Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 104 (2021) 653–658

www.elsevier.com/locate/procedia

54th CIRP Conference on Manufacturing Systems

Upscaling strategies for polymer additive manufacturing: an assessment from economic and environmental perspective for SLS, MJF and DLP

Sebastian Thiede[a,]*, Mathias Wiese[b], Christoph Herrmann[c]

[a]Manufacturing Systems, Faculty of Engineering Technology, Department of Design, Production & Management, University of Twente, De Horst 2, Building 20, Enschede, 7522 LW, The Netherlands
[b]Polymer Additive Manufacturing Center, AUDI AG, Auto-Union-Straße 1, Ingolstadt, 85045, Germany
[c]Chair of Sustainable Manufacturing and Life Cycle Engineering, Institute of Machine Tools and Production Technology, Technische Universität Braunschweig, Langer Kamp 19b, Braunschweig, 38106, Germany

* Corresponding author. Tel.: +31534892907; *E-mail address:* s.thiede@utwente.nl

Abstract

Without a question, additive manufacturing (AM) technologies are of strong and even further increasing importance nowadays. While incorporating strong potentials in context of customer-individual geometries, there are challenges when it comes to upscaling of production volumes due to long process times. The upscaling characteristics also differ among the available AM technologies. Against this background, this paper introduces and analyses different upscaling strategies from AM process perspective (for MJF, SLS and DLP) in context of economic and environmental performance criteria.

Keywords: Type your keywords here, separated by semicolons ;

1. Introduction

Over the last decades, additive manufacturing (AM) clearly stepped out of being a niche technology for rapid prototyping of development parts towards being an integral part of today's manufacturing landscape. AM allows innovative and customer specific designs which can be produced in lot size one, e.g. without high efforts for tooling [1]. Nowadays more and more applications can be found for both metal and polymer based additive manufacturing e.g. in the automotive, aerospace, apparel, or medical industry [2]. As example for the automotive sector, Figure 1 gives an overview of the additive manufacturing market which underlines the increasing demand on AM based final parts. Huge progress was also made in developing and improving AM process technologies and so manifold solutions can be found nowadays.

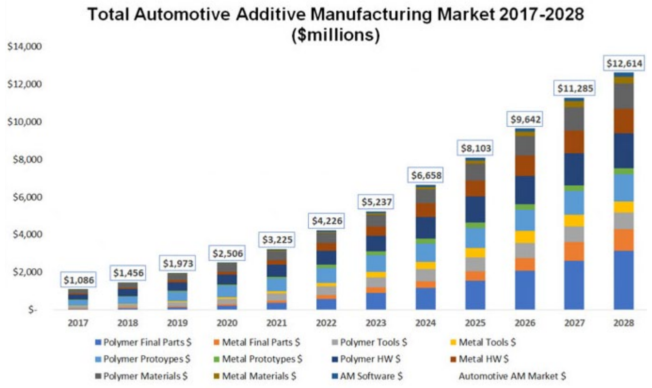


Fig. 1. Automotive additive manufacturing market 2017-2028 [3]

However, due to relatively long process times, upscaling AM based production volumes into at least small or medium

10.1016/j.procir.2021.11.110

series is still a challenge which conflicts with the increasing demand. Upscaling is understood here as scalability of the processes for higher total production volumes of specific parts or part families. Especially for the case of AM based production this might also include customer specific variations. Obviously established manufacturing technologies like injection molding or forming are available for efficiently producing large volumes but are also questionable for those variations and smaller series due to high tooling costs. Advanced AM processes might be an alternative here but there is the question which technologies are most promising.

Against this background, this paper addresses the characteristics and economic as well as energy related impact of upscaling strategies for selected AM processes. The focus is on polymer additive manufacturing for automotive end-use parts - selective laser sintering (SLS), multi jet fusion (MJF) and digital light processes (DLP) are the process representatives that are most feasible for those applications and used in the given industrial setting [2]. It is crucial to emphasize that within this paper just the AM process characteristics itself will be considered, further processes and interdependencies along the whole process chain (e.g. post processing) are explicitly not addressed, dedicated work on that can be found in [4]. The focus is also on the process related aspects while dealing with given products, changes in product/part design are certainly an interesting way to improve scalability but not in scope here. After some technical background on the considered AM processes, the methodology is described which will be finally applied in a case study based on an automotive component.

