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Streaming in Additive Manufacturing: Analyzing the Impact on the Powder Bed Fusion of Metals Process Chain

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Abstract

Streaming is a popular concept in the music and movie industry and has helped solve problems related to file distribution, storage capacity and intellectual property protection. In recent years, streaming has also become a research topic for the manufacturing sector, e.g., to collect data for predictive maintenance, advanced machine control concepts, or over-the-air updates. After initial studies have investigated the feasibility of streaming for additive manufacturing technologies, the question how streaming will affect the process chain remains open. In the music and movie industries, new business models and customer experiences have been created, leading to billion-dollar businesses and the creation of companies such as Netflix and Spotify. By drawing parallels from music and media to the AM industry this paper gives an overview of potential innovations fostered by streaming in the domain of Additive Manufacturing (AM) such as file distribution and novel process control possibilities. Furthermore, the impact of these innovations on the process chain is discussed by the example of Powder Bed Fusion of Metals with Laser Beam (PBF-LB/M).

Keywords: Additive Manufacturing; Powder Bed Fusion; PBF-LB\M; Streaming

Introduction

Streaming has changed the music industry tremendously [1]. Streaming was firstly used for illegal file sharing but overtime transferred the industry into cloud-based business models allowing the rise of a multi-billion-dollar enterprises and has brought fourth companies such as Spotify [2]. Moreover, streaming has changed how music is consumed and produced [1]. A similar pattern can be observed in the media industry in which streaming movies and videoclips changed business models, production and consumer behavior as well [3]. Current developments such as [4–6] provide evidence that streaming is a concept that can also be used for the production domain and in Additive Manufacturing (AM). These approaches use the layer-wise nature of the AM production in a way that the manufacturing information is streamed layer by layer. This is comparable to video streaming where the single frames of a video are streamed one after another. The music industry relies on the same concept of breaking a file into smaller data packages and use partly the same protocols to stream data as the video industry such as the Real-time Transport Protocol. Looking at the similarities of both music and video streams to AM streaming concepts such as [4,5] and the historical development of the music and media industry it is likely that the introduction of streaming will impact AM, related process steps and the value creation using AM.
This work assesses the potential impact of streaming on AM using the example of Powder Bed Fusion of Metals with Laser Beam (PBF-LB/M). Therefore, the paper is structured as follows: Firstly, the state of the art for PBF-LB/M and its process chain is given and potential innovations for PBF-LB/M enabled by streaming are elaborated. Afterwards the impact of these innovations on the process chain are discussed, following by a conclusion and outlook.

State of the art

PFB-LB\M is a process where metal parts a produced layer by layer [7]. Laser exposure introduces energy into a metal powder that melts and solidifies. In literature one can find different process chains for PFB-LB\M varying in detail, process steps and point of view, e.g. [7,8].

In the scope of this work we use the following process chain definition which is depicted in Figure 1:

Tessellation: Most AM data preparation software works on basis of the STL format which represents 3D models as a set of triangles [9]. Therefore, the first step after the design is to tessellate the 3D model transferring it into a STL file.

Part Orientation: The orientation of a part plays a crucial role in PBF-LB\M as the orientation influences several factors such as buildup of thermal stress or the need for support. Therefore, determining an appropriate orientation by the means of a rotation angel for the part is important to ensure part quality. [10]

Support Generation: Depending on the geometry of a part, support structures are required to ensure a stable printing process and part quality. For instance, the energy introduced by the laser exposure results in heat accumulation and needs to be dissipated in order to avoid or minimize thermal stress and distortion. Support is generated based on rules such as the overhang angle of a part and based on experience. [11]

Nesting: In general, in PBF-LB\M multiple parts can be produced in one build job. In the step of nesting the placement of the parts to be printed in the build chamber is defined. Thereby considerations which part to produced next and how to achieve a high package density and thus high machine utilization are considered. [12]

Part Orientation, support structures and nesting are intertwined and influence each other. For instance, the part orientation determines which areas need support and thus influences the support generation. Increasing the packaging density in nesting by changing the part orientation is another example of interdependencies of the process steps. Therefore, in some cases it might necessary to iteratively repeat the process steps of part orientation, support generation and nesting before proceeding with slicing.

