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ASSESSING THE PERFORMANCE OF ADDITIVE MANUFACTURING APPLICATIONS

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Abstract

Additive manufacturing offers vast potentials in the development of competitive products. As technological readiness level increases and novel software solutions arise, engineers can fully exploit the design advantages AM has to offer, namely design freedom. To successfully implement AM products in industry, decision makers must see a clear advantage in producing a design additively, that is a trade-off of AM costs and benefits. AM parts can improve product performance, e.g. weight savings, or improve processing, e.g. manufacturing objectives. AM has the potential to create value on both dimensions, but many studies consider exclusively either the product- or the process performance by assessing the costs of an isolated part. To close this gap, this work presents a framework for evaluating the value of additive and conventionally manufactured products by comparing the product-related to the process-related performance. The framework is applied to a case study consisting of a flying vehicle with an annular wing. Results show that AM products can be competitive if design advantages are used to leverage both, the product- and the process-related performance.

Keywords: Additive Manufacturing, Decision making, Design costing

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1 INTRODUCTION

Additive Manufacturing (AM) refers to a set of technologies that fuses materials in layers to create objects from 3D model data. Selective Laser Sintering (SLS) and Selective Laser Melting (SLM) are two relevant techniques for the production of high quality parts in which a laser beam thermally fuses the polymer and metal powder material, respectively, to form a consolidated slice of the parts' cross section. The building platform is lowered, the coater applies the next powder layer and the process is repeated until the 3D part is completed (ISO/ASTM 52921:2013). SLS doesn't require support structures and therefore allows the direct production of very complex geometries including overhangs, internal structures and functional elements at low lead times. With these advantages AM offers new possibilities in the design and processing of competitive products.

Recent technical advancements and the readiness of the industry increases the rate of end-user production. In fact, the manufacturing readiness level (MRL) of AM ranges from 5 to 10 differing by technology and application (Roland Berger, 2013). For dental applications MRL reaches up to 10 as full rate production is demonstrated for restorations made with SLM (EOS GmbH/BEGO USA). In the case of aerospace, AM reaches an MRL of up to 9 - a low rate production for selected aircraft parts. In 2015, the U.S. Federal Aviation Administration (FAA) certified and cleared the first 3D-printed sensor housing to be equipped inside a commercial jet engine from GE (Kellner, 2015).

Novel software solutions support the design engineer to fully exploit the possibilities AM has to offer. Algorithms consider support structures during topology optimization and thereby reduce fabrication and clean-up costs (Mirzendehdel, 2016) or help the designer in reconstructing topology optimized results to generate a high quality solid CAD part (Stangl, 2015). Software providers integrate novel AM tools to provide the design engineer with a seamless CAD-CAM workflow. AM has reached technical maturity and with a compound annual growth rate (CAGR) of 35.2% in 2014 (Wohlers, 2015) it has appeared on the radar of many decision makers in industry.

To successfully implement and market AM products, decision makers must see a clear advantage in producing a design additively, when looking at the trade-offs of costs and benefits. Producing a conventional design additively can be economically viable for small complex parts made by SLS for a production volume up to 9'000 - 14'000 pieces (Ruffo, 2006; Hopkinson, 2003) due to tool-less manufacturing. For a redesigned part, considering AM design advantages (e.g. integration of functions, geometric freedom allowing undercuts, etc.) and limitations (e.g. lack of tight tolerances), a more significant economic benefit can be achieved. A small complex electronic component made by SLS is competitive up to a yearly lot size of 87'000 pieces compared to injection moulding (Atzeni, 2010). This AM gain is a result of a part count reduction, as production and design benefits are leveraged. To go one step further, AM offers the opportunity to increase the performance of the product, such as increasing the eigen frequencies of a satellite antenna by topology optimization (Herrera, 2014). Existing studies often evaluate the competitiveness of AM based on the consideration of a small, complex, isolated component by focusing either solely on costs or performance. However, AM has the potential to create value along both dimensions: the product and the processing performance of an application.