2. Technical Background

As base for further understanding of the individual process characteristics, brief descriptions of SLS, MJF and DLP are given in the following. More details can be found e.g. in [1].

2.1. Selective Laser Sintering (SLS)

SLS belongs to the group of powder bed fusion (PBF) technologies. The functional principal bases on the selective melting and fusing of powder particles through a focused CO_2 laser. The powder in the build chamber is maintained at a temperature just below the melting point of the powdered material. For building up a new layer a thin layer of powder is spread across the build area and the existing part layer using a counter-rotating powder leveling roller. This layer is then treated by the laser and this process is repeated until the build is completed [1,5]. Overall process speed depends on the scanning speed, laser beam diameter and the cross-section area of the different layers [5].

2.2. Multi Jet Fusion (MJF)

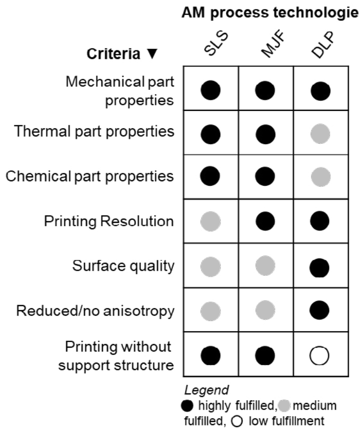
As MJF also belongs to PBF there are strong similarities to SLS when it comes to the handling of powder through recoating of layers in the build chamber. However, in MJF the fusing processes is different and uses a combination of agents for detailing and fusing applied by an inkjet printhead and heat from an infrared lamp. During an overpass of the integrated heater and printhead array, the inkjet printhead selectively deposits the fusing and detailing agent on the cross sections defining a part layer in the powder bed. Following that, the thermal energy from the infrared heater is transferred to the highly absorbent fusing agent, forming the new part layer [6,7]. In contrast to SLS, MJF is able to process complete cross sections of a part layer in a single overpass before recoating, resulting in higher process speeds [8]. To improve the part quality, so called two pass modes are available which include an additional overpass of the array over the layer.

2.3. Digital Light processing (DLP)

In general, DLP systems are based on a vat photopolymerization (VP) process, working with a light mask projector [9]. These technologies build a part in a layer-wise approach by selectively curing a liquid photosensitive resin when exposed to a UV-light mask [1, 10]. For that, the build platform or carrier is submerged in a resin reservoir. CLIP (Continuous Liquid Interface Production) recently emerged among those technologies and delivered high production speed paired with a variety of programmable resins to form end-use parts [11]. Within that, an oxygen-permeable and optically transparent window creates a dead zone, a thin layer of oxygen, between its surface and the photopolymer resin. From beneath, a digital light processor irradiates a defined cross-section layer of the three-dimensional object into the liquid and solidifies the exposed sections of photopolymer resin. During the build process the build platform continuously moves upwards while maintaining a thin gradient of polymerization between the previously cured layer and the dead zone – this prevents the cured resin from sticking to the reservoir. Through this continuous process a three-dimensional object is formed. After finishing the print, the part and its necessary support structures can be removed from the build platform. Typically the part is additionally cured in a heating chamber to enhance the mechanical and thermal properties [12].

2.4. Comparison of processes

Figure 2 shows a qualitive comparison of the considered processes. In general all processes are capable to produce automotive parts in defined qualities and size, but they differ in terms of the resulting properties of produced parts. SLS and MJF as PBF based technologies are characterized by very good mechanical, chemical and thermal properties of the parts and the benefit that no support structures are needed. DLP typically shows better performance when it comes to print resolution (more detailed prints possible), less anisotropy and increased surface quality. A disadvantage is the need for support structures to enable the printing process. For all three process technologies, industrial applications can already be found and all are in general suitable for automotive series production [2]. However, while process descriptions and empirical work can be found for all those AM processes, there is a research demand for investigating and comparing upscale characteristics.



