

Comparison of different fidelity mass analyses

*Jacek Mieloszyk, Andrzej Tarnowski, Tomasz Goetzendorf-Grabowski, Mariusz Kowalski and
Bartłomiej Goliszek*

Faculty of Power and Aeronautical Engineering, Institute of Aeronautics and Applied Mechanics, Warsaw University of Technology,
Warszawa, Poland

Abstract

Purpose – Aircraft structure mass estimation is a very important issue in aerospace. Multiple methods of different fidelity are available, which give results with varying accuracy. Sometimes these methods are giving a high discrepancy of estimated mass compared to the real mass of the structure. The discrepancy is especially noticeable in the case of small aircraft with a composite structure. Their mass properties highly depend not only on the material but also on technology and the human factor. Moreover, methods of mass estimation for unmanned aerial vehicle (UAV) platforms are even less established and examined. The purpose of this paper is to present and discuss various methods of mass estimation.

Design/methodology/approach – The paper presents different procedures of mass estimation for small UAVs with a composite structure. Beginning from the simplest one, where mass is estimated basing on a single equation and finishing with a mass estimation based on finite element method model and three-dimensional computer-aided design model. The results from all methods are compared with the airworthy aircraft and conclusions are discussed.

Findings – Mass of flying aircraft was estimated with different methods and compared. It revealed levels of accuracy of the investigated methods. Moreover, the influence on structure mass of human factor, glueing and painting is underlined.

Practical implications – Mass of the structure is a key factor in aerospace, which influences the performance of the aircraft. Thorough knowledge about the accuracy of the mass estimation methods and possible sources of discrepancies in mass analyses provides an essential tool for designers, which can be used with confidence and allows for the development of new cutting-edge constructions.

Originality/value – There are very few comparisons of mass estimation methods with an actual mass of manufactured and functional airframes. Additionally, mass estimation inaccuracies based on technological issues are presented, which is seldom done.

Keywords FEM, CAD, Aircraft design, Mass analysis

Paper type Research paper

Nomenclature

Symbols

- ρ = air density [kg/m^3];
- CD = aerodynamic drag coefficient;
- CL = aerodynamic lift coefficient;
- g = gravity acceleration, $9.81 \text{ [m/s}^2\text{]}$;
- m = mass [kg];
- V = flight velocity [m/s];
- S = reference area [m^2];
- D = aerodynamic drag [N]; and
- P = power [W].

Definitions, Acronyms and Abbreviations

- UAV = Unmanned Aerial Vehicle;
- RC = Remote Control;
- NORD = Numerical Optimization Results Demonstrator;
- GFRP = Glass Fiber Reinforced Polymer;
- CAD = Computer Aided Design;
- FEM = Finite Element Method;
- CG = Center of Gravity; and
- CFRP = Carbon Fiber Reinforced Polymer.

Introduction

Mass estimation and its reduction is one of the most important factors in aircraft design (Chen, 2012; Raymer, 2012; Zhang *et al.*, 2014). There are many mass estimation techniques that can be used in the design (Dababneh and Kipouros, 2018). The greater the take-off mass of the aircraft, the more energy is required. The total mass of the aircraft consists of few main components. In the aircraft, particularly in the unmanned aerial vehicle (UAV), usually one can distinguish the following mass components: airframe, propulsion system, avionics, payload and fuel or batteries. The payload is a design requirement. Mass of the avionics depends on the class of aircraft and mission it is designed for, therefore it would not vary too much. The most significant mass factors are placed in the airframe itself. It has to be as light as possible but also withstand stresses, be rigid enough to avoid coupling with aerodynamics, e.g. wing twist divergence or flutter vibrations. Moreover, the aerodynamic loads acting on the aircraft must be considered. Airframe mass impacts also other mass components. If the mass of the structure rises the total mass of the aircraft increases, which results in higher demand for the power needed to fly. As a consequence propulsion system has to be bigger and

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The findings of the work give valuable insight into the design and manufacturing processes of structures, from which designers can benefit.

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it will consume more fuel. By keeping the mass of the airframe as low as possible also the mass of other components can be reduced as indicated.