This work addresses the question of how and where AM can create more value than costs, that is to leverage the added value from the customer's perspective. Therefore, we introduce the terms of product- (PdP) and process performance (PcP). PdP is a function of all product-related characteristics that contribute to its performance. An increase in PdP implies a functional benefit in the operation of the product, e.g. weight savings of a civil aircraft thereby resulting in fuel savings, increased payload capacity, or faster cruising speeds, depending on the operation scenario of the customer. On the other hand, the PcP quantifies the manufacturing performance. Both PdP and PcP are combined into a conceptual framework for assessing the value of additively and conventionally manufactured parts. This framework is applied to a case study consisting of a new flying vehicle with an annular wing which is evaluated for an AM and a machined design approach; the PdP indicators are weight and bending stiffness, and the PcP indicator is the total manufacturing cost.

This paper proceeds as follows: Section 2 presents the conceptual framework. The framework is applied to the case study of a flying ring in Section 3 and Section 4 presents the results. Section 5 compares both design strategies and discusses the strengths and the limitations of the framework. Section 6 concludes.

2 CONCEPTUAL FRAMEWORK

2.1 Definitions

Product Performance (PdP)

This work introduces the term "ProDuct Performance" (PdP) as a metric for assessing the objective achievements of a product in terms of an operational benefit for the customer before being converted to cost benefits. The product performance is a function of all product-related characteristics, e.g. weight savings (kg), stiffness (N/mm^2), breaking forces or stresses (N, N/mm^2), lift-to-drag ratio (L/D) for aerodynamic efficiency, work density of springs (J/kg), etc.:

$$f_{PDP} = f(weight\ savings, stiffness, strength, \ldots \quad impact\ energy, life\ time, work\ density, \ldots) \tag{1}$$

Process Performance (PcP)

The term "ProCess Performance" (PcP) is the metric of manufacturing performance. It is based on the key process indicators of the manufacturer in the target areas of costs, quality, flexibility and delivery according to Schönsleben (Schönsleben, 2016). The PcP is defined as a function of the number of manufacturing steps, the total manufacturing costs, manufacturing lead time, quality, scrap rate, order fill rate, lot size, capacity utilization and response time:

$$f_{PCP} = f(\text{man. steps}, total\ man.\ costs, man.\ lead\ time, quality, \ldots \quad scrap\ rate, order\ fill\ rate, lot\ size, cap. utilization, response\ time) \tag{2}$$

Total Manufacturing Cost (TMC)

In this study the PcP is expressed by the Total Manufacturing Cost (TMC) metric and is calculated by applying Activity Based Costing Methodology (ABC) (Drury, 2008). We consider a cost structure including equipment cost (depreciations expenses), labour costs and material costs. Modelling uncertainty has been kept into account by providing, where necessary, low and high estimates for: material prices, labour rates, operation time and raw materials consumption. Calculations do not include, the cost of design, energy, space rental and ancillary equipment. The production context for each alternative manufacturing route is selected to be appropriate for an efficient low volume production. The duration of labour-related work steps is specific to the case study and are estimated based on own investigations.

2.2 Product and Processing Performance: A Performance Assessment Framework

The conceptual framework shown in Figure 1 assesses the value of a product by comparing its product and processing performance to the product and processing performance of a similar product. PdP and PcP indicators are quantified for two or more designs and contrasted. The path, represented by the arrow in Figure 1, indicates how the value of the product has changed compared to a reference. Although there are cases where the value of a product moves along multiple paths, for the sake of simplicity, five very likely scenarios numbered from A to E are explained in the following:

A: Increased product performance, reduced processing performance

The product features an improved performance at premium cost. This case is typical in the aircraft industry shifting from metal to composite designs. Envisaged weight reduction of an aircraft by up to 20% (Blower, 2014) increases its product performance. However, composite materials are with 20 to 100 € per kg more expensive compared to aerospace grade alloys and the manufacturing process requires tooling and plenty touch labour. Therefore, compared to machined aluminium, the total manufacturing costs increases and the process-related performance decreases. The higher PdP offered by advanced composites comes at premium cost. However, customers (e.g. airline operators) are willing to pay for such product performance advantage if the value proposition can be converted into cost savings (e.g. fuel cost savings) during the operation of the product. In fact, in civil aviation a weight reduction of 1 kg of an aircraft similar to an A350 yields in lifetime fuel burn cost savings of € 1500 to 4300 (Kaufmann, 2008; Lee, 2001).