AM process technologies

Criteria ▼	SLS	MJF	DLP
Mechanical part properties	●	●	●
Thermal part properties	●	●	◐
Chemical part properties	●	●	◐
Printing Resolution	◐	●	●
Surface quality	◐	◐	●
Reduced/no anisotropy	◐	◐	●
Printing without support structure	●	●	○

Legend
● highly fulfilled, ◐ medium fulfilled, ○ low fulfillment

Fig. 2. Qualitative comparison of AM processes based on [8,13,14]

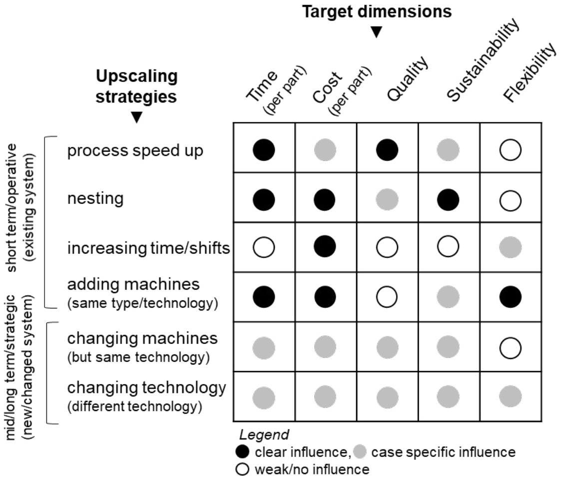
3. Methodology

The objective of this analysis is to investigate the upscaling characteristics of SLS, MJF and DLP as feasible technology options for the series production of automotive end-use parts. As indicated before, this analysis is solely based on the AM process itself – connected supporting processes along the value chain are not considered. After the general derivation of possible upscaling strategies, further information about the pursued methodology is given.

3.1. Upscaling strategies

When considering the options for upscaling additive manufacturing processes, in general six different strategies can be distinguished. An overview of those upscaling strategies and an estimation of their impact on different manufacturing target dimensions is given in Figure 3. The six strategies can be further distinguished into operative (that can take place within existing manufacturing systems) and more strategic options (that are typically addressing new or replanned systems). The assessment is based on technical characteristics as described in literature (e.g. [1]) and industrial experience.

- Increasing the **process speed** is an obvious operative strategy with direct positive effect on time per part and therewith production capacity. It can be applied if a degree of freedom is available at machine (e.g. able to run faster) or part (lower requirements for e.g. filling or surface quality) level. There is typically a conflict of goals with the quality of the part and related process robustness that might lead to counteracting impact on costs and sustainability (e.g. through lower quality rate).
- **Nesting** is referring to the bundling of several parts (of similar or different types) within one printing job. Through that, parts are combined and/or stacked in (multiple) building planes in the building chamber. This leads to better utilization of the machine and thus less time per part with typically limited negative impact on product quality as long as it complies with process-specific guidelines (critical nesting factor should not be exceeded). While machine time and e.g. energy demand of the machine are better utilized, positive effects on both costs and sustainability can be expected.
- From organizational perspective, upscaling of capacity can be achieved through **increasing planned production time**, e.g. through addition of further shifts. While normally not impacting the time per part or quality rate, this obviously increases the total product output and also the flexibility of the AM manufacturing system but might increase the costs. Adding more operators is also an organizational measure but since the focus here is on the AM process itself – which runs rather automated – this is neglected.
- If the previous options are not possible or preferable, the **addition of more machines** (of same type/technology) is a direct way to multiply the potential output and increase flexibility of the manufacturing system. If this leads to an over-dimensioned setting the costs per part might increase due to additional investments, higher space demand etc.
- From a more strategic perspective, **changing machines** (but still keeping the general AM technology) is another option, e.g. if new or better machines are available on the market. An impact is given on all target dimensions, but the direction and quantity depends on the specific case.
- Even more, **changing the AM process technology** also changes the upscaling characteristics of the system with potential impacts on all target dimensions. New technologies might also offer advanced opportunities for flexibilization, e.g. while new part families might be producible now.



Target dimensions ▼

	Upscaling strategies ▼	Time (per part)	Cost (per part)	Quality	Sustainability	Flexibility
short term/operative (existing system)	process speed up	●	◐	●	◐	○
	nesting	●	●	◐	●	○
	increasing time/shifts	○	●	○	○	◐
	adding machines (same type/technology)	●	●	○	◐	●
mid/long term/strategic (new/changed system)	changing machines (but same technology)	◐	◐	◐	◐	○
	changing technology (different technology)	◐	◐	◐	◐	◐

Legend
● clear influence, ◐ case specific influence
○ weak/no influence

Fig. 3. Comparison of process related AM upscaling strategies and their influence on typical manufacturing objectives

3.2. Experiments and estimation

In order to understand the upscaling characteristics of the selected AM processes SLS, MJF and DLP experiments were carried out and the resulting time and energy requirements were measured. Through variation of process parameters the effect of upscaling strategies process speed or nesting could be further investigated. Through selection of part and process parameters, comparable and acceptable part quality was ensured. Besides conduction of physical measurements, further data was obtained through estimation of process times through nesting software and AM machine control. Energy demands were estimated based on the process times and power demands measured in previous energy studies [15].

