IMPLEMENTATION OF LIGHTWEIGHT DESIGN IN THE PRODUCT DEVELOPMENT PROCESS OF UNMANNED AERIAL VEHICLES

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Abstract

The development and manufacturing of unmanned aerial vehicles (UAVs) require a multitude of design rules. Thereby, additive manufacturing (AM) processes provide a number of significant advantages over conventional production methods, particularly for implementing requirements with regard to lightweight construction and sustainability. A new, promising approach is presented, with which, through the combination of very light structural elements with a ribbed construction, an attached covering by means of foil is used. This contribution develops and presents a development process that is based on various development cycles. Such cycles differ in their effort and scope within the overall development, and may only comprise one part of the development process, or the entire development process. The applicability of this development process is demonstrated within the framework of a comprehensive case study. The aim is to develop an additively manufactured product that is as light as possible in the form of a UAV, along with a sustainable manufacturing process for such product. Finally, the results of this case study are analyzed with regard to the improvement of lightweight construction.

Keywords: Additive Manufacturing, Design for Additive Manufacturing (DfAM), Lightweight design, Design for X (DfX), Case study

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1 INTRODUCTION

The development and use of unmanned aerial vehicles (UAVs) have substantially gained importance over the last few years. In addition to use in the military sector, there are more and more civilian uses. For example, UAVs can be used for monitoring technical installations, for surveying or exploring large areas for agriculture or archaeology and for transporting goods (Valavanis and Vachtsevanos, 2015). For the development and production of UAVs, additive manufacturing processes have been increasingly used in recent years. In general, such processes have the advantage that the components can be transferred from CAD to production directly after development, without the necessity of additional work steps, such as the procurement of tools or the programming of tool paths. As Junk and Coté (2012) show, development times and costs can be drastically reduced in this manner. Moreover, the wide distribution documented by Wohlers (2014) and the rapidly growing market for additive processes make this technology quite interesting for the production of UAVs.
A further advantage of additive processes is that, as a rule, material is only required for the actual component. The supporting structure, which has a very small share of the total building volume, is the only waste. On the other hand, with conventional production, the components are machined from a slug, with up to 50% of the material being lost as shavings. In a comprehensive study by Yoon et al. (2014), it was shown that, in many cases, the consumption of energy in the manufacturing process is also significantly lower in comparison to forming and machining processes. In doing so, special features of the additive manufacturing method would have to be taken into account. The paper of Campbell, Bourell and Gibson (2012) is available for this purpose; it addresses the production-ready design of components that are produced in layers.
In addition, additive manufacturing processes offer further advantages that are particularly important for the production of UAVs. Thus, in addition to metals, it is also possible to use various plastics that enable a lightweight construction method. Furthermore, such processes in layers enable the implementation of complex shapes with free-form surfaces for the wings and tail units. Also, complex internal shapes, such as reinforcements and trusses in the fuselage are easily implemented. Finally, additional geometric elements, such as brackets for servomotors or ports for cables, can be easily integrated into the components of a UAV, without the necessity for additional work steps.

2 LITERATURE REVIEW OF 3D-PRINTED UAVS

Due to the aforementioned advantages, Additive Manufacturing (AM) processes have been increasingly used in the production of UAVs for several years (see Table 1). As a rule, plastics, such as ABS, PLA and PA, are used as the building material. Both the selective laser sintering (SLS) of plastic powders and the fused deposition modeling (FDM) of plastic filaments are used as manufacturing processes for such plastics. In doing so, the additive manufacturing of the individual parts - Rapid Prototyping (RP) - is often carried out in combination with a subsequent assembly. In addition, however, AM is also used for the production of molds that are used as tools (Rapid Tooling, RT) for manufacturing components, such as those made of carbon fibers.
A first example of a UAV that was produced with the assistance of SLS is provided by the "SULSA", which was developed by Marks (2011) at the University of Southampton and is based on designs of aircraft from the Second World War. The laser sintering method was used as the manufacturing process, and polyamide was used as material. In doing so, the fuselage and the wings were completely 3D-printed as shells, with reinforcements (“stringers”) on the inside.
In the same year, with the "Mini-UAV" from the University of Malaysia in Pahang, Zaha et al. (2011) presented an alternative construction method that leads to significant weight savings. The wing is carried out with a ribbed design, which is subsequently covered with a foil. The individual parts of the fuselage and the vertical and horizontal stabilizers were connected to each other using a profile made of carbon. The engineering and design with ABS material led to a very robust UAV.
In 2012, the University of Virginia presented the "Wendy" UAV, a replica of a tried and tested design from remote control (RC) model making. This UAV, presented by Easter et al. (2013), was created using the FDM process, which, due to the simple machine technology, is more favorable than SLS. ABS was used as the construction material.
A flexible approach for a UAV that was also manufactured using FDM is the "Variable AirSpeed Telescoping Additive Unmanned Air Vehicle VAST AUAV" developed by Stern and Cohen (2013) at

