Available online at www.sciencedirect.com
ScienceDirect
Procedia CIRP 57 (2016) 716 – 721
www.elsevier.com/locate/procedia

49th CIRP Conference on Manufacturing Systems (CIRP-CMS 2016)

A Framework for Integration of Additive Manufacturing Technologies in Production Networks

Patrik Spalt*[a], Thomas Bauernhansl[ab]

[a]Institute of Industrial Manufacturing and Management, University of Stuttgart, 70569 Stuttgart, Germany
[b]Fraunhofer Institute for Manufacturing Engineering and Automation IPA, 70569 Stuttgart, Germany

* Corresponding author. Tel.: +49-711-970-1919; fax: +49-711-970-1927. *E-mail address:* patrik.spalt@ipa.fraunhofer.de

Abstract

Flexibility in manufacturing operations is becoming increasingly important to industrial firms, due to e.g., increasing market demand volatility and shorter product life cycles. Additive manufacturing technologies show great potential in adding flexibility to manufacturing operations through nearly unlimited freedom in product design, very high product mix flexibility, decentralized production and the ability to produce new product variants after a very short period of time. This could result in shorter lead times, lower stock levels, higher product availability and lower transportation costs. Therefore companies have to incorporate the increased flexibility in their decision, especially on the production network level, when they decide whether to use additive manufacturing or not. Current methods are not able to take into account all of these flexibility types and the respective benefits. The application of an appropriate method could lead to a realistic evaluation and an increased use of additive manufacturing technologies. This paper evaluates state of the art methods, especially from the field of strategic production network planning. The main contribution of this paper is the development of a framework for integration of additive manufacturing technologies in production networks using the Real Option value as target criteria. Finally, we discuss where further research is needed in order to develop an applicable method based on the presented framework.

Keywords: Additive manufacturing; Production networks; optimization model; Real Options

1. Introduction

Additive manufacturing is said to be one of the disrupting technologies which will dramatically change the world of industrial production [1]. The main cause is, that flexible operations will become one of the most important competitive differentiators, and additive manufacturing technologies are able to tremendously increase flexibility in manufacturing operations. Reasons are nearly unlimited freedom in product design, very high product mix flexibility, decentralized production and the ability to produce new product variants after a very short period of time. This could result in shorter lead times, lower stock levels, higher product availability and lower transportation costs [2]. Due to that companies have to incorporate the increased flexibility in decision making [3], especially on the production network level [4], when they decide whether to use additive manufacturing or not. As we show in section three, current methods are not able to take into account all of these flexibility types and the respective benefits. Additionally, the question where and how many additive manufacturing machines have to be located cannot be answered in a structured way. The application of an appropriate method could lead to better production network designs, a realistic evaluation and an increased use of additive manufacturing technologies. In this paper, we first describe the state of the art applications of additive manufacturing. Based on this, we analyze the most important factors influencing the decision whether or not to use additive manufacturing, especially the influence of additive manufacturing technologies on flexibility. In section three, we discuss why current approaches are not sufficient when deciding how and when to integrate additive manufacturing in production networks. In section four, a

doi:10.1016/j.procir.2016.11.124

framework for the integration of additive manufacturing in production networks and its application is presented. Finally, a summary and remarks for further research are provided.

2. Additive Manufacturing and Flexibility

2.1. Current Applications of Additive Manufacturing

The term additive manufacturing can be defined as "(…) the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methods." [5]. Synonyms include *additive fabrication, additive processes, additive techniques, additive layer manufacturing,* and *freeform fabrication*. For a comprehensive overview of different additive manufacturing technologies, see [6]. Current applications of additive manufacturing are still mainly prototyping, tooling and highly personalized medical parts such as tooth implants [7]. All of these applications have in common that parts are produced in very small numbers. These applications appear mainly in the four industrial sectors automotive, aviation, tool making, and medical with different technology readiness levels*. In the automotive industry, current applications have levels from four to six, in aviation, five to seven, which denotes that the systems have shown the general capability for application but are not ready for production in a realistic setting. Technology readiness levels are higher in tool making (seven to nine) and medical (nine to ten), which indicates that these sectors are able to use additive manufacturing in real production settings [7,8]. Despite this limited use, researchers and practitioners predict great market growth (approximately nine billion dollars by 2025) for direct manufactured parts in these industries [9]. Spare parts production has a particularly high potential to use additive manufacturing technologies [10].