One example, from the field of AM, is the redesign of a laser cutting head displayed in Figure 1a. A laser cutter is used to cut or engrave materials with a CO2 laser. The laser cutting head is guided on a moveable axis and holds the deflection mirror and the focus lens. The bottom of the lens is purged by compressed air to prevent its contamination during the operation due to sublimation dust. The additive version is made from AlSi12 with SLM and incorporates internal channels that improve the cleaning effect on the bottom of the lens by optimizing the air outlet (Leutenecker-Twelsiek, 2016). When produced conventionally the manufacturing cost amounts to approximately Fr. 300 with a required maintenance effort of 50 minutes (5 times à 10 min) or 30 Fr. per week. Manufacturing the additive version is more expensive and costs up to Fr. 700, however, the enhanced product performance entails a clear maintenance benefit that can be converted to a cost benefit: by reducing the lens contamination, maintenance can be reduced to only 10 min or Fr. 5 per week. Thus, the AM part is economically competitive after five months of service lifetime.

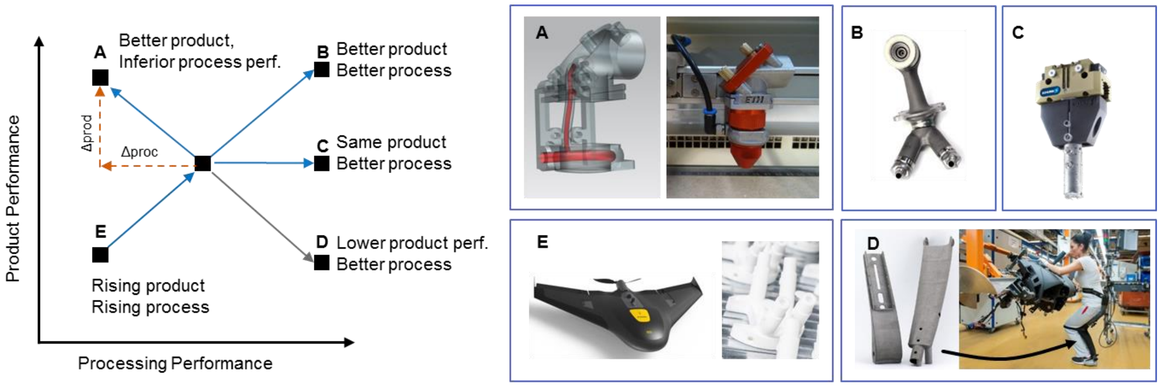


Figure 1. Product- and processing related performance framework, Laser cutting head (A) (Leutenecker-Twelsiek, 2016), GE fuel nozzle (B), SCHUNK eGrip (C), Chairless Chair (D), Trimble UX5 (E)

B: Increased product performance, increased processing performance

The product performs better and can be manufactured at a reduced cost. This is the case of several AM aerospace studies, with GE's fuel injection nozzle being a popular example. Each of the new Leading Edge Aviation Propulsion (LEAP) engines have 19 fuel nozzles that are built from a cobalt-chromium powder. On the processing side, 3D printing allowed the engineers to simplify the design and reduce the number of brazes and welds from 25 to 5 and reduce the part count from 18 to 1. (GE Global Research, 2016). This reduces production costs compared to a labour intensive welding and assembly technique (LaMonica, 2016). On the performance side, weight savings of 25% could be achieved and intricate cooling pathways result in 5 times the durability. Such scenarios require high a degree of invention in identifying the most promising applications and radically rethinking design approaches.

C: Constant product performance, increased processing performance

The product performance is kept constant, while the processing performance is increased. With increasing competitive pressure, companies seek to offer the same product performance at lower manufacturing cost. The German expert for gripping and clamping Schunk, launched SCHUNK eGrip, the world's first fully automated design and ordering tool for additive manufactured gripper fingers. SCHUNK eGrip is a browser-based, license-free tool that automatically configures the gripper fingers around a part, calculates the price and estimates the delivery. Schunk clamis that eGrip reduces design costs for grippers by up to 97%, reduces delivery time by up to 88% and reduces the price by up to 50% (Schunk, 2016). eGrip was created to cut costs, increase process flexibility, reduce lead time and thus to improve the performance of the process.

