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How can AM factories match cost and lead time requirements? Configuration and optimization of AM factories for different production programs

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Abstract

Additive Manufacturing (AM) is increasingly moving into factories. To promote its industrialization, this contribution analyses cost and lead time performance of AM factories. The performance impact of different production programs is identified by varying order inflow and post processing sequence. Only under restricted conditions, the factory performance allows novel approaches such as on demand manufacturing. To widen up these restrictions, organizational and technical improvement measures are proposed.

Keywords: Additive manufacturing; Digital Direct Manufacturing; Factory configuration; Manufacturing systems; 3D printing; Industrialization; Discrete event simulation

1. Introduction

Additive Manufacturing (AM) encompasses layer-wise production technologies that base directly on CAD-Data (ASTM International, 2013). In comparison with conventional manufacturing technologies, its underlying principle allows for two substantial advantages – In literature also referred to as complexity and individuality advantage. On the one hand, highly complex geometries are facilitated and restrictions such as tool-accessibility and undercuts are widened up (Kranz et al., 2015; Weller et al., 2015) facilitating efforts such as weight reduction and integration of parts or functions (Schmidt, 2016; Schmidt and Emmelmann, 2015; Weller et al., 2015; Guo and Ming, 2013; Emmelmann et al., 2011; Petrovic et al., 2010). On the other

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hand, AM works universally for different products without specific tools or equipment. In consequence, efficient manufacturing of small quantities in short lead time is expected. Individual products and functional prototypes are relevant applications making use of that advantage (Conner et al., 2014; Campbell et al., 2012; Petrovic et al., 2010), as well as the idea to produce spare parts only on demand and thus to reduce or eliminate spare parts stock (Möhrle et al., 2016).

Laser Beam Melting (LBM), a laser powder bed fusion process for metal products, is considered highly relevant for products that need to satisfy industrial requirements. Regarding dimensional precision, surface topology, mechanical strengths and availability of materials, it outperforms comparable AM technologies (Gibson et al., 2015, p. 144; Grund, 2915; Gu et al., 2012; Murr et al., 2012).

Aerospace, medical and machine building industries particularly benefit from the above mentioned advantages and thus increasingly adopt LBM. The growth of machine unit sales by ca. 30% p.a. over the last decades leads to first AM process chains on factory scale. For example, GE aims to produce more than 30.000 injection nozzles for its LEAP Engine, and Airbus aims to produce more than 30 tons per month in metal AM processes. Several contract manufacturers produce on two digit numbers of LBM machines (Wohlers et al., 2017; Roland Berger, 2016; 2013).

To provide sufficient manufacturing capacities for the expected technology diffusion, over the next years LBM factory structures that match the presented requirements need to be installed (cf. Schröder et al., 2015).

In Chapter 2, the LBM process chain is introduced. Chapter 3 defines the target of the analysis, derives the design of experiment and describes a discrete event AM factory model. Chapter 4 provides insight into the results. Chapter 5 contains the conclusion and indicates further research needs.

2. Technology background: The LBM process chain

Only under restricted circumstances the LBM parts can be used in as fabricated conditions. With the goal to deliver end-usable parts, post processing with conventional manufacturing technologies is required. The general LBM process chain is presented in Fig. 1 and can be split up into the sections pre-, in- and post-process, followed by further downstream processes. Some process steps need to be carried out only when prescribed by part specifications and can be considered optional. Basically, data processing only needs to be conducted when a product is manufactured first time. (Möhrle and Emmelmann, 2016)