2.2. Advantages

Additive manufacturing machines have very low changeover costs, which leads to smaller economic batch sizes [12]. This has two effects: The first is the increasing product mix flexibility and, thus, lower stock levels and lower customer response time. The second is the tendency to decentralize the production networks due to smaller production facilities. By decentralizing production, companies can reduce lead times and, due to that, the demand risk of the production network. This results in lower safety stock levels and higher customer satisfaction. In some cases, a switch from make-to-stock to make-to-order networks, with stock levels of zero, would be possible [13].

However, cost is not the only factor affected when producing with additive manufacturing. With the help of additive manufacturing technologies, companies are able to produce highly customized products. In addition, as customized products match the preferences of the specific customer more closely, they can be sold for higher prices. Therefore, it is an important question for additive manufacturing technologies how the price surplus will be yielded depending on the customer segments [1,14].

2.3. Disadvantages

In section 2.1 we argued that the application of additive manufacturing currently concentrates on a few industrial sectors, especially on prototyping, tools and medical implants. The reasons are manifold. One reason is the low technology readiness levels, which are caused by the low process reliability and the small number of available materials [7]. Moreover, there are still open legal questions, especially about liability [6]. Besides these technical aspects there are two main economical disadvantages associated with the usage of additive manufacturing technologies: Firstly, the low build rates [11,13], which lead to relatively high investments for additive manufacturing machines. Secondly, the high prices for granulates [7,11,13]. These two cost factors account for approximately 60-80 percent of the total production costs depending on the technology used [2,7,11,13].

2.4. Relevant flexibility demand and potentials in the case of additive manufacturing

All advantages shown in section 2.2 have one thing in common. They add flexibility to the production system and to the production network. Flexibility can be defined as "the ability of an open, dynamic socio-technical system to adapt itself based on flexibility potentials relevant to changes of the system itself or its environment." [15] This potential-oriented definition of flexibility allows to differentiate between flexibility demand and flexibility potentials. The definition of flexibility can be extended by defining that flexibility has to be planned in advance with preplanned limits. In contrast to that, changeability [16] or structural flexibility [4] can be used to react to future developments which are not planned and the system can adjust itself to the outside of the preplanned limits. Flexibility demand is triggered by system-relevant changes. These changes can be internal or external [17]. Examples for internal changes can be unplanned disruptions in production facilities. They cause a demand for flexibility, namely additional capacity to compensate the losses caused by the disruptions. An external change might be customers asking for more specific products. This would cause a demand for more variants and, therefore, for more flexible operations regarding product mix [15].

Since flexibility (and the respective uncertainties) will be modeled in the presented framework, it is necessary to match the advantages with the respective flexibility types [18,19]. This is summarized in Figure 1. The first flexibility type is *product mix flexibility*. This becomes important due to a global

* The technology readiness level is a method to describe the maturity of technologies. It is based on a scale from one to nine with nine being the most mature.

trend towards high numbers of product types with lower volumes and, therefore, increasing volatility of demand

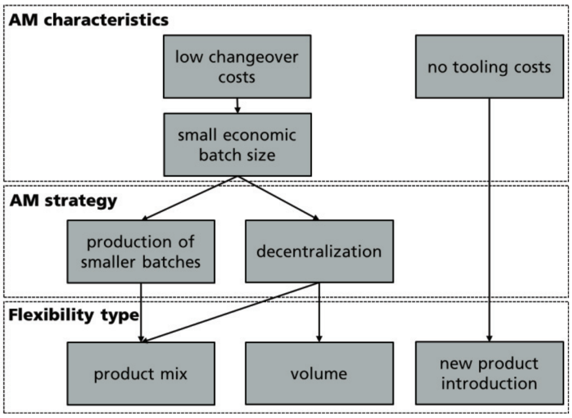

Figure 1: Relationship of AM characteristics, strategies and flexibility types

forecasts of each product type. Production networks with higher product mix flexibility can react faster to a change in product mix without increasing costs disproportionately. This type of flexibility can be created by low changeover cost and smaller economical batch sizes. With smaller batch sizes the network can react faster to an occurring demand. *Volume flexibility* becomes more important, especially because product lifecycles become shorter and the economic and political disruptions affect global demand. Therefore, production networks which are able to adjust their rate of production to changing demand without disproportional cost increase add value to the company. As already mentioned, additive manufacturing leads to smaller economical batch sizes and, therefore, promote decentralized network designs [20]. In decentralized networks production is closer to the customer, which means the network is able to determine what to produce at a later stage. In the meantime, it can gather more information about the actual demand. The results are lower misallocation costs resulting from higher product mix and volume flexibility. The third flexibility type which is important to additive manufacturing is *new product introduction flexibility*.