Slicing: PBF-LB/M is a layer wise process. Therefore, before printing the nested build job is sliced meaning slicing the geometry into layers with a specific height. Moreover, the allocation of processing parameters such as the hatching pattern and the scanning speed is considered here as part of the slicing process. [7]

Printing: In the printing process the information of the sliced build job is used to fabricate physical parts. A recoater applies a layer of metal powder on a powder bed. Subsequently, a laser selectively scans over the powder bed and melts the powder according to the sliced data. The melt solidifies and the process is iterated until all layers are printed. [7]

Post Processing: Most parts due not reach the desired properties as built. Therefore, several post processing steps such as heat treatment, removal of support structures or surface finishing can be required. [11]

Quality Control: There are various measures for quality control along the process chain from in-situ monitoring of the process, e.g. using optical tomographic, to ex-situ control such as CT-scans. [13]

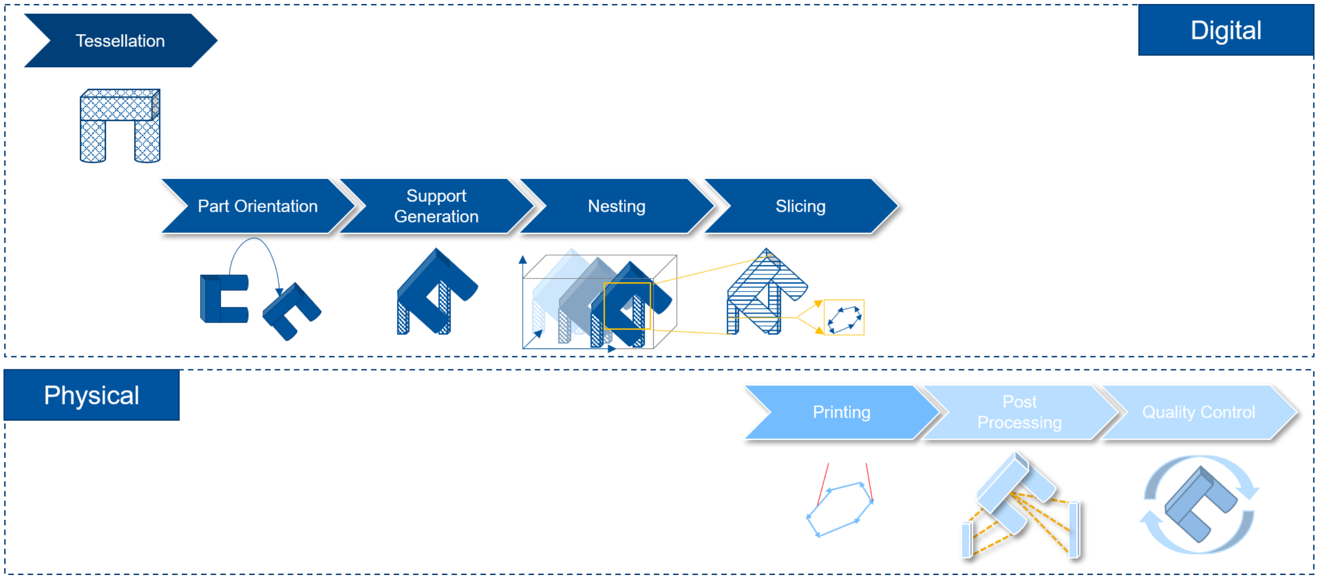

Figure 1 Process Chain of PFB-LB\M

Innovation enabled by streaming

New technologies often lead to innovations which can be of different kind of nature, e.g. improving in an incremental or radical way [14]. Often only after time the actual impact and unexpected uses cases become apparent, e.g. streaming in the music industry was intended to avoid music piracy and to ease file distribution, but changed the consuming behavior towards music in the long run [2]. Today, for instance, it is more lucrative to focus on single rather than album production [2] which is an impact that was not intended when introducing streaming for music. Subsequently, it is not clear yet which impact streaming as new technology for the AM domain will have. However, due to the similarities of streaming in other industries and other technological developments, we are exploring possible innovations that streaming will foster for AM.