3.3. Economic assessment

Given the technical focus on upscaling strategies of selected AM processes, a simplified cost modelling is applied for the calculation of the economic impact. Interesting cost models for AM can be found in e.g. [16-18]. Within this study, calculations based on process times which are brought together with machine cost rates and energy demands. Machine cost rates are calculated based on the necessary machine investment (values taken from publicly available sources) allocated over a time frame of five years with an assumption of 2000 working hours per year. Energy costs are calculated based on process energy demand multiplied with a price of 0.20 €/kWh.

$$Production\ costs\ \mathrm{C} = process\ time\ [h] * (machine\ cost\ rate\ \left[\frac{€}{h}\right] + energy\ demand\ [kW] * energy\ price\ \left[\frac{€}{kWh}\right])$$

Manual operator costs are neglected given the focus on the automated AM process itself. It needs to be mentioned that labor costs can indeed add up to a significant share on operating costs, but this is also quite specific depending on product, production setting and organizational aspects. Focus is here on the technical upscaling characteristics of processes. Also material demand and related costs are not considered since this is rather indirectly related to upscaling questions.

3.4. Environmental assessment

Similar to other studies [19] the energy demand is considered for the environmental assessment, but the clear focus is on the AM process itself. Further upstream or downstream processes over the value chain are not considered. It is calculated based on the measured/estimated process times and measured power demand of the different machines in operating mode. Similar to the economic assessment, material demand is neglected here since it is just indirectly related to upscaling and would also impede comparability. Studies also show that for SLS and MJF energy demand is dominating the connected carbon footprint, at least if powder is assumed as being recyclable [15]. However, for DLP support structures are needed which causes additional material demand but is not in focus of this study.

4. Application

The case study was conducted based on an automotive exterior trim part. Its geometrical dimensions, volume and property requirements are well suited for additive manufacturing through SLS, MJF and DLP. Experiments were carried out on industrial grade machines with variations in batch sizes through different part nesting. For MJF varying processing modes (one pass vs. two pass) were analyzed as example for process speed variations. However, it needs to be noted that this might lead to inferior quality.

Descriptions of the part and process characteristics can be found in Table 1 and Figure 4. The following results discuss the three different process technologies and their relation to upscaling strategies and related target dimensions.

Table 1. AM process overview for case study

Process technologies	SLS	MJF	DLP/CLIP
Machines	EOS P396	HP4210	Carbon M1/2,L1
max. parts/batch	250	145	2/8/24
Power processing [kW]	3.3	7.7	0.16/0.8 (L1)
Machine costs rate [€/h]	30	22.5	20-115

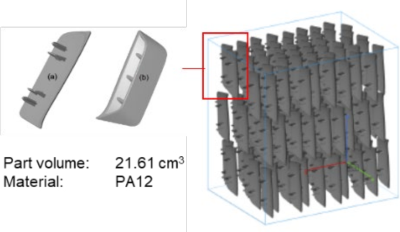


Fig. 4. Part specification and nesting setting for MJF with 145 parts

4.1. Nesting and process times

Figure 5 shows the relation of relative batch sizes to total printing time for one batch and the derived time per part. The three different process technologies lead to quite different behavior here. When producing more parts per batch, despite involving different planes SLS shows rather continuous behavior in terms of time sensitivity – which rather depends on the total print volume. The minimum process time for single part is approx. 4.6h which is extended to over 30h for the full batch of 250 parts. In contrast to that, MJF has a more discrete behavior which is directly depending on the height and, thus, number and characteristics of planes (three planes in this case) that occur through the nesting process. Once a new plane is needed anyway, additional parts in the same plane do not lead to longer process times. While up to 50 parts can be produced within 5.6 hours (1 Pass) or 6.8 hours (2 Pass), a total of 13.3/17.2 hours are needed when using all three planes up to the maximum batch size of 145 parts.