the Massachusetts Institute of Technology. It is produced from a mixed construction method of carbon components and components from a 3D printer. As a special feature, this UAV has telescopically extendable wings, in order to enable optimal conditions at different flying speeds.
The "Barcelona UAV", presented by Domènech Arboleda (2014), is composed of a total of approximately 30 components made of PLA, which was manufactured using the FDM process. In this case, an extremely lightweight construction was achieved, in which the wing load lies in the area of model airplanes that are produced by plastic foams, such as the "Easy Star II" model (Mischler, 2011).

Table 1. Comparison of developed UAVs using additive manufacturing (adapted from Junk and Schröder, 2016)

Name	SULSA	Mini-UAV	Wendy	VAST	Barcelona UAV	AMRC	ALF 1
Year	2011	2011	2012	2013	2014	2014	2015
Institute	University of South-ampton	Universiti Malaysia in Pahang	University of Virginia	Massachu-setts Institute of Technology	Universitat Poly-tecnica de Catalunya	University of Sheffield	University of Applied Sciences Offenburg
AM	SLS	FDM	FDM	FDM	FDM	FDM	FDM
Wing	RP	RP	RP	RP	RP	RT	RP
Fuselage	RP	Profile	RP	Profile	RP	RP	RP
Materials	PA	ABS, Carbon profile	ABS	ABS, carbon profile	PLA	ABS, carbon fibres	ABS, Carbon rovings

The AMRC Design and Prototyping Group of the University of Sheffield (2014) selected a different approach with the "AMRC - Fixed wing powered UAV". Here, additive manufacturing processes were used to carry out a hybrid construction method. In some cases, the components were made directly from ABS using the FDM process. On the other hand, moulding tools made of ABS were also produced and refined using the FDM process; these were used to manufacture components made of carbon fibers. Thus, in this example, both rapid prototyping and rapid tooling were used.
Another approach in manufacturing particularly lightweight UAVs using AM was presented by Junk and Schröder (2016). With this demonstration model named "Autonomous Aircraft 1" ALF 1 of the University of Applied Sciences in Offenburg, the wing was carried out with a ribbed construction method and reinforced by means of glued roving made of carbon. The wing was divided into segments and then glued over with foil during assembly. Thereby, with the design and subsequent 3D printing, the devices for the servomotors and the control sticks of the flaps can be easily integrated. The fuselage was designed as a complete shell, with reinforcements on the inside. Such fuselage also houses the drive, the control and the payload. This UAV showed good flight characteristics during the flight test, and it has the sufficient robustness to withstand even hard landings on a grass runway, without any damages.
With all the examples presented so far, all of the components, or at least a large proportion of the components, were produced with additive processes. The FDM process was predominantly used, because the systems required for this purpose are significantly more affordable than the systems for laser sintering. The components of the UAV consist of an external shell and a supporting structure on the inside. This results in relatively heavy designs, which in most cases weigh significantly more than UAVs made of foam material of comparable size.
The paper of Moon et al. (2014) investigates the basic possibilities of lightweight construction through the use of different lattice structures inside the wings of the UAV. In contrast to the UAVs presented so far, such lattice structures were produced using the Polyjet Modelling process (PJM). Such process uses a liquid photopolymer that is cured by means of UV light. Given a low layer thickness of less than 30 µm, very fine structures can be printed. However, this high resolution also leads to extremely long printing times in comparison to the FDM process. The segments were then tested and optimized for pressure and elastic deformation. However, only segments (and not complete UAVs) were investigated, such that this investigation only provides basic solutions.

3 REQUIREMENTS FOR LIGHTWEIGHT DESIGN USING ADDITIVE MANUFACTURING

In order to reduce the consumption of material and energy during the production of an UAV using AM, in this paper, various development methods are investigated and their application is shown. The particular sequence of the work steps in the process chain of AM must be observed. Initially, design takes place with the assistance of CAD software. In doing so, the individual components of the UAV are developed and drawn. A large number of restrictions must be observed during this step. First, the aerodynamics and the strength of the components must be ensured. In addition, manufacturing-related boundary conditions also play a role. Above all, the components must be able to be produced with the assistance of AM, and then must also be mountable. From the point of view of sustainability and lightweight construction, care should be taken to ensure that as little as possible material is consumed during production, and that the energy required for the production and operation of the UAV is as low as possible.