File distribution

STL is a de-facto standard for exchanging 3D models in the AM process chain [9] with more sophisticated formats such as 3MF gaining more attention [15]. When it comes to 2,5D data so data after slicing that is send to the PFB-LB\M machine there is no common standard. Proprietary formats and solutions tailored to specific machines are set in place by the machine manufacturer. However, a standardized AM exchange would ease the workflow from CAD to manufacturing data. Moreover, standardization of interfaces would help speeding up the manufacturing process and in general increase the process flexibility. [15]
Location-independent manufacturing is an expected benefit of a standardized exchange format [15]. Different studies have shown that the distributed manufacturing would for instance increase customer welfare [16] or allow to optimize the productivity of production networks [17] but is not yet backed by the respective information technology communication (ICT) solutions [17]. Drawing parallels to music and video streaming which allows to distribute respective content to users world-wide and on-demand, streaming could help overcoming the ICT inadequacies as it could be used to distribute manufacturing information directly to the point of need. That way innovation in business models such as local spare part supply on demand [18,19] could be supported by streaming.

Intellectual property protection

The legal aspects especially in regard to intellectual property (IP) play an important role for value creation using AM [20,21]: securing the data exchange in outsourcing AM production to service provider [22], ensuring file integrity [23] and avoiding product piracy [24]. Most of the so far introduced streaming approaches for AM [4,6,23] evolve from IP protection stemming from a lack of cyber-security. Among other measures streaming helped to overcome IP issues in the music and video industry by transforming the data into an un-tangible product [1,3] making it available temporary and hence harder to copy and manipulate. The same principle is used in [4] and additional security features tackling counterfeiting [6] and attacking the integrity of the manufacturing data [23] can be addressed by streaming for the AM domain.

Process control

The realm of the Internet of Things (IoT) in Industry 4.0 having the capability to analyze process data in real time can lead to huge benefits in operational efficiency [25]. As real time streaming data is used in [23] for cyber-security purposes, the data could moreover be used to detect issues in the printing process (e.g., detecting defects or warping). Combing such a capability with the ability to control the printing process layer wise using approaches such as [5] poses the innovation for closed-loop process control increasing quality and process stability. Detecting faults such as overheating or warpage could be minimized or even corrected by adjusting the next layer in real time.

Quality control

In-situ process monitoring is often used for quality control in PBF-LB\M [13]. Abdullah et. al introduced an in-situ quality control mechanism in which streaming is used to detect deviations in the printing process in real time [23]. A video camera observes the building process and streams the recorded frames in real time back to the system where the manufacturing information from the build job comes from. This allows to compare the actual printed layers with the intended layers and their according printing parameters. This approach is designed to increase cyber-security and detect unwanted changes in the printing commands such as changed vectors or parameters. Moreover, this and similar approaches using streaming of the real time printing process can be used for online quality monitoring. Detected faults and deviations could be used to take counter measures in real time such as aborting an erroneous printing process and thus reducing scrap. Further applications for streaming in-situ data are likely if the monitoring is video or image based as in [23], as the technology developed for video streaming is also directly applicable to in-situ data."

Production Planning

Streaming data from machines on the shop floor into the manufacturing execution system (MES) opens the opportunity to increase the efficiency in production by optimized scheduling of production tasks [26]. In AM a standard machine interface e.g., using OPC UA [27] can report failures to the MES in which this information could be used to reschedule the respective build job. Using streaming as described related to process control, one could interact even before rescheduling. If a fault in a single layer is detect one could react by streaming a next layer without the toolpath for the faulty part. That way it would no longer be necessary to abort the entire job and thus the scrape rate and printing time could be reduced. Moreover, this information could be used in the MES to only reschedule the respective part. Monitoring approaches to detect deviations [13] and to extracting to which part the deviations belongs already exists [28].