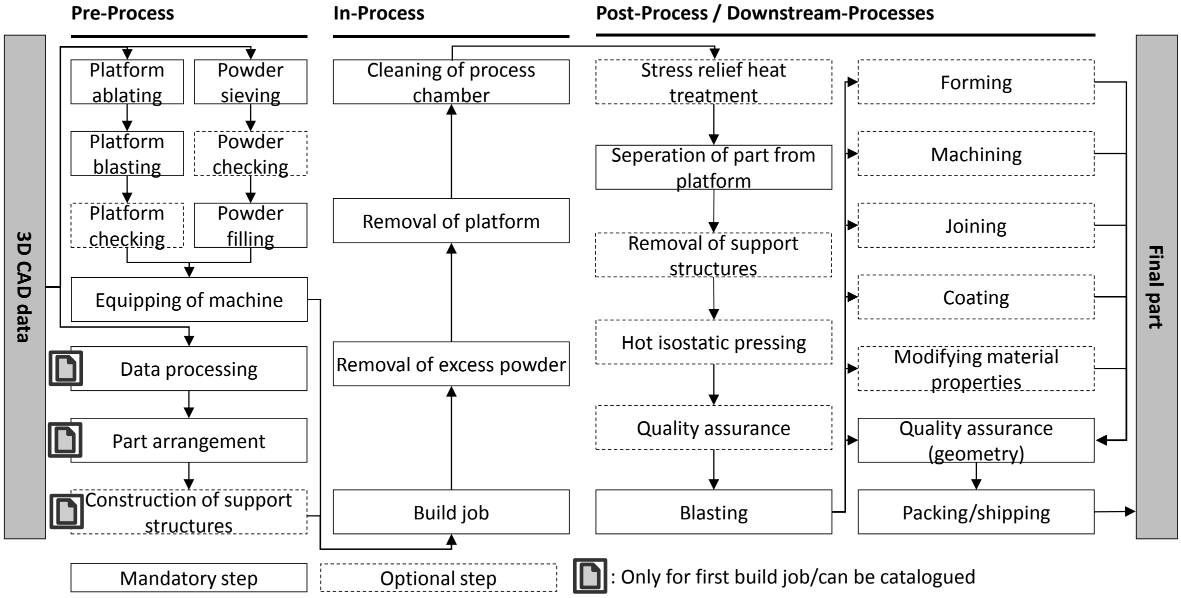

Fig. 1. LBM process chain adapted from Möhrle and Emmelmann, 2016

During pre-process, both the machine and data are prepared. Metal powder is sieved, checked and loaded into the LBM machine. A substrate platform as process requisite is ablated, blasted and checked. Subsequently, the machine can be equipped and process conditions (preheating, inert gas atmosphere) established. In parallel, CAD part models are arranged to a build job (set of all parts to be manufactured at once) and support structures are constructed. (Gibson et al., 2015)

During in-process, the LBM process is conducted and the build job manufactured. The powder bed principle makes removal of excess powder necessary. Afterwards the platform (including fabricated products) is removed and the process chamber cleaned, returning the machine into idle state.

During post-process and downstream processes, the manufacturing steps required to transform the parts into final conditions (geometry and material properties) are conducted. As a first step, stress relief heat treatment is required before separating parts from platform to evite deformation in consequence of residual stress (Mercelis and Kruth, 2006). Having performed those steps, support structures can be removed (in current manufacturing setups performed by abrasive cutting in manual processes) (Hebert, 2016). For parts with high fatigue requirements, hot isostatic pressing may be required (Herzog et al., 2016; Hebert, 2016; Wycisk et al., 2015; Atkinson and Davies, 2000). Further processes, such as quality assurance, blasting and basically any conventional manufacturing (cf. DIN 8580) technology can follow to achieve final part conditions. Some technologies, such as forming, will be evited in most cases by additive manufacturing of end-contour near geometries.

So far, economic aspects of AM, such as process time and cost estimation models, have been thoroughly researched (Thomas, 2016; Baumers et al., 2016, 2012; Achillas et al., 2015; Schröder et al., 2015; Rickenbacher et al., 2013; Lindemann et al., 2013; Atzeni and Salmi, 2012). However, those approaches base on certain premises that do not allow a detailed perspective on

- full process chain resource requirements from 3D CAD data to final part

- the performance regarding cost and lead time requirements

3. Analysis

3.1. Target

The most discussed applications for AM are resulting from two main (expected) advantages: Lower cost and shorter lead time as compared to conventional manufacturing technologies. Lower cost can mostly be achieved when manufacturing highly complex geometries (e.g. fuel nozzles) and/or low quantities (e.g. prototypes). Short lead times are required when reducing stock through AM (e.g. spare parts on demand, cf. Möhrle et al., 2016) or producing parts on a critical path of other processes (e.g. prototypes during the product development process). Both aspects may form the fundamental target for an AM factory. Depending on the specialization of a factory, it can be clearly defined towards one aspect, a blend of both or even be unknown.

