

Barz, Andreas; Buer, Tobias; Haasis, Hans-Dietrich

Working Paper

Quantifying the Effects of Additive Manufacturing on Supply Networks by Means of a Facility Location-Allocation Model

Bremen Computational Logistics Group Working Papers, No. 2

Provided in Cooperation with:

Computational Logistics Junior Research Group, University of Bremen

Suggested Citation: Barz, Andreas; Buer, Tobias; Haasis, Hans-Dietrich (2015) : Quantifying the Effects of Additive Manufacturing on Supply Networks by Means of a Facility Location-Allocation Model, Bremen Computational Logistics Group Working Papers, No. 2, University of Bremen, Computational Logistics Junior Research Group, Bremen

This Version is available at:

<https://hdl.handle.net/10419/142134>

Standard-Nutzungsbedingungen:

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

Terms of use:

Documents in EconStor may be saved and copied for your personal and scholarly purposes.

You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.

If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.

Quantifying the Effects of Additive Manufacturing on Supply Networks by Means of a Facility Location-Allocation Model

Andreas Barz, Tobias Buer, and Hans-Dietrich Haasis

Bremen Computational Logistics Group Working Papers, No. 2

December 2015

Recommended citation:

Barz, Andreas; Buer, Tobias and Haasis, Hans-Dietrich (2015): Quantifying the Effects of Additive Manufacturing on Supply Networks by Means of a Facility Location-Allocation Model. In: Bremen Computational Logistics Group Working Papers, No. 2.

Bremen Computational Logistics Group Working Papers provides open access to papers which are (co-)authored by members of the [Computational Logistics](#) group at [University of Bremen](#).

Editor:

Prof. Dr. Tobias Buer

Computational Logistics Junior Research Group

Faculty of Business Studies & Economics | FB7

University of Bremen

Bibliothekstr. 1, 28359 Bremen, Germany

<http://www.cl.uni-bremen.de>

A member of [LogDynamics](#)

This manuscript ...	
...was <i>not</i> peer-reviewed	✓
...has been peer-reviewed	
...is a postprint and has been accepted for publication (see recommended citation)	
...updates working paper No.	—

Quantifying the Effects of Additive Manufacturing on Supply Networks by Means of a Facility Location-Allocation Model

Andreas Barz¹, Tobias Buer¹, and Hans-Dietrich Haasis²

¹Computational Logistics, Cooperative Junior Research Group of University of Bremen and ISL - Institute of Shipping Economics and Logistics, {barz, tobias.buer}@uni-bremen.de

²Chair in Maritime Business and Logistics, University of Bremen, haasis@uni-bremen.de

Abstract

Additive manufacturing (AM), or nonstandard 3D printing, disseminates in more and more production processes. This changes not only the production processes, e.g. subtractive production technologies are replaced, but will in all likelihood impact the configuration of supply networks. Due to a more efficient use of raw materials, transportation relations may change and production sites may be relocated. How this change will look like is part of an ongoing discussion in industry and academia. However, quantitative studies on this question are scarce. In order to quantify the potential impact of AM on a two-stage supply network, we use a facility location model. The impact of AM on the production process is integrated into the model by varying resource efficiency ratios. We create a test data set of 308 instances. Features of this test set are different geographical clusters of source nodes, production nodes, and customers nodes. By means of a computational study, the impact of AM on the supply network structure is measured by four indicators. In the context of our study, AM reduces the overall transportation costs of a supply network. However, the share of the transportation costs on the second stage of a supply network in the total costs increases significantly. Therefore, supply networks in which production sites and customer sites are closely spaced improve their cost effectiveness stronger than other regional configurations of supply networks.

1 Introduction

Due to the technological enhancement of *additive manufacturing (AM)* over the past years, AM starts to replace subtractive production technologies. In some fields of use, AM is competitive, because it reduces production costs and at the same time improves the range of features of components. But if one production technology is replaced by another this can change production and logistics processes as well. Still it appears that the focus in research is on improving the actual AM production technology, although industry and academia are aware of possible broader implications of AM, e.g. on *supply networks*. Potential implications of AM on supply networks are discussed. Tuck et al. (2007), Fawcett and Waller (2014), Cottrill (2011), Christopher and Ryals (2014) and Waller and Fawcett (2013) study and evaluate implications of AM, but they are of a qualitative nature. We are not aware of study that measures impacts of AM on supply networks and quantifies these effects. Only a few quantitative assessments like a case study of Khajavi et al., 2014

on a spare parts supply chain in the aeronautics industry are available which, however, focuses on accounting issues. Quantifying the impact of AM on supply networks appears to be important in order to support managerial decisions on the structure of the future supply network.

The contribution of this study is as follows. We quantify the effects of AM on a two-stage supply network. Raw material is transported from sources (e.g. a port) to production sites and then to customer locations. We model this problem as a well-known multi-stage facility location problem. A data set of 308 instances is generated that covers a broad range of geographical distributions of the nodes in the network. The effect of AM is integrated by using different *buy-to-fly*-ratios which represent the efficiency of material usage in a production process. By comparing less efficient buy-to-fly-ratios (i.e., traditional production) with more efficient ratios (i.e., AM), we can compare different optimal network configurations. This is done for each of the 308 instances. Four indicators measure the performance of the generated networks. In contrast to our previous study (Barz et al., 2016), the evaluation is significantly extended: instead of 3 instances a set of 308 instances is generated and used for testing. We included several structures in these instances, in particular with respect to the geographical distribution of nodes as well as a different clustering of nodes. Therefore, broader and validated statements are possible.