<u>Impact on the process chain</u>

The elaborated potential innovations require the ability to stream information at different stages of the process chain. Often the process chain is distributed between different entities such as a design owner, service provider and process parameter owner [22] especially when relying on outsourcing. The above-mentioned innovations have to be integrated in this distributed process chain in order to successful transfer them into application. By analyzing the impact of streaming along the PBF-LB\M process chain on different process steps we deduct necessary adjustment to the existing workflow. Therefore, we refer to the process chain mentioned above embedded in a supply chain having a design owner, a service provider and an end-customer. In the supply chain the design owner is responsible for the tessellation before handing over the digital part to the service provider. The service provider does the data preparation from part orientation until slicing, as well as printing the part and quality control. This is the common process as the service provider typically holds the expertise in preparing the digital file for printing. Moreover, process steps like nesting can only be done knowing the available machines and their size as well as having the different orders at hand that could stem from multiple different customer. The process chain and the task of the different entities is depicted in Figure 2.

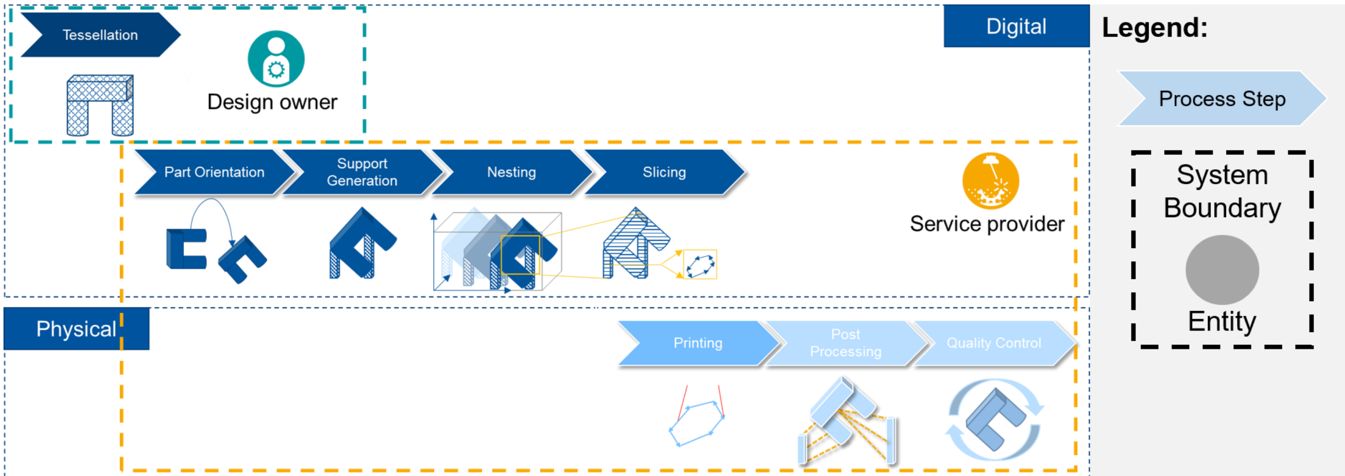

Figure 2 State of the art system boundaries in the PBF-LB\M process chain

Impact 1: Separation of data preparation and printing

Using streaming for file distribution can ease the distribution of manufacturing information within a single work shop up to entire production networks. In the case of a single work shop there might not be no impact on the process chain besides providing a digital way to sending manufacturing information to AM machines. However, distribution in production networks. e.g. for on-demand spare part supply, might impact the process chain as streaming would result in a cross-company data exchange. Streaming the manufacturing information to the machine can only be done after the data preparation has be completed and the layer-wise data is available. In the case of cross-company distribution data preparation and printing are done by separate entities.
Furthermore, when file distribution is linked to further measures targeting IP protection, it is necessary to have data preparation and printing handled by two different entities. That way one can avoid sharing the 3D model [4] or include signatures [6] to counteract counterfeiting.