D: Reduced product performance, increased processing performance

The product performance is inferior compared to the reference product but it can be manufactured at lower cost. The Chairless Chair displayed in Fig. 1d is an exoskeleton developed by Noonee AG and highlights how a company uses AM to prepare production upscaling. The exoskeleton allows assembly-line workers to relax their muscles and to sit down during work. A premium version is made from titanium powder by SLM. It is over-dimensioned with high bending and torsion stiffness's and comes at high cost. However, it allows the engineers to modify the design continuously until customer expectations are fully satisfied. With transition to series production, production performance increases at the cost of the product performance: special features, such as the remotely controlled electronic locking mechanism for different sitting positions are substituted by mechanical solutions. Furthermore the series part is made from injection moulded plastics which reduces bending and torsion stiffness from over-dimensioned to target values (Meboldt, 2016).

E: Uprising product & process performance

Product and process performance are inferior compared to industry standards at the specific point in time, but move upwards along both PcP and PdP. The introduction of a new product to the market is bound to a certain extent of uncertainty about fulfilling customer expectations, sales, etc. AM can eliminate the need of creating specialised tools and moulds when introducing a new product, thus reducing the upfront investment and leaving room for minor modifications before ramping up production. Consider the Trimble UX5 autonomous drone for cartography in Figure 1e: its first version is machined from foam, however, its product performance wasn't sufficient to meet market requirements in terms of stiffness, strength and weight. Therefore, Trimble redesigned the drone using tubes made from carbon-fibre reinforced plastics and SLS connection elements to increase stiffness, strength and reduce weight (product performance). However, the manufacturing process remained challenging: the assembly of the frame is done manually and it is difficult to control the precise amount of glue to join the tubes to the connection elements. Variations in the amount of adhesive can influence quality in terms of strength and weight balance. Hence, the engineers integrated channels into the AM connectors to optimally distribute the adhesive in such way to safely connect the joining elements with the same amount of adhesive (Meboldt, 2016). This design change positively affects the processing performance. The use of AM makes the drone lighter and its production more efficient.

3 CASE STUDY: ANNULAR WING OF A FLYING RING

3.1 Aerodynamic Flying Ring Drone Structure

Traditional quadcopters are agile and carry high payloads but they are not efficient in forward flight, with typical lift-to-drag ratios comparable to a fruit fly. New vehicles like the flying ring vehicle depicted in Figure 2 (top), however, can fly on the side, relying on an annular wing to provide additional lift, thereby allowing the rotor blades to only have to compensate for drag (Gill, 2016). The case study consists of the flying ring being developed at the Institute of Dynamic Systems and Control (IDSC) at ETH Zurich. The flying ring is composed of four rotors and a control unit that are fixed to a stiff structure. The annular wing has a symmetric E169-iL profile and is connected to the stiff carrier structure. The outer diameter of the ring amounts to 700 mm. The flight regime is specified to a velocity of around 10 m/s with an angle of attack of 15 °. Target applications of such drones can be found where agility is a key performance indicator such as racing, or more generally, entertainment.

The annular wing has to meet many performance targets, such as the aerodynamic efficiency, the torsion stiffness, etc. In this case study the following two product-related performance targets are selected: first, a maximum weight of 200 g for the annular wing is targeted to comply with motor specifications. Second, the bending stiffness (N/mm) is used to assess the stiffness of the structure. The higher the bending stiffness, the more dynamic manoeuvres can be performed with the drone. The PcP is assessed by the total manufacturing costs. Two design approaches are assessed: a conventional design made by machining a lightweight foam (Section 3.2), and an additive design (Section 3.3).

3.2 Conventional Design

Figure 2 (middle) shows the conventional design approach of the annular wing. It consists of a machined foam core with recesses to reduce weight and a lightweight foil that is applied on the foam to provide the necessary surface quality.

The manufacturing steps are shown in Figure 3. For machinability, the wing is separated at the maximum profile thickness at a length of 31.8 mm and at 95 mm . The diameter is split into six pieces of the trailing (Figure 2, middle), the forward and the after leading edge, respectively, to fit into the Roland MDX-540 milling machine. Therefore, three Rohacell IG-F 51 plates with dimensions of 400 x 400 x 50 for the leading and 400 x 400 x 80 for the forward and 400 x 400 x 40 for the trailing edge are used.