In this paper, for the purpose of mass estimations methods evaluation, two UAV composite structures will be examined. The first one is a 5 kg UAV in the flying wing configuration (Tarnowski *et al.*, 2018) shown in Figure 1. It has a composite structure made with composite wet layup vacuum technology. The composite is mostly a glass fiber reinforced polymer sandwich structure, reinforced with unidirectional carbon fiber reinforced polymer in the critical parts of the structure. The UAV went through the whole design process from the conceptual stage to the detailed design and manufacturing, finally being airborne. Depending on the phase of the design mass was estimated with basic engineering methods through mass estimation based on the finite element method (FEM) and computer-aided design (CAD) models. All types of mass estimations are shown in the paper and compared with the mass of the manufactured airframe.

The second type of the investigated structure is a wing of a 25 kg UAV in the quad plane configuration (Goetzendorf-Grabowski *et al.*, 2020) Figure 2. This aircraft is also manufactured with composite wet layup vacuum technology. The UAV, which is currently on its first flight, will be built in short series and several copies of the outer wings' segments were manufactured. All segments were carefully measured and all discrepancies from the mass estimation were noted. In this

Figure 1 UAV NORD – numerical optimization results demonstrator



Figure 2 UAV in quad plane configuration – Chimera



example influence of the manufacturing technology and human factor can be observed and analysed.

In the following chapters of this paper different mass estimation technics are presented and the derived results were shown, for the considered UAV structures. As the final result, all mass estimations methods are evaluated and compared against the actual mass of manufactured structures.

Conceptual mass estimation

The procedure of conceptual mass estimation is based on obtaining equilibrium of lift force with the weight of the aircraft: equation (1) and equilibrium of thrust and drag forces equation (2). The power needed for the flight can be expressed with equation (3). Including the overall efficiency of the propulsion system, the total required power is given by equation (4). At this initial stage, the total mass of the aircraft is assumed to be accumulated in the point of the centre of gravity (CG) of the aircraft whilst aircraft rotation motions are not considered. For electric propulsion endurance, with specified power consumption for particular mission parts, can be calculated with equation (5), where m_f is the mass of the batteries and k is the batteries' energy density.

Total mass for the flight can be estimated by adding all mass components, equation (6). Mass of the payload has been a requirement and was kept constant. The mass of the propulsion system and the mass of the batteries have been designing parameters and were scaled. With the rising demand for power for flight, the mass of the propulsion system was also raised to maintain the power demand. The number of batteries was increased until the required flight endurance was reached. The very important mass component is the airframe mass. A simple but useful method of mass estimation is by using empirical formulas, which are derived from the measurements of aircraft structures similar to the one being designed. There are many example formulas derived by different researchers for different types of structures. Depending on the structure type and quality of manufacturing, measured by mass, equations' coefficients can be adjusted. Overview of equations for aircraft mass estimation, formulated by different authors, is shown in (Noth, 2008). It is also a major drawback of the method, as it is very sensitive to the coefficients in the structure mass estimation equations. The designer has to be sure what type of structure the aircraft has and which coefficients to use in the equation to obtain results with minimum mass inaccuracies. The second drawback due to the simplicity is that the method gives only the total mass of the structure without information about the structure component's masses and moments of inertia. This method very well suits the conceptual phase of the design to make initial mass estimations. It can be also used for preliminary multidisciplinary design and optimization of aircraft (Noth, 2008; Finger, 2020). Detail description of the used design procedure can be found in (Mieloszyk and Tarnowski, 2019):

$$m \cdot g = \frac{1}{2} \cdot \rho \cdot V^2 \cdot C_L \cdot S \quad (1)$$

$$T = \frac{1}{2} \cdot \rho \cdot V^2 \cdot C_D \cdot S \quad (2)$$

$$P_{\text{flight}} = T \cdot V \quad (3)$$

$$P_{\text{total}} = \frac{P_{\text{flight}}}{\eta} \quad (4)$$

$$t = \frac{m_f \cdot k}{P_{\text{total}}} \quad (5)$$

$$m = m_{\text{airframe}} + m_{\text{payload}} + m_{\text{propulsion_sys}} + m_{\text{batt}} \quad (6)$$