From production management and queuing theory, it is known that consistently low lead times require lower utilization of production equipment, and thus increase cost (Nyhuis and Wiendahl, 2012). The presented analysis deals with the question, to which extend short lead times and low cost can be combined under practice conditions. Moreover, measures are presented to overcome the observed trade-off between the two targets.

Practice-oriented inputs build the foundation for the analysis. That means that system inputs are taken from real production setups: The time approach was taken from ongoing operations at LZN Laser Zentrum Nord GmbH, and the considered production programs are practice-inspired.

3.2. Design of experiment

Let us assume a factory structure (machines and workers) is configured to fit average capacity requirements of production program within the planned timeframe. By planning in a way that removing one discrete resource of any kind would create a bottleneck, waste of resources is avoided. From the planned factory structure, the annual factory structure cost can be calculated. The lead time depends in a factory context on the process times (that can be calculated by the current time approach) and the utilization of the equipment. Although the planning process avoided bottlenecks, the inflow of orders can lead to temporary bottlenecks and thus increase lead times. In short, in Fig. 2 two parameters which impact cost and lead time can be extracted: The order inflow, leading to temporary bottlenecks when tending to larger lot sizes and the post processing sequence. Both parameters will be varied as model input in the experiment. The parameters are part of the production program, which will remain constant for the residual parameters (geometry and total number of parts).

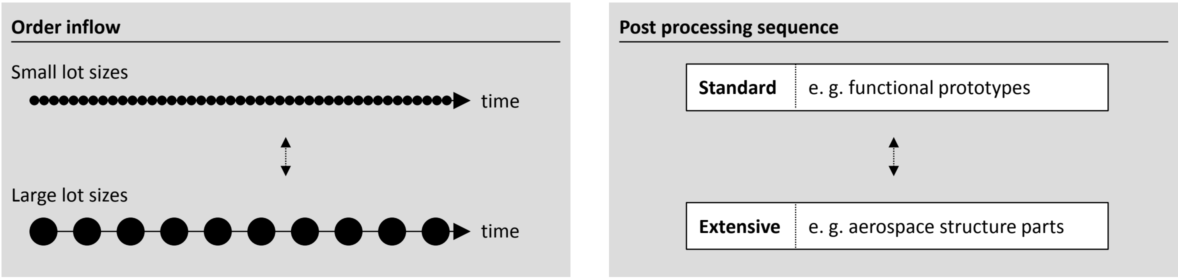

Fig. 2. Parameters varied in the experiment

Starting point is the factory structure planned in the way mentioned above. The order inflow lot sizes Q will be varied in decimal powers, beginning with ideal single piece manufacturing (lot size 1). The lot sizes will follow the equation

$$Q = \frac{D}{n}$$

whereby D is the total demand of the production program and unchanged for all scenarios. n is the number of single orders, which will be issued in equal time intervals.
The analysis will be performed for two sequences (the concrete sequence is provided in Fig. 5)

- a standard post processing sequence for functional parts (e.g. prototypes in general engineering)
- an extensive post processing sequence, which is required under special conditions (e.g. aerospace structure parts)

3.3. AM factory model

To evaluate AM factory structures regarding the relevant targets (with special respect to cost and lead time), a discrete event model of the AM process chain has been created and implemented in *Simio* modelling environment. As indicated in Fig. 3, the model requires the input parameters

- factory structure definition (number and type of the factory elements, cf. Möhrle and Emmelmann, 2016),
- performance parameters for each production step and
- a production program considered for simulation.

