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Investigation of Influencing Variables on Sustainability of 3D-Printing and Fused Deposition Modelling

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Abstract *A variety of different additive manufacturing processes have been available for the last three decades. This paper investigates energy and material consumption using 3D colour printing 3DP and Fused Disposition Modelling FDM as example. On the basis of several measurements of energy consumption a comparison of the specific energy consumption with other generative technologies is fulfilled. In 3DP several variables, in which resource consumption can be reduced are investigated and compared. For example the influence of the geometry and the positioning of the part in the construction space on the consumption are investigated. But also the measuring of different batch sizes is compared. The FDM system offers the opportunity to choose from different filling methods in order to reduce materials consumption as well as manufacturing time and thereby costs. Therefore the achievable material strengths as well as the material and energy consumption of this FDM system are investigated. Furthermore an economic comparison of the filling methods is given. Using the results found, the use of 3DP and also FDM can initially be optimized so that less energy, resources and manufacturing time are required.*

1 Introduction

The energy requirements both of a growing world population and of the industrial sector are continually on the rise. This puts a strain on the environment and leads to increased emissions, climate change and a scarcity of fossil resources [1]. For companies this not only means a rise in energy costs and a tightening of environmental regulations, as for example laid down in the Kyoto Protocol on international climate protection, but also a direct responsibility to increase sustainability by cutting back the negative effects of energy consumption. In the European Union, a majority of consumed resources are used to generate power, which at the same time is responsible for a considerable amount of the CO_2

emissions produced in the EU [2]. If companies take measures to save energy and apply it more efficiently, that in turn means a decrease in emissions and in the depletion of raw materials and puts less pressure on the environment. Energy used efficiently leads to a minimization of energy costs, so that the competitiveness of the company and its products can be enhanced [1].

Apart from these challenges in the field of energy consumption, companies are also being confronted with changes in market requirements. With many of today's products there is a demand for more variety and smaller quantities, as customers prefer individual rather than mass products [3]. Technical progress means that the life-cycle of a product is considerably shorter, depending on the manufacturing sector. In order to satisfy the demands of the market, companies must customize their product development and product development time [3]. One way of doing this is by using Additive Manufacturing (AM) technologies.

2 Presentation of both additive manufacturing technologies examined

Additive Manufacturing is the term used to describe the quick manufacture of samples or prototype construction parts in successive additive layers. The original material is strengthened or solidified layer by layer by applying energy to it. The separate layers are thereby bonded or fused. The original material may be powdery, fluid or solid. This depends on the chosen technology [4].The two techniques, 3D-Printing (3DP) and Fused Deposition Modeling (FDM) represent two important methods in the broad spectrum of AM technologies, with a considerable market share [5]. Both methods are characterized by low acquisition costs and operating costs of the equipment when compared to laser-based techniques like, e.g. Laser Sintering (LS) or Selective Laser Melting (SLM). 3DP is one of the few techniques that can produce color models, which makes it particularly suited for the production of presentation models and for the currently booming market of 3D figures. FDM technique stands out due to its very initial costs. A lot of the devices for home use on the market today, many of which are available for an price of less than EUR 1.000, are based on this technology [6].

Over the past years, the consumption of material and energy, and thus the sustainability of the various techniques, has been researched by several authors. Baumers et al. as well as Kellens at al. have conducted detailed studies of the energy consumption of laser-based AM technologies [7, 8]. In the meantime, these and other results have been incorporated into an extensive meta-study by Yoon et al. [9]. This study not only compares the energy consumption of several additive methods, but also sets it in relation to subtractive and forming processes. However, this study focuses mainly on a comparison of energy consumption, which is to say, the other aspect that is important for an evaluation of sustainability, material consumption, is not included in the research. The materials which were used and the energy required for each of the steps in production with 3DP and also with FDM are shown in Fig. 1. In this procedure the virtual model from CAD is first preprocessed by reading the data into the control computer, in which printing is prepared with the help of the print software which controls the hardware. Then the virtual model which has been sliced into separate layers is entered as print-data into the device.