DLP again looks different: similar to MJF the process time mainly depends on the height of the printing job - but due to technical restrictions normally just one plane can be printed at once. Thus, the time per printing job does not change in between the different DLP machines (M2 or L1) and depending on the batch sizes. However, maximum batch sizes are significantly lower with just 8 parts for the M2 and 24 parts for the L1, respectively. The time per part can be calculated based on total printing time and the printed parts. SLS and MJF show similar behavior and end up in a similar order of magnitude with 0.09 h/part for MJF (1 Pass) and 0.12 hours/part for both MJF (2 Pass) and SLS. DLP shows significantly higher time per part which is a result of lower possible batch sizes.

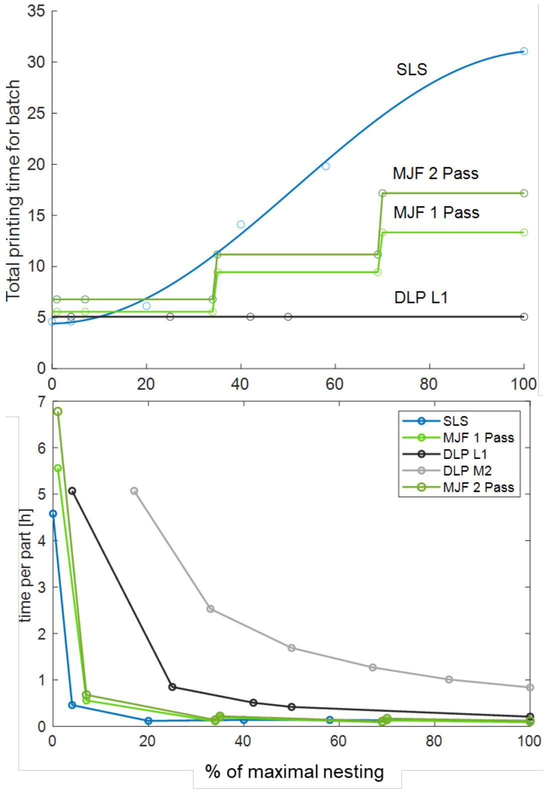


Fig. 5. Effect of batch size variations through nesting on total time for batch (upper figure) and relative time per part (lower figure)

4.2. Production capacities

The previous analysis showed the different characteristics of the three AM processes and also the favorability of applying nesting strategies. For series production it can be assumed that always the maximum batch size will be used. Given that, Figure 6 shows the production curves for producing an order size of 1000 parts.

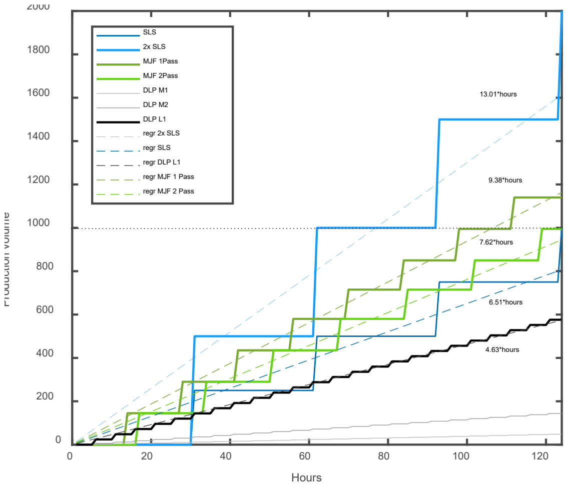


Fig. 6. Comparison of AM processes for production of 1000 parts

Again, the different characteristics of the processes become very clear with SLS and MJF having relatively high batch sizes leading to distinctive, sudden increase of production output once a batch is finished. DLP (L1) shows a more balanced output behavior which can actually be favorable when it comes to further processing of the parts and reduction of inventory. However, the production capacity of the DLP L1 is significantly lower compared to SLS and MJF. The regressions help to compare the process capacities here: MJF (even with 2 Pass mode) can finish the order earliest, followed by SLS (approx. 15% slower). This can even be accelerated through applying the MJF 1 Pass mode, but the resulting quality might not be comparable. To increase the production capacity, the addition of a second machine is another strategy which is shown in Figure 6 for the example of SLS. With that, the output can be of course produced significantly faster - assuming that orders run parallel would lead to a time reduction of 50%.