Having conducted a model run on a set of input data, the yearly factory structure cost and the average lead time per product (from order entry until product is finished, without shipment, cf. Gunasekaran et al., 2001) as well as further logistic targets are provided as output values.

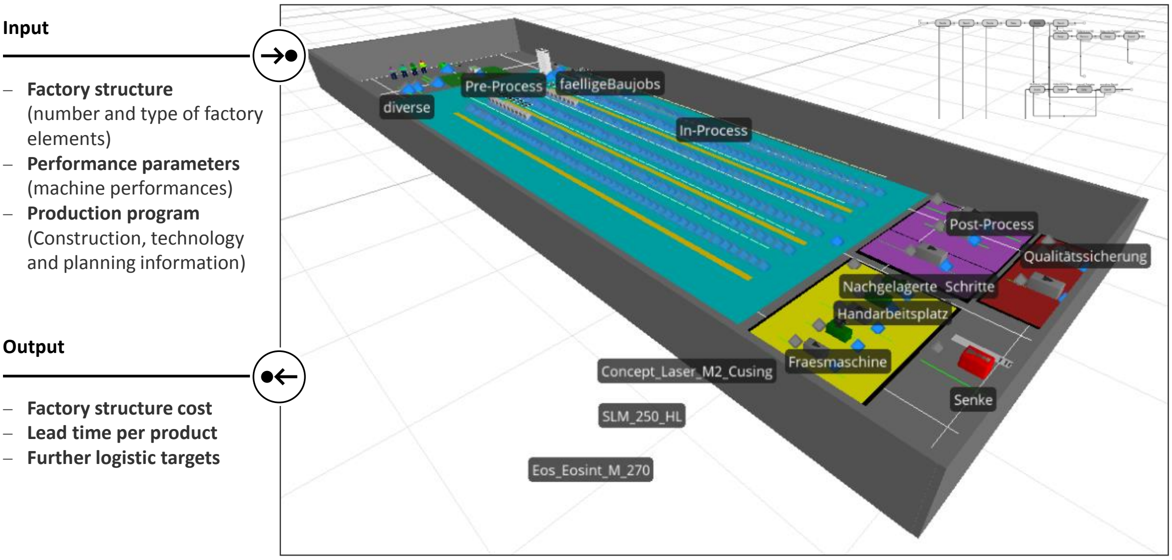

Fig. 3. Discrete event model for evaluation of AM factory structures

The model employs a driver-based time approach for all steps of the AM process chain, which is illustrated in Fig. 4. In the model, orders and build jobs are represented by tokens. For each process step (see section 2), the setup, process and teardown time is calculated and the token delayed, as defined by its individual order-dependent driver variables. Depending on the process steps, only a subset of the drivers may be active. Moreover, required workers and auxiliary resources (such as platforms) are seized. The dynamic system behavior is reflected through the model's ability to simulate the simultaneous flow of orders in the manufacturing system. A deep-dive on the time approach in a static context can be found in Möhrle and Emmelmann (2016).

The token flow is basically realized with the FIFO principle, with basic production planning and scheduling (PPS) rules active to optimize setup times.