This article is structured in five sections. After this introduction, Section 2 will give a brief overview of AM and describe technological aspects which probably will have implications on the structure of supply networks. Section 3 introduces our two-stage supply network together with a facility location-allocation model. In particular, the generation of the used data set is described. In Section 4 we present and analyse the results of a computational study. Section 5 concludes the paper.

2 Implications of additive manufacturing

The concept of AM is introduced. related conceptSection 2.1 explains the term AM. Among the advantages of AM discussed in the literature, two will be explained in detail. That is, functional integration of parts in Section 2.2 and a higher resource efficiency for production in Section 2.3.

2.1 Definition of additive manufacturing

Within the scientific community there is a set of several synonym for AM and the technology respectively. Nevertheless, AM is the most often used term. It is an umbrella term for many different technologies. AM usually is divided in subcategories dependent for what the AM-technology is used for. These subcategories are rapid manufacturing for producing serial parts, rapid prototyping for producing prototypes and models, and rapid tooling for production tools for production like moulds. However, in the non-scientific community AM is rather unknown term. The most common mainstream term 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).

Regardless of the many different synonyms in the scientific and non-scientific community there is no overall-agreed definition on AM respectively on 3D Printing until now. In this contribution we follow Gebhardt's 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).

The industrial development and research on AM started mid of the 20th century (Breuninger et al., 2013). But AM is not a new technology in general or was invented at that time. A first patent which could be considered AM at least partly reaches back to 1903 (Peacock, 1903). In the past, the technology was especially used for producing models or prototypes. In this case it is referred to as rapid prototyping. With the ongoing development of additive manufacturing (AM) the technology is capable of printing final products today. Therefore classical production technologies could be replaced by AM (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 in the aerospace industry 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

When using classical production technologies usually several production steps have to be performed and several precursors have to be assembled to get the final product. Because of that the production planing becomes more complex. But with AM this is going to change. AM enables the functional integration in one production step. That means, apart of a post-processing of the final product it may be produced in a single production step (Gibson et al., 2015). An assembly of precursors is not necessary. Therefore the number of production steps decreases and production planing will be simplified.

This functional integration has not to be limited to a single company. Imagine an Original Equipment Manufacturers (OEMs) printing the final product in one production step. Precursors which were originally produced by a supplier are directly integrated in the AM-process. Therefore actors could drop out of the supply network and its structure will change.

2.3 Higher resource efficiency

For AM processes only the material which is actually needed for the final part is used. Regardless of the dedicated technical process the unused raw material can be (re-)used for the later production of other parts. Therefore less material is required (Waller and Fawcett, 2014) and AM may increase the resource efficiency during production. 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*. The term refers to the weight ratio of “...wrought material that is purchased as a block that is required to form a complex part” (Gibson et al., 2015). Our computational experiments do not address aerospace production in particular but AM-production in general. Nevertheless we will use the term in this paper for addressing resource efficiency.

3 An optimization model for a two-stage supply network

For quantifying the effects of AM on supply networks a facility location-allocation model was used. The main characteristics of the considered supply network are discussed in Section 3.1. In

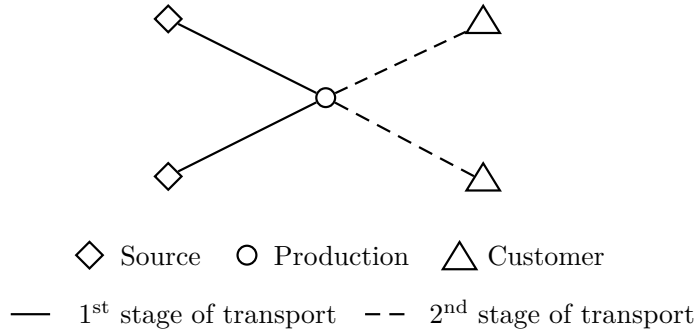


Figure 1: Basic structure of supply network

Section 3.2 the corresponding facility location-allocation model is introduced. Section 3.3 explains data generation in order to create 308 test instances.

3.1 Definition of supply network

We assume a stylized two-stage *supply network*. According to Section 2.2 manufacturing of products requires one production step only. This should apply for both, AM and classical production technologies. In our model the different technologies are represented by different buy-to-fly ratios (see Section 3.3.2). A buy-to-fly-ratio α of 5 means that five units of material are bought and thereof only one unit goes into the final product. Therefore, the focus is on a two-stage supply network that consists of three types of nodes: source nodes, production sites and customers (see Fig. 1). On the *first stage* of such a network the raw materials are transported from the source nodes (e.g. a harbour) to the production sites. There, the raw material is transformed into a final product. Afterwards, the final products are transported from the production sites to the customers on the *second stage* of the network.

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 or final products at the production sites is forbidden. The production sites have a capacity restriction on the number of products to be manufactured. In contrast, transport relations between the nodes have no capacities. This is reasonable, because network design is a rather long-term problem and transport capacities, in particular road transport, are usually easily adaptable.

3.2 Two-stage capacitated facility location problem

According to Section 2.3 the use of AM might reduce the required raw materials in order to produce final products. Therefore, quantity of goods to be transported will change. But this change is not the only implication for the supply network. Beyond that the questions arises, whether the locations of our facilities are still adequate in order to supply our customers if AM is applied within

the network? In the operations research literature, this question is a well-studied. There, the problem is classified as a facility location problem. Many models for this problem are discussed, a comprehensive survey is presented by (Klose and Drexl, 2005).

