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Resource Analysis Model and Validation for Selective Laser Melting, Constituting the Potential of Lightweight Design for Material Efficiency

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***Abstract*— Selective Laser Melting (SLM) offers significant potential for a sustainable way of production. Raw material in form of metallic powder can directly be reused and the selective nature of the process offers new potential for resource economization. We introduce a mathematical model, which allows conclusions about the influence of parameters like part volume (influenced by lightweight design) and exposure parameters onto the resource consumption in an SLM process. For this purpose, time and energy consumption are classified in process shares as a function of volume and process parameters. The introduced approach is validated by experimental methods under the consideration of part volume, exposure parameters and batch size. While the approach shall be independent of the manufactured material, the experiments are executed for the aluminum alloy AlSi10Mg. The measurements quantify the impact of the part volume and process parameters on the resource consumption and provide recommendations for improvements regarding an increased material efficiency. Additionally, the established model can be used to analyze manufacturing costs for single parts or series productions. The results illustrate the importance of lightweight design methods for an efficient and sustainable production by powder bed fusion methods like SLM.**

Keywords: Selective Laser Melting, structure lightweight design, small batch production, sustainability, energy consumption, resource efficiency

1 INTRODUCTION

Due to the incremental creation of material, Additive Manufacturing (AM) shows unrivaled freedoms in design. This facilitates the production of complex shapes often favored in lightweight design solutions, e.g. developed with structural optimization methods like topology optimization. Simultaneously, the manufacturing principle offers the possibility for an efficient use of resources [1, 2], since it follows the same principle as Structural Optimization for lightweight constructions by creating material only were it is necessary. This already shows the interdependency of the technologies. For a lightweight part, less material needs to be processed and thus resources can be economized in the SLM production compared to a not lightweight optimized design. Even when lightweight design is not beneficial to the performance in the operation phase of the part, it can lead to better material efficiency in production. Since the metal processing SLM-process ("Selective Laser Melting") is standing on the edge to first small batch productions [1, 2] in several industry sectors [3, 4], it is important to analyze the resource consumption to ensure the sustainability of the process. Furthermore, it is important for industrial enterprises to analyze the processing times and resource consumptions and therefore costs before deciding about the series production of a part. Since the creation of material consumes time and physical resources, the volume of the design could be the main factor regarding the resource efficiency in AM and is therefore the main focus in this work.

Topology optimization is conceived to find an optimized material distribution for a given load case within a predefined design space and therefore to reduce the design volume to a minimum [5]. However, Topology Optimization is usually used for application-specific implications in the operation of a part and so far not motivated by material efficiency considerations in the production process. Therefore, this work investigates the correlation between the degree of lightweight optimizations and the resource consumption in the SLM process.

2 STATE OF THE ART

2.1 Key Process Steps of Selective Laser Melting

The powder bed based SLM method uses a laser-beam to melt and fuse metallic powder particles in selected areas to a solid material. It is a two staged cyclic process, in which a coater system applies a new powder layer after the exposure of the previous. In-between the exposure and the application of a new layer, the powder bed is lowered by the thickness of one layer, so that the laser-focus-level is again on top of the powder. During the process, the material is created incrementally in sections and layers that are processed with different strategies and distinct parameter sets. The control over every increment allows, on the one hand, the high degree of freedom in design, and therefore the manufacturing of the complex structures. On the other hand, it causes a high complexity regarding the process control and the resulting material quality. Figure 1 illustrates the basic principle, [6–8] provide further information.

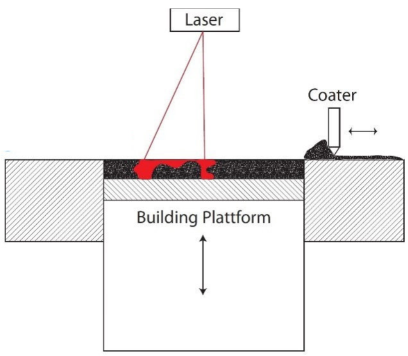

Figure 1: Basic principle of the SLM process. The powder bed is placed on a mobile building platform, while a laser source is melting the material and a coater unit is applying new layers.

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The nature of the process evokes the necessity of a resource consuming support structure, which depends on the part design and build orientation. Furthermore, the resource consumption depends on the chosen process parameters such as laser exposure parameters. The process runs in an inert gas atmosphere, potentially with a heated building platform to reduce the characteristic residual stresses in the generated material [9]. Like most materials, AlSi10Mg can be produced without any platform heating. This can result in increased residual stresses and therefore in distortion of the part. The process ability and resulting material properties however, are not impacted in a negative manner [10]. A full SLM production cycle requires several peripheral devices (e.g. chiller for laser unit, sieving unit, lifting tools, vacuum, wet separator, belt saw) as well as optional post treatment (e.g. heat treatment, grit blasting, additional subtractive manufacturing).

2.2 Sustainability Considerations Regarding AM

Most known publications focus on polymer proceeding processes; only Kellens, Mognol and Le Bourhis deal with the SLM process [11–13]. A broad literature review regarding the sustainability of all AM technologies is carried out by Ford, Gebler, Kohtala and Huang [14–18]. Ford [14] identifies sustainability benefits of AM especially in the extended product life, reconfigured supply chains and improved material efficiency. Early research in this field was undertaken by Luo [17], regarding the energy consumption of Fused Deposition Molding (FDM), Stereolithographie (SL) and Laser Sintering (LS) of plastics.

Telenko, Faludi and Morrow [19–21] compare different AM technologies like LS or Direct Metal Deposition with conventional manufacturing techniques like injection molding, regarding energy-, material and time consumption under the consideration of the batch sizes. A manufacturing specific design, which would make use of the advantages of AM, is not considered. Fordand Huang [14, 18] point out the need for further studies in the area of technology comparisons. Telenko [19] compares different LS machine types and divides the process into basic consumption for pre-heating and a job dependent consumption.