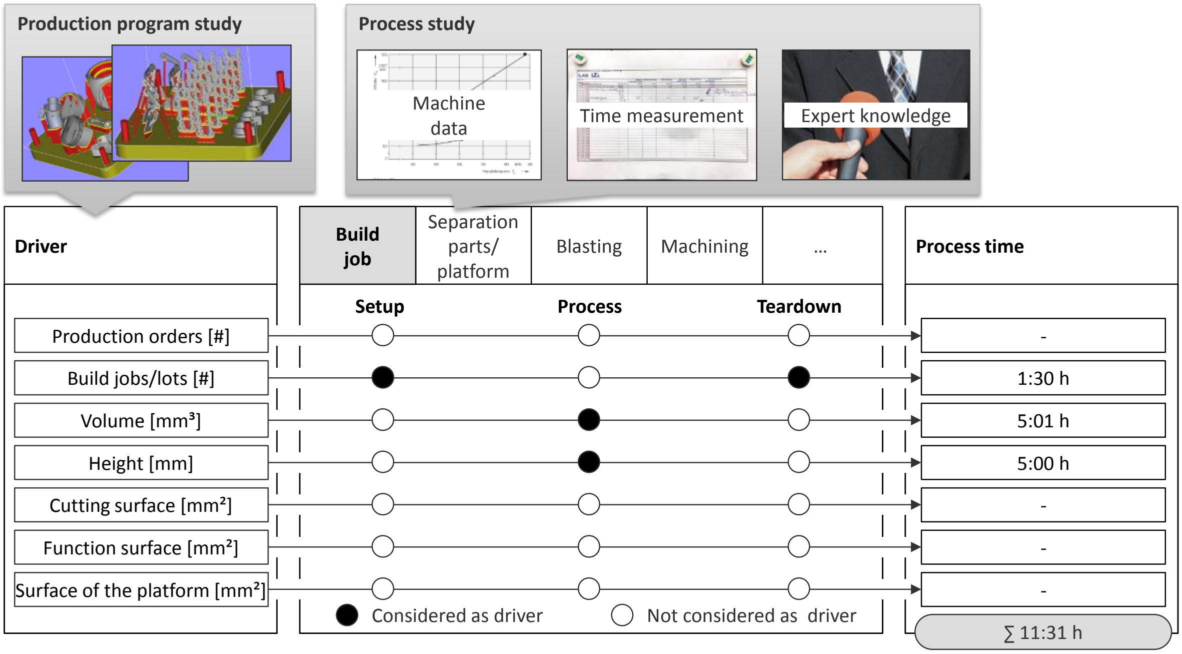

Fig. 4. Time approach per process step

4. Results and discussion

The results of the performed experiment are presented in Fig. 5. The factory structure for the standard post processing sequence leads to annual cost of EUR 3.8 m (c. EUR 1.900 per kilogram including material cost), one fourth of the amount is in post processing. For the extensive post processing sequence, only post processing cost is affected and increases annual cost to EUR 6.8 m (c. EUR 3.200 per kilogram including material cost).

On lot size 1, the average lead times per product are 1.8/2.4 calendar days (numbers for standard post processing in first, for extensive in second place). At order lot sizes of 100, the lead times are 4.4/6.4 calendar days and still at a decent level for most applications. The highest investigated lot size of 1.000 leads to 19.4/31.5 calendar days lead time, which tends to be inappropriate for applications that require fast delivery.

