.

The raw material to manufacture a final product is assumed to be homogenous. Precursors are also not considered. The amount of the transported goods (raw material and final products) is measured in tonnes. The costs for transporting the materials and final products are calculated as tonne-kilometers (tkm) using the distance in kilometres weighted by the weight of goods to be transported.

A source node can supply multiple production sites. A production site can supply multiple customers. However, the demand of a customer has to be fulfilled by only one production site. Furthermore, a storage of raw materials

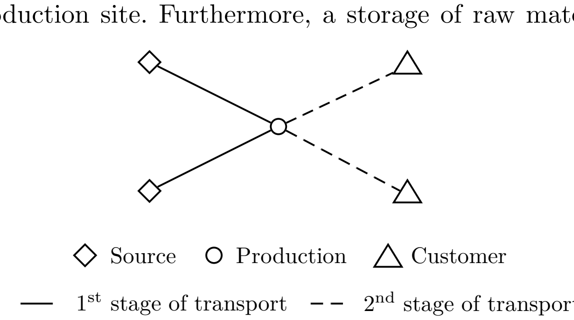

Fig. 1. Basic structure of supply network