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Challenges Of Production Planning And Control For Powder Bed Fusion Of Metal With Laser Beam: A Perspective From The Industry

Lukas Bauch[1], Andreas Wilhelm[1], Moritz Kolter[1], Johannes Henrich Schleifenbaum[1]
[1]Digital Additive Production / RWTH Aachen University, Aachen, Germany

Abstract

Due to technological advance, the Additive Manufacturing (AM) technology Powder Bed Fusion of Metal with Laser Beam (PBF-LB/M) is in widespread industrial use. PBF-LB/M offers the flexibility to generate different geometries in one build job independent of tools. Therefore, exploiting tool-dependent economies of scale is not required for efficient manufacturing of various complex geometries in small quantities. However, PBF-LB/M production lines are capital intensive and include post-processing steps. Thus, high utilization and low work in process must be ensured to minimize costs, but reaching high utilization contradicts minimizing work in process and throughput time. In production planning and control (PPC), the trade-off between those production logistics key performance indicators (KPIs) is optimized. The advantage of flexibility to manufacture various geometries in one build job of PBF-LB/M comes with challenges for PPC. In this work, those challenges are analysed to derive implications for improvement, based on interviews with experts from the industry. Results show a need for PBF-LB/M specific PPC. The need is higher the greater the technological control of PBF-LB/M and the volume of a product program of a company are. Unlike for Conventional Manufacturing (CM), nesting and scheduling cannot be addressed separately in PPC for PBF-LB/M. Thus, the optimization of production logistics KPIs is more complex due to more degrees of freedom. Combined with a typically shorter planning horizon for AM, this requires automated optimization software tools for combined nesting and scheduling. Currently, PPC that considers AM characteristics does not address CM steps in the post-process adequately, even though they cause a large proportion of effort and time. Furthermore, high automatization parallel to heterogenous manual tasks require a low number of workers with training in various skills.

Keywords

Powder Bed Fusion of Metal with Laser Beam, Production Planning and Control, Nesting, Scheduling, Production Management, Production Technology, Additive Manufacturing

1. Introduction

Additive Manufacturing (AM) is defined as a process of joining materials to make parts from 3D model data [1]. There are different AM process types, that are characterized by a layer- or unit-wise generation of a workpiece [2]. With technological advance, the AM process Powder Bed Fusion of Metals with Laser Beam (PBF-LB/M) is in widespread industrial use [3]. PBF-LB/M is an AM process, in which a layer of metal powder is distributed on a powder bed. Subsequently, the powder bed is scanned selectively by a laser beam to melt and solidify the metal powder according to a digital build plan. Afterwards, another metal powder layer is applied and scanned with a laser beam. This cycle consisting of applying a powder layer and

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scanning is repeated, until the workpiece is fully generated. [1][2] This work principle offers the flexibility to generate different geometries in one build job independent of tools. Therefore, exploiting tool-dependent economies of scale is not required for efficient manufacturing of various different complex or customized geometries. [4][5]

During the implementation and use of AM, companies face different challenges in the competition. An extensive discussion of challenges for the implementation of AM can be found in [6][7][8][9]. These challenges can be assigned to the following categories [6]:

- Production technology (e.g., reliably achieving high quality [10], qualification of materials [11])
- Production management (e.g., production planning and control (PPC) [12])
- Business strategy (e.g., adaption of business models [13])
- Business administration (e.g., adaption of the product development process to AM specifics [14])

Mastering challenges of production technology and production management is considered as a directly perceptible motivator for customers. Business strategy and administration are regarded as hygiene factors, that are a basic requirement for successful implementation of AM. Unlike motivators, hygiene factors are only indirectly visible to customers. Until now, challenges regarding the motivator production technology such as stable processes, high quality, and material are focused for AM, as they address basic needs of customers. Challenges like PPC in the category of motivator production management are addressed less. [6][12]

This work focuses on PBF-LB/M because it is the most common metal AM process and in wide industrial use [3]. PBF-LB/M production lines are capital intensive [4] and include post-processing steps [15]. In contrast to tool-dependent economies of scale, machine investment-dependent economies of scale exist [4]. Thus, high utilization must be ensured to minimize costs. This contradicts minimizing work in process and throughput times. In PPC, the trade-off between production logistics performance and costs is optimized. [16][17] The advantage of PBF-LB/M to flexibly manufacture various geometries in one build job comes with challenges such as joint optimization of nesting and scheduling for PPC in production management [6][18].