Baumers [22] divides the energy consumption for LS into a built height-, built time-, geometry- and job-dependent share. The analysis identifies the manufacturing time as the highest energy consumer in the polyamide processing LS technique. The author therefore advises to improve the machine by isolation. Alternative methods like reduction of machining time by part volume reduction is not alluded.

Kellens and Le Bourhis [11, 13] examine the time and energy consumption of the SLM process by tracking the electricity consumption. The results are implemented in a sustainability analysis. The works are based on a time dependent energy consumption approach.

Mognol and Zhang [12, 23] investigate the impact of part orientation, layer thickness, support design and manufacturing time for the SLA, FDM, Inkjet and SLM technology. The investigations are based on simple geometrical forms suited for the experiment, which do not represent a realistic AM part with a suitable design. The orientation is evaluated under the process specific limitations, since it influences the surface quality, accuracy and part properties. Mognols [12] research regarding SLM does not show any significant impact of the support structure on the energy consumption. Also, the change of exposure parameters does not show any impact. But since the machine vendor‘s parameters are used, the extent of parameter change is unknown. Mognol [12] draws a correlation between build time and energy consumption. Therefore, Mognol [12] advises to reduce the built height, but does not consider the mutual dependency between built height, suitable orientation and exploitation of building space for small batch productions. Sreenivasan [24] also identifies the powder bed heating and therefore the building time as the main consumer in the LS process.

The generation of less waste, the possibility to create optimized lightweight structures, the consequently reduced transportation as well as cost during the use phase are mentioned by Gebler and Chen [15, 25] as some of the key factors for sustainability through AM. Furthermore, Ford [14] determines larger production volumes and the use of the design freedom offered by AM (regarding lightweight as well as integrated assembly) as most relevant. According to Atzeni [26], these factors could have a bigger impact than the avoidance of tooling investment due to AM. Ford [14] points out the need for more case studies in this area on different products, application fields and organizations.

Topology Optimization for AM is presented by Brackett, Ibabe, Salonitis and Zegard [27–30]. Even though the process-dependent limitations are taken into consideration, the potential for a material efficient manufacturing is not mentioned.

2.3 Recycling of Aluminum and Titanium

One of the benefits regarding the sustainability of powder bed methods like SLM is the direct recirculation of the used powder material. According to Petrovic [31] 95-98 % of the metal powder can be recycled. Since polymers degenerate during the process, only a certain amount can be reused. Methods for an optimum mixing ratio are examined by Dotchev [32].

While the extraction of primary aluminum consumes considerable amounts of energy (GER-value »Gross Energy Requirement« of 270 MJ/kg), the recycling is considered efficient (16 MJ/kg) [33, 34]. AlSi10Mg can be recycled in a closed loop without losses in quality [16]. Primary titanium in contrast, is more energy consuming (361 MJ/kg). Due to process-induced contaminations like oxidation or cooling lubricant, the recycling of titanium is associated with quality losses and therefore uncommon [35, 36, 37]. Since no lubrication and only a low oxidation is resulting from the SLM process, the technology could be a source for easily recyclable titanium. The following work deals with aluminum, but it should be kept in mind that the benefits regarding titanium could be even higher, since the higher mechanical values will facilitate the design of a part with even less volume.

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3 MATERIAL AND METHODS

3.1 Methodology and Research Objective

A prevalent method of environment impact analysis is "Life Cycle Assessment" (LCA). The LCA requires detailed knowledge of material flows and input/outputs during each of these different phases of the product life cycle [38]. However, the required data on AM process and in particular the SLM process is still limited [18].

By classifying consumption shares, a new approach to analyze the resource consumption is developed based on Telenko and Baumers [19, 22]. This approach enables statements about the impact of different parameters like the design volume or manufacturing parameters. It is independent of the part design, material or batch size and can therefore be used for consumption estimations.

The success of SLM will depend on the ability to use the benefits of the technology, which are mainly based on new part designs. Due to the incremental nature of SLM and the limitations of the process, e.g. residual stresses and distortions, designs for classical manufacturing techniques are often less suitable for additive production and less efficient than parts designed explicitly for SLM [39]. This holds also true in terms of material efficiency. A lightweight design developed for SLM with structural optimization will potentially use less resources in additive production. Therefore, this work analyzes the influence of the part volume on the resource consumption. In particular, the developed model and experimental validation aim at constituting and quantifying the potential of lightweight design for resource savings during SLM production.

The main objectives of this work are therefore:

1. Develop and validate a mathematical model, which can predict resource consumption (e.g. time, energy or powder) for the production of a part by SLM.
2. Evaluate the impact of parameters (e.g. part volume, manufacturing parameters or built orientation) onto the resource consumption.
3. Assessing the potential of lightweight design for material efficiency in SLM production based on the proposed model.

3.2 Part Design and Structure Optimization

A wheel carrier is used as an industry-relevant part within the scope of this work. Combining the benefits of integral- and lightweight construction in one part, the developed wheel carrier provides an excellent example of the advantages of Additive Manufacturing in a small batch production. In order to quantify the influence of lightweight construction and therefore the use of numerical structural optimization on the consumption of resources during the manufacturing process, various design concepts of the wheel carrier were developed.

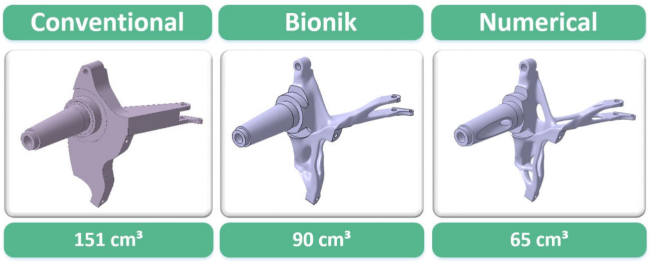

Figure 2: Examined design concepts. 1: Conventional design, 2: Bionic design, 3: Numerically optimized design.