4.3. Economic and energy assessment

After those time related analyses, the final assessment is dealing with the impact on costs and process energy demand. Figure 7 gives a comprehensive overview of the results again based on the production scenario of an order with 1000 parts. Significant differences can be seen among the processes which are caused by the different processing times, hourly machine cost rates and power demands. Including the average values leads to a portfolio with four quadrant whereas the target area is in the left bottom where both low costs and low energy demand can be achieved.

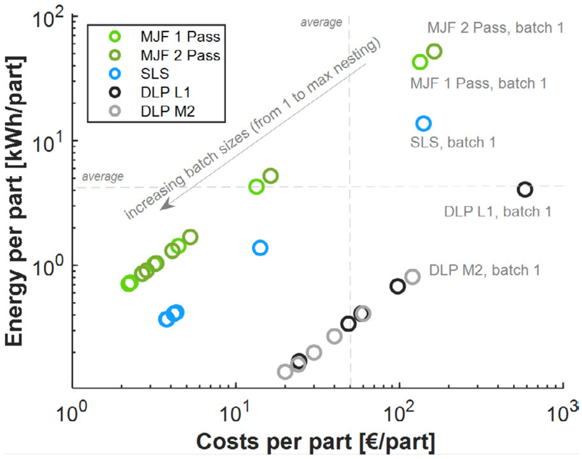


Fig. 7. Costs and energy per part for AM processes and batch sizes

Interesting conclusions can be drawn based on the results: For producing just a single part, DLP (with machine M2) is the best option from both costs and energetical perspective. Even more, when fully utilising nesting opportunities, DLP M2 is always the most energy efficient option for producing the parts. The diagram also makes very clear that fully utilising the printing space through nesting is very favourable and leads to significant reduction of costs and energy demand in all scenarios. In comparable batch scenarios, SLS shows better performance in terms of specific energy demand compared to MJF which is caused by high power values of the MJF machine. In contrast to that, MJF performs better from cost perspective while less process time combined with lower machine costs are of main influence here.

4.4. Discussion of results

The case study reveals interesting results which underline the different characteristics of SLS, MJF and DLP. The results are of course case specific but also give some generalizable insights regarding the impact of different upscaling strategies.

- The case study points out the different characteristics and effects on time, costs, or energy demand of **changing process technology**. This is a strong leverage with effects of 20-80% depending on which processes and target dimensions are compared. Also conflicts of goals can be found, e.g. for DLP as being the most energy efficient but for larger volumes also most costly process technology.
- **Nesting** has a major impact on the economic and environmental impact. While just producing single or few parts should be avoided and full utilization of the printing space is best, the study shows that at least a batch size of approx. 20-40% of the maximum batch size should be targeted to capture the main improvement effects. The improvement effect on both costs and energy demand is still recognizable but limited after that.
- The effect of changing **process speed** can be seen for the example of MJF while comparing the faster one pass with the two-pass mode. Using the one pass mode leads to time, costs and energy saving of over 20% - however, potential effects on product quality need to be taken into account.
- **Adding machines** is a quite obvious upscaling strategy which directly multiplies the production capacity as shown for the example of SLS. With that, this strategy also enables to bring relatively low-capacity processes towards relevant production volumes. As example, with just two DLP L1 machines significant more, balanced/continuous, and versatile output compared to SLS and MJF can be reached which makes it an interesting strategy from this perspective (but with higher costs per part).
- For DLP also the effect of **changing machines** is underlined – three machine types are available here which differ in terms of output, power demand and machine costs. This has strong impact of over 50% on resulting costs and energy demand in the given production scenario.

5. Summary and Outlook

While higher volumes of AM based parts are of increasing relevance, this paper analyses the upscaling strategies for SLS, MJS and DLP processes. Results underline the different characteristics of the AM processes and potential conflicts of goals in between technologies and economic as well as environmental objectives. SLS and MJF are most feasible when it comes to high total volumes and least costly production. However, if versatility and low energy demand is of interest, DLP is also an interesting alternative. As indicated before, this upscaling study is focusing on the AM process itself while leaving out effects on manufacturing system level, e.g. through post processing steps. Further work needs to be done here, for MJF first analyses are conducted in [4]. Additionally, material demand was intentionally left out in this paper to focus on the core aspects and strategies of upscaling. Since there might be interacting effects e.g. with quality rates, nesting strategies or support structures (DLP) future work should take material demand (and recycling) into account. Last but not least, the study here is based on a specific example from automotive industry. While this should be quite representative and results are to some extend generalizable, insights should be backed up by further studies and brought into transferable models.