Additive manufacturing adds this flexibility because additive manufacturing networks can introduce new products very quickly thanks to digital development and production processes.

3. State of the art: Integration of additive manufacturing in production networks

In this section, four requirements for a method for the integration of additive manufacturing in production networks are formulated, based on the characteristics shown in section two. These requirements are matched with state of the art methods.

3.1. Requirements

In order to address all characteristics (advantages and disadvantages) shown in section two, a method for assessing the value of additive manufacturing technologies in operations has to fulfill the following requirements:

(1) **Production network level:** The method has to cover not only one production line or factory, but the whole production network, because decentralization can lead to substantial benefits and the use of several additive manufacturing machines leads to economies of scope.

(2) **Optimization:** The method has to lead to optimized network design, because otherwise an evaluation can also be conducted on rather suboptimal designs [21].

(3) **Monetary evaluation criterion which covers flexibility:** The decision whether and how to integrate additive manufacturing technology in a production network is clearly a strategic investment decision with high investment cost and high impact on the company's performance. Additionally, decisions in network design are characterized by high uncertainty and high degrees of flexibility. Therefore, it is necessary to evaluate this investment with a cash flow-based monetary evaluation approach (also including higher sales prices) which also takes into account flexibility, e.g. approaches based on Real Options [22].

(4) **Flexibility types:** Flexibility is one main driver towards creating value with additive manufacturing technologies. The main types are: product mix flexibility, volume flexibility and new product introduction flexibility. These have to be included in the evaluation method.

3.2. Approaches for profitability analysis of additive manufacturing

Holmström discusses different scenarios to include additive manufacturing in the production network. His approach gives some qualitative guidelines but does not represent a structured method [13].

Khajavi evaluates different network configurations of a spare parts supply chain based on production costs. The approach does not include an optimization approach or a monetary target criterion which is based on cash flows or covers different flexibility types [23].

3.3. Approaches for strategic production network planning

There are several approaches to strategic network planning or network design which include the production network and are able to optimize the design by solving a linear mixed integer problem. Kohler develops an approach to evaluate different supply chain designs [24]. The approach considers technological specifications and is cash flow-oriented. It is limited because flexibility types are not explicitly modeled. New products cannot be added to the product portfolio. Also from a monetary perspective flexibility is not included.

Bundschuh [25] and Friese [26] present a deterministic dynamic decision problem for the special case of automotive production networks. The models presented are deterministic dynamic linear optimization models. The models are based on cost. Change in sales prices is not included. Flexibility is covered partially in terms of volume and product mix flexibility. One discount rate is used throughout the whole optimization problem.

Prinz et al. [27] and Lanza et al. [28] developed approaches based on a linear optimization problem. The target function, however, includes quantitative and qualitative criteria. Flexibility types are not explicitly modeled and new products cannot be introduced while optimization runs.

Peters uses a stochastic optimization model for capacity and investment planning based on Markov Chains. The target criterion is the total cost of the production network. Flexibility types are not modeled explicitly and not covered in the monetary evaluation [29].

3.4. Real Options approaches

Real Options approaches have two important advantages: Firstly, they allow to evaluate flexibility monetarily. Secondly, they use a risk free discount rate to value the investment because the demand is risk-adjusted [22]. This is important because investment decisions in production networks do not face the same risk in each period of the optimization problem.

Bengtson et al. develop an optimization model based on Real Options for a manufacturing system. The optimization model uses a linear mixed integer problem. The model is capable to include several products and production lines. Only product mix flexibility is analyzed. It uses very restrictive assumptions: products consist only of one part, there is no set-up time and the parameters of the stochastic process used to simulate demand does not vary over time. Even though the model itself is very restrictive, it shows that the application of linear optimization problems in combination with Real Options is possible. Also, the knowledge on how to apply the model, especially the integration of a Monte Carlo simulation is of great value for the presented framework [30].
Huchzermeier uses a Real Options approach to evaluate supply chain configurations [31]. The model includes demand risk and exchange rate risk. It is simulated in a Monte Carlo simulation. There is no optimization model for the generation of supply chain configurations. Moreover, it does not provide a structured method for application.

Sudhoff presents a model of mobility options on production networks, which includes several sources of uncertainty. There is no optimization model to generate different production network configurations [32].