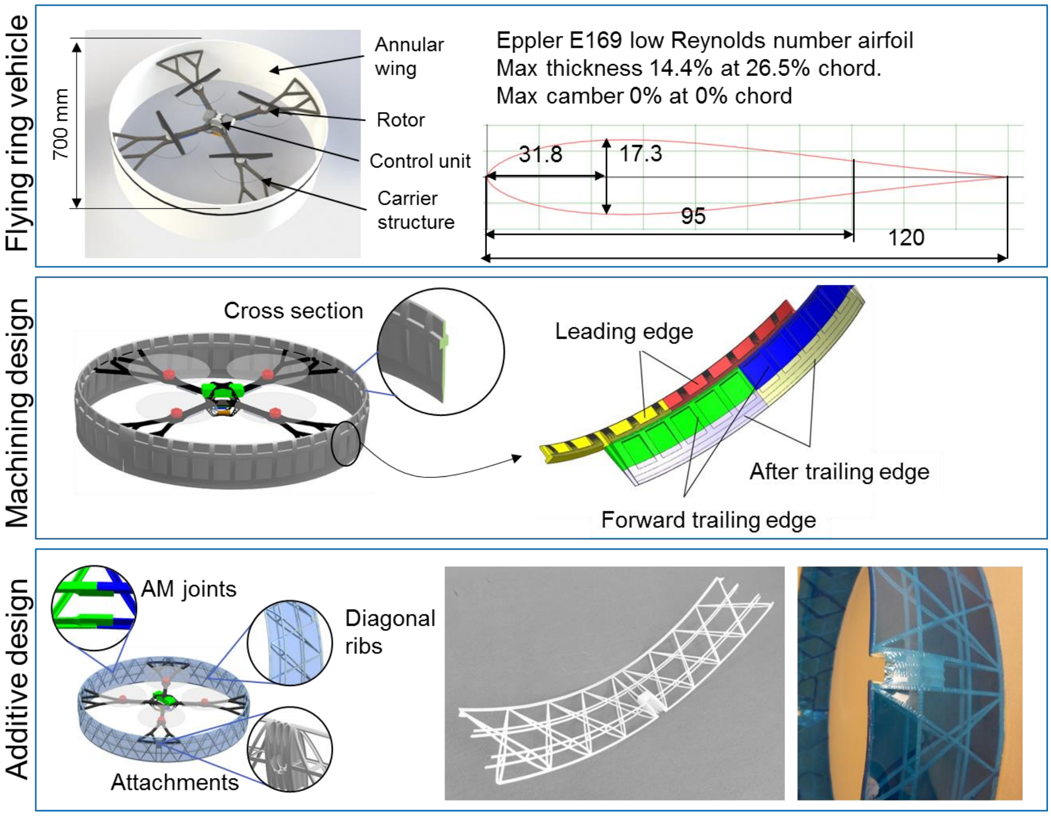
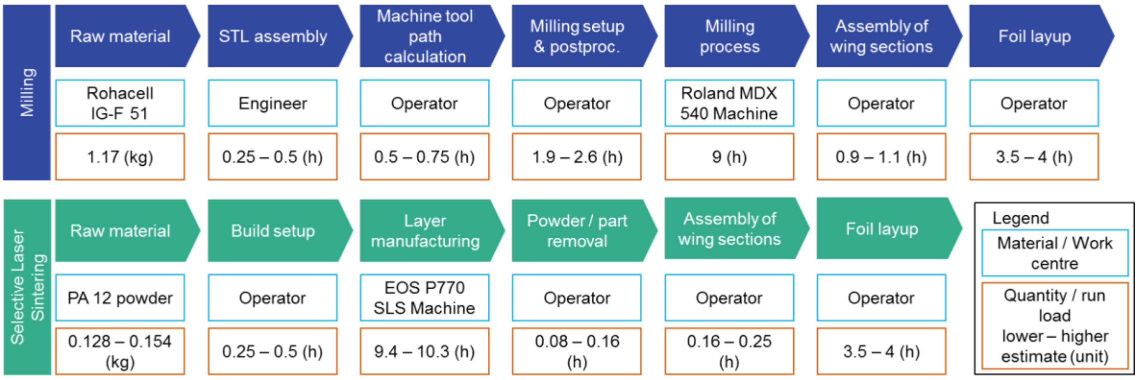


Figure 2. Flying ring vehicle (Gill, 2016) with E169 airfoil profile (top), machining (middle) and additive design (bottom)