In the following pre-processing step, on the basis of the STL data from the CAD software, in addition to positioning in the installation space and the generation of the layers, support structures above all are generated with the assistance of particular software. This is crucial for material consumption, since the arrangement and positioning in the installation space can significantly influence this. In addition, the degree of filling of the components can also be varied with FDM. As Junk's investigations (2014) show, as the degree of filling increases, a higher weight and a higher strength of the components are achieved. In addition to material consumption, this also has an influence on the strength of the components. By critically examining the results from pre-processing, initial optimizations can be undertaken as early as this stage to improve the design. This "short development cycle" avoids material-consuming and time-consuming defective prints in the subsequent process steps as shown in Figure 1.

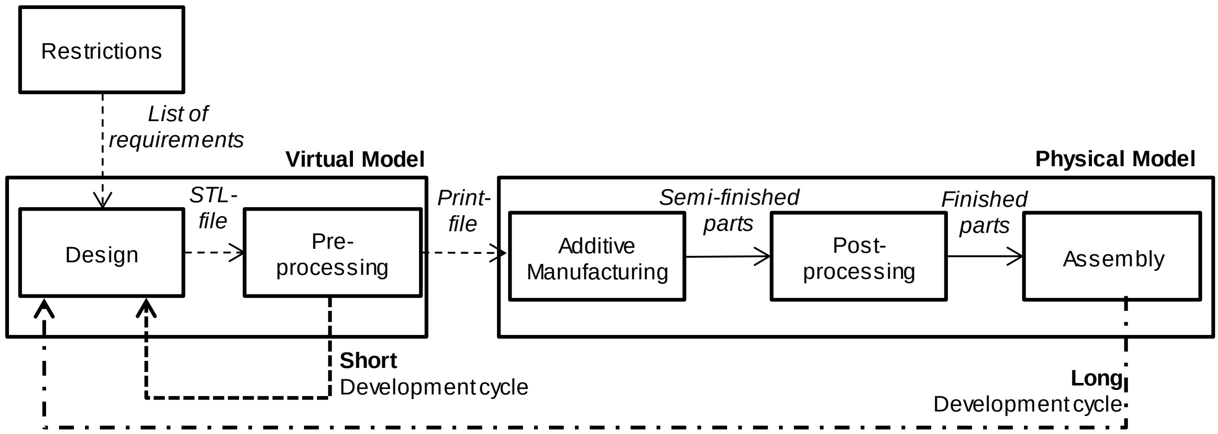

Figure 1. Development cycles in Design for Additive Manufacturing (adapted from Junk and Schröder, 2016)

In the subsequent process step, the actual build-up of the physical model takes place after reading the print data. Electrical energy is required primarily for the movement of the axes and the heating of the extrusion nozzles to approximately 280 °C for the building material. In the case of ABS as construction material, the building chamber must also be heated to a temperature of approximately 70 °C. From the point of view of sustainability, attention must be paid here to a short manufacturing period, since this can reduce energy consumption.

Finally, the post-processing of the semi-finished 3D model ("green body"), for which the support structures are removed, is carried out. In the best case, no additional energy consumption occurs, because the supports are removed mechanically by, for example, breaking up or trimming them. In the case of complex geometries, however, support structures are unavoidable. These are removed in a chemical process, in an alkaline bath for several hours. The lower the proportion of support structures, the lower the consumption of energy and raw materials for the removal of the supports. Defects and optimization measures that are only now discovered can be taken into account in the design upon the production of the components following the "long development cycle".

3.1 Case study for the implementation of lightweight construction with AM

In order to demonstrate the application of the two possible development cycles, a UAV was developed and additively manufactured using the FDM process. This UAV, designated "Autonomous Aircraft 2" ALF 2, was based on the principle of the flying wing (see Figure 2); that is, separate horizontal stabilizers were not used. Both the fuselage, and the wing and the horizontal stabilizer, are made by means of AM. As the construction material, PLA is used instead of ABS for the ALF 1. In the 3D-printed state, such material has a significantly higher tensile strength and a higher ultimate strength (see Table 2). This is based on the fact that, among other things, ABS in the printed state does not have the full density of the raw material. On the other hand, printed PLA achieves a degree of filling of 100%, and thus properties comparable to the solid material. In addition, the price is significantly lower than for ABS from OEM. The components were manufactured using a FDM process with an extrusion nozzle from 3D printers of the "Felix" brand, version 3.0. Lightweight design is carried out so that no supporting structure is necessary. Thus, post-processing is considerably simplified. The total length of the UAV is approximately 825 mm, and the wingspan is approximately 2000 mm.