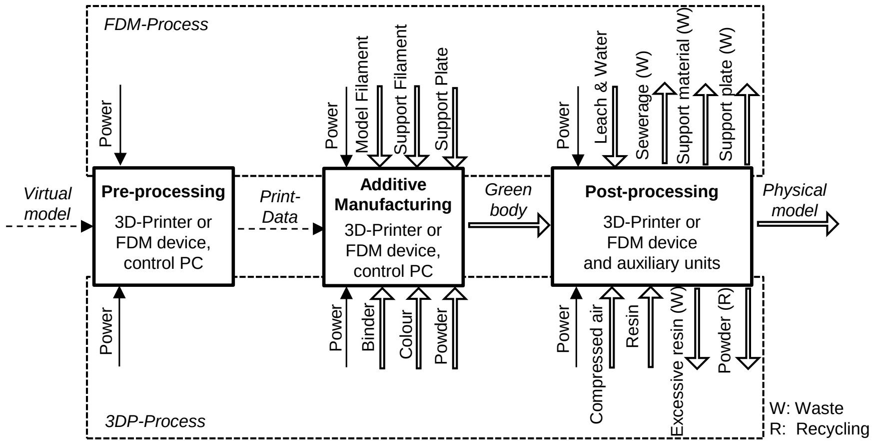


Fig. 1: Application of materials and energy in 3DP and FDM process

In the 3D-Printer (Z450 from ZCorporation) a real 3D model is formed by joining layers of polymer plaster material with a liquid binder. With colored models the color is added to the surface layer by an additional printing head. Powder serves as a supporting agent for the construction part which at this point is described as a "green body" due to its unstable and unfinished form. In a subsequent postprocessing procedure the superfluous powder, which can be used again untreated, is blown off by compressed air. Furthermore the construction part is manually infiltrated with a two-component synthetic resin, in order to increase its strength and the brilliance of its color. Manual infiltration usually results in excess resin being left behind. Now the physical model can be put to use.

In FDM technology plastic filaments were melted and extruded as construction material layer by layer in a viscous state onto a support plate by means of a heated extrusion nozzle. Additionally a second plastic material is used in the FDM device (HP Designjet 3D colour) for a supporting structure. ABS is usually used as construction material. It is available in a limited range of colors – therefore components are monochrome. The support filament has to be removed afterwards as waste by the use of an alkaline bath (leach) in a Support-Removal-System.

3 Comparison of specific energy consumption

In the initial approach the energy consumption is examined by taking random measurements on a sample component. This sample component is a throttling valve. Using both AM technologies two throttling valves were manufactured, based on CAD-model (one for each method with a component volume of approx. 124 cm^3). At the same time the electrical power consumption of the machines during preprocessing, manufacturing and the subsequent postprocessing was measured [10]. Measurements were carried out with the help of a Standby-Energy-Monitor. Therefore all electrical consumers were connected together to the monitor. When 3DP technology is used energy consumption is between 1860 Wh and 2161 Wh, depending on the positioning of the construction part in the construction chamber. This is equivalent to a specific energy of approx. 14.7 kWh/kg or respectively 17.4 kWh/kg. In comparison 7791 Wh was required in the additive manufacture of the same component with FDM. This is equivalent to a specific energy of 48.1 kWh/kg or respectively 61.4kWh/kg depending on and the degree of filling of construction material (e.g. “full” or “low density”) and the volume of the supporting material.

Differences can also be seen in the greatly varying lengths of processing time – 5h 38min with 3DP compared with 11h 56min with FDM. Fig. 2 illustrates the required specific energy (proportionate to weight, minimum and maximum value) whereby two further additive manufacturing methods were compared. The values quoted in literature for specific energy consumption vary considerably, as they are strongly influenced by a wide range of different parameters [9]. The results from the test mentioned above show fairly good correlation with these values from literature. It has become apparent that, e.g. in 3DP the energy consumption during post-processing, which is largely done manually, depends heavily on the experience and skill of the operator, as well as the complexity of the geometry that has to be de-powdered. In contrast, the measurements collected during the manufacturing process are not contingent upon the operator. It now becomes evident that FDM technology consumes considerably more energy than 3DP technology. That can be explained by considering the operational procedure. With FDM the device uses a great amount of energy in the preparation phase in order to reach an operating temperature of 270°C for the extrusion nozzle and jets as well as 70°C in the construction chamber, whereas the 3D-printer in 3DP technology merely needs a temperature of 38°C.

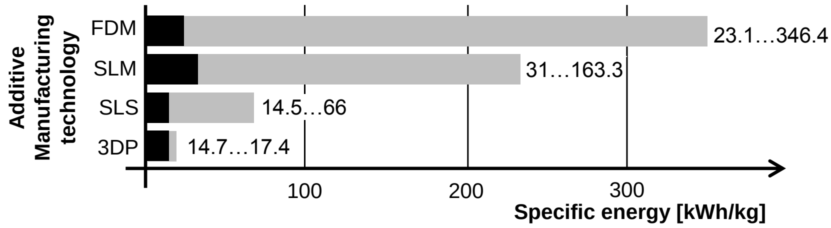


Fig. 2: Comparison of specific energy for different AM technologies [9]

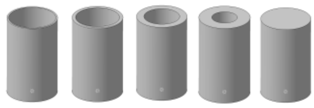
In particular the length of time required for FDM is highly dependent on the geometrical shape of the construction part. In this procedure the jet must cover every single point on the layer, first printing the outer contours and then the interior surface. Increasingly complex construction parts show a high ratio of surface to volume (e.g. housings or sculptures) and lead to a rise in energy consumption and duration of the production process. In addition FDM-technology requires supportive structures, which must be removed after production in an alkaline bath heated to 70°C. In the postprocessing phase of the 3D-printer the construction parts dry within 90 minutes when warmed, independent of the geometry of their structure.