The preparation of the STL assembly files for machining takes 15 - 30 min for an experienced engineer and the calculation of the toolpath for the milling process takes from 30 up to 45 min for an experienced operator. The set up time for machining including clamping, re-clamping of raw materials, supervision in critical machining periods and part removal amounts to 114 - 156 min for an experienced operator. Machining time with a precision of 0.5 mm amounts to a total of exactly 9 hours, with 5.5 hours for both trailing and 3.5 hours for the leading edges. The assembly of the resulting wing sections is done manually by applying an adhesive. An experienced operator needs from 54 up to 66 min to glue all single elements. Adhesive costs and necessary tools to accomplish the operation are neglected in the cost calculation. In the final step, an adhesive is applied and cured at room temperature on the wing structure. Then, the adhesive is heated and the lightweight foil is applied on the structure. During cooling, the foil shrinks, resulting in a nearly wrinkle-free, aerodynamic surface. The wing is ready to be mounted on the carrier structure of the drone. This step takes from 210 up to 240 min for an experienced operator. Assumptions regarding material, labour and equipment rates are shown in Figure 3. Milling equipment rates in the low estimate account for a machine price of Fr. 18’000, depreciated over 4 years, with a yearly available capacity of 2470 hours. For the high estimate, a machine price of Fr. 22’000 depreciated over 4 years, with a yearly available capacity of 1’560 hours has been assumed.

3.3 Additive Design

The AM design depicted in Figure 2 (bottom) is a rib-spar structure with integrated connection elements, which is then covered with a lightweight aerodynamic foil. The lightweight structure is split into four elements to fit the build envelope of the EOS P 770 SLS machine. The net volume of the CAD model is 95.2 cm^3. For the calculation of the actual PA12 powder consumption, a yield rate between 75% and 90% has been assumed, accounting for characteristic powder losses of the SLS process. SLS allows the production of complex geometries with sufficient accuracy without supports. Build preparation takes between 15 and 30 minutes for one experienced SLS operator and the building time amounts from 9.4 to 10.3 hours based on a building rate of 28 mm/h to 32 mm/h (EOS) for a bounding box with a total height of 300 mm. Part and powder removal takes between 5 and 10 min.



Labour, equipment and material rate assumptions:

Work Centre	*Description*	*Unit*	*Rate Low*	*Rate High*	*Description*	*Unit*	*Rate Low*	*Rate High*
	Roland MDX-540	hour	Fr. 1.82	Fr. 3.53	EOS P 770	hour	Fr. 15.26	Fr. 32.05
	Operator Cost	hour	Fr. 70.00	Fr. 100.00	Operator Cost	hour	Fr. 70.00	Fr. 100.00
	Engineer Cost	hour	Fr. 80.00	Fr. 110.00				

Materials	*Description*	*Unit*	*Rate Low*	*Rate High*	*Description*	*Unit*	*Rate Low*	*Rate High*
	Rohacell	Kg	Fr. 161.54	Fr. 165.38	PA 12 Powder	Kg	Fr. 175.00	Fr. 250.00

Figure 3. Manufacturing steps of the machining (top) and the additive (middle) design approach, Assumptions (bottom)

The four structural elements are then assembled to a full ring which takes between 5 and 10 min. Process steps and time to apply the foil for the AM design are comparable to the foam design. Finally, the ring is ready for mounting on the carrier structure and the drone assembly is complete. SLS equipment rates in the low estimate account for a machine price of Fr. 600’000, depreciated over 6 years, with an yearly available capacity of 6’552 hours, compared to Fr. 800’000, 6 years and 4’160 hours for the high estimate. It is reasonable to assume a higher yearly available capacity for the SLS process, as the manufacturing can occur unattended by an operator overnight and even over weekends.

4 RESULTS

4.1 Product Performance of the Annular Wing

4.1.1 Weight

Figure 4 compares the measured weight of the two approaches. It is subdivided into the weight of the structure, the adhesive and the aerodynamic foil. It can be seen that the milled foam weighs 98 g compared to the PA12 structure made by SLS weighing 120 g. The milling concept requires 43 g of adhesive, mainly for the joining of the wing sections. For the SLS concept, plug connections are used to assemble the wing sections. Approximately 10 g of adhesive are necessary to apply the foil to the structure. Both wing concepts weigh less than 200 g. The results show a total weight of 150 g for the milling concept compared to 139 g for the AM design. This is a decrease of 11 g or approximately 7%.

