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Environmental and technical evaluation of additive manufacturing: Enabling process chain perspective by energy value stream mapping

Mathias Wiese[a,b,*], Christopher Rogall[b], Nadja Henningsen[b], Christoph Herrmann[b,c], Sebastian Thiede[d]

[a] *Polymer Additive Manufacturing Center, AUDI AG, Auto-Union-Straße 1, Ingolstadt, 85045, Germany*

[b] *Chair of Sustainable Manufacturing and Life Cycle Engineering, Institute of Machine Tools and Production Technology, Technische Universität Braunschweig, Langer Kamp 19b, Braunschweig, 38106, Germany*

[c] *Fraunhofer Institute for Surface Engineering and Thin Films (IST), Bienroder Weg 54 E, Braunschweig, 38108, Germany*

[d] *Manufacturing Systems, Faculty of Engineering Technology, Department of Design, Production & Management, University of Twente, De Horst 2, Building 20, Enschede, 7522 LW, The Netherlands*

Abstract

Additive manufacturing (AM) currently evolves from a prototyping process to an alternative manufacturing process for end-use parts, advancing into fabrication of low to medium product volumes. Moreover, increasing awareness of environmental impacts of manufacturing lead to the necessity of holistic evaluation among traditional evaluation criteria in the technical and economic domains. However, existing evaluation approaches seldom consider a complete AM process chain and are lacking a production-oriented notation which enables comparability across technologies and support in identification of improvement potentials on technical and environmental level. To address this gap, this paper highlights the way from structured data acquisition to setup of an energy value stream map (EVSM) for AM process chains in end-use part production, augmenting methods of lean manufacturing by the energy dimension. Consequently, it contributes to a holistic and transparent process chain perspective to assess AM as a manufacturing alternative. The proposed methodology is applied to a case study covering two different process chains, a first based on powder bed fusion via Multi-jet Fusion (MJF) and a second utilizing vat-photopolymerization via Continuous Liquid Interphase Printing (CLIP). While the MJF process chain's energetical hot spot is situated in the printing process itself, the hot spot for CLIP is found in thermal post-processing, exceeding the comparably efficient printing process by magnitudes and ultimately resulting in higher energy intensity per part compared to the MJF process chain. These results highlight the necessity of a holistic evaluation method for complete AM-based process chains and their influence on the product properties. Insights may help engineers, designers and decision makers in pre-selection of suitable manufacturing strategies with a more complete view on AM process chains.

Keywords: Additive manufacturing; rapid manufacturing; process chains; value stream mapping; sustainable manufacturing; decision support

1. Introduction

In the recent years, additive manufacturing (AM) technologies and materials advanced from use in prototyping into the domains of end-use part production, e.g. with vat-photopolymerization (VP) and powder-bed fusion (PBF) in the automotive industry [1]. Backed by institutional and governmental funding programs, projects to fully integrate AM processes into series production lines are conducted as joint efforts of automakers and system providers [2, 3]. Continuing this development, AM's relevance for the production of end-use parts is expected to increase further within the next years [4].
Among others, two technologies amid VP and PBF, namely Continuous Liquid Interphase Printing (CLIP) and Multi-jet Fusion (MJF), recently proved to be meeting requirements of series parts in different applications [1]. As a consequence, the production systems where these series-ready technologies are embedded in become more complex and competitive, including further post-processing and finishing measures to match part

* Corresponding author. Tel.: +49 841 89987209
E-mail address: mathias.wiese@tu-braunschweig.de (Mathias Wiese).

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requirements. These process chains and resulting value streams need to be understood and optimized in order for AM to be a viable alternative in end-use part manufacturing considering the technical, economic and environmental dimensions of the production system.
This paper contributes to this understanding by applying the energy value stream mapping (EVSM) methodology to AM value chains. As shown by a case study covering process chains of the mentioned processes CLIP and MJF, the approach aids assessment and comparison of different AM process chains with focus on technical performance and energetic hot-spots, fostering holistic process chain oriented decision making in production with AM and its ongoing industrialization.

2. Background for the considered AM technologies

In the following, the working principle and main characteristics of the two AM technologies covered in this paper are briefly introduced referring to Figure 1. Both introduced technologies have been utilized in realization of automotive series applications and thus can be treated as formally qualified for series production in demanding environments, e.g. with high mechanical and thermal requirements (see [1] for a structured review of applications and requirements).