It has become clear that none of the presented approaches fulfill all four requirements. However, strategic production network planning approaches, especially those based on linear optimization problems, represent a valuable methodological core of the framework presented in section four.

4. Framework for Integration of additive manufacturing in production networks

4.1. The framework and its integrated modules

The framework proposed in this paper consists of four integrated modules as shown in Figure 2. The first module is the network module (module A). This module visualizes the current structure of the network. This is of great importance, because defining the scope of the optimization problem is a major challenge when dealing with production networks. It consists of nodes (module B1) and edges (module B2). Nodes are the actors of the network, e.g. markets, factories, production lines or additive manufacturing machines. The edges connect the nodes and define their relation, e.g. if there is a linkage (material flow) between two production lines, the distance between additive manufacturing machine and customers or the height of the transportation cost between two factories. This is shown in Figure 3. The second module is the risk module (module B). The risk module describes the uncertainty the production network has to react to.

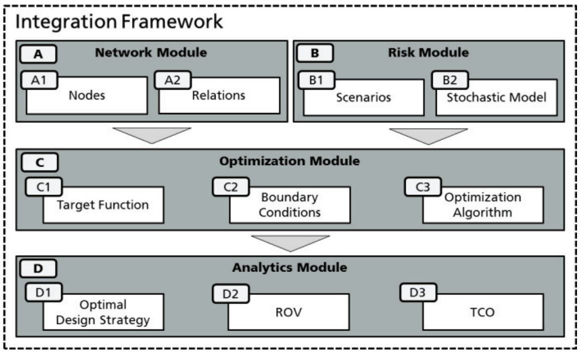

Figure 2: Structure of the AM integration framework

As we argued in section two, the main benefits of integrating additive manufacturing will be based on demand flexibility: volume, product mix and new product introduction. Therefore, in this framework only demand uncertainty will be part of the analysis. Consistent demand scenarios will be generated in module B1. This is a necessary step to understand the different alternatives of the demand behavior.

Based on the scenarios in module B2 the demand $D_i(t)$ is described by a stochastic process which can be defined by the following equation [33]:

$$dD_i(t) = \mu_i D_i(t)dt + D_i(t)\sum_{j=1}^{N} \sigma_{ij} dW_j(t) \qquad (1)$$

The vector $D = (D_1, \ldots, D_N)$ describes the demand for the correlated products $(i, \ldots, N)$. The drift rate of the process is described by vector μ_i. The volatility matrix σ_{ij} describes for

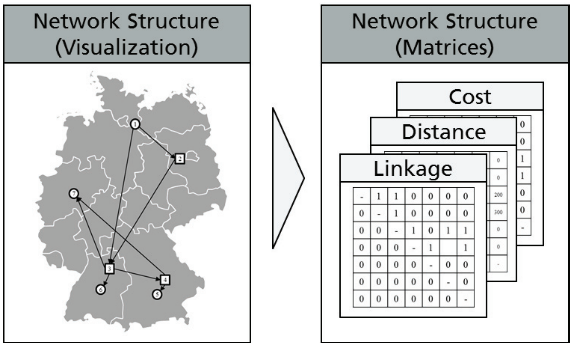

Figure 3: Network Structure from visualization to matrices

each combination of i and j the volatility depending on their correlation. The Wiener Process $W_j(t)$ is defined by a Brownian motion with $W(t) - W(s) \sim \sqrt{t-s} \cdot N(0,1) - N(0, t-s)$ with $N(0,1)$ being a normal distributed random number with mean of 0 and variance of 1. This multivariate stochastic process has to be simulated by a Monte Carlo simulation because analytical solutions are very complex and time consuming [32,33].

The third module is the optimization module (module C). It contains a linear mixed integer optimization problem which is defined by three sub-modules. Which target function (C1) to use depends on the company's target system. However, as shown in section four, the maximization of the net present value is an appropriate target criterion with one drawback, namely the usage of one interest for all periods of the optimization problem. Therefore, this framework uses a Real Options approach (which is based substantially on the net present value) for the target function. The boundary conditions (C2) define all constraints for the solution, such as capacity limits, investment limits and other assumptions, e.g. no backlog from earlier periods. The algorithm which solves the optimization problem is described in module C3.

This framework uses the CPLEX Solver because it´s one of the most efficient solvers available [28]. The fourth module is the analytics module (module D). The output of the module is shown in Figure 4. This module visualizes the solution of the network optimization and it´s characteristics. The solution is visualized in the optimal design strategy module (D1).