Figure 2 shows the three different design concepts of the wheel carrier. The first concept represents a *design for conventional* manufacturing techniques, followed by a *bionic design* created under the use of topology optimization. It represents an optimized solution of the structure under the defined boundary conditions. The load case s cenario was derived from a set of defined brake braking scenarios of an ultralight vehicle. The structural optimization is based on high safety factors. The third design represents a further optimization iteration to gain a higher degree of lightweight and therefore material saving. In order to create the numerical optimized structure, a topology optimization based on a Solid Isotropic Material with Penalization (SIMP)-technique was used. After defining the design space illustrated in Figure 2 (concept 1) and defining the boundary conditions and implementing the applied forces, the goal of the optimization is to maximize the stiffness under the use of 30 % of the pre-defined design space. Neither the *bionic design (2)* nor the *numerically optimized design (3)* can be produced with conventional manufacturing techniques.

3.3 Machine and Parameter Setup

The experiments are carried out with a commercial SLM system (EOS M 400), equipped with a 1 kW laser unit (YLR-Series, wavelength 1070 nm). The use of an enhanced building volume (up to approx. 398 x 398 x360 mm³), build layer thickness (90 µm), laser power and bidirectional coating enable the production of multiple parts in one run and a reduced build time per part. These factors allow a high productivity. Therefore, the system is well suited for the consideration of small batch production of medium sized parts.

The building platform is heated to 165 °C during the experiments in order to reduce the process characteristic residual stresses [9]. Furthermore, the machine is equipped with nitrogen generators to gain inert gas out of pressurized air. Since most commercial systems run on an external inert gas supply, the generators are turned off and the machine is running on an external argon supply to gain a higher practical relevance of the results. The energy supply of the chiller unit is connected to the main machine requiring no extra measurement. The energy consumption of further peripheral units used (sieving unit, lifting tools, vacuums, wet separator and belt saw) is measured separately.

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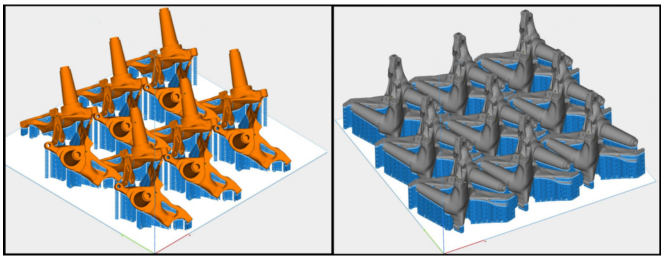

Higher Quality Max. Batch Size

Figure 3: Possible building setups. Left: part orientation suitable for stable production. Maximum of 12 parts. Right: Part orientated for a maximum batch size, regardless of producbility and resulting quality. Maximum of 18 parts.

A material-efficient filigree type of support is used. Part orientation and support are shown in Figure 3. The part is orientated in a suitable way to gain a high part quality regarding surface roughness, material defects and process stability. The *"higher quality"* orientation enables a total of 12 parts per job. A higher job fill rate of 18 parts per job can be achieved by the alternative orientation "*maximum batch size"* (see Figure 3 right). However, the alternative "*maximum batch size"* orientation is less suitable regarding the process stability and manufacturing quality. The massive support structures of this setup are difficult to remove and result in a bad surface quality. The sudden change of exposure cross-sections can lead to surface cracks, increased distortion, a flawed coating mechanism and possibly to a jamming of the coating unit due to the separation between the support structure and the part itself and therefore to a stop of the manufacturing process.

The work is executed using water atomized AlSi10Mg powder with a particle size distribution (PSD) range of 12.28 µm–43.22 µm (D_{10} and D_{90} values). The choice is based on the parts' application as well as the high scientific relevance and market share of the powder type. [1, 40] A rotating stripes exposure strategy (see Figure 4) is applied, using down- and upskin areas as well as a contour exposure for an improved surface quality.

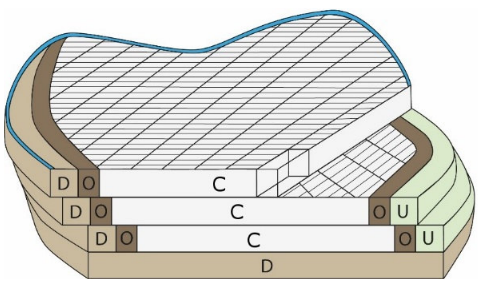

Figure 4: Layer dependent exposure strategy using rotating stripes and exposure areas for varying thermal boundary conditions. Blue: contour; core »C«; downskin »D«; upskin »U«; overlap »O«.

	Power [W]	Speed [mm/s]
Contour	500	1000
Upskin	500	1100
Downskin	900	5000

Table 1: Original exposure parameters.

For the exposure of support and part volume, *original exposure parameters* of the machine vendors' are used. Table 1 contains individual minor parameter values used for an improved surface quality. Table 2 presents *alternative exposure parameter*s.

	Power [W]	Speed [mm/s]
Contour	900	420
Downskin	900	5000

Table 2: Alternative exposure parameters (upskin deactivated)

4 Novell Process Analysis Regarding Resource Consumption

4.1 Classification of Resource Consumption

The process energy consumption is affected by several parameters. While the following job factors (digital pre-processing parameters) are investigated in this work, the machine factors are considered as fix setup conditions.