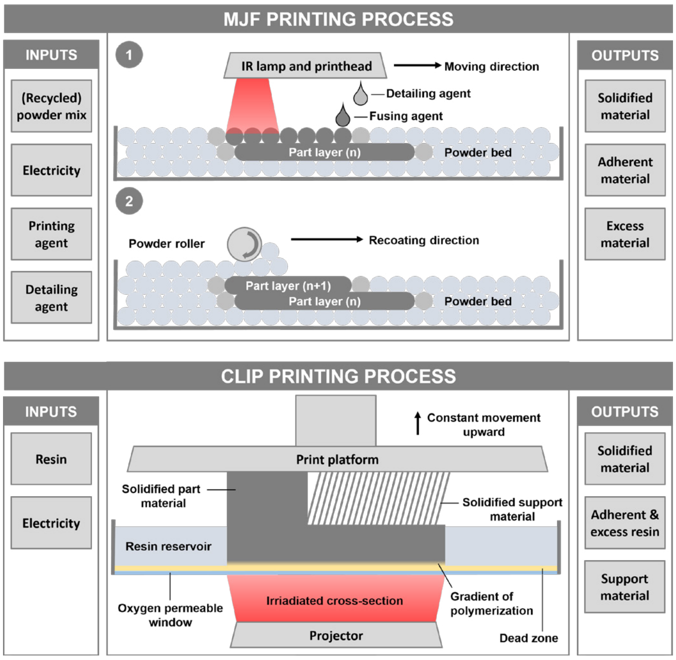


Fig. 1. Illustrations of the printing process mechanisms for MJF (top) and CLIP (bottom) with respective main inputs and outputs (adapted from [5] and [6])

2.1. Multi-jet Fusion (MJF)

As a member of the PBF technology family, multi-jet fusion (MJF) is characterized by its basic mechanism of fusing areas in a powder bed by heat energy [7]. The process most commonly utilizes thermoplastic polymers like Polyamide 11 (PA 11) and Polyamide 12 (PA 12) with a well-controllable melt behavior and the opportunity to partially recycle excess material for subsequent prints [8, 9]. MJF's is defined by application of fusing and detailing agents through an inkjet printhead, which is followed by heating of the powder bed through an infrared (IR) heater (see step 1). This way, thermal energy is transferred to the highly absorbent fusing agent, melting and fusing a new part layer. This first step is followed by a recoating sequence, where a powder roller spreads a thin layer of new material across the powder bed (step 2). After recoating, the next fusing sequence is carried out [9, 10]. In contrast to multiple other PBF technologies, MJF is able to fuse complete cross sections of a layer in a single overpass of the integrated IR and inkjet array and thus achieves comparably high process speeds [11]. Together with a bigger build envelope, MJF reaches considerable productivity. However, the PBF technology demands some mandatory post-processing steps. These comprise controlled cooling of the build envelope to prevent part warpage, unpacking of parts from the cold powder bed, reconditioning of excess material for recycling and removal of adherent powder through, e.g., glass bead blasting [12, 13]. Additional finishing steps like vibratory grinding can follow for the improvement of surface properties due to the mediocre surface quality achievable in PBF processes.

2.2. Continuous Liquid Interphase Printing (CLIP)

Relying on photosensitive resin-based materials, the CLIP technology is a member of the VP technology family [7] and is strongly related to digital light processing (DLP), utilizing a light mask projector as the central machine element [14]. Starting a build, the print platform is submerged in the resin reservoir. Through an optically transparent and oxygen-permeable window from beneath, the digital light processor irradiates the respective cross-section layer of the part to be produced into the liquid and triggers the solidification of the exposed resin. During the build process, the print platform constantly moves upwards to maintain a thin gradient of polymerization between the previously solidified resin and a dead zone, where resin solidification is inhibited by oxygen. Through this continuous process, the part and support structures (e.g. for overhangs) are formed [6, 15]. Like other VP technologies, CLIP requires further post-processing steps to provide a ready-to-use part. These comprise washing of the build platform and parts to remove adherent uncured resin after the print. This is followed by removal of support structures, dependent on the part geometry and orientation. Also, thermal curing of the green parts is required to improve the part properties [12, 15]. In direct comparison to PBF processes, the CLIP technology can realize considerably higher surface detail (apart from support structure attachment marks) and smaller part features, also benefiting from more gentle post-processing. However, smaller build envelopes and process speed result in far lower productivity.