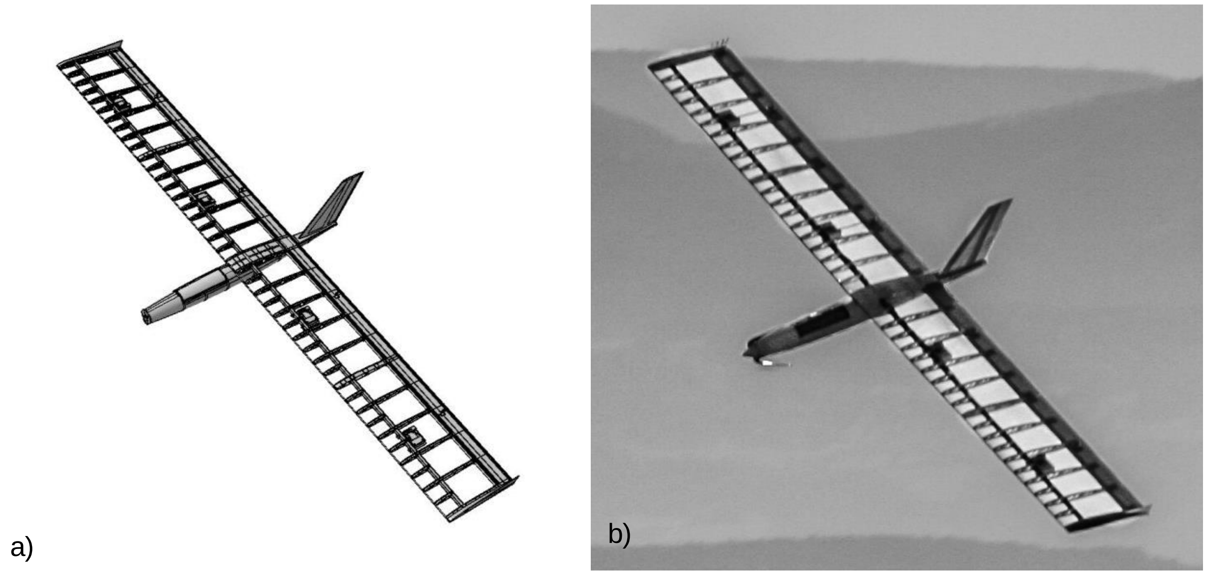

Figure 2. UAV named ALF 2: CAD model (a) and UAV during flight test (b)

The fuselage and the horizontal stabilizer are produced as a complete shell, which is provided with sufficient strength through reinforcements. For the wings, a design principle that deviates from most of the models presented in Table 1 is used. For most of them, a design for complete shells is printed, but they are very heavy. Only the two approaches with rib structures lead to a significant weight reduction. In order to achieve this particularly lightweight design, only the fuselage, the rudders and the flaps are implemented as a complete shell; the largest part of the wing consists of a lattice that is covered with a foil. In doing so, the advantages of AM are utilized, in order to make this lattice structure easy to manufacture and as resource-conserving as possible.

Since the building chamber of the FDM printer used allows only components up to a maximum height of 255 mm, the fuselage and the wings are divided into segments. In a subsequent assembly process, the segments are connected to one another by inserting them or through adhesive bonding. In order to avoid the time-consuming gluing of the individual rovings during assembly, this approach uses carbon pipes with square and round profiles. During development, the profiles were designed such that the wings can withstand a maximum deflection of 60 mm at a load of 6 g. Finally, the necessary components for drive and control are also integrated into the UAV.

3.2 Example of a short development cycle

A short development cycle involves pre-processing. Thus, defects or optimization possibilities that are discovered during pre-processing can be directly reported back to the design process, in order to improve the product. In addition, the short development cycle can be used to carry out basic investigations. For example, the purpose of constructing lattice structures in the fuselage of the UAV, there was an investigation of the angle to the base area from which no supporting structures are necessary. This question is important because, on the one hand, the additional support structures constitute an increased consumption of material. In addition, by doing without support structures, the protracted washing out of the supports in the alkaline bath during post-processing can be avoided or at least significantly shortened.