With ongoing advancement in overcoming challenges in the category of production technology to address basic customer needs, the question arises, if and how companies in the industry are already facing the challenges regarding PPC as they become more important for differentiation. Furthermore, the scientific community and practitioners from industry need to know the expected future trajectory of challenges concerning PPC for PBF-LB/M for target-oriented development of solutions for PPC.

With the given considerations, this work aims to:

- Identify if and which challenges concerning PPC for PBF-LB/M the industry is currently facing
- Derive implications, which solutions are required now and in the future for successful PPC for PBF-LB/M

For this purpose, relevant state-of-the-art literature regarding PPC for AM and PBF-LB/M is analyzed and presented in section 2. Subsequently, seven interviews with experts from the industry are planned, conducted, and analyzed.

2. State-of-the art regarding PPC for PBF-LB/M

PPC aims for an allocation of orders and resources over time to realize a company's output and logistics performance according to customer demands. This includes for instance planning, initiating, and controlling of manufacturing tasks. Decisions like capacity adjustments of personnel or initiating orders from the purchasing department to the supply market are other typical tasks. Furthermore, PPC spans monitoring of orders and capacity as well as triggering of adjustments in case of deviation from the production plans. [19][20]

2.1 PBF-LB/M production planning

2.1.1 Nesting and Scheduling

Before the physical fabrication of a geometry with PBF-LB/M, nesting and further data preparation in the digital pre-process are required. Nesting includes binning, orientation, and positioning of parts. [18] One or multiple 3D models are grouped to be processed in a build job (binning) and imported into a data preparation software. Using the data preparation software, the rotation angle of the models (orientation) and their position in the build space (positioning) are defined. In the next step, support structures are designed, that fixate the part at the build plate. During the subsequent step slicing, machine code is computed according to the layer-wise work principle. [21]

The data preparation step of nesting is important for PPC. In contrast to Conventional Manufacturing (CM), nesting and scheduling problems are interrelated and thus cannot be addressed separately for optimizing the trade-off between production logistics cost and performance [18][22]. Decisions like binning parts into one build job with urgent due dates for on-time delivery or with similar z-height to increase productivity can interfere with scheduling decisions and vice-versa. [18][23]

The joint nesting and scheduling optimization problem receives high attention in the scientific community. In [18] a taxonomy for clustering publications with the topic of nesting and scheduling problems is proposed. The taxonomy includes six categories based on the part (multiple), build (single or multiple build jobs) and machine (single, multiple identical, multiple different AM machines). [18]

In [12] an architecture for a PPC system including nesting and scheduling of build jobs during data preparation for a multitude of AM plants is presented. It aims at considering requirements for an integration into operational enterprise software systems to maximize machine utilization to decrease costs. Therefore, different modules of Enterprise Resource Planning (ERP), Product Lifecycle Management (PLM), and Manufacturing Execution System (MES) are considered. An implementation of the proposed PPC is not demonstrated and validated. Furthermore, nesting and scheduling problems are arranged as separate steps in the presented process flow for creation of production orders. [12]

2.1.2 Process planning

Before nesting and scheduling, the sequence of operations and processes for manufacturing of a component are defined in process planning. The overall physical PBF-LB/M process requires different mandatory and optional CM process steps after the finished build job is removed from the machine, like stress relief treatment, separation of parts from the build plate, support and powder removal, surface treatment, or other heat treatment. [24][25]

Choosing the best suiting manufacturing steps of a process chain is the task of process planning [26]. AM process planning is very complex due to many degrees of freedom with a multitude of manufacturing technologies and design options to choose from. Besides the post-process step options, there are alternative AM options for the in-process, such as Binder Jetting (BJ) with their own mandatory and optional post-processing steps. Therefore, process planning also must consider other AM options than PBF-LB/M if they are available. Moreover, the choice of manufacturing steps interferes with adjustment of the component design. The manufacturability of a design must be considered, depending on the technologies involved in the process chain. [24][27][28][29]