Mass-based on structure engineering calculations

Engineering calculations of the structures can be considered as middle fidelity mass estimation methods. These methods require more detailed input data but also give more valuable results, e.g. the number of composite layers distribution along the wingspan. Still, these methods are not too overwhelming to make manual calculations although now they are done with help of computers (Elham *et al.*, 2013). As a consequence aircraft designer has initial information about masses of separate structure components, material usage for different components and material distribution. These methods are not to be treated as detailed design, as to manufacture all the components, technology and specific details of the structures have to be considered. These results can be used to estimate total mass, the CG position of the structure and the most significant moments of inertia which are crucial for stability analyses (Mieloszyk *et al.*, 2020).

Mass and moments of inertia calculation have been performed for characteristic points of the flight envelope for both UAVs. Specific load factors versus airspeed have been identified and calculated according to airworthiness regulation (EASA, 2017 – CS-23) and are presented in Tables 1 and 2.

For further analyses, the most demanding conditions of flight envelope for structural design have been selected (and marked in tables), which resulted in the biggest mass of calculated structural elements. For numerical optimization results demonstrator (NORD) UAV, this condition is achieved for load factor $n = -5.5$ and airspeed $V = 35$ m/s, whilst for Chimera UAV load and airspeed are, respectively, $n = 6.8$ and $V = 35$ m/s.

Mass-based on computer-aided design and finite element method models

Structure analyses are always required during aircraft design. Global FEM models created for this purpose are

Table 2 CHIMERA Wing main mass components for different loads

Load envelope	Mass [kg]				Moments of inertia [kg/m ²]		
	Spar Cap	Spar web	Wing skin	Total mass	Ixx	Iyy	Izz
A	0.15	0.01	0.18	0.35	0.52	0.05	0.49
C	0.26	0.01	0.18	0.46	0.60	0.04	0.57
D	0.23	0.01	0.18	0.42	0.58	0.05	0.54
E	0.10	0.01	0.18	0.30	0.49	0.05	0.46
F	0.10	0.01	0.18	0.29	0.48	0.05	0.45
G	0.05	0.01	0.18	0.25	0.45	0.05	0.42

often made even before detailed CAD documentation. They contain primary structures' geometry and select materials. FEM models will not be as detailed as CAD models and may contain some simplification, but they can still be a good base for structure mass estimation (Nigam *et al.*, 2015). If the project is advanced and contains a detailed CAD model it can be used for comprehensive mass calculation (Benaouali and Kachel, 2017; Choi *et al.*, 2007).

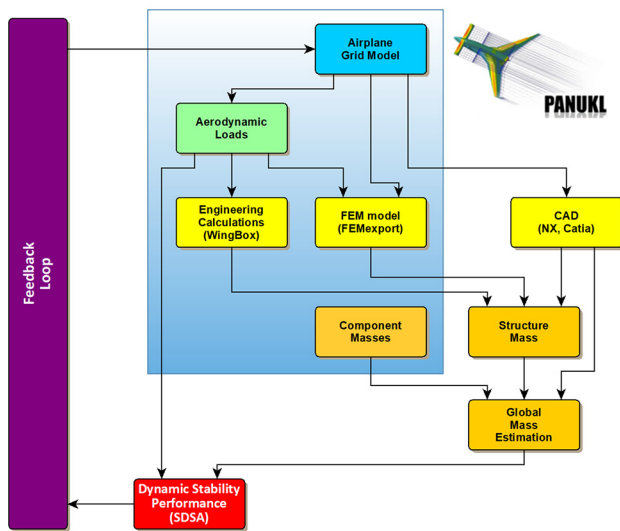
Structure mass calculation can be assisted by a combination of software tools that have major tasks other than mass estimation but could provide the required information. The fundamental data necessary to estimate the mass of the structure are loads acting on the airframe, especially aerodynamic loads. The idea to combine aerodynamic loads (PANUKL, 2020) with FEM analyses (Calculix, 2019) presented by Goetzendorf-Grabowski and Mieloszyk (2017) was enhanced by modules to calculate the mass of the structure. Additionally, the initial estimation of masses and estimations given by CAD systems allow verifying the correctness of the calculation. The block diagram of the software environment is presented in Figure 3. The FEM models of NORD and Chimera wings derived by described methodology, which were then used for the mass estimations are presented in Figure 4.