Job factors:

- building height
- batch size
- part orientation
- part volume
- support design
- exposure strategy and parameters

Machine factors:

- used machine and periphery
- temperature of building platform
- settings coater system (e.g. speed)
- settings inert gas system (e.g. differential pressure, thermal conductivity of used gas)
- generation of gas (external vs. generator)

It has to be taken into account that the part orientation limits the building height and batch size. Furthermore, it defines the necessary support design. Therefore, part orientation, building height, batch size and support design are interdependent and therefore define a *building setup* (see Figure 3). The interaction between part orientation and exposure time due to changing laser tracks is neglected based on the results of Mognol [12].

The following classification of energy consumption intends to evaluate the impact of job and machine factors. Alternative classifications found in the literature can be useful for different observations. Based on Telenko [19], the total energy consumption of an SLM manufacturing cycle has to be divided into two main shares (see Figure 5). A *„static" base load* describes the standard consumption necessary to prepare and start the process (e.g. establishing process conditions). This share is independent of the manufactured parts and contains the consumption necessary to attain the operational state of the machine and to remove parts and powder (including all use of periphery).

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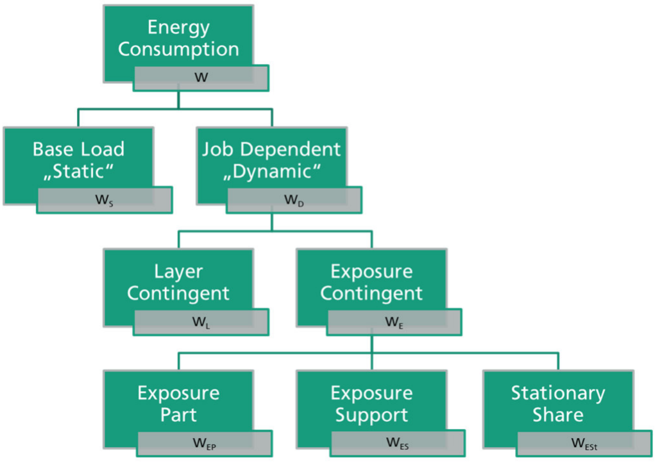

Figure 5: Breakdown of energy consumption of the SLM process.

Baumers' [22] division of the job-dependent *dynamic* share is tailored to a specific test specimen. Therefore, it is not suitable for the examined part. In this approach, the *dynamic* main is divided into a *layer* ("built height-") and *exposure contingent* and is therefore depending on built height, batch size, support and part orientation. Under the assumption that the coater movement is negligible, the *layer contingent* is merely consisting of the power P_{stat}, which is necessary to maintain the stationary state of the machine consisting of data processor, control unit, chiller and heater consumption. The *exposure contingent* is divided into the *exposure of the part* and *support* consisting solely of the laser's energy consumption. At the same time, the stationary machine state has to be maintained. This *stationary share* is equal to the *layer contingent*, due to neglecting of coater movement, but is classified separately in order to enable a clear statement regarding the impact of the job factors. Furthermore, it has to be taken into account that the stationary consumption could increase by heat dissipation due to the growing size and therefore radiating surface of the powder bed during the process. The exposure duration within one layer can also influence the *stationary share*, since the heat induced by the laser beam is supporting the platform heating. This effect is neglected in this work, since it is hard to quantify experimentally and should therefore be regarded in further investigations. The simplification could result in a proportional shift within the *exposure contingent*, but will not influence the global results. Therefore, the energy consumption can be described as follows:

$$W = W_s + \sum_{i=1}^{\frac{h}{d}} P_{stat_i} t_i + n\left(\phi V + P_{sup} t_{sup}\right) \tag{1}$$

t_i: dwell time in layer i.
n: batch size
ϕ: exposure power density (depending on exposure parameters)
V: part volume
P_{sup}: power support exposure
t_{sup}: time support exposure

The formula is split into a measurement friendly structure following the division of Figure 5 under the assumption that P_{stat} is not significantly depending on the building height:

$$W = W_S + W_D \tag{2}$$

$$W_D = W_L + W_{ESt} + n(W_{EP} + W_{ES}) \tag{3}$$

$$W_L = P_{stat} \Delta t \frac{h}{d} \tag{4}$$

$$W_{ESt} = P_{stat}\left(t - \Delta t \frac{h}{d}\right) \tag{5}$$

$$W_{EP} = \phi \mathrm{V} \tag{6}$$

$$W_{ES} = P_{sup} t_{sup} \tag{7}$$

Known parameters:

- d: layer thickness
- h: built height
- n: batch size
- t: measured manufacturing time
- W_D: measured energy consumption
- t_{sup}: exposure time support

Parameters to determine:

Δt: Time for layer application (inc. delay time) was measured over 87 layers by hand (μ = 10.28 s, σ = 0.12).

P_{stat}: Power during stationary state (heating, setting of filter system, data processor etc.) was measured while the process paused in the first layer for 28 hours. The first 4 hours have not been taken into account to ensure a stationary thermal state of the machine. Measurement was repeated four times (μ = 4.608 kW, σ = 0.074).

The exposure time t_{sup} for the support is determined based on laser track distance and the respective exposure speed. With Δt, this method can also be used to calculate the total manufacturing time. P_{sup} is estimated by assuming a typical degree of efficiency of 40 % [41]. Since the full laser power of 1 kW is necessary for the support exposure, a consumption of 1.4 kW was assumed for P_{sup}. By measuring t and W_D, the exposure power density ϕ remains the only unknown parameter and can therefore be determined by using Equations (2) to (7).