References

[1] Gibson, I., Rosen, D. W., & Stucker, B. (2014). Additive manufacturing technologies (Vol. 17). New York: Springer.

[2] Wiese, M., Thiede, S., Herrmann, C. (2020). Rapid manufacturing of automotive polymer series parts: A systematic review of processes, materials and challenges. Additive Manufacturing, 101582.

[3] 3Dnatives Website (2020): The growth of automotive additive manufacturing, https://www.3dnatives.com/en/additive-manufacturing-automotive280620184/

[4] Wiese, M., Dér, A., Leiden, A., Abraham, T., Herrmann, C., Thiede, S. (2020). Dynamic modeling of additive manufacturing process chains for end-use part manufacturing. Accepted for publication at CIRP CMS 2021

[5] Gebhardt, A., Kessler, J., Thurn, L. (2018). 3D printing: understanding additive manufacturing. Carl Hanser Verlag GmbH Co KG.

[6] S. G. Rudisill, A. S. Kabalnov, K. A. Prasad, S. Ganapathiappan, J. Wright, Three-dimensional (3D) printing: US2018/0272602A1

[7] Emamjomeh, A., Prasad, K. A., Novick, M. A., & Fung, E. M. (2019). U.S. Patent No. 10,392,512. Washington, DC: U.S. Patent Office.

[8] Bourell, D., Kruth, J. P., Leu, M., Levy, G., Rosen, D., Beese, A. M., & Clare, A. (2017). Materials for additive manufacturing. CIRP Annals, 66(2), 659-681.

[9] Abdulhameed, O., Al-Ahmari, A., Ameen, W., & Mian, S. H. (2019). Additive manufacturing: Challenges, trends, and applications. Advances in Mechanical Engineering, 11(2).

[10] Verein Deutscher Ingenieure (2014), VDI 3405: Additive Fertigungsverfahren: Grundlagen, Begriffe, Verfahrensbeschreibungen.

[11] Galantucci, L. M., Guerra, M. G., Dassisti, M., & Lavecchia, F. (2019). Additive Manufacturing: New Trends in the 4 th Industrial Revolution. In Conference on the Industry 4.0 model for Advanced Manufacturing.

[12] DeSimone, J. M., Ermoshkin, A., Ermoshkin, N., & Samulski, E. T. (2015). U.S. Patent No. 9,205,601 (Continuous liquid interphase printing). Washington, DC: U.S. Patent and Trademark Office.

[13] Ligon, S. C., Liska, R., Stampfl, J., Gurr, M., & Mülhaupt, R. (2017). Polymers for 3D printing and customized additive manufacturing. Chemical reviews, 117(15), 10212-10290.

[14] Jasiuk, I., Abueidda, D. W., Kozuch, C., Pang, S., Su, F. Y., McKittrick, J. (2018). An overview on additive manufacturing of polymers. Jom, 70(3), 275-283.

[15] Wiese, M., Leiden, A., Rogall, C., Thiede, S., & Herrmann, C. (2021). Modeling energy and resource use in additive manufacturing of automotive series parts with multi-jet fusion and selective laser sintering. Procedia CIRP, 98, 358-363.

[16] Tagliaferri V, Trovalusci F, Guarino S, Venettacci S. Environmental and Economic Analysis of FDM, SLS and MJF Additive Manufacturing Technologies. Materials (Basel). 2019 Dec 11;12(24):4161.

[17] Baumers, M., Dickens, P., Tuck, C., Hague, R. (2016). The cost of additive manufacturing: machine productivity, economies of scale and technology-push. Technological forecasting and social change, 102.

[18] Busachi, A., Erkoyuncu, J., Colegrove, P., Martina, F., Watts, C., & Drake, R. (2017). A review of Additive Manufacturing technology and Cost Estimation techniques for the defence sector. CIRP Journal of Manufacturing Science and Technology, 19, 117-128.

[19] Kellens, K., Mertens, R., Paraskevas, D., Dewulf, W., & Duflou, J. R. (2017). Environmental impact of additive manufacturing processes: does AM contribute to a more sustainable way of part manufacturing?. Procedia Cirp, 61, 582-587.