For both airplanes, detailed CAD documentation was created. It contains all information about the geometry, materials used and technology needed for the manufacturing processes. Based on this detailed information it was possible to make the mass analysis of the entire structure using individual masses of parts used to form them. Figure 5 shows CAD models of the wings of the airplanes.

Comparison of the computed masses, with FEM and CAD models, are compared against the weighed manufactured structures and are presented in the next chapters.

Table 1 Nord Wing main mass components for different loads

Load envelope	Mass [kg]				Moments of inertia [kg/m ²]		
	Spar Cap	Spar web	Wing skin	Total mass	Ixx	Iyy	Izz
C	0.06	0.01	0.16	0.22	0.29	0.17	0.46
D	0.06	0.01	0.16	0.23	0.30	0.17	0.46
E	0.09	0.01	0.16	0.25	0.32	0.17	0.49
F	0.10	0.01	0.16	0.26	0.32	0.17	0.49

Figure 3 Scheme of the software environment

Actual structure masses measurement

Constructed structures of the UAVs allow making assessments of the mass estimation models. Figures 6 and 7 show the mass breakdown of the centre body and wing of the NORD UAV. It has to be noted that the structure was a prototype built with help of students and the human factor in the manufacturing of

the structures is clearly visible. The amount of adhesive applied in the centre body is 4.3% of its mass, on the other hand, the amount of glue in the wings is 26.3%. The mass difference of the left and right wings is 2.1%. Mass estimation techniques in most cases do not include manufacturing technology aspects. The additional mass of the adhesive can be only included by empirical measurements of similar structures manufactured in the same facility. With gained experience by the staff, after manufacturing several structures and improving the quality of production processes, replication with small discrepancies can be achieved. It is also noticeable that the percentage of paint in the case of the centre body is 15.4% and in the case of the wings is 9.3%. The difference is not as big as in the case of the adhesive mass, but still noticeable. The shape of the centre body is more complex and contains many access panels compared to the wings Figure 5. Composite structures have natural surface imperfections. To make the high-quality access panels in a complex shape, a significant amount of filler putty and paint has to be applied.

It is also a general rule that composite parts with more complex shapes tend to be heavier and with bigger discrepancies to the mass estimation models – Figure 8. These parts are more vulnerable to the manufacturing human factor and staff's experience because more resin can be accumulated in the corners of the complex shapes.

The lighter the element, the more scattering in the mass of the manufactured parts occurs. It is clearly visible by comparing Figures 8 and 9. Smaller parts are generally harder