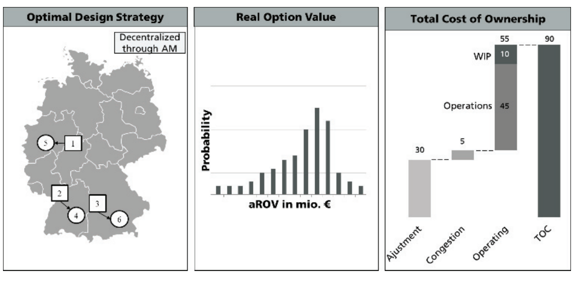

Figure 4: Output Visualization of Module D

This module shows where to locate how many additive manufacturing machines for the different scenarios, and which part of demand they produce.

The Real Option Value (ROV) module (D2) visualizes the distribution of the ROV of the optimal design solution. Because it is important to understand the cost drivers of the specific solution, the framework also provides the TCO of the optimal solution (D3).

4.2. Application of the framework

An optimal production network design and Real Option value of the investment into the network requires four steps to be taken. Figure 5 shows this procedure with the respective modules of the framework. In step 1, the network structure hast to be described as a graph. This is done in module A. In step 2, the risk-free demand has to be simulated. By adjusting the demand we can use the risk-free discount rate to discount the expected values in each period of the optimization problem. The simulated demand is described by one vector (one dimension for each product type) for each period. The network structure data and the simulated demand define the parameters of the optimization problem.

In step 3, the optimization problem is solved and the result is a ROV value for one optimized network design. To include the uncertainty in the framework, we conduct steps 2 and 3 n times. By using several simulation and optimization runs we create a distribution of ROV. In step 4, we can interpret the expected solution for ROV as average ROV (aROV) over all optimization runs.

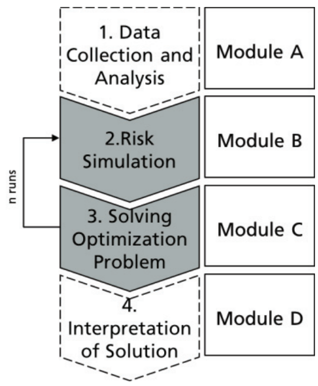

Figure 5: Application procedure of the framework

5. Summary

This paper shows that additive manufacturing technologies can add flexibility to production networks and when deciding whether or not to use additive manufacturing technologies, production cost is not a sufficient criterion. Four requirements for an appropriate method were derived. Based on these requirements, a framework for the integration of additive manufacturing technologies in production networks was presented. The main contribution of the framework is that it leads to an optimal network structure by using a linear optimization approach. As a target criterion the Real Option Value was used, because this enables us to incorporate different flexibility types in the evaluation monetarily. Applying a method based on this framework has two effects: Companies can use additive manufacturing technologies more effectively because they can decide how to integrate additive manufacturing based on a structured approach. In return, this leads to an increasing market for additive manufacturing system suppliers and, therefore, for the whole ecosystem of additive manufacturing.

Further research is needed to develop a detailed method based on the presented framework. Particularly the modeling of the multivariate demand uncertainty and its integration into the optimization problem is of great importance.