In order to model the two-stage supply network at hand, we decided to use the *two-stage capacitated facility location problem* (TSCFLP) in the formulation presented by Klose and Drexl, 2005 with a slight adjustment. In the TSCFLP we are given a set N of nodes. N is divided into a set I of source nodes, a set J of *potential* production sites, and a set K of customer locations.

$$\min z_1 = \sum_{i \in I} \sum_{j \in J} t_{ij} x_{ij} + \sum_{k \in K} \sum_{j \in J} d_k c_{kj} z_{kj} + \sum_{j \in J} f_j y_j \quad (1)$$

$$\text{s.t.} \quad \sum_{j \in J} z_{kj} = 1 \quad \forall k \in K \quad (2)$$

$$\sum_{j \in J} s_j y_j \geq \sum_{k \in K} d_k \quad (3)$$

$$\sum_{k \in K} d_k z_{kj} \leq s_j y_j \quad \forall j \in J \quad (4)$$

$$\sum_{j \in J} x_{ij} \leq p_i \quad \forall i \in I \quad (5)$$

$$\sum_{j \in J} x_{ij} = \sum_{k \in K} \alpha d_k z_{kj} \quad \forall j \in J \quad (6)$$

$$x_{ij} - p_i y_j \leq 0 \quad \forall i \in I, j \in J \quad (7)$$

$$z_{kj} - y_j \leq 0 \quad \forall k \in K, j \in J \quad (8)$$

$$x_{ij} \in \mathbb{N}_0 \quad \forall i \in I, j \in J \quad (9)$$

$$y_j \in \{0, 1\} \quad \forall j \in J \quad (10)$$

$$z_{kj} \in \{0, 1\} \quad \forall k \in K, j \in J \quad (11)$$

The capacity of source i and production site j are given by p_i ($i \in I$) and s_j ($j \in J$), respectively. For each customer location $k \in K$ the demand d_k is given. The fixed cost for opening a production site j are given by f_j ($j \in J$). Transport costs arise at the production sites, they are indicated by t_{ij} with $i \in I$ and $j \in J$. On the second stage of a network, the transport costs per unit from a production site $j \in J$ to a customer location $k \in L$ are given by c_{kj} .

The *decision variables* are x_{ij} , y_j , and z_{kj} ($i \in I, j \in J, k \in K$). x_{ij} indicates the transport volume in tonnes from source node i to production site j . The binary variable y_j indicates, if a production site is in use $y_j = 1$ (referred to as *open*) or not $y_j = 0$. The binary variable z_{jk} indicates if production site j supplies customer location k . The TSCFLP is given by (1) to (11).

The objective function (1) minimizes the total costs that are made up from the transport costs on the first and the second stage of the network plus the costs for opening a production site. Constraint (2) ensures that each customer is supplied by exactly one production site. Constraint (3) ensures that the open production sites on the whole are able to satisfy the demand of all customers. Constraint (4) guarantees that the capacity of a production site suffices to satisfy the demand of the customers supplied by this production site. The capacity of a source has to be larger

Table 1: Considered allocations of 90 nodes into source, production, and customer nodes

Allocation	# source nodes	# production nodes	# customer nodes
A_1	10	20	60
A_2	10	60	20
A_3	20	10	60
A_4	20	60	10
A_5	30	30	30
A_6	60	20	10
A_7	60	10	20

than the transport volume of the assigned production sites (5). Restriction (6) defines the flow balance, the inflow of each production site has to be equal to the outflow. Storage is not possible. Constraint (7) ensures that a source does not supply more raw materials than required by an open production site. Restriction (8) guarantees that a production site is open if it supplies goods to a customer locations. Constraints (9) to (11) define the decision variables.

In contrast to the model of Klose and Drexl (2005), we include the parameter α in restriction (6). This parameter is denoted as *buy-to-fly ratio*. It indicates the efficiency of the production process, lower values of α stand for a higher efficiency. This parameter is changed during the computational experiments in order to introduce the higher resource efficiency of AM into the model.

3.3 Generation of test data

The parameters of the TSCFLP represent the required input data for the test. Basically, the following parameter are considered:

- The nodes of a supply network, in particular
 - the number of source nodes, production nodes and customer nodes as well as
 - the geographical distribution of these nodes,
- the buy-to-fly ratio α , and
- some other parameters, whose values are constant for all instances.

We consider seven node allocations, eleven different geographical distributions, and four buy-to-fly-ratios. Overall, 308 instances of the TSCFLP were created. This compares to Barz et al., 2016 where only three instances were used. Therefore, the study at hand is much more significant with respect to the evaluation.

3.3.1 Generating supply networks

A supply network consists of three types of nodes: source nodes, production nodes, and customer nodes. Like Barz et al., 2016, the total number of nodes is set to 90. Most networks of this size can be solved by CPLEX in a few minutes. Seven allocations of these 90 nodes are used to generate networks. The seven allocations into source nodes, production nodes, and customer nodes are shown in Table 1.