3. Methodology

3.1. Value stream mapping in AM

Among other methods for holistic process representation, value stream mapping stands out regarding its user value for assessing process performance in a simple and understandable manner [16]. Through assessment of all processes in the value stream and their related material and information flows, all non-value adding activities are identified and consequently re-

duced or eliminated [17, 18]. Since introduction of the original method and its sole focus on technical and informational aspects of value chains, multiple approaches were presented to enhance VSM's capabilities to also cover process chain sustainability aspects.
Erlach and Westkämper extended material and information flows by energy flows in energy value stream mapping (EVSM) [19], which allows to identify energetical hot-spots and wastages. Beyond this, some researchers developed approaches to include even more dimensions towards sustainable manufacturing [20]. Also, simulation-based VSM approaches are presented to overcome the static character of the original method and enable analysis of dynamics within the value streams, partially even able to reflect multi-product value streams [21]. As presented by Romero and Arce [22], VSM experiences a great uptake in industry and research across many manufacturing sectors. However, only few researchers made use of these methodologies in evaluation of AM-based manufacturing systems. Kurdve et al. [23] compared a traditional manufacturing approach with a powder-based AM value stream for manufacturing of metal parts and improved the AM scenario through change in material and finishing operations. Pushparaj et al. [24] used the VSM approach to assess and improve economics of a value stream based on Fused Deposition Modeling (FDM) through grouping and simultaneous printing of parts. Wiese et al. [25] developed a simulation based process chain model for MJF in AM-based end-use part manufacturing for automotive components and applied the EVSM methodology for summary and aggregation of the calculated performance indicators.
Building on these first applications of VSM in AM, this paper further highlights the process from data acquisition to setup of an EVSM for AM process chains. Using measurement guidelines, we bridge this gap to holistically assess AM process chains regarding their technical and energetical performance in series manufacturing and provide essential data for subsequent steps like simulation and scaling of the production system. While technically all mentioned VSM approaches are applicable, this paper builds on extension of the EVSM approach [26] to distinguish between different energy demands of machine states. This greatly blends in with the derivation of machine states via the VDMA 34179 standard as presented in the following section. For this paper, tracking of process times, inventories and product flow as presented in the original VSM approach [17] is enhanced with tracking of energy demand of the different process stages in alignment with Erlach's approach. Furthermore, the methodology distinguishes between value adding activities and non-value adding activities and thus contributes to identify and reduce the latter. This distinction is a central aspect in establishment of energy and resource efficiency in manufacturing value chains [27].

3.2. Data acquisition and processing

In order to obtain the data for creation of energy value stream maps, involved equipment in the process chain needs to be analyzed regarding its different machine states and the associated energy consumption. After this, distinguishing between value adding and non-value adding states is possible. The VDMA 34179 standard for measurements to determine the energy and resource demand of machine tools for mass production [28] can be used as a measurement reference, meeting the requirements for a value stream analysis [26]. As usual manufacturing steps are conducted in a time domain of minutes, continuous measurements over at least one processing cycle (including machine states for powering up and down, standby and further) for a designated product should be conducted with a sampling rate in the second domain. Depending on the underlying process, the data might be noisy and requires further processing such as smoothing (e.g. LOESS, PAA smoothing) for interpretation. Exemplary, the following Figure 2 shows the generated load profile, derived machine states and value adding phases of an HP 4210 MJF printer in production.

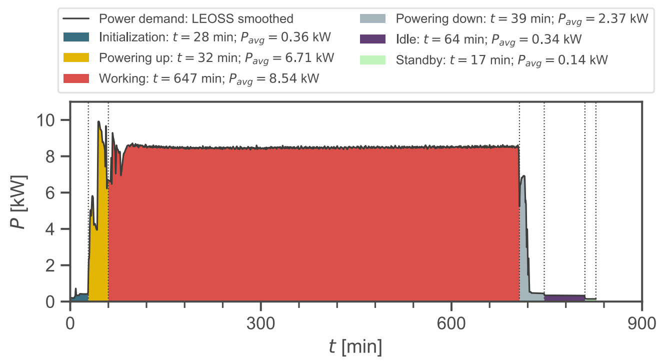


Fig. 2. Obtained load profile for a full print on an HP 4210 MJF printer with different machine states and value adding phase (red)

At first, the machine passes an initialization for about 28 min at an average power demand of 0.36 kW and then powers up for 32 min at P_{avg} of 6.71 kW. During the working state, the machine adds value to the product (indicated in red) for about 647 min at P_{avg} of 8.54 kW. Finishing the print, the machine powers down (t= 39 min, P_{avg} = 2.37 kW) and subsequently enters the idle (t= 64 min, P_{avg} = 0.34 kW), respectively standby state (P_{avg} = 0.14 kW).
This procedure needs to be applied equally for all involved equipment types to determine machine states and state-dependent power demands, which is shown later in Figure 4.