2.2 PBF-LB/M production control

2.2.1 Process monitoring

In PBF-LB/M process monitoring, data is recorded during the process with different sensors and used for quality assurance, increasing machine uptime, and ensuring a reliable process. In research, novel process sensors are developed, sensing techniques are improved and their fit for specific parts and materials is assessed. [10]

In [10] and [30] literature reviews of possible process defects during the PBF-LB/M process and acoustic, optical, tomography, and thermal in-situ sensing approaches to detect those defects are presented. The obtainable information with process monitoring is valuable for PPC. For instance, if the data indicates that an error is detected during a print job that still requires several days until it is finished, the print job can be aborted. With the information from process monitoring, engineers are supported in finding what caused the error and can take measures to avoid the error from reoccurring. Taking corrective measures after a process is finished or aborted is an open-loop process control approach. [10][30][31][32].

Research also pursues the aim of real-time closed loop control of the additive generation of a part with PBF-LB/M. Observable and derived signature parameters (e.g., melt pool temperature, melt pool geometry) should be used to predict quality measures and adjust controllable process parameters (e.g., laser power and scanning speed) before an unwanted deviation of geometric, mechanical, or physical part properties occurs. [10][33][34]

2.2.2 Traceability

DIN ISO 9000 defines traceability of products as the ability to trace the origin, processing history, and distribution and location after delivery [35]. The capability of tracing parts within the production environment is essential for successful PPC in volatile circumstances like frequent changes in customer orders, incorrect planning or transition times or technical disturbances [36]. Due to the flexibility of manufacturing of different geometries independent from tools [4], various parts go through the PBF-LB/M process chain during the same time. This makes it challenging to manually identify and trace the state and location of various parts in the process chain, but this knowledge is essential for production control [36]. To enable traceability in logistics, tagging parts with detectable marks is a pursued solution [37]. In [37] requirements and different work principles of tagging of additively manufactured parts like RFID chip and embedded geometrical features like QR codes or unique pores, impurities, and other optical markers are reviewed.

3. Methodology

3.1 Planning and conducting interviews

To obtain information according to the research aim, industry experts with multiple years of AM experience who are currently involved in and/or responsible for AM operations are contacted and interviews are held. The used methodology for planning and conducting expert interviews is derived from [38]. The interviews are conducted by the authors of this work. Because the data is of qualitative and not quantitative character, an in-depth interview using a semi-structured interview guide is chosen for data retrieval. Depending on the answers to questions formulated in the interview guide, follow-up questions are possible to go more into detail. This enables a relatively free and personal conversation to get deep insights into a topic. The questions are formulated in an open way and suggestive questions are avoided. Suggestive questions could influence the answers in an unwanted way, for instance asking if a specific challenge for PPC is relevant, instead of asking if and which challenges are relevant at all, before going into detail for specific challenges.

The questions of the semi-structured interview guide are set up as follows:

1. How does your AM and PBF-LB/M production look like?
2. Which components are or will be produced?
3. How are orders planned and controlled?
4. How is quality of the components ensured?
5. Which problems do you encounter regarding planning and controlling?

Experts for PBF-LB/M of company internal AM providers (CI) and AM service providers (SP) that offer parts and services to external customers are determined as interview partners. To enable the interview partners to speak freely about sensitive topics like quality issues, names, companies, and the retrieved information are anonymized. As conversation media, an online video conference platform is used.