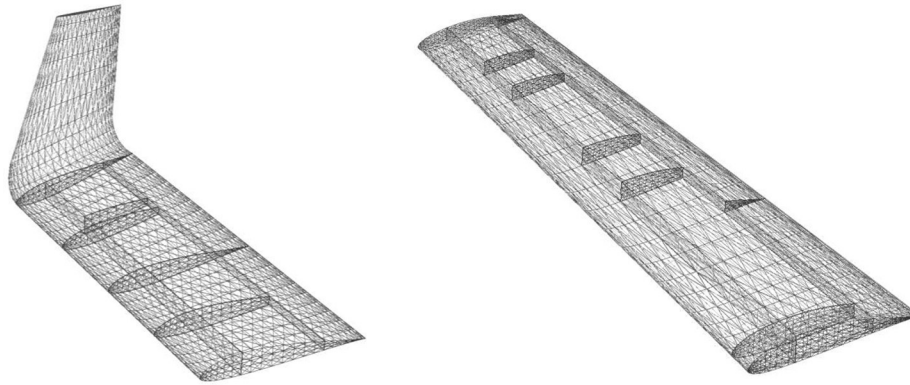
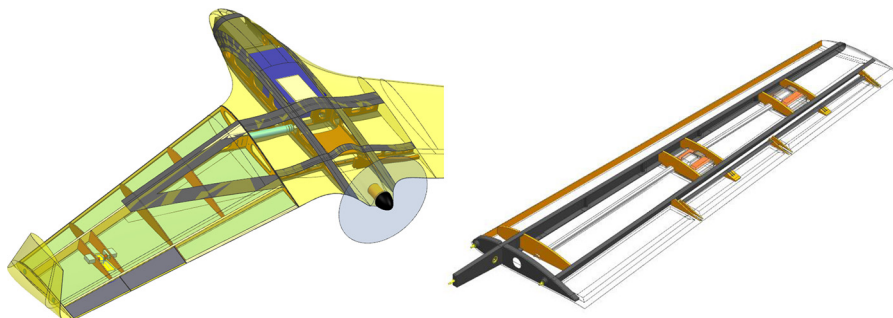
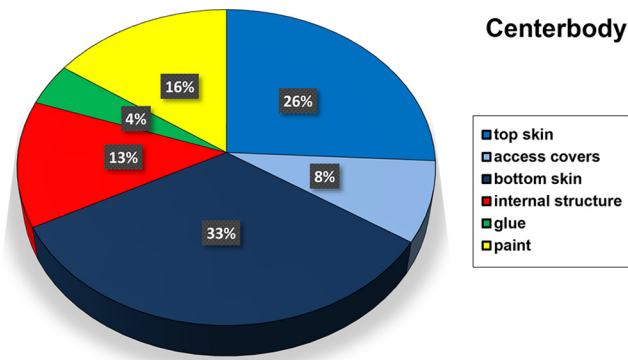
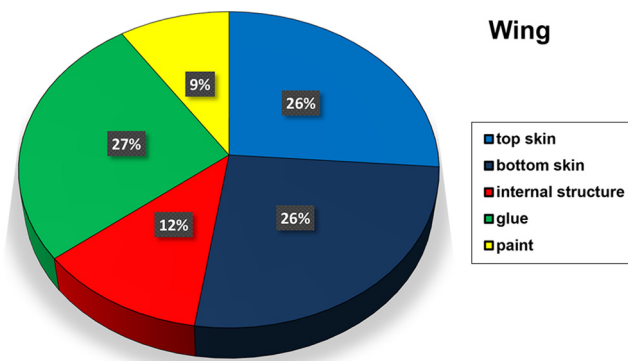
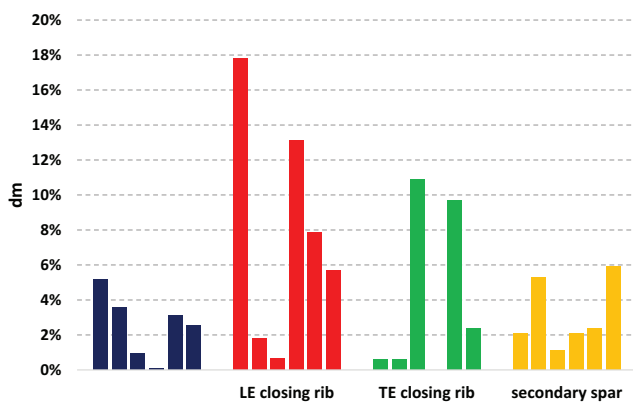
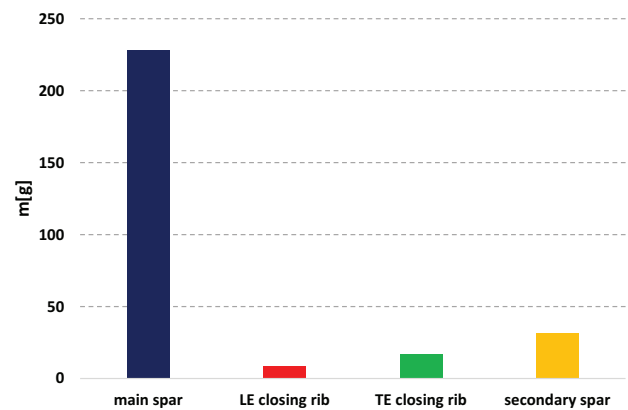
Figure 4 Examples of FEM models used for mass estimation a) NORD wing, b) Chimera wing**Figure 5** Examples of CAD models for mass estimation a) NORD wing and centre body, b) Chimera wing