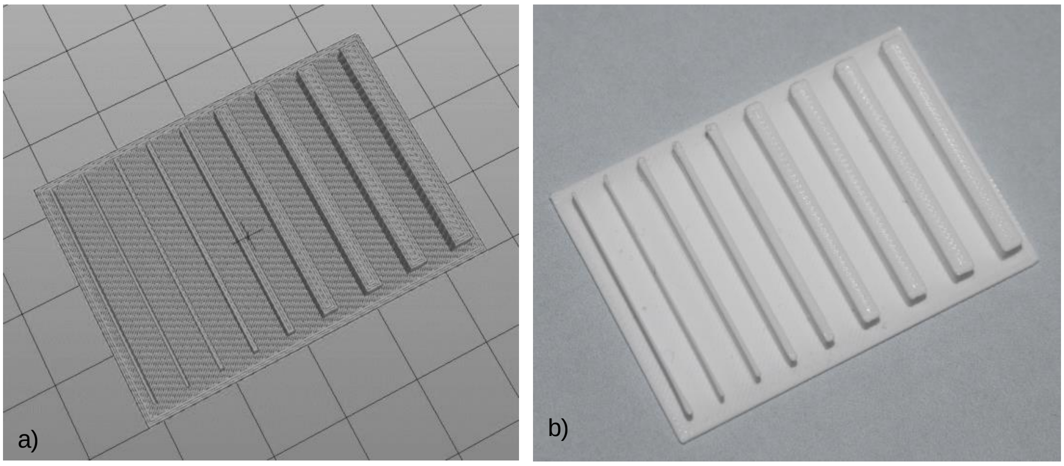

Figure 3: Determination of the process limit minimum wall thickness in Pre-processing (a) and as 3D printed test component using FDM (b)

Additional investigated fundamental questions include the minimum wall thickness that can be achieved (see Figure 3) and the ability to manufacture holes without supporting material (see Figure 4). It has been found that holes of up to a minimum diameter of 1 mm are easily possible. With the minimum wall thickness, a dimension of 0.35 mm has arisen; that is, only one path of filament material is applied by means of the extrusion head. Thus, it could be shown that, with this printer, significantly less wall thickness is possible than, for example, with the FDM printer for the production of the ALF 1, which could not fall below a minimum wall thickness of 1 mm (see Table 2). This thinner wall thickness in combination with the higher strength of the PLA material offers significantly more design freedom in design, and a much higher potential for lightweight design.

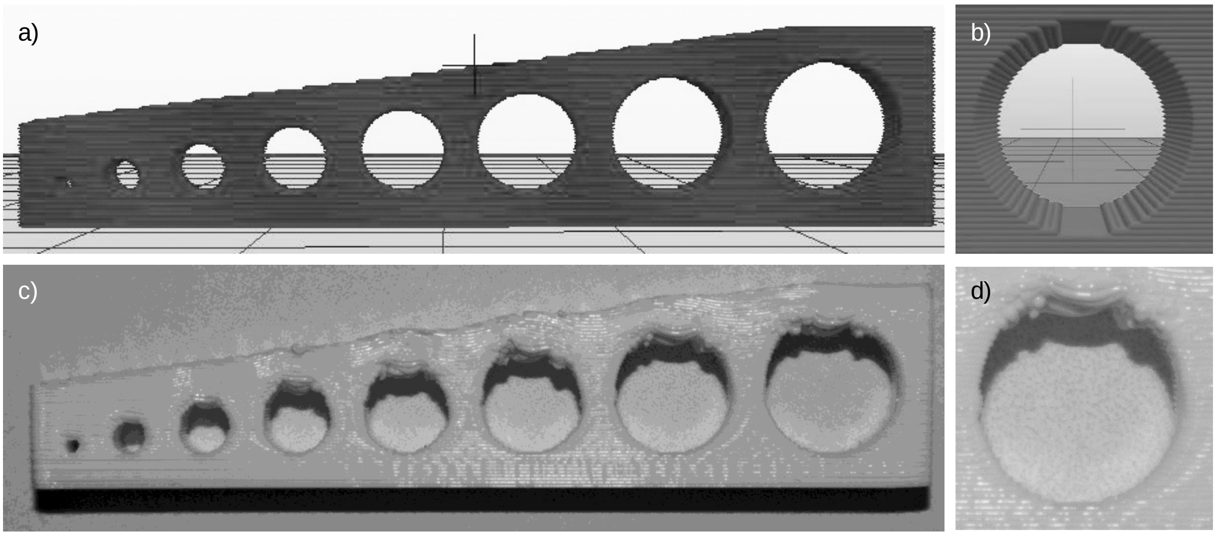

Figure 4. Determination of the process limit for the production of holes without support structure in Pre-processing (a) with detail of the gradation of the individual layers (b) and as test component using FDM (c) with detail of incidence in the upper region of the hole (d)