4.2 Experimental Analysis

Based on a *reference experiment A,* the impact of the topology optimization and therefore part volume is examined in a second *experiment B*. Furthermore, the impact of the presented alternative exposure parameters is investigated in *experiment C*. Several parts in one manufacturing process could lead to a down time in between the exposure of different parts. The introduced segmentation of energy consumption does not consider any impact by batch sizes. Therefore, *experiment D* is conducted to validate the approach for small series productions. The four necessary experiments are visualized in Figure 6 and will be introduced in the following. All experiments are executed with the *higher quality* part orientation.

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Experiment A: reference sample
Manufacturing of a single *numerically optimized design* in center position.

Experiment B: impact of part volume
Manufacturing of a single *bionic design* in center position. Slight change of support design is necessary due to the changing part geometry. The impact of the part volume is determined by comparing *bionic* vs. *numerical* design (see Figure 2).

Experiment C: impact of exposure parameters
Repetition of *experiment A,* using *alternative*- instead of *original exposure parameters* (see Table 1 vs. Table 2).

Experiment D: scale effects regarding batch size
Manufacturing of 12 *numerical optimized designs* manufactured in the *higher quality building setup* (see Figure 3).

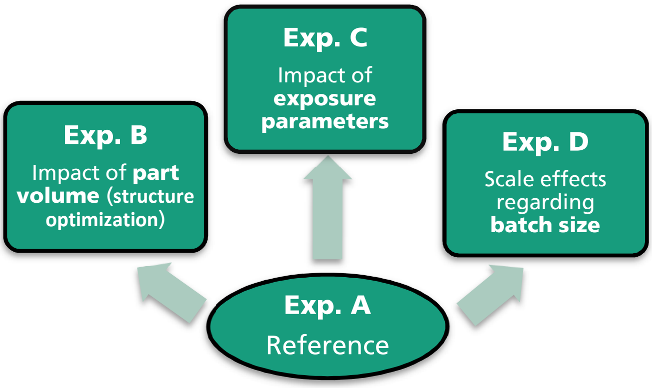

Figure 6: The test series consisting of 4 experiments to study the impact of exposure parameters, batch size and part volume (focus of investigation marked in black).

The conducted experiments are also used to investigate the powder and therefore material loss, besides the resources energy and time. The amount of powder loss is obtained from four gravimetric measurements per experiment. A complete mass balance is obtained by measuring the weight of powder and the building platform before the start of the process as well as the amount of powder (after sieving) and the building platform (now including the built parts and support) after the manufacturing process. The reasons for powder loss are diverse. Smaller powder particles are removed by the inert gas flow in the process chamber and end up in the machine's filter system. Unwanted side products like welding beads, powder agglomerations or metallic condensate are separated in sieving processes and filters. Also, during the process of the powder handling and cleaning of the machine equipment, powder adhering to surfaces is getting lost. [42]

The powder used in the SLM process requires atomization. No reliable data exists on embodied energy and CO_2 footprint of this type of powder. For consideration in this work, the embodied energy and CO_2 footprint are calculated theoretically using the following estimations: According to Petra Icha [43], the average CO2 emissions based on the German energy mix in 2015 were 535 g/kWh. The production of common aluminum requires roughly 15700 kWh per ton [33]. Lachmayer [44] postulates that 10 % of the energy required for the raw material production is necessary to atomize the raw material to powder usable for the SLM process. For completeness, a fictive way of transport of 1000 km by truck (97500 gram of CO_2 per ton and km) is assumed [45]. Due to the possible recycling of the removed support material, the impact of support material is not considered.

5 Results and Discussion

5.1 Energy Consumption and Manufacturing Duration

Referring to Figure 6, the *base load* of the process is divided into the following operational steps:

- machine **preparation**
- **heating** of building platform
- **flushing** with inert gas of the building chamber
- powder **removal**

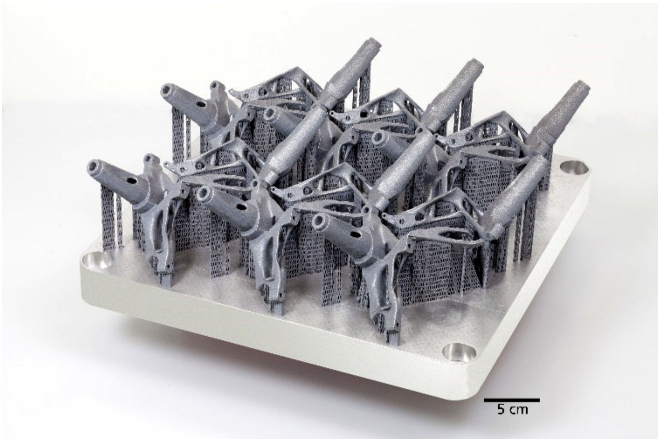

Figure 7: Manufacturing result of Experiment D.

Working time of and energy consumed by the machine are measured for each operational step in all four experiments, leading to the conclusion on the power consumption. The results are shown in Table 3. Furthermore, the peripheral units consumed a total of 1.02 kWh (σ = 0.33) during the operational steps. The total *base load* per manufacturing cycle therefore takes 7.31 kWh.

The manufacturing result is shown exemplarily for *Experiment D* in figure 7. The results of the measurements are shown in Table 4. The *layer contingent* was determined under the use of Δt and P_{stat} resulting in a consumption of 0.01 kWh per layer. Since all experiments are based on the same building

	Preparation	Heating	Flushing	Removal
Power [kW]:	0.52 (σ = 0.07)	6.23 (σ = 0.30)	0.09 (σ = 0.04)	1.45 (σ = 0.94)
Duration [h]:	0.5 (σ = 0.12)	0.5 (σ = 0.02)	0.2 (σ = 0.08)	2.0 (σ = 0.41)
Resulting Consumption [kWh]:	0.26	3.11	0.02	2.90

Table 3: Measured consumption for base load.