Figure 6 NORD centre body break down into mass components**Figure 7** NORD wing break down into mass components**Figure 8** Mass divergence from mean for different elements (particular copies)

to manufacture and even small changes in the composite layup and amount of resin application have a noticeable impact on the percentage difference in mass of the manufactured parts. On the other hand, small parts have little contribution to the overall mass of the structure.

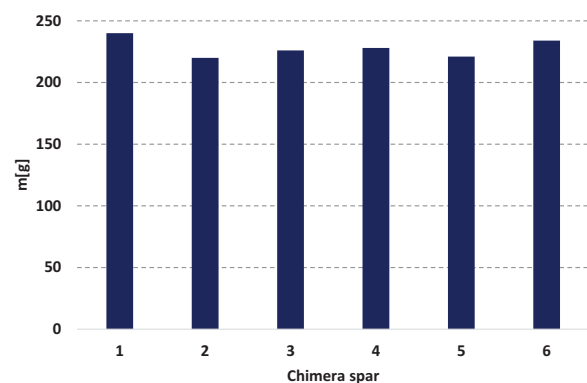
An example of manufacturing Chimera wing's spars shows how the manufacturing process can be improved, achieving a good replication ratio. Wing's spar is part of the primary structure carrying main loads. Therefore, it contains many types of composite materials and is challenging to manufacture. Before mastering the final manufacturing process a few

Figure 9 Mass of structure components

attempts had to be taken and details of manufacturing technology improved. In the course of the Chimera project, six wing' spars were manufactured. Figure 10 shows the comparison of its masses. The single highest discrepancy from the average mass of the manufactured spars is 5.2%, but in the other cases, it is less.

Comparison of mass models with the actual structure

Comparing single elements of the structure show interesting trends – Table 3. The simplest engineering methods estimate only the primary structure mass. Moreover, the evaluated mass is significantly underestimated compared to the manufactured component. The middle fidelity FEM mass estimation model gives more accurate results compared to the measured values, but still far from it. Finally, the CAD model gives satisfactory

Figure 10 Chimera main spar masses**Table 3** Chimera wing components masses in grams

Element	Engineering	FEM	CAD	Measured
Main spar	261	155	248.3	228.2
LE closing rib	–	30.5	5.8	8.7
TE closing rib	–	0.01	12.5	17.0
Secondary spar	–	64	38.3	31.4

results for the design phase of the project. It is also noticeable that heavier elements' mass is better estimated than lighter ones. This observation is also related to the earlier conclusion that heavier elements are manufactured with better replication and tighter mass tolerance.

Figures 11 and 12 show the comparison of different mass estimation models with the manufactured structures of the NORD and Chimera wings. Mass of glue and paint average percentage is also included in the estimates, based on the measurements of the NORD structure. Engineering mass models noticeably underestimate the actual mass of structures, especially the simplest engineering model. More advanced models based on FEM and CAD techniques are much closer to the measured masses. The differences between the structure itself are quite small but it gets bigger when comparing the masses of glue and masses of paint. The masses of glue and paint in the mass models are an average percentage of the pure structure mass. If the manufactured structure has established repeatability the estimates match well, but if the human factor in the manufacturing process occurs the estimates diverge. In the case of the NORD UAV, an increased amount of glue was applied (Figure 11) whilst Chimera UAV has an unusually thin paint layer – Figure 12. Mass estimates divergence from the manufactured parts can also be a quality indicator.