3.1 Preparation and interpretation of interview results

For the preparation and interpretation of the interview results, a qualitative content analysis methodology with inductive category development based on [39] is applied. First, dimensions for structuring the interview results are formulated derived from the research problem. Second, the dimensions for structuring are further refined iteratively after assessments of a partition of the documented material. Third, the whole documented material is paraphrased, and the resulting statements are ordered to the previously defined dimensions. In the fourth step, a summative check of the prepared interview results is performed. For the analysis of the prepared results, the production volume, the control of production management and the control of production technology of the different companies are ranked. A higher rank means a higher production volume, control over production or production management respectively. The built ranks have an ordinal scale and do not indicate specific distances between the ranks. Moreover, the highest rank does not imply, that the production volume or the degree of control reached a limit without further potential for improvement. Assigning the same ranks to more than one company is possible in case the interview results do not indicate a clear difference. To ensure objective ranking, the authors of this work define the ranks individually at first. If the rank of a company is ambiguous after the individual assessment, it is adjusted by a majority vote afterwards. The stated challenges regarding PPC for PBF-LB/M are analysed considering the anonymized company profile and strategic focus as well as the defined ranks (production volume, control of production technology, control of production management) to fulfil the research aim, stated in section 1.

4. Results and interpretation

The interviewed CI set their strategic focus on R&D and company internal supply of AM parts as well as services. SP1, SP3 and SP4 have a strategic focus on scaling up the production volume with series applications and SP2 to exploit the niche of high-quality and performance AM parts. Table 1 contains a summary of the paraphrased statements regarding production volume, production technology, and production management. The result of the ranking is depicted in Figure 1. The interviewed CI tend to have a smaller production volume and less PBF-LB/M system capacity than SP. Moreover, both control over production technology and production management of SP tend to be higher. The results indicate a correlation of production volume, control of production technology and control of production management. With increasing control of production technology by PBF-LB/M manufacturers, this points to a growing importance of PPC in the future. Fulfilling basic customer requirements by control of production technology seems to be a barrier for finding more positive AM business cases and investment into more PBF-LB/M system capacity.

Table 1: Paraphrased statements of the interviews with experts from the PBF-LB/M industry