Both cases require to separate the task of data preparation and printing to two different entities. Referring to the supply chain and process chain this would mean that the task of data preparation needs to shift to the design owner or a new entity. Shifting to the design owner can be problematic as the nesting process could involve multiple orders from different costumer which could not be respected by a single design owner leading to nesting with low packing density and thus low machine utilization. Here order managing platforms such as Xometry[1] or Protiq[2] could come into play taking the task of data preparation as they would be able to bundle multiple orders and optimizing the efficiency of machine utilization and distribution of build jobs within a production network. Figure 3 shows how the process steps might be split up between design owner and service provider due to Impact 1.

Impact 1.1: Process parameter

Determining the optimal processes parameters in PBF-LB\M is a complex task due to many different influencing factors [22]. Transferring process parameters from one machine to another machine is often also not possible. Therefore, separating printing from slicing might be problematic if the machine is not known or would require an exchange on process parameters from the service provider to OEM. Process parameters itself are

[1] www.xometry.com
[2] www.protiq.com

Separating the information about the vectors to be printed and the process parameters could help to overcome this barrier. This is for instance possible with the streaming protocol published in [5] by only streaming the vectors of a layer and having the machine specific process parameters saved directly on the machine controller.valuable IP [22] and thus this might pose a barrier to distributed manufacturing requiring respective ways to exchange process parameters in a secure way.

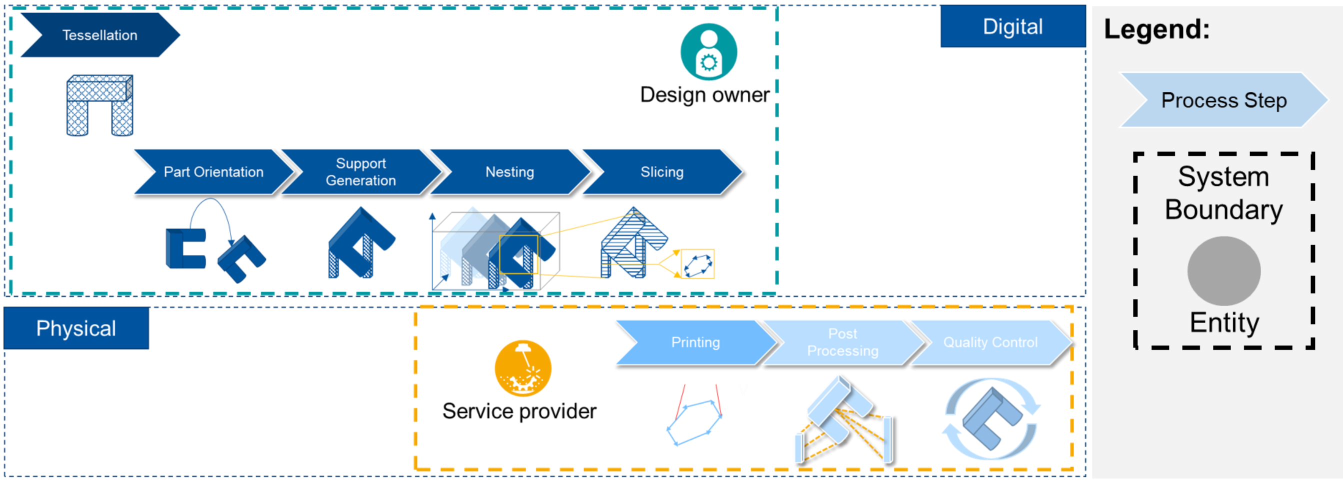

Figure 3 Change of system boundaries in the PBF-LB\M process chain by impact 1

Impact 1.2: Quoting and post processing

In PBF-LB\M a service provider can print different parts from different customers in the same build job. Calculation of costs and routing the different parts to the right customer, requires the knowledge of the nesting process for the specific build job. Hence, if nesting and printing are handled by different entities it might become hard to calculate costs and moreover matching parts to the customers or the downstream processes in post processing. Transferring the respective information along the PBF-LB\M process chain is thus a task for streaming or might limited distributed manufacturing using streaming to build jobs dedicated to a single customer.