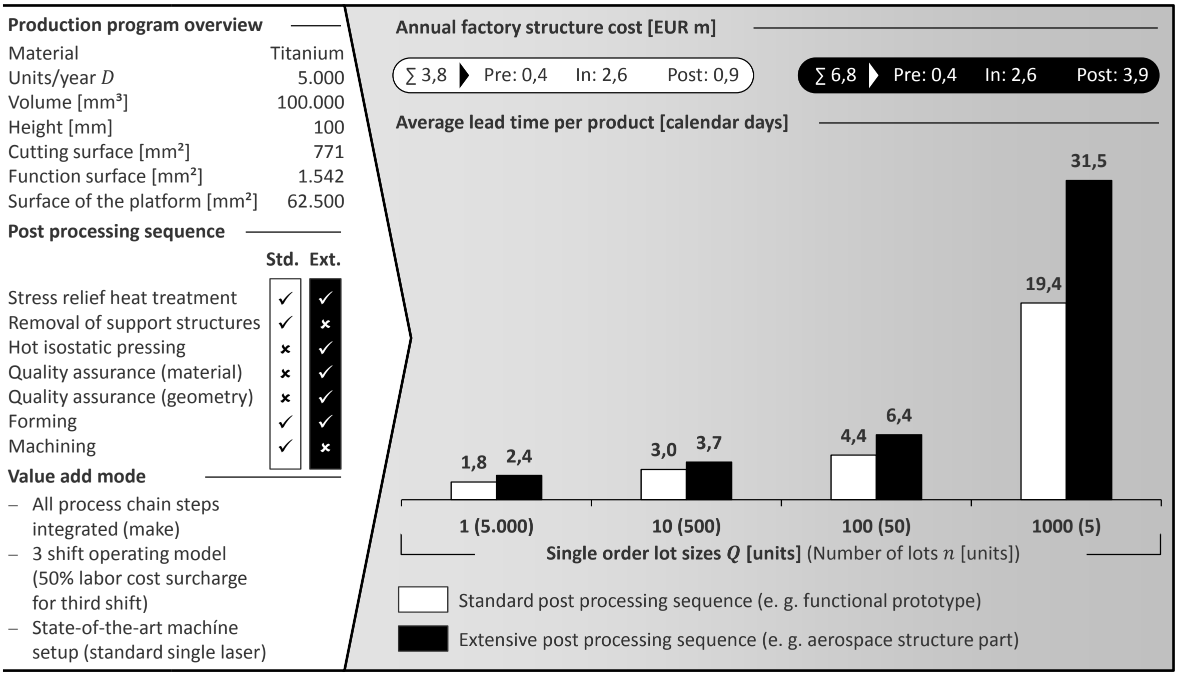

Fig. 5. Input and output data of the experiment conducted

The results of the analysis show the expected system behavior: Fewer larger lots lead to increasing lead times. Extensive post processing leads to substantially higher cost and lead time. Moreover, the lead time difference between standard and extensive post processing increases further with higher lot sizes. This is due to the higher number of temporarily over-utilized resources.

In practice, the order income distribution will not follow all the assumptions of the analysis. Especially the production programs of factories with ad-hoc orders (e.g. AM contract manufacturers) are characterized by a stochastic order inflow in terms of order entry points of time, geometries, lot size and post processing sequences. Additionally, single resources might be in a long term bottleneck state. In consequence, observed lead times are not seldom between 5 and 15 calendar days, which corresponds to the higher lead times of our analysis.

Many innovative applications for AM require consistently short lead times. In the example of on demand manufacturing of spare parts for capital-intensive goods, the target for LBM manufactured spare parts goes down to below 1 calendar day (Möhrle et al., 2016). To achieve that order of magnitude, it becomes clear that improvements have to be made.

With the presented analysis, the quantitative effect of measures (also known from operations management) falls into place:

- Ensure a production program oriented factory configuration to avoid both bottlenecks and excess resources
- Flatten distribution of order income (e.g. by splitting noncritical large lots or shifting order times)
- Make capacities flexible (installation of more capacities at own site or use of external capacities)

To further reduce process time and cost of the AM process chain, technology advances are required. From a sensitivity analysis performed on the modelled process chain, the following measures were identified to promise the best combination of impact on cost and implementation effort:

- Improvement of LBM productivity (melting rate and recoating speed)
- Automated removal of support structures
- Reduction of machine prices

To predominantly achieve a lead time reduction, in Möhrle et al. (2016) a high impact of the following measures was recognized:

- Elimination of stress relief heat treatment and hot isostatic pressing (e.g. by pre-heating the build chamber or lowering part specification)
- Order-independent preparation (setup) of machines (especially LBM)

5. Conclusion and outlook

In this contribution, a perspective on the behavior of AM factories was given, considering the performance requirements cost and lead time. It was shown, that short lead times that enable innovative applications are only under ideal conditions (ideal factory configuration and flattened order income) within reach. However, in practice those conditions can typically not be found, leading to substantially higher lead times. For mitigation, several organizational and technical measures on cost and lead time improvement were proposed. By their implementation, the factory performance can be increased to a level that allows novel applications for AM value chains.

There are several adjacent topics to be covered. The evaluation of real production scenarios, considering production planning and scheduling mechanisms can provide further opportunities for improvement. Against the background of the raising need for AM factories, a method for configuration of factory structures is required, taking into account the multi-objective correlation of cost and lead time. Lastly, technical advance especially for LBM is required to improve productivity and to ensure finished goods on quality.

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