Figure 4 shows an investigation of the holes with which a supporting structure is no longer necessary. Moreover, a sample part for investigating the wall thickness is also shown in Figure 3 thereby, it can be seen that, as a rule, it is only possible to create discrete wall thicknesses, due to the path of the extrusion head. Thus, during design, care must be taken to ensure that wall thicknesses cannot be produced arbitrarily, but are produced only as a discrete function of the path and the material.

3.3 Example of a long development cycle

The long development cycle is necessary if defects and optimization measures are discovered only during the manufacturing of components or later during assembly. For example, it can be seen that, in the rear area of the wings and in the area of the servomotors, the foil can be applied only poorly. Therefore, in this case, with a modified design of the connecting parts between the segments and the bracket for the servo motors, there had to be a reaction to this problem. In addition, the servo brackets had to be reconstructed in such a way that the control sticks protrude upwards out of the housing. This can prevent them from being damaged during a hard landing (see Figure 5).

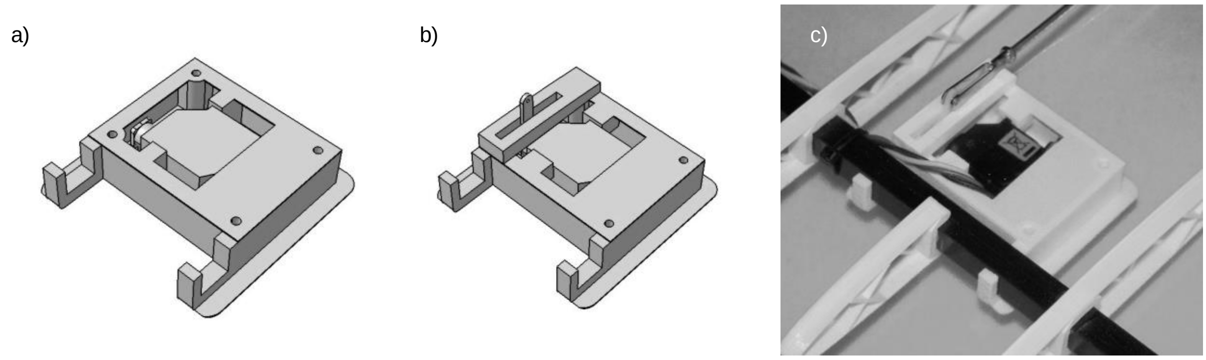

Figure 5. Design of servo bracket before (a), after passing through the main development cycle (b) and as 3D-printed (FDM) and mounted component (c)

In addition, many tests are only possible with real prototypes. These include, on the one hand, basic tests, such as the determination of the density of the material at different degrees of filling. On the other hand, they include specific tests on components, such as the bending strength of a wing or the determination of a suitable adhesive in order to connect the individual components.

The development of the wing segments is initially based on the new design of a rib by means of a lattice structures on the inside. The stability of the wing is ensured by a square tube made of carbon, which absorbs the torsional stress. On the front and rear edges of the wing, round profiles are used for stabilisation. This rib serves as the basis for numerous variants - so-called "special ribs". It has been found that short intermediate ribs are necessary in order to tension the foil without warping. Variants that are used to store the flaps must also be developed. In the middle of the wing, one variant that enables a screw connection to the fuselage is required. Finally, "edge curves" are necessary at the two wing ends. The wing, with all variants of the ribs from the CAD software, are shown in Fig. 6. In addition, the inner structure of the mounted wing is clearly visible through the transparent foil.