4 Examination of influencing variables in 3DP

4.1 Influence of the component volume and component surface on the consumption

A number of measurements were made with simple test geometry to examine the influence of the geometric variables (volume and surface) on the consumption of material and power. This geometry is a hollow cylinder of which the wall thickness was gradually increased until a solid cylinder was achieved (see Tab. 1). A comparison of the consumption of power, binding agent and resin, as illustrated in Fig. 3, shows that there is obviously a direct connection between the consumption of powder and the volume of the component.

This is based on the fact that the component volume also corresponds to the volume of the powder required and, furthermore, that no powder is required for support. Excess powder is blown off and reused completely. Since the resin penetrates mainly the surface, it could be assumed that there is a connection between the size of the surface and the consumption of resin. In the experiments the consumption of resin showed quite different results. The consumption of resin has proven to be mainly proportional to the component volume. For this example about 0.4 g/cm^3 of resin is required for each component volume.



Type	12.5%	25%	50%	75%	100%
Volume V [cm³]	2.47	4.94	9.83	14.82	19.63
Surface A [cm²]	62.02	61.05	58.27	54.40	41.23
Ratio A/V [-]	25.1	12.4	5.9	3.6	2.1
Construction time [min]	57	57	58	59	59

Tab. 1: Variation of the volume and surface of a sample component.

The electrical consumption for the layer build-up rather correlates mainly with the build-up time, i.e. the time required for the actual building process. This value obviously mainly depends on the envelope volume, which means reducing the volume, as with the hollow cylinder, has barely any effect on the electrical consumption. In this case which represents a very small specimen the consumption of electrical energy is approx. 12 Wh/cm^3.

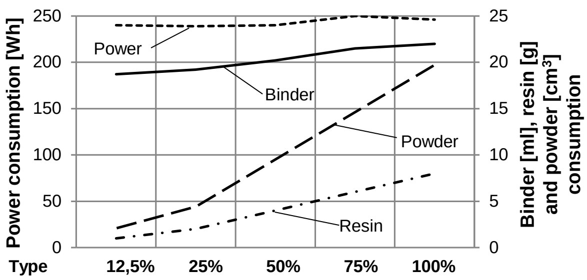


Fig. 3: Consumption of power, powder, binding agent and resin for different types.

The reason is that the area which is "run over" when printing a component layer is considerable for this consumption. And it barely makes any difference whether this surface subsequently belongs to the component or not (cavity). After all, the consumption of binding agents only indicates a low increase in relation to the volume of the component. The binding agent consumption curve is similar to the energy consumption curve. As a result, there is also a similar connection between the envelope volume of the printed component and the consumption. In this example, the consumption per envelope volume is about 0.95 to 1.1 ml/cm^3.

An explanation for this is that the printing jets for the binding agents are cleaned regularly after printing several layers (see also section 4.2). The resulting binding agent consumption therefore mainly depends on the number of printed layers. However, whether the component is a solid or hollow cylinder only has little influence on the results. Another reason is that the saturation with binding agent on the surface with a penetration depth of approx. 2 mm is higher than in the core of the component [11]. That is why components with a high surface-volume A/V ratio tend to consume a greater amount of binding agent respectively to their volume.

4.2 Influence of the position on the consumption of electric power

The consumption of the power required to drive the motors during the 3DP is influenced mainly by the position of the component in the installation space. That is why the specimen “Type 100%” from section 4.1 was set down at five different positions in the installation space during the preprocessing before measuring the energy consumption. The printing heads for the binding agent and ink move on the gantry in x direction, whereas they are moved together with the gantry in y direction (see Fig. 4). The construction platform moves downwards in vertical z direction as soon as a layer has been printed completely.