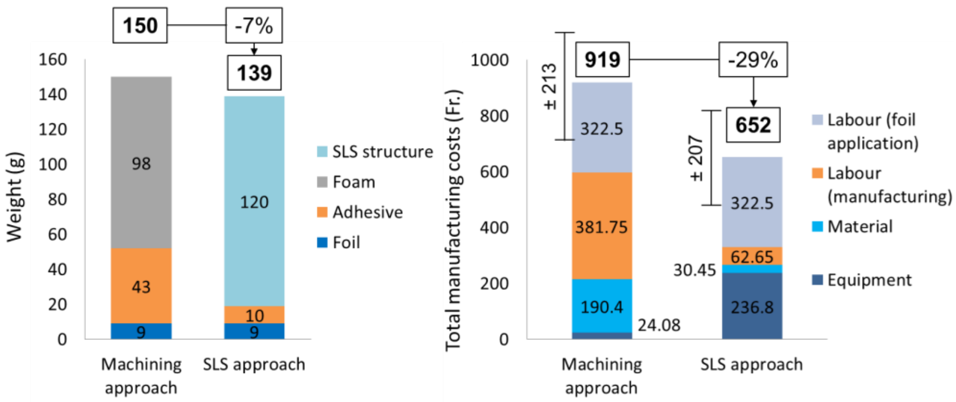


Figure 4. Weight (left) and Total Manufacturing Cost (right) comparison

4.1.2 Bending Stiffness

The bending stiffness (N/mm) of the structure is derived from a linear elastic FEM analysis using ABAQUS. Similar to a cantilever beam, the structure is clamped at one end and a total force of one Newton is uniformly applied on the free end. It is assumed, that the aerodynamic foil does not contribute to the structural stiffness and therefore it is omitted in the analysis. Figure 5 shows the downward deflection of an eighth of a conventional (left) and an additive (right) wing section. Results show a maximum downward deflection of 12.2 mm for the conventional design and a deflection of 9.5 mm for the additive design. Thus, the conventional design exhibits a bending stiffness of 0.082 N/mm compared to 0.105 N/mm for the additive design. This corresponds to an increase of 28%.

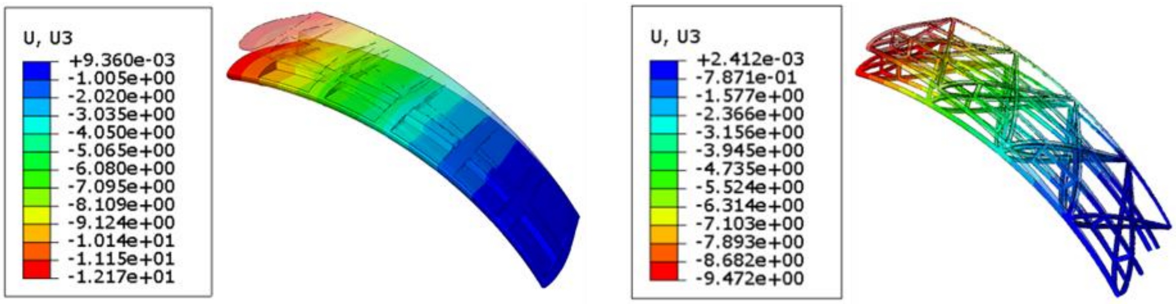


Figure 5. Comparison of the bending stiffness in N/mm for the conventional (left) and the additive (right) design

4.2 Process Performance of the Flying Ring

4.2.1 Total Manufacturing Costs (TMC)

The TMC of the conventional and the additive design are displayed in Figure 3 (right). The TMC is divided into labour, equipment and material costs for the production of one annular wing. The cost of the application of the foil amounts to Fr. 245 up to Fr. 400 with an average cost of Fr. 322,5. It can be seen that labour (Fr. 381,75) and material (Fr. 190,4) are predominant costs in the machining concept, whereas equipment costs are comparatively low (Fr. 24,08). The TMC of the milling concept amounts to Fr. 919. The TMC of the AM concept is driven by high equipment costs (Fr. 236,8) compared to low material (Fr. 30,45) and labour (Fr. 62,65) costs. The TMC for the AM design amounts to Fr. 652. In this case, AM allows a cost reduction of approximately 29% compared to a machined design.