Overall mass properties are compared with the flying airplane (Table 4) on the example of the NORD UAV. During the

Figure 11 NORD – aircraft mass estimation methods comparison for the wing

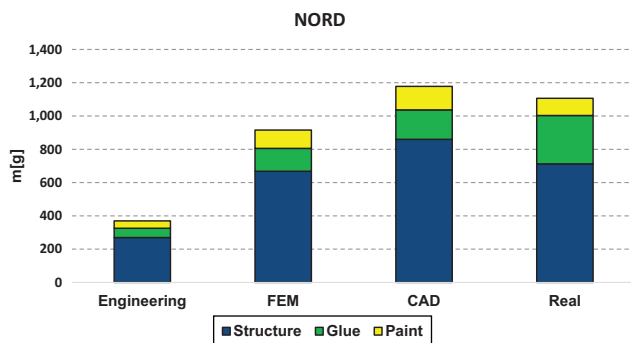


Figure 12 Chimera – aircraft mass estimation methods comparison for the wing

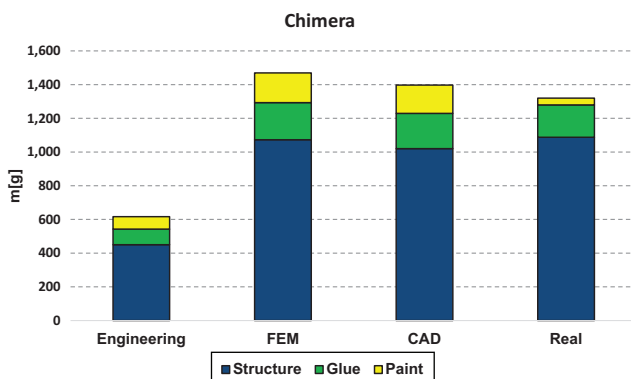


Table 4 Nord Masses and moments of inertia

Parameter		Engineering	FEM	CAD	Measured	
					min x_CG	max x_CG
m	[kg]	1.1	3.13	4.37	5.04	4.74
m _{struct}	[kg]	0.26	2.8	3.23	3.3	3.3
CGx	[m]	–	0.687	0.665	0.63	0.664
Ixx	[kg/m ²]	0.391	0.91	1.4	1.587	1.587
Iyy	[kg/m ²]	0.295	0.292	0.544	0.571	0.511
Izz	[kg/m ²]	0.686	1.18	1.6	1.994	1.935

course of the test flights, NORD UAV was flying with different balance weights and CG positions, which is indicated in Table 4. All the mass models include additional mass properties of the most significant equipment such as motors and batteries. Reviewing the results from Table 4 the basic engineering methods can be used for initial structure calculations, but they give very crude estimates of the mass of the complete structure. FEM models containing primary structures give closer results to the airworthy aircraft. Total mass is still far away from the actual one but gives the designer an initial estimate. The position of CG has already quite a good estimate. Moments of inertia are not perfect compared to the real structure. Still, they maintain appropriate proportions and can be used for initial performance and dynamic stability analyses, which should be verified later on. CAD models give the best estimates compared to flying aircraft. Although, even they can be further improved. It has to be noted that the more detailed the CAD model is the more exact are the estimates of the mass properties. FEM and CAD models are also very sensitive to the parameters of the wing skin materials and thickness. Due to the large area of the outer surfaces, they form a significant percentage of the overall mass. Even a small change of surface thickness or material density has a big impact on the general estimates of the mass properties.

Conclusion

The paper compares different mass estimation models with actual aircraft structures. The measured structures were built and used in airworthy operations. The mass estimates contain also adhesive and paint masses, as well as a human factor influencing the manufacturing process.

By comparison of the results from different methods with the measured mass properties, a few conclusions were drawn. The more sophisticated the analysis model the better results were achieved. Results from middle fidelity FEM mass estimation models can be used for further aircraft design analyses, but have to be verified and improved later on. High fidelity CAD mass estimations give good results but are still sensitive to the thickness and material properties of the large surface areas. Due to the manufacturing processes factors built aircraft structures cannot be treated as a perfect reference for mass estimation models because masses of the manufactured structures will also vary between each other.

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Corresponding author

Tomasz Goetzendorf-Grabowski can be contacted at: tgrab@meil.pw.edu.pl