Company Code	Production volume	Production technology	Production management
CI1	1 medium sized system and low production volume	Metal AM less under control compared to polymer AM. Often the first printing trial fails. Problems with support generation (where, how, what angle). Automation of post-processing would be desirable, because of currently high manual effort.	Use of company standard ERP module also for AM, but thoughts about switching to an AM specific solution exist. Short horizon for production planning of 1 -3 weeks. Production planning for post-processing is based on experience. Machine utilization is rather low, therefore no focus on increasing build space usage. Traceability is easy because of small production volume. Identification of applications for AM is hard because in other departments there is no AM knowhow.
CI2	1 medium sized system fully used and 1 large sized system in procurement	Current qualification requirements are in a known span and controlled. For new requirements, new QM concepts are required. Qualification effort is sometimes underestimated. Tensile test included in all print jobs according to industry requirements. Frequent geometrical measurements and chemical analysis.	Standard ERP and planning tool for prioritization from CM is used also for AM but does not work properly because of incompatibility of R&D and production requirements. High manual effort for nesting and scheduling. Errors in data preparation can lead to failed prints. For known parts, historic data and knowledge is used for production planning. For new parts, the printing time is calculated using the AM system software and an estimation by experience for the post-process.
CI3	2 large sized systems and 1 medium sized system of different suppliers	Metal AM with various other AM technologies in AM center. Only prototypes and jigs/fixtures, no production/series parts. Quality measures according to customers' requirements. Part identification and failed prints currently most important topics.	Use of AM specific and customized ERP/MES system led to improvement in productivity and operations but also customer satisfaction and communication. Growing pain points and learning curve during implementation of new ERP/MES and after 2 years still room for improvement. Pricing in metal too complex to use build in auto-quoting function. Short planning horizon of 1-2 weeks. Company-wide approval process is used but too slow for utilizing AM flexibility for time-sensitive parts.
SP1	8 medium sized systems and ~20000 parts per year	Use of materials in combination with parameter sets from AM system suppliers instead of third-party material suppliers. Failed prints occur. Often more parts printed than required to have backup solutions in case of quality issues. Monthly machine inspections. No use of in-situ process monitoring.	Use of a standard ERP and magnetic board for production planning. Integration of ERP and MES is perceived as a challenge. MES suppliers were screened but no fit for the individual requirements. Physical documents on the shopfloor. Intentions for paperless production exist. Horizon for production planning from a few days up to two weeks. Production planning is very complicated. Currently KPIs are not monitored in production management, but machine utilization is assessed. Powder is reused but quality requirements can interfere with powder efficiency. Big potential for saving manual effort in production planning is an MES with automated nesting and scheduling.
SP2	12 systems of 3 different suppliers and 15-60 parts per week	Statements regarding quality challenges: Claim of very high capability and focus on quality as well as quality control (feedstock, material lab, tactile and optical testing, CT and optical measurements, in-situ process monitoring). Integration of conventional technologies with a focus on CNC milling.	Use of ERP system, MES with a strategic software partner is in testing phase. AM is the most complex technology for MES integration. Planning horizon for PBF-LB/M is shorter than for CM with CNC milling. Currently no paperless production, but this is a clear goal. Overall Equipment Effectiveness and utilization are not prioritized KPIs because of focus on high performance and only result in a part of manufacturing cost. Traceability and software environment for joint production planning of AM and CM with integrated CAM functions would be beneficial.
SP3	10 systems and ~1000 parts per moth	No significant statements regarding quality problems. Many different post-processing technologies in-house. Different quality control measures for parts and feedstock according to customer requirements. Destructive tests only in fixed intervals. System calibration only in case the optic system is changed or after maintenance.	Use of self-developed MES to fit individual requirements. Use of different KPIs (scrap rate, on-time delivery, customer complaints, utilization, build space usage). Inquiries via sales and online portal. 2d nesting and scheduling complex like a puzzle problem. Nesting and scheduling impossible without software support for more than 3 machines. Estimating process step duration using experience is hard and inaccurate for post-processing. Partially paperless production. Quality control via visual inspection or with measurement methods as required by customer including powder reuse management.
SP4	12 systems and ~2000 parts per month	No significant statements regarding quality problems. Many different post-processing technologies in-house. Different quality control measures for parts including in-situ process monitoring and feedstock testing according to customer requirements. Different AM and CM post-processing technologies integrated.	Very high utilization. OEE ~70-80% achievable, goal is >60-70%. Use of other different KPIs (e.g., utilization, throughput times, on-time delivery, first time right). Inquiries via AM marketplaces, sales, other business segments, MES. Mostly manual and challenging scheduling and nesting. Partially paperless production. Use of self-developed MES to fit individual requirements with documented traceability of documents, machine planning and process monitoring. Estimation of process step duration based on experience. Different planning for series and non-series parts. Quality control via visual inspection or with measurement methods as required by customer including powder reuse management.

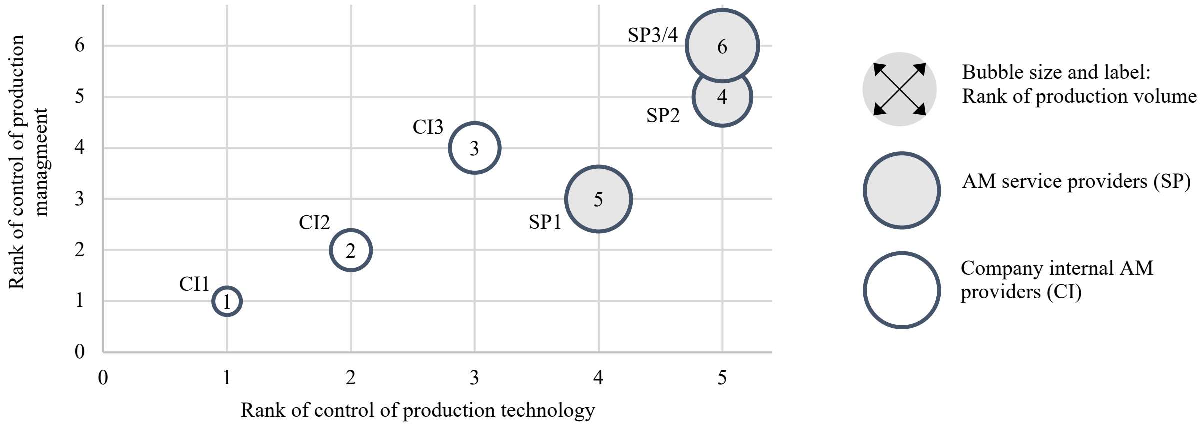

Figure 1: Ranking of the interviewed companies according to their production volume, control of production technology and control of production management