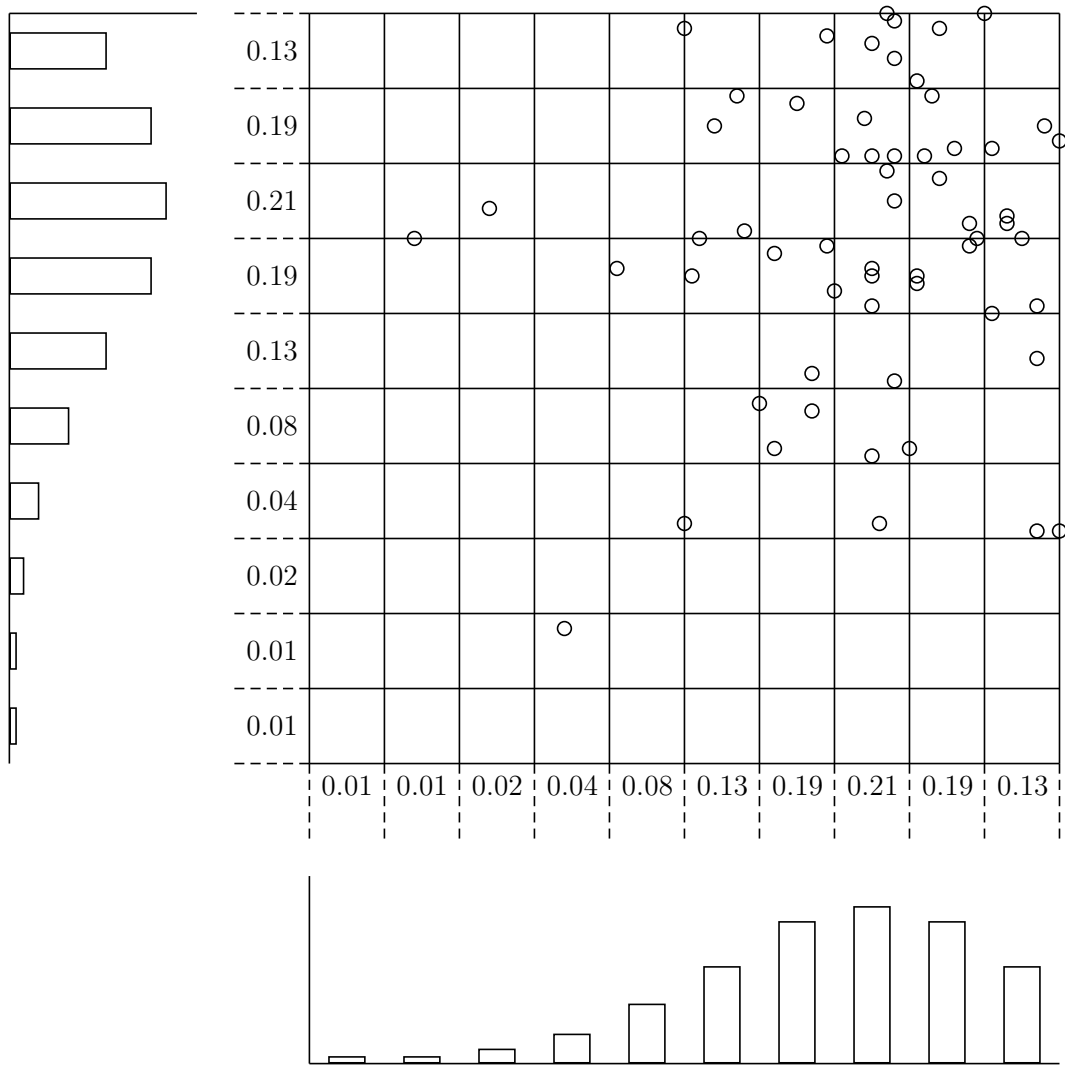


Figure 2: Example distribution of 60 nodes using normal distributions on the x-axis and y-axis, respectively.

The *geographical distribution* impacts the transport costs and supply relationships significantly. Many different kinds of node clusters are imaginable. For example, industrial parks (i.e., production nodes) close to seaports (i.e., source nodes) or far away in the hinterland. The same applies to production or customer nodes. A clustering of source nodes might happen supported by geographical characteristics, e.g. access to the sea. Clusters could form because of urbanization which might imply fallow lands in other areas of a country. Different clusters of the three node types were considered in order to take some of these characteristics of a network into account.

The geographical node distribution assumes a 100×100 grid. As Fig. 2 shows, the x-axis and the y-axis are divided into segments with a width of 10 units, respectively. 100 squares emerge. Given an allocation A_i ($i = 1, \dots, 7$) the nodes are placed randomly and independently of each other on a square. In order to generate a clustering of nodes, different normal distributions are used. However, for each type of node the same normal distribution is applied. In the example of Fig. 2, the mathematical expectation is set to 75 on both axes with a standard deviation of 20. 60 production nodes are placed randomly. As predefined by the normal distribution a cluster of nodes in the north-east area emerges.