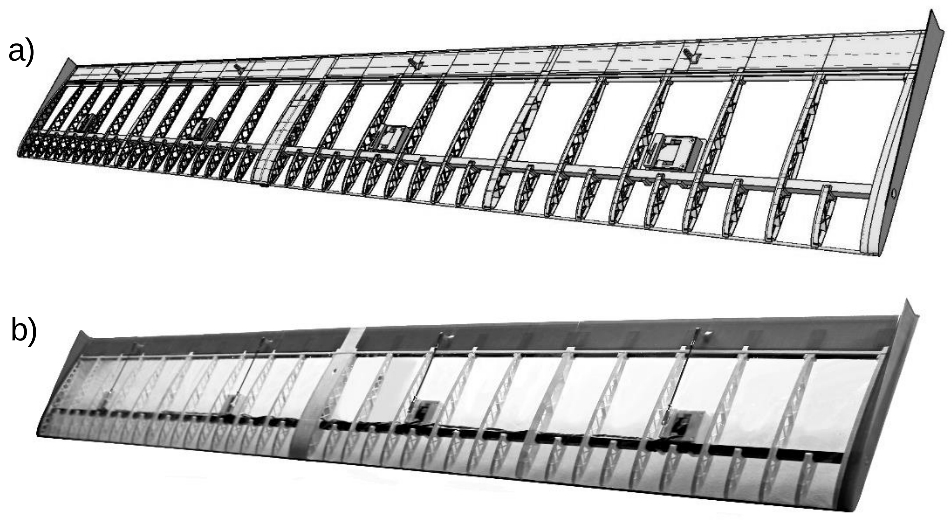

Figure 6. Design of the wing in the CAD software (a) and mounted wing with components from 3D printing using FDM (b)

4 TECHNICAL AND ECONOMIC EVALUATION AND DISCUSSION

The UAV with the designation ALF 2, which was produced using generative manufacturing, can now be compared with other models in terms of lightweight construction. The surface load that results from the ratio of the total mass of the UAV and the wing surface is suitable as a comparison parameter. However, the exact dimensions of the airfoil geometry and the weights of the UAV are not sufficiently known in all cases that represent the state of the art in the literature. To simplify the comparison, the wingspan load (that is, the ratio of the total mass of the UAV and the length of the wings) is used in this case (see Figure 7). In addition, the wing load of a typical model airplane made of foam, as is commercially available, namely the "Easy Star II" model (Mischer, 2011), is considered as the comparison measure

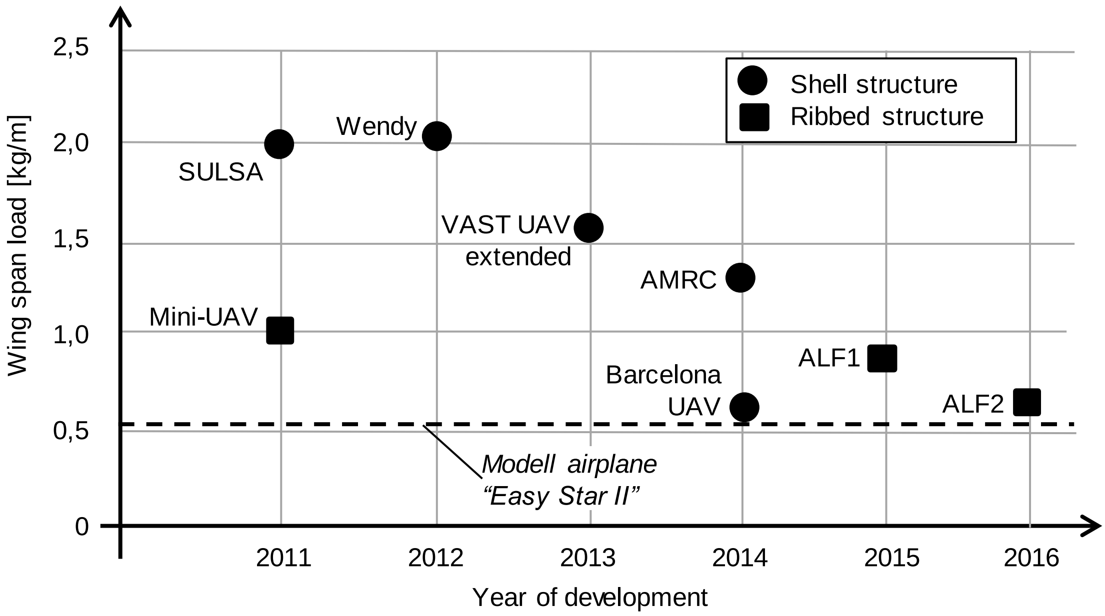

Figure 7: Comparison of the wingspan load for various 3D-printed UAVs with model airplanes made of foam (adapted from Junk and Schröder, 2016)

In this comparison, a distinction is made between two construction methods. On the one hand, the UAVs for which at least the wings are printed as a complete shell are considered. An additional category is comprised of UAVs, the wings of which are made of a ribbed construction, which is subsequently covered with a foil. The UAVs with a complete shell tend to feature a higher wingspan load. The comparison shows that the wingspan load of the UAV, as developed in recent years, has gradually decreased. On the other hand, with the UAV that uses a ribbed construction method with a cover, significantly lower wingspan loads must be found that, with the ALF 2 model presented here, are already very close to the comparison model made of plastic.