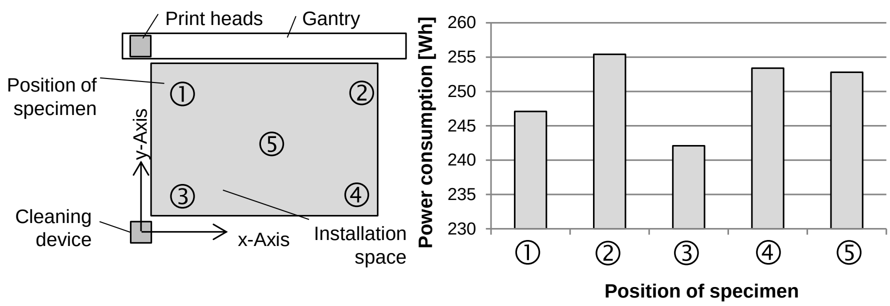


Fig. 4: Positioning of specimen (left) and power consumption (right)

The power consumption measurement results for 3D printing (manufacturing phase only) in different positions is illustrated in Fig. 5. It is clearly revealed here that the lowest consumption of electric power is in the position #3 nearby the position of the cleaning device. This device is regularly run into by the gantry after printing some layers to clean the print heads. If, however, the print heads have to cover long distances to the component, as for example in position #2, the consumption increases, since the motors require more power to move the gantry. Overall not a great deal is saved due to the improved positioning, however, since the difference between the minimum and maximum value is merely 6 %.

4.3 Influence of the batch size on the consumption

In each of the previous tests only one component was produced in order to determine the direct influence of the geometry. In the following tests only the batch size was changed in order to determine the effect on the consumption values. The degree of utilization η of the installation space increases together with the batch size. A ball bearing (part volume: 43.2 cm^3, envelope volume: 81.1 cm^3) was used as the sample component (see Fig. 5, left). It was produced in batch sizes of one, three or six items. The positioning of all batches corresponds to position #3 in section 4.2. However, this increased the degree of utilization in three stages from η=5% to 17 % and on to 35% in the tests.

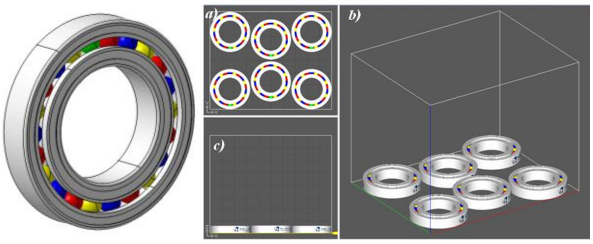


Fig. 5: Deep groove ball bearing (CAD, left) and positioning in the installation space (Screenshot, right, η=35 %): a) top view, b) isometric view, c) side view

In the evaluation the degree of utilization of η=100 % corresponds to the volume defined by the surface area of the installation space and the height of the component (approx. 15 mm). The consumption of powder, binding agent and energy was measured during the production phase. The evaluation of the results also shows here that there is a direct connection between the powder consumption and the volume of the components and that therefore the powder consumption cannot be reduced by increasing the degree of utilization. This is different with the consumption of energy and binding agent in the manufacturing phase.

As shown in Fig. 6 these consumptions do not increase to the same degree as the powder consumption. Therefore considerably lower consumptions can be expected by increasing the batch size and hence the utilization of the installation space in relation to the component volume. The reduction in energy consumption is explained by the fact that the travel distance to the individual parts and to the cleaning station is divided by several components. The considerable reduction of binding agent consumption is based on the distribution of the spray losses when cleaning the printer heads among several components, resulting in a reduction of the losses per component.

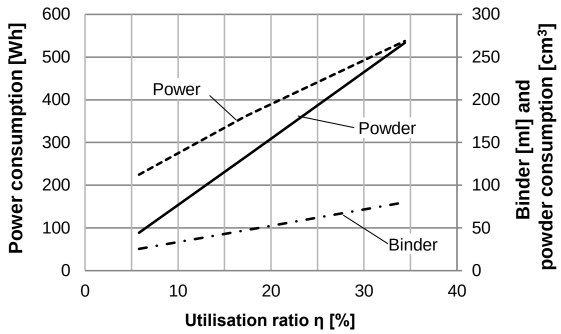


Fig. 6: Consumption of energy and material at different utilization ratio η.

In summing up the results of several surveys it has become apparent to what degree the utilization factor impacts energy consumption (Fig. 7). In this analysis, the envelope volume of the components had been taken into account, as it is more meaningful for the actual utilization of the build area, while the influence on the results is immaterial with regard to energy consumption, as shown in section 4.1. This consequently shows that a significant reduction of energy consumption is only possible if the packing density in the build area is as high as possible.