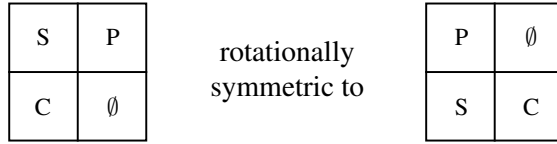


Figure 3: Comparison of rotationally symmetric distributions of clusters

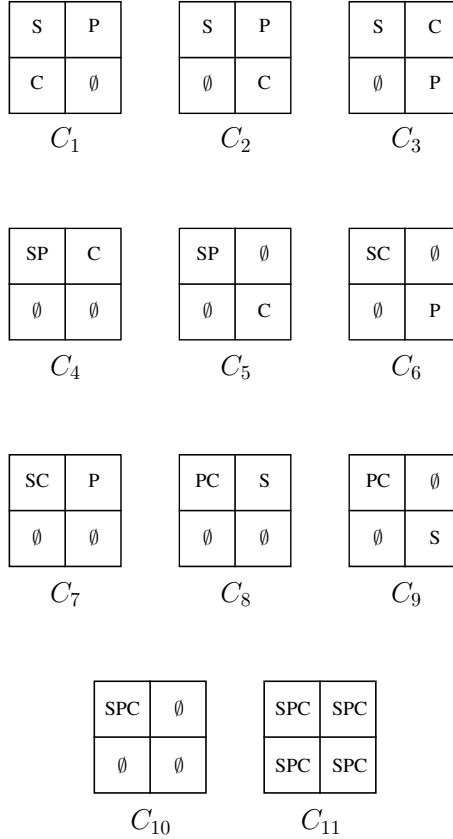


Figure 4: The eleven studied cluster combinations

A node distribution in a network is identified by quadruple (nw, ne, sw, se) . Each element of the quadruple represents the position of a node cluster. nw, ne, sw, se denote the north-west, north-east, south-west, and south-east region of the grid. Possible values of nw, ne, sw, se are S, P, C, \emptyset indicating a source node, production node or a customer node or no clustering. Graphically, this is illustrated like a square in Fig. 4.

From all possible combinations of clusters on the grid, only eleven are considered. The main reason to exclude cluster combinations from the study is rotational symmetry among the quadruples. An example for rotational symmetry of clusters is given in Fig. 3. Symmetric quadruples do not have to be considered because they represent no unique arrangement of clusters.

In addition to these structures one additional structure was created with all nodes evenly distributed. Fig. 4 shows all network structures that were used for the computational experiments. Overall eleven different structures were created.

3.3.2 Buy-to-fly ratio

The buy-to-fly expresses the resource efficiency of a production process. According to Heck et al. (2014), Lindemann et al., 2013, and Arcam-AB (s. a.), the buy-to-fly ratio for AM varies between (almost) $\alpha = 1$ and $\alpha = 3$. For subtractive production the buy-to-fly ratio varies between $\alpha = 10$ and $\alpha = 40$ as reported by Dutta and Froes (2015) and Whittaker and Froes (2015) for real-world scenarios. Four different buy-to-fly ratios are considered to allow for a broad spectrum, i.e., the buy-to-fly ratio α is set to 2, 5, 10 and 20.

3.3.3 Other parameters

The TSCFLP allows to set different capacities for sources p_i and production sites s_j , cost for opening production sites f_j as well as demand of customers d_k . All of these were defined once and are constant for all instances. The values are:

- Capacities p_i of each source nodes $i \in I$ are unlimited, i.e., $p_i := 99999999$ and have therefore no impact on the simulation.
- Capacities s_j of each production site $j \in J$ are uniform randomly drawn between 100 and 500.
- Cost f_j for opening a production site $j \in J$ are set to $f_j := 5000$. This value equals the average tkm for a transport in the supply network from a source node to customer node.
- The demand d_k of each customer $k \in K$ is drawn uniform randomly between 1 and 100.

4 A computational study

The 308 instances of the TSCFLP (cf. Section 3.2 and 3.3) are solved by the mixed-integer programming solver CPLEX 12.5.1 from IBM. To measure the performance of a supply network, the indicators presented in Section 4.1 are used. The results of the computational experiments are discussed in Section 4.2.

4.1 Performance indicators

The structural effects of AM on supply networks are measured and discussed by means of the indicators z_1 to z_4 :

1. z_1 , the total costs of the network as defined by the TSCFLP's objective function (1).
2. $z_2 := \frac{1}{|K|} (\sum_{j \in J, k \in K} d_k \cdot c_{kj} \cdot z_{kj})$, the average transport costs per customer on the second stage of the supply network. The second stage considers transports between production sites and customer locations only.

The first stage transportation costs between source nodes and production sites are not considered because a lower buy-to-fly ratio requires less raw materials which obviously reduces the first stage transportation cost. However, the demand of the customers is independent of the buy-to-fly ratio which is why the transport volume on the second stage is constant. Therefore z_2 might provide useful information about to what extent transport costs are affected by different locations of production sites.

3. $z_3 := z_3^{1st} : z_3^{2nd}$ the proportion of total costs z_3^{1st} arising on the first stage versus costs z_3^{2nd} arising on the second stage of the supply network.

$$z_3^{1st} := \frac{\sum_{i \in I, j \in J} t_{ij} \cdot x_{ij}}{\sum_{i \in I, j \in J} t_{ij} x_{ij} + \sum_{j \in J, k \in K} d_k c_{kj} z_{kj}}$$

$$z_3^{2nd} := \frac{\sum_{j \in J, k \in K} d_k \cdot c_{kj} \cdot z_{kj}}{\sum_{i \in I, j \in J} t_{ij} \cdot x_{ij} + \sum_{j \in J, k \in K} d_k \cdot c_{kj} \cdot z_{kj}}$$

4. $z_4 := \sum_{j \in J} y_j$, the number of open production sites.

4.2 Discussion of results

Table 2 shows the rounded median indicator values for 308 instances of the TSCFLP. The instances are divided into four groups with different buy-to-fly ratios of $\alpha = 2, 5, 10, 20$. So, each group comprises 77 different networks. In addition Fig. 5 shows the median and the 10%- and 90%-quantile of the indicators with different buy-to-fly ratios relatively to $\alpha = 20$. The instances haven been solved by the mixed-integer programming solver CPLEX 12.5.1 from IBM.