Table 2: Comparison of the two UAVs, ALF 1 and ALF 2

	ALF 1	ALF 2
Material	ABS	PLA
Density (3D-printed)	0.97	1.3
Tensile strength (3D-printed) [MPa]	28.5	54.1
Ultimate strength (3D-printed) [MPa]	7.8	18.7
Additive manufacturing device	HP Designjet 3D	Felix 3.0
Minimum wall thickness [mm]	1.0	0.35
Construction material [cm^3]	878.5	547.9
Support material [cm^3]	356.2	0
Manufacturing time [h]	143.5	222.7
Wing load [kg/dm^2]	43.8	27.2

In this case, the significant reduction in the wingspan load could be achieved through the use of a printer, which can produce smaller wall thicknesses (see Table 2). Due to this low wall thickness, the consumption of model material could be significantly reduced, by a total of 37.6%. This is particularly remarkable since the PLA material has a slightly higher density compared to ABS. Since the material PLA has a tendency to soften under heat, the usage should be made so that the UAV is set to the sunlight only for a limited time. In terms of sustainability, the production of the ALF 2 took place completely without support material, which also significantly reduced production costs. However, due to the somewhat slower speed, the printing time for the ALF 2 was approximately 55.2% higher than for the ALF1, which was produced on an industrial 3D printer. Overall, this consistent lightweight construction for the ALF 2 was able to reduce the surface load by 37.8%, compared to the ALF 1. In comparison with the "Mini-UAV" with a wing load of 62.5 kg/dm^3 (Taha et al., 2011), which was also produced with a ribbed construction method, the ALF 2 represents a reduction of approximately 56.5%.

5 SUMMARY AND OUTLOOK

This article investigates the possibilities for the implementation of unmanned aerial vehicles with additive manufacturing in the product development process. In doing so, it engages in the state of the art, which has already produced initial models at different universities around the world. Such models have mainly been produced using the FDM process in combination with ABS material. In doing so, various processes, such as rapid prototyping and rapid tooling, are employed. Mixed construction methods in combination with carbon reinforcements are often used. The carbon may be used in the form of packets made of individual rovings or as finished round or square profiles.

Thereby, it could be determined that two construction methods are currently predominant. On the one hand, the shell construction method, with which the wings and the fuselage are designed as a complete shell with reinforcements on the inside. The second variant is a ribbed construction method, with which the wing is covered with a foil. The investigation has shown that the ribbed construction method is preferable from the point of view of lightweight design, since it generally leads to smaller wingspan loads.

An analysis of the product development process shows that different optimization cycles, with the goal of lightweight design, are used. With the short development cycle, the first design steps can be taken directly after pre-processing, in order to improve the ability to manufacture and to reduce the weight. With the long development cycle, defects that are discovered in the additive manufacturing of the individual parts of a UAV, during post-processing or during the subsequent assembly of the individual parts into a product are reported back to the design process for the purpose of elimination and optimization.

In a case study the development of a wing for a UAV with a ribbed construction method is demonstrated. In this example it could be shown, how the two development cycles can be applied practically. In doing so, a 3D printer was used, and this allowed a significant reduction in weight due to the feasibility of very thin wall thicknesses. Thus, basic investigations could be carried applying the “short development cycle”: for example, reducing the consumption of support material by means of production-ready design. During the “long development cycle” the design of the servo brackets could be improved. In addition, it could be shown that, through the design of variants, all components for the wing can be designed with a ribbed construction method. During the development and the usage of the UAV it was learned, that by selection of the 3D printer the minimal wall thickness is influenced. The material PLA offers advantages in the processing chain but also the essential disadvantage of softening in sunlight.

A comparison of the wingspan load shows the current trend to reduce such load up to a range that today can only be achieved by model airplanes made of foam material. Since, regarding wingspan load, the ALF 2 model is already comparable with the foam material models, no further reduction in weight should be in the forefront of development. Rather, the use of alternative drive concepts should be investigated. The transparent wings offer a good option for using solar cells. Such cells would no longer have to be mounted on the outside of the wing, which generally leads to interfering edges and necessitates an elaborate shaping of the solar cells. Since, in addition to a battery, the additional weight of the solar cells has to be considered in this alternative drive concept, extreme lightweight design is required in this application.

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