4.3 Performance Assessment of the Annular Wing

Figure 6 shows the product- and the process-related characteristics contributing to the overall performance of the annular wing for a machined and an additively manufactured design approach. The product-related characteristics, namely the variation in the bending stiffness (N/mm) and the weight (1/g) are plotted against the process-related characteristic, namely the inverse of the total manufacturing cost (1/Fr.). The product-related performance characteristics are individually compared to the PcP. The increase in the bending stiffness of 28% (Figure 6, blue) leads to a better product performance as a

higher stiffness allows the drone to perform more challenging manoeuvres. The PdP increase of the AM design comes at a cost benefit of 29%. Therefore, the variation in bending stiffness over the TMC can be classified into scenario B (see section 2, Figure 1), as both indicators increased.
The variation in weight savings (Fig. 6, orange) amounts to 7% and comes at cost benefits. Therefore, we could classify the relation of weight to cost into scenario B.

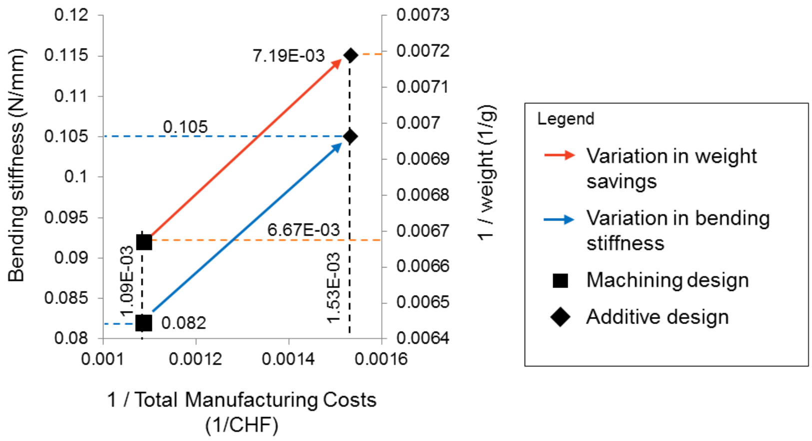


Figure 6. Comparison of the product and process performance of the annular wing

5 DISCUSSION

Results show that AM can impact the processing and the product performance. On one hand, the cost and the duration of labour related work steps could be reduced. In particular, the assembly of the wing sections takes less time due to the possibility of AM to integrate functional connection elements into the structure. On the other hand, lightweight stiffeners can increase the bending stiffness, thereby contributing the PdP. Further advantages of an AM design, that are not directly considered in this study are the reduced manufacturing lead time and the increased response time. AM can enhance the processing performance of a product, if there is the potential to reduce the number of parts and eliminate time-consuming assembly operations.
The performance of a product was assessed by individually comparing single performance indicators such as weight/TMC and stiffness/TMC. In this case, the PcP and both PdP indicators increased, making the decision easy. However, in other scenarios, indicators can exhibit opposite paths, making a decision more ambiguous. In the case of the annular wing, both concepts exhibit weights below 200 g, thereby fulfilling the requirements. Thus, the weight criterion, as long as fulfilled, might have a lower importance to decision makers. Weighing factors could be an option to include the importance and to combine single characteristics into an overall performance indicator facilitating the decision making. In future, both concepts will be tested on the drone, performing highly dynamic manoeuvres to validate the design. The wing will be put to test in a wind tunnel to assess aerodynamic properties. Finally, the framework will be extended with weighing factors combining the PdP- and the PdP-indicators into PdP- and PcP-functions of which the fraction will result in a single performance value.

6 CONCLUSIONS

This research aimed to support decision makers in the context of AM product development and implementation. A performance assessment framework comparing the product- and the process-related performance of a product was proposed. The performance assessment framework was applied to a novel annular wing by opposing a machining to an AM design approach. Weight savings and bending stiffness were used as PdP and total manufacturing costs as PcP indicators. The AM design exhibits an increased bending stiffness by 28%, an decreased weight by 7% and a reduced TMC by 29% compared to the machining approach. The bending stiffness could be increased at constant processing effort by integrating revolving stiffeners into the AM design. Despite the high cost of SLS equipment, the TMC decreased by reducing the costs of labour and material.

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