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height, the *layer contingent* consumes 3.37 h and 15.53 kWh of the *job dependent share*. P_{stat} is calculated based on the stationary share. The power density ϕ is calculated by dividing the *exposure part* W_{EP} by the parts volume. The determined data corresponding to Figure 6 (see Table 4) is visualized in Figure 10.

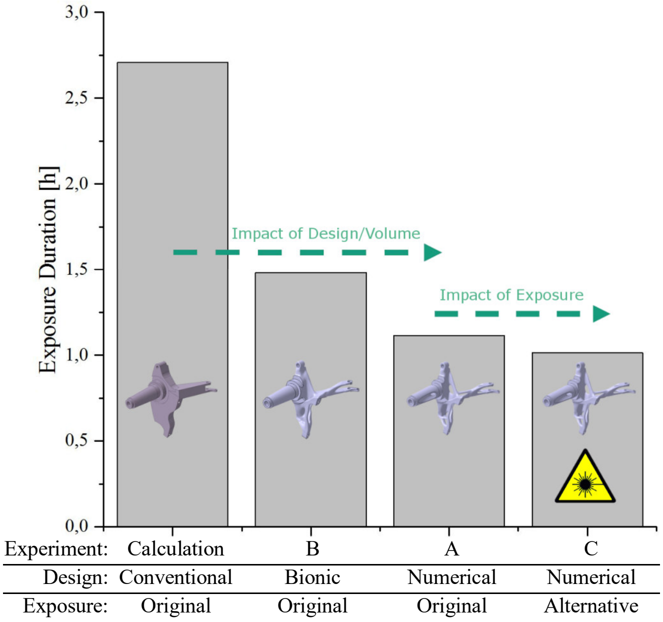

Figure 8: Part and support exposure duration depending on volume (design) and exposure parameters. Results show the consumption for a single wheel carrier. For detailed data, see Table 4.

<u>Experiment B: impact of part volume:</u>

As expected, the reduced part volume shows a strong reduction of *part exposure* time, and therefore also of the energy consumption shares *exposure part* and *stationary share*. A comparison of the part exposure durations is shown in Figure 8. The resulting impact on the energy consumptionis compared in Figure 9. The power density shows a slight deviation due to the change of part volume (6 %). This can be explained by the alternative arrangement of laser tracks due to the change of shape.

<u>Experiment C: impact of exposure parameters:</u>

In contrary to Mognol's [12] observations, the results show that the power density is also correlating with the exposure parameters (-25.1 %). Therefore, the energy consumption can be significantly affected by the choice of exposure parameters.

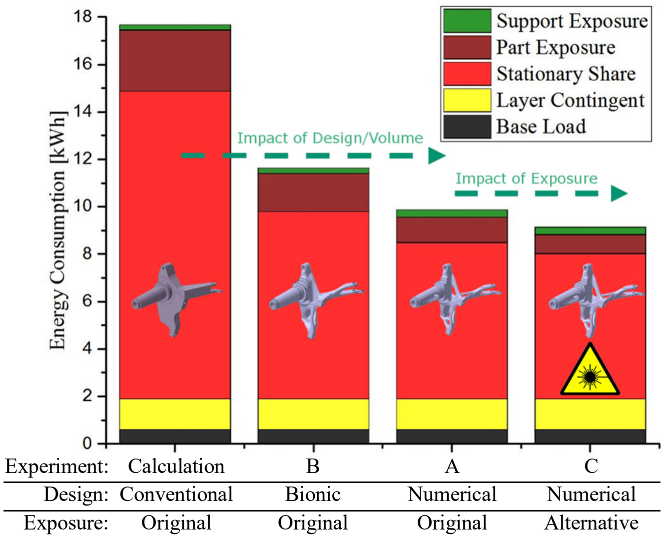

Figure 9: Energy consumption depending on volume (design) and exposure parameters. Results show the consumption for a single wheel carrier considering a batch size of 12 per manufacturing cycle. For detailed data, see Table 4. For legend definition, see Figure 5.

<u>Experiment D: scaling effects regarding batch size:</u>

To compare the scalability, the results of *Experiment D* are considered part-specific in the last column of Table 4. The results show that the exposure duration is slightly extended by 1 %. This supports the mentioned theory of down time between the exposure of different parts, which is the time to reach the laser track entrance point of the next part. However, due to the slight extent, this effect will be neglected for theoretical consideration. The values marked in green support the assumption that the scalability effects can be neglected.

The Equations (2) to (7) are proven valid by the measurements and can therefore be used to compute the

	A: Numerical Optimized Design	B: Bionic Design	C: Alternative Exposure	D: Complete Batch (12 Parts)	D: Batch per Part
Energy Consumption [kWh]	23.51	25.27	22.78	112.08	9.34
Production Time [h]	4.80	5.08	4.70	20.67	1.72
Exposure Duration [h]	1.43	1.71	1.33	17.30	1.44
Layer Contingent [kWh]	15.53	15.53	15.53	15.53	1.29
Exposure Contingent [kWh]	7.98	9.74	7.25	96.55	8.05
Stationary Share [kWh]	6.59	7.90	6.13	79.71	6.64
Exposure Part [kWh]	1.08	1.60	0.81	13.08	1.09
Exposure Support [kWh]	0.32	0.25	0.32	3.78	0.32
Duration Support [h]	0.14	0.11	0.14	1.68	0.14
Duration Part [h]	1.29	1.60	1.19	15.60	1.30
Power Density [kWh/cm³]	0.0167	0.0177	0.0125	0.0168	0.0168

Table 4: Measured experiment data and derived values. Green values: Verification of scalability. Data is visualized in Figure 8 and 9.

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resource consumption of the *conventional design* (see Figure 2) produced by SLM. The necessary power density ϕ is unknown. However, the variations in power density between the numerically optimized design and the bionic design show a small variation of about 6 %. But since the bionic design is more massive and therefore closer to the conventional design, the power density measured for the *bionic design* is used. The calculated resource consumptions are added in Figures 8 and 9.