4. Case study: EVSM for DLP and MJF process chains in end-use part manufacturing

4.1. Assumptions and limitations for the case study

For this case study, certain assumptions apply to the respective processes. Firstly, the process chains are constituted of single machines for each process, meaning that there is no equipment operated in parallel. This way, the products sequentially flow through the respective process chain and dynamics originating from parallel operation of multiple resources per process are neglected in favor of reduced complexity and focus of the paper on the applied EVSM methodology. Consequently, insights reflect the properties of a 'base configuration', a minimum functional process sequence. Both process chains reflect the necessary processes from base material to delivery of a raw

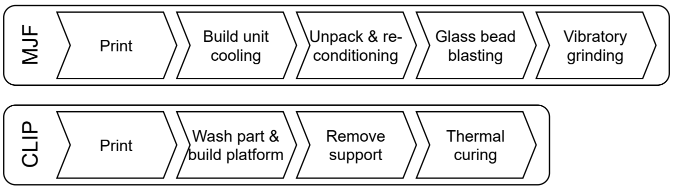
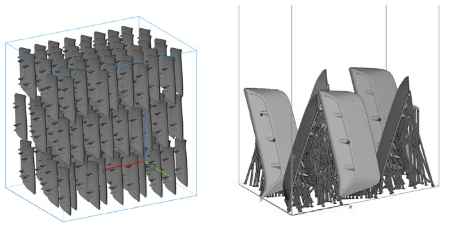


Fig. 3. Process chain sequence for MJF and CLIP

part with comparable properties, which is ready for further finishing like painting.

4.2. Production task and resulting process chains for MJF and CLIP

As a production task for this case study, an automotive exterior trim part is selected to be produced via MJF and CLIP. All presented data bases on measurements and observations of the two associated process chains. Prior to build execution, the print jobs are prepared as summarized in Table 1. For MJF, a HP 4210 printer is used which realizes a batch size of 144 parts in PA 12 material within an operation duration of 755 min in fast print mode. Being significantly smaller, the Carbon M2 printer selected for the CLIP process produces 6 parts in EPX 82 material within an operation duration of 310 min. In contrast to the self-supporting powder bed in the MJF process, support structures need to be added in production via CLIP.



Process	MJF	CLIP
Printer	HP 4210	Carbon M2
Batch size	144	6
Material	PA 12	EPX 82
Duration	755 min	310 min

Table 1. Print job specifications for the production task

The different nature of the technologies imply different process chains, as illustrated in Figure 3.

For MJF, the print is followed by an unsupervised cooling phase, which equals the print duration, before the build unit is transferred to an unpacking station for removal of the parts from the build unit and its reconditioning for subsequent prints. Unpacked parts still are covered in adherent powder, which leads to the following step of glass-bead blasting in an automated blasting chamber. This process removes adherent powder and prepares the part for the finishing step of vibratory grinding for surface smoothing.

Printing with the CLIP process leaves the parts on the build platform of the printer covered in unsolidified resin. Consequently, the build platform and adherent parts need to undergo a washing cycle in a specific part washer. After this washing cycle, parts are ready for removal from the build platform and de-supporting. The green parts then need to undergo a final thermal curing cycle in an oven for the material to reach its end-use properties.

4.3. EVSM generation and analysis for MJF and CLIP

In a first step towards EVSM, the used equipment along the process chain is analyzed regarding its different machine states and the resulting energy consumption while distinguishing between value adding and non-value adding states. To obtain this data, energy measurements in alignment with the VDMA 34179 standard [28] were conducted along the process chain. The acquired data results in seven power profiles for the four machines used in the MJF process chain (printer, unpacking station, automated glass bead blasting chamber, vibratory grinder) and three machines in the CLIP process chain (printer, part washer, curing oven). These profiles underwent load profile analysis in order to derive the different machine states and product-related energy consumption as shown, e.g., by Teiwes et al. [29]. A high level overview of the resulting power profiles and the value adding phases during operation (highlighted in red) is provided in Figure 4 together with the respective EVSM elements. For noise reduction, the graphs have been smoothed using the LOESS method.