If the production technology is controlled well, scaling up the production volume is possible but requires improved PPC. With increased production volume and control over production technology, the awareness for challenges for PPC rises. SP3 and SP4 with the highest ranks regarding both production technology and production management use company-own AM specific MES. SP2 is currently testing an AM specific MES from a software supplier. In contrast, CI1, CI2 and SP1 with lower ranked control of production technology use already available but unsuitable software solutions or find workarounds like a magnetic board. Furthermore, highly ranked companies have a stronger focus on optimizing production logistics KPIs like utilization and on-time delivery in production management. To achieve good production logistics KPIs nesting and scheduling is important but due to the lack of suitable available software solutions it remains a challenge. Especially estimating of the post-processing throughput time is challenging but required to plan for on-time delivery. Currently, PPC that considers AM characteristics does not address CM steps in the post-process adequately as well, even though they cause a large proportion of effort and time.

SP1, SP3 and SP4 aim for an increased production volume by more series applications. The results indicate that the effort for e.g., identifying the application, design for AM, communication with customers, and PPC per part variant is significant. Contrary to what is often claimed for AM, this leads to lower costs if economies of scale in series production are exploited, although there is no impact of tool dependent economies of scale. Thus, the strategy of SP1, SP3 and SP4 is to solve challenges of PPC and acquire orders for series applications by exploiting AM benefits while keeping costs low and production logistics performance high. SP2 pursues the strategy of high quality and performance by integration of PBF-LB/M and subtractive manufacturing instead of focusing on cost and economies of scale.

For all companies, experience of employees is critical in PPC. For companies with high ranks, long printing durations parallel to heterogenous manual tasks in the post-process require adapted personnel planning with low number of workers but training in various skills. Pursued solutions are systems with the aim to schedule prints so they finish during work hours or flexible planning including the individual preferences and skills.

5. Summary and outlook

In this work, an analysis of challenges for PPC for PBF-LB/M based on expert interviews is presented. For companies in an early phase of technological adaption of PBF-LB/M production management has only low relevance. For companies with larger production volume and control over production technology challenges for PPC are highly relevant. With technological advance of PBF-LB/M manufacturers, this points to a growing importance of PPC in the future. ERP, MES, and data preparation solutions do not entirely fulfil the requirements from the industry. Companies jointly use CM and AM processes, but integrated software solutions for PPC for CM and AM are not in use. Thus, an automated solution for nesting and scheduling to optimize production logistics and costs for the whole AM and CM process chain is required. Furthermore, companies need software solutions for paperless traceability in production control and to reuse historic data in production planning. Further research is needed to derive a catalogue of requirements for PPC of PBF-LB/M considering the findings of this work.

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Biography

Lukas Bauch (*1995) has been research associate of the chair for Digital Additive Production DAP at RWTH Aachen University since 2021. Before that, he completed a Master of Science degree in industrial engineering. Since 2019, he has been part of various research and development projects both in industry and academia focusing on Additive Manufacturing and Digital Production.

Andreas Wilhelm (*1993) has been research assistant of the chair for Digital Additive Production DAP at RWTH Aachen University since 2019. Since 2019, he has been part of various research and development projects both in industry and academia focusing on Additive Manufacturing and Digital Production.

Moritz Kolter (*1996) is a group manager and research associate at the chair for Digital Additive Production DAP at RWTH Aachen University. He holds a Master of Science in Mechanical Engineering from Technical University of Munich. Since 2017 he has been part of various research and development projects both in industry and academia focusing on Additive Manufacturing and Digital Production.

Johannes Henrich Schleifenbaum (*1978) Univ.-Prof. Dr.-Ing. Dipl.-Wirt.-Ing. Johannes Henrich Schleifenbaum has been holding the Chair Digital Additive Production DAP at RWTH Aachen University since 2016. Furthermore, he has been managing director at Aachen Center for Additive Manufacturing since 2018.