Impact 2: Additional feedback loops for process control

Both layer-wise process control and quality control using streaming require monitoring systems and feeding information into systems in which the actual printed layer and the target layer can be compared. In case of process control this would moreover require a real time feedback loop and short latency in the control mechanism in order to adjust the following layer based on the comparison and detection of deviations. In the state of the art such a feedback loop from the printing process directly back to slicing in data preparation does not exist. Moreover, proprietary data formats and lack of open interfaces [9,29] pose a barrier to the innovations in process and quality control. Realizing these innovations would impact the process chain by new interfaces for the feedback loop from process monitoring to data preparation and an interface to the machine which works layer-wise.

Impact 3: Connecting MES and machines on control level

Besides the interfaces to be established for process control and quality control using streaming, an additional data exchange for the potential innovation in production planning is required to propagate the information if a single part is aborted during a build job. To reschedule the part in real-time this information needs to be feed into the MES and hence impact the process chain by another feedback loop. The feedback loops resulting from Impact 2 and 3 are shown in Figure 4.

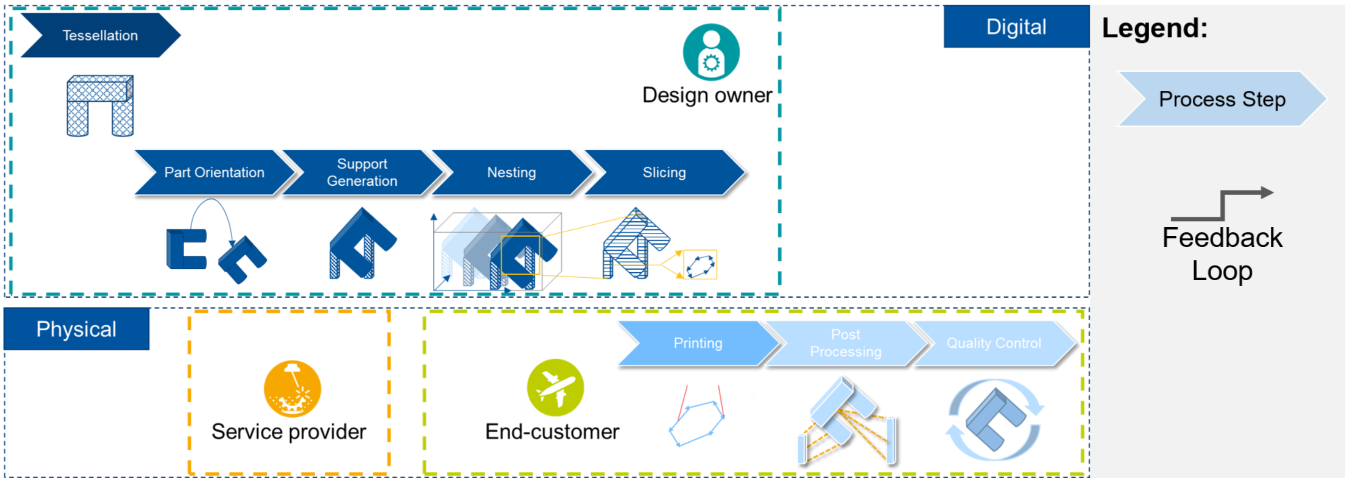

Figure 4 Additional feedback loops in the PBF-LB\M process chain due to impact 2 and 3