It goes without saying, that the discussion of the effects of AM on the structure of supply networks is only valid for the instances at hand used for our stylized model. Nevertheless, this provides a new method of analysing effects of AM on network structures.

Looking at the median z_1 , the total costs decrease in all cases with an improved (i.e., lower) buy-to-fly ratio. In addition, even the quantiles are always below the median value for $\alpha = 20$ (see Fig. 5). We conclude, that in 80% of all compared instances an improved buy-to-fly ratio respectively a switch to AM-production will lead to reduced total costs of the network.

Concerning z_2 an improvement of α will lead to lower transportation costs between production sites and customer locations on average per customer. However, with the given data the quantiles always reach the median of the $\alpha = 20$ -case (see Fig. 5). But different from the effects on z_1 , a lower α will not always reduce z_2 .

With respect to z_3 , the proportion of transportation costs on the first stage and on the second stage shifts to the second stage. However, using AM changes the proportion of tkm required on the first stage versus those required on the second stage of the supply network in the same way. This might be counter-intuitive, because z_2 indicated a total reduction of transport costs on the second stage. The reason for this is, that the buy-to-fly ratio α leads to significantly stronger reduction of the required tkm on the first stage. Especially for $\alpha = 2$ the quantile range is very broad (see Fig. 5). Compared to $\alpha = 20$ the share of tkm for $\alpha = 2$ on the second stage is over three times higher.

The number of open production sites z_4 is slightly reduced using a better α . Because the values of

Table 2: Median of the Performance Indicators with Four Buy-to-fly Ratios for 77 Instances

Indicator	Buy-to-fly Ratio α			
	$\alpha = 2$	$\alpha = 5$	$\alpha = 10$	$\alpha = 20$
z_1	49,408	64,489	84,437	125,940
z_2	1,217	1,429	1,471	1,523
z_3	30 : 70	43 : 57	54 : 46	68 : 32
z_4	3	3	3	3

the other performance indicators change a lot more depending on α we conclude that the *number* of production sites used does not affect the costs of the supply network much. However, when applying a better buy-to-fly ratio in the network, other possible production sites are opened and therefore the structure changes.

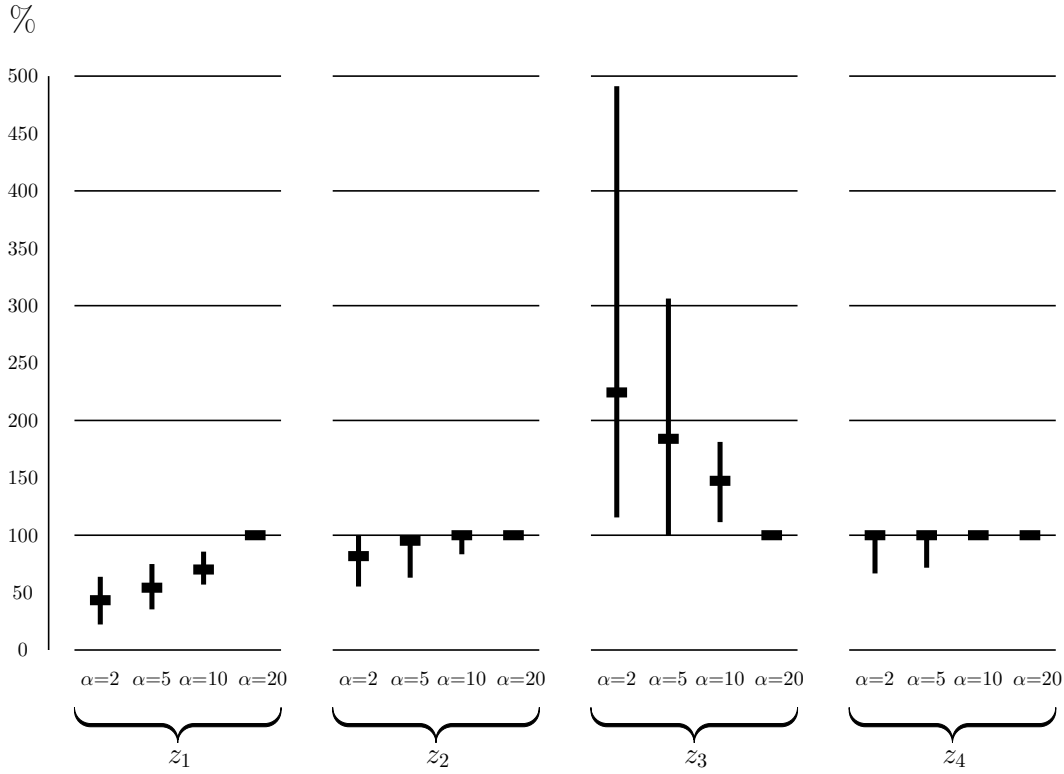


Figure 5: Median and Quantile of Performance Indicators for different α relative to $\alpha = 20$

Apart from an overall analysis a more detailed view on the cluster structures as well as on the allocation of nodes show that the results are especially dependent on the number of the customers and clusters of at least two types of nodes. Table 3 shows the median values of the performance indicators classified for the allocation of numbers and clusters of nodes.