4.3.1. Technical and energetic performance

Looking at the EVSM of the process chains, the involved processes behave very differently. For MJF with an overall lead time of 1733 min and a calculated takt time of 12 min, the lead time is mainly determined by the printing and cooling process with their equal duration of 755 min. Following processes like unpacking and reconditioning of the build unit, glass bead blasting and grinding are comparably short, ranging from 11 to 133 min of in-process time. A similar pattern exists for the energy use in the MJF process chain. With an energy intensity of 675 Wh per part (EI VA + EI NVA), the printing process demands for the highest energy share along the process chain. Subsequent processes with energy requirements range between 5.6 Wh (vibratory grinding), 7 Wh (unpacking & reconditioning) and up to 72 Wh (glass bead blasting, including energy for compressed air). In general, the value adding share of energy (EI VA) is high. One exception is the unpacking and reconditioning process, where the build unit is refilled after extraction of the parts from the powder bed, resulting in a higher share of non-value adding energy. A different pattern is visible in the CLIP process chain. While the total lead time of 1153 min is lower than the one in the MJF process chain, the main contribution to lead time is found at the end of the process chain, namely in the thermal curing process with a duration of 814 min. Similarly, the energy intensity during thermal curing is high and results in a comparably higher energy intensity per part than found in the MJF process chain (2136 Wh per part). However, the capacity utilization in the final curing step is comparably low and likely can be significantly improved by curing multiple print jobs at once. In a sequential process however, this would increase the lead time due to the execution of multiple prints before curing parts from multiple prints in a single batch. The calculated takt time of 192 mins in the CLIP process chain is significantly