Impact 4: Business models

Streaming in music industry has changed business models tremendously [1]. Likewise, it could have an impact on current business models in the AM domain and the process chain, e.g. shifting the production of parts to the end-user in a co-production scenario. Streaming approaches such as [4,5] could be used to do so. Original equipment manufacturers (OEM) could stream manufacturing information directly to printers located at the point of need, e.g. in the production facilities of a customer. This might reduce lead times and logistical efforts or the number of spare parts that have to be in stock. In regard to the process chain this results again in Impact 1 separation of data preparation and printing. Moreover, this concept would short cut service provider as printing would move to the end-customer and all other process steps would stay at the design owner in this case the OEM. Here another entity providing digital warehousing or other types of sourcing platforms might take certain portions of the process chain. Figure 5 visualized how the process chain might be divided among design owner, service provider and end-customer in case of short cutting the service provider using streaming.

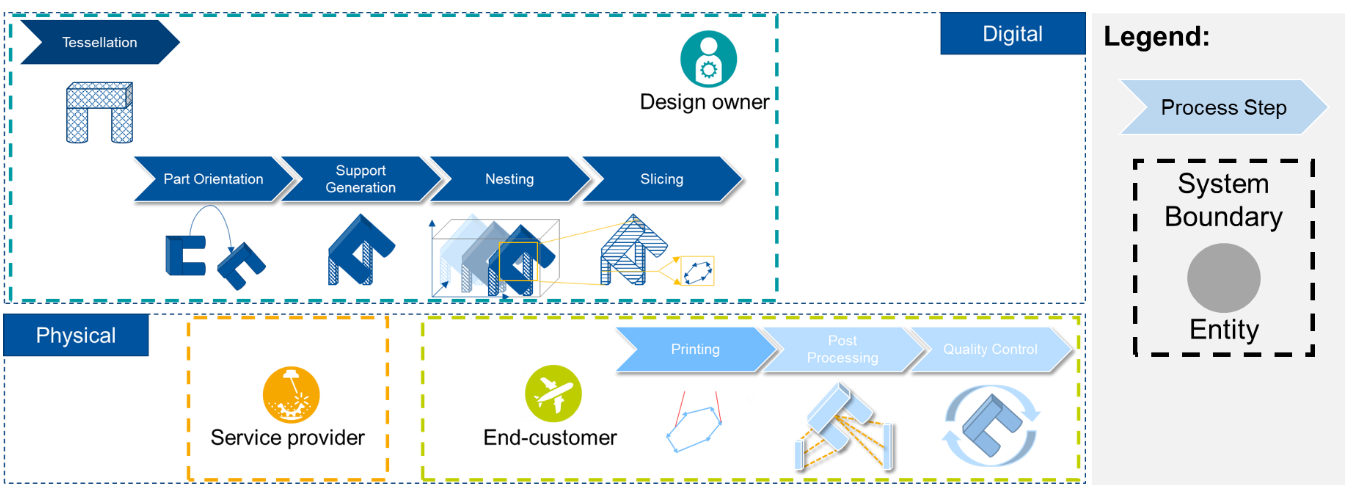

Figure 5 Change of system boundaries in the PBF-LB\M process chain by impact 4

Conclusion and Outlook

By drawing parallels to other technologies and the historical development in the music and video industry this paper presents how streaming might innovate in AM. The potential innovations range from file distribution, process control, production planning, IP protection to quality. Furthermore, the impact of these innovations on the process chain by the example of PBF-LB\M are discussed. Showing that streaming has the potential to innovate along the process chain but also to introduce changes in the tasks of different entities involved such as design owner, service providers and end-customer. Moreover, new business models could be supported by streaming leading to changes in the shares of the different entities.

Predicting the actual impact of new technologies – in this paper streaming – might be supported by certain evidence and analysis, however, remain speculative to a certain extent. Therefore, this paper is likely not to present the real impact of streaming and innovations for the AM domain, but gives an outlook on potential future scenarios. Thereby, it provides a guideline for future developments and is a first starting point for design owner, service provider and end-customer on how to prepare for such developments.

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