Overall, the results show the importance of the part volume regarding manufacturing time and energy consumption. The parts volume is primarily impacting the exposure duration (see Figure 8). The energy share *part exposure* necessary for fusing the material seems relatively low (including the savings by change of design). However, the reduced exposure duration has a major influence on the energy consumption. The savings in the *stationary share* are disproportionately high compared to the effect on the *part exposure* consumption (see Figure 9). The change of exposure parameters also shows similar but minor effects. Furthermore, it has to be taken into account that the flexibility regarding the change of exposure parameters is limited due to physical effects (e.g. necessary energy application), machine limitations (e.g. max. exposure speed) and the quality of the manufactured material. Therefore, the change of design offers higher potential regarding material efficiency. Figure 9 shows a pronounced *stationary share*. It seems reasonable that the heating of the building platform is consuming a major share. Therefore, it could be advisable to turn off or lower the heating if the part allows this without any losses regarding its distortion.

5.2 Effect of Batch Size in Comparison to Design

To quantify the impact of the batch size per building job, the Equations (2) to (7) are used to consider the *maximum batch size* setup vs. the *higher quality* setup of Figure 3. The figure demonstrates the maximum of parts in one building process as the maximum fill rate without consideration of producibility. To analyze the impact of the presented job factors' volume, exposure parameters, and building setup consisting of orientation, batch size and building height, a full factorial experimental design is created and the resulting energy consumption and manufacturing times are computed (see Table 5). The impact of the considered job factors are quantified by the dimensionless value of the "standardized effect", which describes the difference between two variable states (t-test) under the consideration of the standard deviation (f-test). The shown correlation describes the effect that a factor depends on the setting of a different factor. This means, for example, that the effect of the building setup depends on the chosen design. [46]

The result (see Figure 10) shows a rather low effect of the building setup. This could be due to the limiting interaction between the three connected factors building height, batch size and orientation. An increased batch size, for example, would require an orientation which would increase the building height, which is increasing the *layer contingent*. Furthermore, the importance of part volume and exposure parameters as main factors is evident. The correlation between volume and building setup can be explained by the ratio of *layer contingent* and *exposure contingent*. A growing total exposure volume will reduce the importance of the *layer contingent* and therefore building height. Therefore, alternative building setups can have a different impact depending on the part volume.

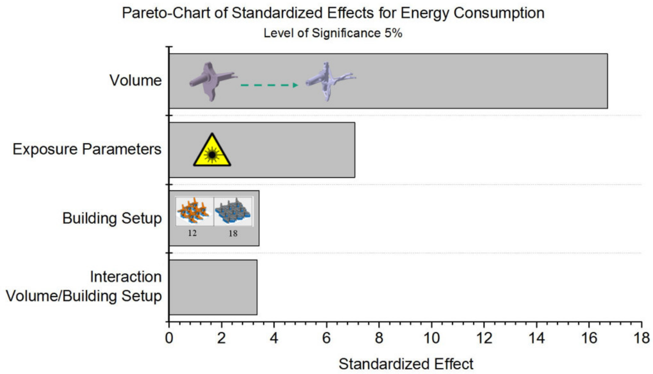

Figure 10: Visualization of job factors' impact on energy consumption by standardized effects for the examined wheel carrier. Orientation, batch size and build height were treated as one parameter (building setup). Non-significant parameters and interactions are not listed. For database see Table 5.

5.3 Effects on Powder Loss

The powder balances measured for the four experiments reveal the powder loss during the manufacturing cycle (see Figure 11). The measurements show that it is advisable to evaluate the loss in relation to the manufactured material, which can be determined by the difference in weight of the building platform including the build parts and support

Building Setup (see Figure 3)	Design Version (see Figure 2)	Exposure Parameters (see table 1 vs. 2)	Energy Consumption per Part [kWh]	Manufacturing Time per Part [h]
Higher Quality	Numerical Design (65 cm³)	Alternative	8,5	1,6
Max. Batch Size	Numerical Design (65 cm³)	Alternative	8,9	1,7
Higher Quality	Bionic Design (90 cm³)	Alternative	10,4	2,0
Max. Batch Size	Bionic Design (90 cm³)	Alternative	10,7	2,0
Higher Quality	Numerical Design (65 cm³)	Original	9,3	1,7
Max. Batch Size	Numerical Design (65 cm³)	Original	9,6	1,8
Higher Quality	Bionic Design (90 cm³)	Original	11,4	2,1
Max. Batch Size	Bionic Design (90 cm³)	Original	11,7	2,1

Table 5: Trial design to determine impact of job factors. Results are based on theoretical calculation.

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structures. The results confirm an impact of volume as well as exposure strategy and batch size. Since the standard deviation is unknown, no statement regarding the significance can be made. However, the results are conclusive, considering that an enhanced volume results in more side products like welding beads or condensate. In relation to the manufactured material, the powder loss is smaller. This suggests that, due to an enhanced volume and thereby exposure cross-section, the emerging side products fall into exposure areas where they can be re-melted and worked into the material. The same, but intensified effect can be seen on the results of the batch production, where side products can fall on other parts. This effect could probably lead to impurities and therefore affect the quality of the final material. Therefore, a *numerically optimized design* could have the side effect of less building defect, due to a reduced amount of re-melted side products.