In case of an allocation A_1 and A_3 (see Table 3) there are 60 customers to be supplied. On the other hand the number of production sites is rather low with 10 or 20, respectively. To fulfill the demand of the customers 9 production sites have to be opened. Only little cost reductions are possible for lower values of α . We conclude that if there are only few possible production sites to choose from, using AM improves the supply network only marginal. There are different allocations from production sites to customers, but overall the benefit through the use of AM is low, because either way almost every production site has to be opened to fulfill the customer's demand.

If production sites and customers are located in the same region of the grid, AM respectively a lower α results in high cost reductions. This is the case for clusters C_8 and C_9 (see Table 3). There, production sites and customers are located in the same region. By applying a lower α especially the average transport costs per customer on the second stage of the supply network drop at least 17% up to 30%. We conclude that even though the production sites and customers are already clustered in the same region the production sites move closer to the customers with a lower α .

Summarizing the computational experiments of the 308 instances we conclude that the general results of Barz et al. (2016) on the effects of AM on supply networks are reflected in our experiments,

Table 3: Median of the performance indicators for different allocations and clusters

Allocation	z_1			z_2			z_3			z_4					
	$\alpha = 2$	$\alpha = 5$	$\alpha = 10$	$\alpha = 2$	$\alpha = 5$	$\alpha = 10$	$\alpha = 2$	$\alpha = 5$	$\alpha = 10$	$\alpha = 2$	$\alpha = 5$	$\alpha = 10$			
	A_1	222,072	304,122	474,792	824,128	1,541	1,754	1,760	1,764	51 : 49	68 : 32	80 : 20	88 : 12	9	9
A_2	47,597	63,483	77,179	106,879	1,006	1,357	1,452	1,486	33 : 67	40 : 60	50 : 50	67 : 33	3	3	3
A_3	251,274	349,079	528,937	936,130	1,930	1,932	1,932	1,932	46 : 54	68 : 32	81 : 19	90 : 10	9	9	9
A_4	23,363	28,285	32,618	36,973	1,423	1,423	1,523	1,523	15 : 85	30 : 70	29 : 71	35 : 65	2	2	1
A_5	21,160	24,949	29,494	39,272	1,178	1,217	1,476	1,476	18 : 82	30 : 70	42 : 58	55 : 45	1	2	1
A_6	43,087	55,979	70,788	103,695	1,042	1,174	1,252	1,414	26 : 74	44 : 56	58 : 42	66 : 34	2	2	3
A_7	82,612	103,604	124,653	174,999	1,515	1,572	1,732	1,996	32 : 68	43 : 57	55 : 45	69 : 31	4	4	5

Cluster	z_1			z_2			z_3			z_4					
	$\alpha = 2$	$\alpha = 5$	$\alpha = 10$	$\alpha = 20$	$\alpha = 2$	$\alpha = 5$	$\alpha = 10$	$\alpha = 20$	$\alpha = 2$	$\alpha = 5$	$\alpha = 10$	$\alpha = 20$			
	C_1	56,136	68,783	89,540	126,811	1,677	1,973	2,058	2,058	21 : 79	39 : 61	50 : 50	60 : 40	3	3
C_2	47,706	67,302	96,302	147,584	1,442	1,432	1,432	1,582	24 : 76	43 : 57	53 : 47	66 : 34	3	3	4
C_3	51,261	67,383	90,039	135,349	1,423	1,573	1,677	1,677	40 : 60	48 : 52	65 : 35	79 : 21	2	3	3
C_4	48,704	59,254	77,179	106,879	1,523	1,758	1,866	1,881	29 : 71	45 : 55	40 : 60	51 : 49	2	2	3
C_5	51,896	65,742	74,422	86,717	1,526	1,849	2,452	2,567	23 : 77	34 : 66	29 : 71	40 : 60	3	3	3
C_6	47,597	63,483	82,933	125,940	1,166	1,450	1,732	1,904	38 : 62	51 : 49	63 : 37	74 : 26	3	3	3
C_7	49,408	64,489	89,624	139,886	1,321	1,468	1,471	1,478	26 : 74	40 : 60	55 : 45	71 : 29	2	2	3
C_8	41,205	55,979	76,080	114,555	816	981	1,056	1,130	35 : 65	43 : 57	60 : 40	71 : 29	3	3	3
C_9	51,884	68,658	93,516	143,233	968	1,400	1,440	1,440	49 : 51	46 : 54	63 : 37	78 : 22	3	3	3
C_{10}	30,317	36,375	43,881	54,926	711	868	872	933	26 : 74	33 : 67	46 : 54	61 : 39	2	2	3
C_{11}	39,939	50,346	64,613	88,923	881	1,012	1,255	1,277	30 : 70	43 : 57	50 : 50	64 : 36	3	3	3

too. The total costs decrease, the proportion of transports costs shifts towards the second stage of transport, the costs of transport between production sites and the customer locations on average per customer drop and the number of production sites used is relatively steady. Additional conclusion are drawn from the different geographical distributions of the nodes and varying numbers of each node type. The biggest improvements by using AM-production arise if the number of possible production sites to chose from is high. However, the number of production sites changes rarely. Furthermore, the effect of AM is large, if the clusters of two types of nodes are located nearby at the same geographical area. This is especially true for production sites and customer locations which are close together. Vice versa the change AM-production in networks with only few production sites to chose, and/or clusters located at different spots results in minor benefits. With respect to supply network effects, AM-production has the highest impact if the supply network is flexible, i.e., if it is possible to change locations of the production sites.