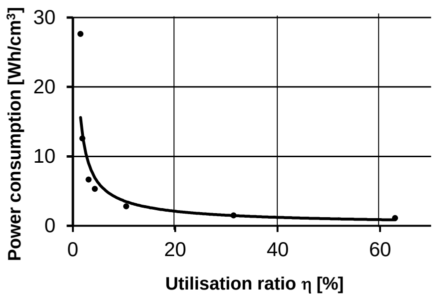


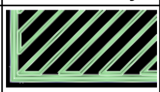
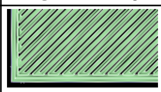
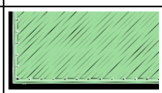
Fig. 7: Impact of the utilization ratio (based on the envelope volume) on energy consumption in the manufacturing phase

5 Examination of the influence of the degree of filling in FDM

A number of components were produced by means of FDM device in the following tests. Test items were produced in batch sizes of three as test components for tensile tests. The test items are positioned in the available space in such a manner that they lie flat on the construction platform, i.e. the layers are parallel to the construction platform. The filling degree of the components is examined as an important influencing factor on the material properties and production costs. It can be set in the software of the FDM system in three variants: "low density", "high density" and "completely full".

5.1 Influence of the degree of filling on the material and power consumption

A comparison of the construction material required shows that it increases, as expected, together with the degree of filling (see Tab. 2). However the consumption of supporting material is the same for all three batches, since the supporting material depends on the geometry, not on the degree of filling. Together with the degree of filling, the consumption of electric power rises during the manufacturing phase from approx. 760 Wh to approx. 1020 Wh. The power consumption during pre- and post-processing, which is in total approx. 1610 Wh, is also not influenced by the degree of filling.

Degree of filling	***Low density***	***High density***	***Full***	***Solid Material***
Schematic illustration [HP 3D Designjet colour documentation]				--
Density [g/cm³]	0.69	0.87	0.97	1.06…1.08 [12]
Yield Strength [N/mm²]	19.1	23.2	28.5	30…55 [12]
Construction material [cm³]	29.9	37.1	41.3	--
Support material [cm³]	11.1	11.1	11.1	--

Tab. 2: Influence of the degree of filling on the material properties and consumption

5.2 Influence of the degree of filling on the material properties

Changing the degree of filling also improves the material properties. In this examination only those test items were manufactured, of which the layers were in the direction of the tensile force (see Tab. 2). Even with the highest degree of filling, the values therefore are considerably below those of solid ABS material from approx. 30 to 55 N/mm^2 [12].

5.3 Influence of the degree of filling on the energy consumption

Aside from the impact of the filling level on material consumption and material properties, there is, of course, also an impact on the specific consumption of energy. As the filling level increases, the specific energy consumption decreases (see Fig. 8). This is due to the fact that with the increase in filling level the density obviously increased much more than the additionally required utilization of energy to achieve the higher filling level.

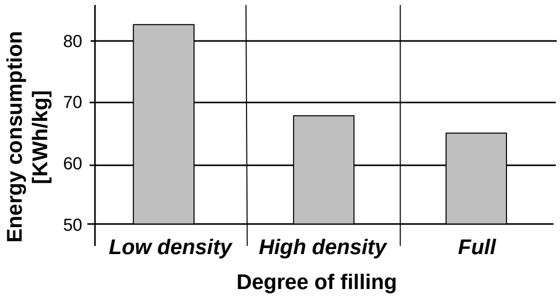


Fig. 8: Impact of degree of filling on the consumption of energy

6 Conclusions

The introduction of the specific power for the layer build-up allows the power costs per installation volume to be compared for different methods. The examinations have shown that the power consumption with FDM is clearly higher than with 3D printing but also higher as laser-based technologies like e.g. LS and SLM.

In 3DP the geometry of the component to be printed also has a considerable influence on the consumption. But the power consumption depends mainly on the printing time, which depends on the envelope volume of the component. Ideal positioning of the components in the installation space also allows the power consumption to be reduced. The batch size also has a huge influence on the consumption. The consumptions per volume unit can be clearly reduced by a high degree of utilization of the installation space of the 3D printer. Here are the greatest saving options in relation to the two other examined influencing factors.

In FDM the examination of the influencing factor "degree of filling" has shown that it has a considerable influence on the material properties. For example, the tensile strength increases together with the degree of filling, but without reaching the value of solid material. The material and power consumption also increases together with the degree of filling. At the same time, the specific energy consumption decreases considerably with the increasing filling level.

Overall it can be seen that in both procedures energy consumption and material consumption can be optimized through various influencing factors. To this end, the manufacturing process and pre- and post-processings have to be analyzed for every single procedure and all phases. Furthermore, the geometry of the component to be manufactured and the batch size turned out to be decisive facto

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