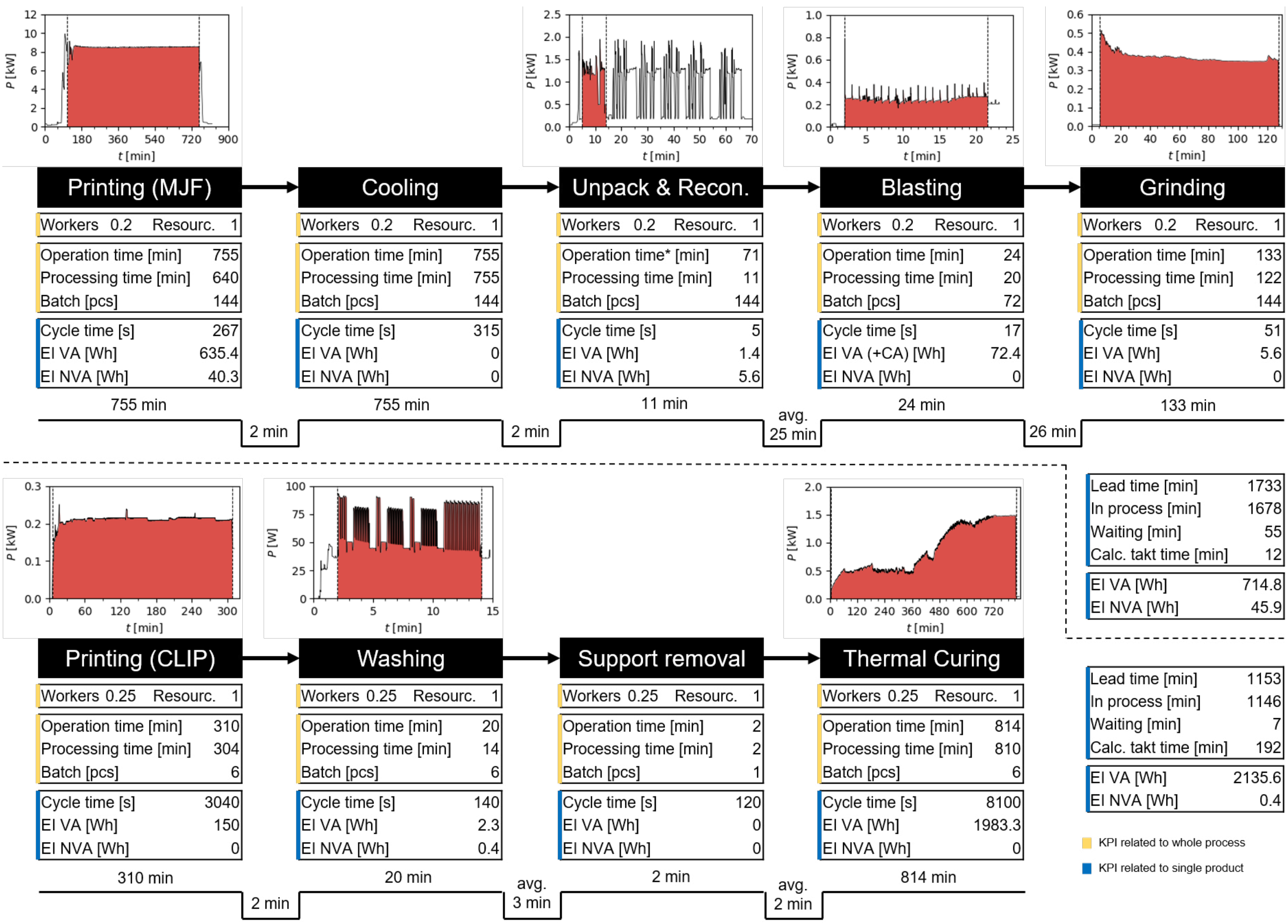


Fig. 4. Generated EVSMs for the MJF and CLIP process chains with load profiles for the involved equipment

higher than the takt time of the MJF process chain. From technical perspective, processes with the highest cycle times represent the bottleneck in the process chain [18], which is the case for cooling (MJF) and thermal curing (CLIP).

4.3.2. *Implications for industrial practice and upscaling*

While both presented process chains achieve comparable product properties for use in automotive applications [1], the process chains behave differently. The applied EVSM methodology enhances transparency and comparability to find the right process chain for a given production scenario with respect to environmental and technical performance indicators. It also underlines, that AM needs to be carefully evaluated dependent on the underlying production scenario, the resulting process chains and their influence on the product properties. From an industrial point of view, both processes would be applicable for different production scenarios. When opting for high throughput respectively short takt times, the MJF process chain can be considered the process of choice. Furthermore, when related to part output, it is utilizing less staff per produced part, which also is a relevant figure industrial production scenarios. Its high throughput comes at the cost of high batch sizes as long as no mixed part production approach is taken. When part demand fluctuates and is generally situated in the low figures, a CLIP process chain can represent a better option for production. Its roughly 10 hour shorter lead time can respond to part orders in a faster way. When scaling of production is necessary to meet the production task, it implies different measures as, e.g., specified by Thiede et al. [30]. As more efficient nesting is a limited option due to the already densely packed build jobs, a next upscaling strategy can be the change to bigger machines (e.g. the Carbon L1 for the CLIP technology) or adding further machines in parallel for higher productivity of the process chain. However, this not only demands higher financial resources but also moving from a sequential process chain to multiple machines operated in parallel. This causes dynamic effects in the process chain, which need to be considered as they can have a great influence on its overall performance [25].

5. Discussion and outlook

In this work, we applied the ESVM methodology to two AM process chains and consequently derived their performance concerning technical and energetic KPIs. While the MJF process chain's energetical hotspot is situated in the printing process itself, the hotspot for CLIP is found in thermal post-processing, exceeding the comparably efficient printing process by magnitudes and ultimately resulting in higher energy intensity per part compared to the MJF process chain. For series production (as showcased in the case study) this implies a competitive advantage for the MJF process. However, if for example the needed batch size is far below the MJF machine's maximum capacity, and only few parts are passing the complete process chain, this energetical advantage might shift to the CLIP process chain. Also, if the thermal curing process is optimized to accommodate more parts at once, the energetical performance can be improved. A clear advantage of the CLIP process chain is the significantly shorter lead time, leading to higher responsivity to fluctuating demands.

With regard to planning and operation of AM process chains, application of the EVSM method in combination with a measurement guideline like VDMA 34179 enables engineers to anticipate the process chain behavior and acquire first data from energy load profiles for, e.g., process chain simulation when moving to more complex process chains with multiple entities. Previous research has shown that the EVSM method also can be applied on top of simulation (see e.g. [21, 22, 25]). Thus, it represents a versatile notation which can be used for initial 'as-is' analysis of value streams and also be extended to 'what-if' scenarios in the sense of decision support as a part of a cyber-physical production system framework. Furthermore, it contributes to a more holistic view on the AM technology, incorporating the whole AM-based value stream while providing the overview for derivation of improvement measures in the sense of lean and sustainable manufacturing.

However, it lacks a concrete view on resource utilization and economic performance of the value chain. To build a more holistic view, incorporating the environmental, the technical and the economic dimensions of a manufacturing system, the method could be supplemented by approaches like material flow analysis (MFA), material flow cost accounting (MFCA) (see e.g. [27]), activity based costing (ABC) (see e.g. [15]) or life cycle impact assessment for the product of the respective value stream (see e.g. [5, 27]).

Further research is conducted to combine these evaluation dimensions and create a holistic evaluation framework for additive manufacturing in series production.

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