5 Conclusions and outlook

The paper at hand represents one of the first studies to measure the effects of additive manufacturing (AM) on supply networks. We use facility location-allocation model to model a two-stage supply network. A test data set of 308 instances is introduced. These instance provide different clusters of source, production sites, and customer locations and represent a wide variety of geographical constellations of a supply network. Different production processes are represented by different buy-to-fly-ratios that influence the amount of goods to be transported in the network.

The computational results confirm the general outcome of Barz et al. (2016) but offer much more detail and validity. Increasing the resource efficiency through AM can have a significant impact on the structure of supply networks. The overall transportation costs decrease, the production sites are located closer to the customers and therefore, the total tkm as well as the required tkm per customer decreases. However, not all supply networks may benefit in the same way. To increase the efficiency of a supply network, it is important that flexible (i.e., switching production sites is possible) and decentralized (i.e., a high number of possible production sites) network structures are available. Then AM-production will have the biggest impact in terms of improving the supply network structure.

Nevertheless, one has to act with caution when generalizing these results. The influencing factors on network design are manifold and the actual dissemination of AM in the future is uncertain. Therefore, a broader study using more general network structures and a wider variety of input data (like e.g. costs, transport demand, locations of nodes or production capacities) which also may depend on specific industries is required. Similarly, extensions of the used model TSCFLP should be taken into account in order to model supply networks closer to reality.

Acknowledgement

The cooperative junior research group on *Computational Logistics* is funded by the University of Bremen in line with the Excellence Initiative of German federal and state governments.

References

Airbus S.A.S. (2014). *Printing the future: Airbus expands its applications of the revolutionary additive layer manufacturing process*. Online.

- Arcam-AB (s. a.). *EBM in Aerospace – Additive Manufacturing taken to unseen heights*. Online.
- Barz, A., T. Buer, and H.-D. Haasis (2016). “A Study on the Effects of Additive Manufacturing on the Structure of Supply Networks”. In: *7th IFAC Conference on Management and Control of Production and Logistics*. in press.
- Breuninger, J., R. Becker, A. Wolf, S. Rommel, and A. Verl (2013). *Generative Fertigung mit Kunststoffen: Konzeption und Konstruktion fr selektives Lasersintern*. Berlin et al.: Springer Vieweg.
- Christopher, M. and L. J. Ryals (2014). “The Supply Chain Becomes the Demand Chain”. In: *Journal of Business Logistics* 35.1, pp. 29–35.
- Cottrill, K. (2011). *Transforming the Future of Supply Chains Through Disruptive Innovation – Additive Manufacturing*. Online.
- Dutta, B. and F. H. S. Froes (2015). “24 - The additive manufacturing (AM) of titanium alloys”. In: *Titanium Powder Metallurgy*. Boston: Butterworth-Heinemann, pp. 447–468.
- Fawcett, S. E. and M. A. Waller (2014). “Supply Chain Game Changers - Mega, Nano, and Virtual Trends—And Forces That Impede Supply Chain Design (i.e., Building a Winning Team)”. In: *Journal of Business Logistics* 35.3, pp. 157–164.
- Gebhardt, A. (2012). *Understanding additive manufacturing: rapid prototyping, rapid tooling, rapid manufacturing*. Munich et al.: Hanser.
- General Electric (2015). *GE Aviations First Additive Manufactured Part Takes Off on a GE90 Engine*. Online.
- Gibson, I., D. Rosen, and B. Stucker (2015). *Additive manufacturing technologies: rapid prototyping to direct digital manufacturing*. 2. ed. New York, NY et al.: Springer.
- Heck, S., M. Rogers, and P. Carroll (2014). *Resource revolution how to capture the biggest business opportunity in a century*. Boston et al.: Houghton Mifflin Harcourt.
- Khajavi, S. H., J. Partanen, and J. Holmström (2014). “Additive manufacturing in the spare parts supply chain”. In: *Computers in Industry* 65.1, pp. 50–63.
- Klose, A. and A. Drexl (2005). “Facility location models for distribution system design”. In: *European Journal of Operational Research* 162.1, pp. 4–29.
- Lindemann, C., U. Jahnke, E. Klemp, and R. Koch (2013). “Additive Manufacturing als serienreifes Produktionsverfahren”. In: *Industrie Management* 29.2, pp. 25–28.
- Peacock, G. (1903). *Method of making composition horseshoes*. US Patent 746,143.
- Tuck, C., R. Hague, and N. Burns (2007). “Rapid manufacturing: impact on supply chain methodologies and practice”. In: *International Journal of Services and Operations Management* 3.1, pp. 1–22.
- Waller, M. A. and S. E. Fawcett (2013). “Click Here for a Data Scientist: Big Data, Predictive Analytics, and Theory Development in the Era of a Maker Movement Supply Chain”. In: *Journal of Business Logistics* 34.4, pp. 249–252.
- Waller, M. A. and S. E. Fawcett (2014). “Click Here to Print a Maker Movement Supply Chain: How Invention and Entrepreneurship Will Disrupt Supply Chain Design”. In: *Journal of Business Logistics* 35.2, pp. 99–102.
- Whittaker, D. and F. H. S. Froes (2015). “Future prospects for titanium powder metallurgy markets”. In: *Titanium Powder Metallurgy*. Boston: Butterworth-Heinemann, pp. 579–600.
- Wohlers, T. (2014). *The future of 3D printing*. Presentation, Inside 3D-Printing Berlin, March 10th 2014.