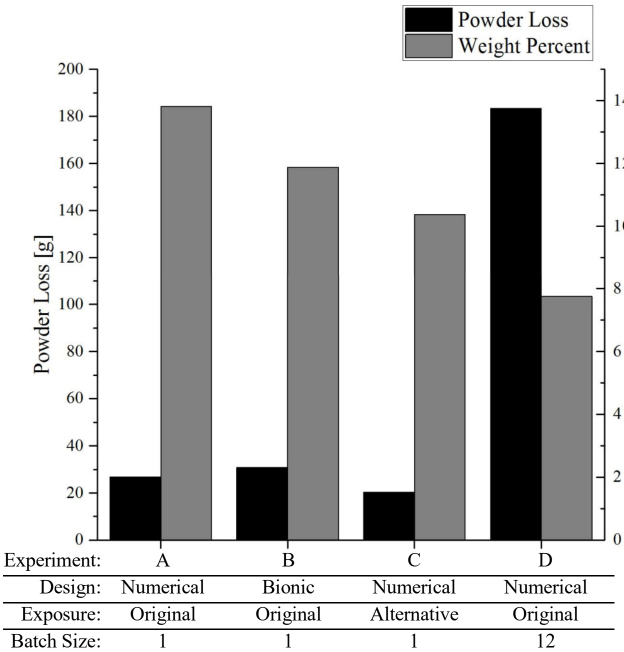

Figure 11: Powder loss and proportion to manufactured material (weight percent).

The change by the alternative exposure parameters is coherent, considering that the total laser track distance is reduced, which is reflected in the time and energy consumption. Furthermore, different energy densities induced by the laser beam can result in different interactions.

5.4 Calculation of CO_2 Emission

The calculated CO_2 emissions include the presented total energy used during the SLM process as well the emission resulting from the lost and melted powder. The base values are presented in the chapter "*Recycling of Aluminum and Titanium*". Considering a batch size of 12 parts, 8.7 kg of CO_2 are resulting from the production of a single *conventional design*, 5.6 kg from the *bionic design,* and 4.7 kg from the *numerical design*. Due to the consideration of the powder consumption the results are not proportional to the design volume or energy consumption.

6 CONCLUSION

The proposed resource consumption breakdown (see Figure 5) and correlating resource analysis model (Equations (1) to (7)) are validated by the experimental data and can therefore be used for consumption estimations of small batch productions. The independence of the batch size for the proposed approach is demonstrated by Experiment D. The resource analysis model is independent of the used material and SLM system. Observed economizations in consumption for the executed experiments are summarized in Figure 12.

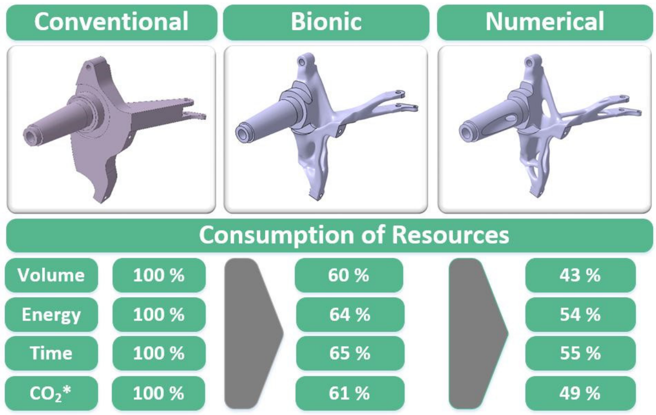

*Figure 12: Consumption of resources by SLM production for different design optimization concepts. 1: Design for conventional manufacturing technologies. 2: Bionic design. 3: Numerical optimized design. Values for the conventional design are derived from theoretical considerations. * CO_2 emissions include process energy consumption and manufacturing of aluminum powder. Other resources like argon or pressurized air are not included.*

In all considered domains (energy consumption, CO_2 emission, manufacturing time and powder loss), the design optimization shows a substantial effect on the resource efficiency. The results suggest that a reduction of part volume (e.g. via design optimization by numerical methods) is the most efficient way for economizations in CO_2 emission, manufacturing time, energy consumption and therefore costs. This thesis is supported by Figure 10 for the regarded case. The choice of parameters (see Tables 1 and 2) and building setup (see figure 3) also shows a certain effect. However, the effects are minor and limited in parameter variation.

<u>Domain manufacturing time:</u>

Figure 8 illustrates the reduction of exposure time. While the duration is mainly influenced by the chosen design and thereby part volume, the choice of exposure parameters also shows a minor but significant effect.

<u>Domain energy consumption:</u>

Figure 9 in combination with Figure 8 shows that the reduced exposure time has a major effect on the total energy consumption. This is not due to the reduced energy necessary for the exposure, but to the reduction of exposure time, resulting in a reduced share to maintain a stationary state of the SLM system. The energy consumption is therefore mainly influenced by the manufacturing time.

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Domain powder loss:

Figure 11 demonstrates a potential for a reduced powder loss due to the reduced volume by design optimization.

Domain CO_2 emission:

Due to the combination of a reduced powder loss and reduced manufacturing time and energy, the CO_2 emission is showing the highest economization.

Besides the potential of design optimization and exposure adjustment, the introduced resource consumption breakdown shows the potential of changes in machine technologies like enhanced laser power, exposure speed, layer thickness, improved insulation, temperature of building platform or new coating systems. These would result in a reduced stationary share, as well as manufacturing time and therefore consumed energy.

Sustainability benefits of lightweight design regarding other alloys like titanium can be higher than for aluminum, despite the higher material prices. This is due to the improved specific strength and stiffness. Therefore, parts with less volume can be developed, saving manufacturing time, energy, and material. The analysis should be applied for other materials to validate his thesis. Also the potential of resource economization by SLM should be demonstrated by comparing the technology with a traditional manufacturing technology should be quantified in further studies.The results illustrate the interdependency of topology optimization and additive technologies. While the production of topology optimized parts usually depends on additive techniques, the latter require volume optimized parts for an economic and efficient manufacturing.

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