References

[1] Piller FT. Mass customization: Ein wettbewerbsstrategisches Konzept im Informationszeitalter. 4th ed. Wiesbaden: Dt. Univ.-Verl; 2006.
[2] Wohlers T. Wohlers report 2014: 3D printing and additive manufacturing state of the industry annual worldwide progress report. Fort Collins: Wohlers Associates; 2014.
[3] Laux H, Gillenkirch R, Schenk-Mathes H. Entscheidungstheorie. 9th ed. Berlin: Springer Gabler; 2014.
[4] Christopher M, Holweg M. Supply Chain 2.0: managing supply chains in the era of turbulence. International Journal of Physical Distribution & Logistics Management2011;41(1):63–82.
[5] Annual book of ASTM standards. West Conshohocken, ASTM International; 2012
[6] Gebhardt, A. Generative Fertigungsverfahren: Additive manufacturing und 3D-Drucken für Prototyping - Tooling – Produktion. 4th ed. München: Hanser; 2013.
[7] Gausemeier, J. Thinking ahead the Future of Additive Manufacturing: Exploring the Research Landscape. Paderborn: University of Paderborn; 2013.
[8] Eisenhut, M. Additive Manufacturing: A game changer for the manufacturing industry?. München: Roland Berger GmbH; 2013.
[9] Vicari A. How 3D Printing Adds Up: Emerging Materials, Processes, Applications, and Business Models. Lux Research Inc.; 2014.
[10] Rommel S, Becker R, Verl A. Supplying spare parts using AM technologies. In: Kempf M, et al., editors. International Journal of Industrial Engineering - 16th Annual International Conference on Industrial Engineering. Stuttgart: 2011. p.462–468.
[11] Atzeni E, Salmi A. Economics of additive manufacturing for end-usable metal parts. The International Journal of Advanced Manufacturing Technology. 2012;62 (9-12):1147–1155.
[12] Schuh G, Stich V. Grundlagen der PPS. 4th ed. Berlin: Springer Vieweg; 2012.
[13] Holmström J, Partanen J, Tuomi J, Walter M. Rapid manufacturing in the spare parts supply chain: Alternative approaches to capacity deployment. Journal of Manufacturing Technology Management 2010; 21 (6):687–697.
[14] Gibson I, Rosen D, Stucker B. Additive manufacturing technologies: 3D printing, rapid prototyping, and direct digital manufacturing. New York: Springer; 2015.
[15] Pibernik R. Flexibilitätsplanung in Wertschöpfungsnetzwerken. Wiesbaden: Deutscher Universitätsverlag; 2001
[16] Westkämper E. Wandlungsfähige Produktionsunternehmen: Das Stuttgarter Unternehmensmodell. Berlin: Springer; 2009.
[17] Nyhuis P. Wandlungsfähige Produktionssysteme: Heute die Industrie von morgen gestalten. Garbsen: PZH, Produktionstechn. Zentrum; 2008.
[18] Slack N. Flexibility as a Manufacturing Objective. International Journal of Operations & Production Management 1983; 3 (3):4–13.
[19] Sethi A, Sethi S. Flexibility in manufacturing: A survey. International Journal of Flexible Manufacturing Systems 1990; 2 (4):289-328.
[20] Bogers M, Hadar R, Bilberg A. Additive manufacturing for consumer-centric business models: Implications for supply chains in consumer goods manufacturing. Technological Forecasting and Social Change. 2015.
[21] Walther G. Nachhaltige Wertschöpfungsnetzwerke: Überbetriebliche Planung und Steuerung von Stoffströmen entlang des Produktlebenszyklus. 1st ed. Wiesbaden: Gabler; 2010.
[22] Copeland T, Antikarov V. Real options: A practitioner's guide. 2nd ed. New York: Texere; 2007
[23] Khajavi S, Partanen J, Holmström J. Additive manufacturing in the spare parts supply chain. Computers in Industry 2014; 65 (1):50–63.
[24] Kohler K. Global Supply-chain-Design: Konzeption und Implementierung eines multikriteriellen Optimierungsmodells für die Gestaltung globaler Wertschöpfungsaktivitäten. Estenfeld: CfSM; 2008.
[25] Bundschuh M. Modellgestützte strategische Planung von Produktionssystemen in der Automobilindustrie: Ein flexibler Planungsansatz für die Fahrzeughauptmodule Motor, Fahrwerk und Antriebsstrang. Hamburg: Kovac; 2008.
[26] Friese M. Planung von Flexibilitäts- und Kapazitätsstrategien für Produktionsnetzwerke der Automobilindustrie. Garbsen: PZH Produktionstechn. Zentrum; 2008.
[27] Prinz A, Bauernhansl T. Risk-Value-Cost-based Optimization of Global Value-adding Structures. Procedia CIRP 2013;7:103–108.
[28] Lanza G, Moser R. Strategic Planning of Global Changeable Production Networks. Procedia CIRP 2012; 3:257–262.
[29] Peters S. Markoffsche Entscheidungsprozesse zur Kapazitäts- und Investitionsplanung von Produktionssystemen. Aachen: Shaker; 2013.
[30] Bengtsson J, Olhager J. Valuation of product-mix flexibility using real options.International Journal of Production Economics 2002; 78 (1):13-28.
[31] Huchzermeier A. Bewertung von Realoptionen in globalen Produktions- und Logistiknetzwerken. In: Hommel U, editor: Realoptionen in der Unternehmenspraxis. Berlin: Springer, p. 207–230.
[32] Sudhoff W. Methodik zur Bewertung standortübergreifender Mobilität in der Produktion. München: Utz; 2008
[33] Hull J. Optionen, Futures und andere Derivate, 8th ed., München, Boston, Mass, Pearson Studium; 2012