USE OF CAD TOOLS FOR WEIGHT ESTIMATION IN AIRCRAFT CONCEPTUAL DESIGN

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Abstract

Advantages and possibilities offer by modern CAD tools in conceptual design are discussed, in order to illustrate these possibilities a method to estimate weight in conceptual design is presented. The present weight method is based on geometry and simple load analyses; the weight is determined from a 3D computer model. The actual method is a compromise between empirical methods and time-consuming methods based on finite element analyses. The method has been applied on commercial aircraft for validation. The present model allows investigation of unconventional and conventional configuration, and possibility of creating different structure layout.

The present results have been compared with other available method in conceptual design. Beside allowing weight estimation modern CAD program offer integration and data exchange with other domain such as computational fluid dynamic, system simulation and production analyses and planning.

1 Introduction

Development of modern aircraft has become more and more expensive; in order to minimize the development cost improvement of the conceptual design phase is needed. One main challenge in the conceptual design is the weight estimation. Weight estimation in conceptual design is often based on statistical or empirical approaches; these methods often extract values from similar aircraft or from historical trend, and are largely used.

Integration of modern Computer Aided Design (CAD) tools such as Pro/Engineer[1] and CATIA[2] offer new possibilities in conceptual design. These tools/software where mainly used later in the design. The present work investigates the possibility of weight estimation based on CAD models and the demands imposed on the CAD model. Discussion on future possibility offer by CAD software beside the weight estimation is also presented.

2 Available information from the CAD model

With weight calculation all modern CAD software allow inertia analyses. The inertia characteristics of the airplane are often needed for stability and control and will be a good complement to other methods, such as DATCOM [1]. In case of unconventional design the inertia is difficult to determine, by using CAD early in the design this information can easily be obtained.

One advantage of integrating CAD tools early in the design, beside weight determination, is the possibility to perform fitting tests with the different sub-systems, such as actuators, hydraulic piping and landing gears for example. Many supplier companies have complete CAD drawing database available for the aircraft manufacturer, allowing integration of real components in conceptual design. For example the external dimension of an engine or an

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[1] Pro/Engineer is a Trademark of Parametric Technologies Inc

[2] CATIA is a Trademark of Dassault Systemes

actuator can be shared without exposing sensitive detail construction; insuring the part manufacturer confidentiality of is product development. The aircraft designer on the other hand has access to data normally introduced late in the conceptual design or in the preliminary design. For instance Pratt&Withney, propose 3D drawing of their engines. Such CAD data can be ex-changed with full control from the manufacturer to determine the amount of sheared data. Typically the designer is interested in external geometry, weight, centre of gravity and the inertia matrix associated to the component.

Modern CAD tools offer the possibility of high parameterization in large scale, for example complete wing or system such as a landing gear. All sub-component can be parameterized and available. This allow the designer to create is aircraft by assembling different components, directly in the CAD program, or in the sizing program.

Modern CAD software also includes finite element analyses (FEM), and the overall computational time is not a major set back for FEM analyses. Opening possibilities for structure optimization early in the design.

During the entire development cycle of an aircraft different methods are used in different phases of the development. If changes are made late in the design their impact on the final results and their tracking back to conceptual design is difficult to realized. By integrating 3D CAD models early in the design the same model, in different complexity levels can be used in the entire development cycle. All models developed later are directly derivate from the model used in conceptual design allowing direct investigation of changes in the conceptual design. The final parts created in the detail design can be based on the geometry used in conceptual design, the structure developed in conceptual design can be “released” into all major components and then be used for detail design. A method based on modern CAD technique allows more flexibility and efficiency in the conceptual design as well as in the complete development cycle.

3 Method of weight estimation

Different methods are available to structure weight of wing and fuselage. Some of the most common methods are presented here.

3.1 Empirical

The empirical approach is the simplest weight estimation method. The weight estimation is based on weight analyses from similar existing aircraft combined with various configuration parameters of these aircraft in order to produce the weight equation. The accuracy of this method is dependent on the different parameters such as the quality and quantity of data

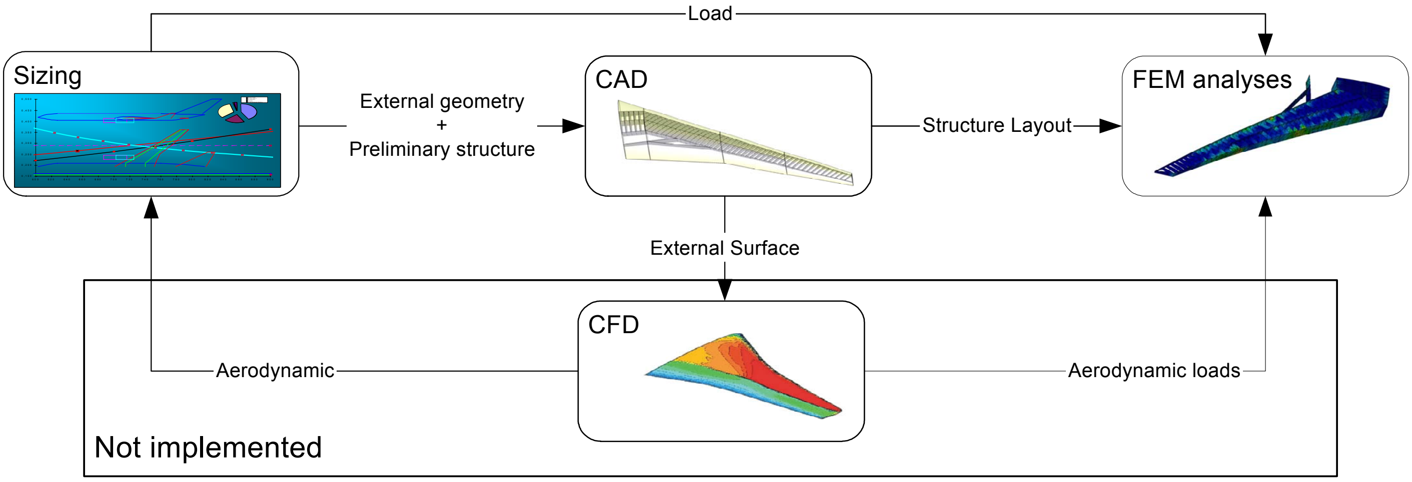

Figure 1 Data flow for the present method

available on existing aircraft and how close the actual configuration is to existing aircraft. This approach is often used in early conceptual design and is describe by Raymer[2], Torenbeek[3] and Roskam[4].

3.2 Classic Plate Theory

Plate theory is a mathematical representation of the wing based on equivalent plate theory and combining Ritz analysis to study the structural response of the wing. This method has shown reliable results for low aspect wings. The plate model does not required detailed structure in opposite to the finite element method. The set back is that this method does not allow fuselage weight estimation.

3.3 Finite element

A finite element analysis is a discretisation of the structure for numerical analyses. The finite element method produces many simultaneous algebraic equations, generated and solved on a computer. Obtained results are rarely exact, however, errors decreases by processing more equations. The calculation time is depending on discretisation level and complexity of the problem. Finite element method is often introduced later in the design, often due to the computational time. However improvement of computer performance allows the use of finite element method in the conceptual design.

3.4 New need, new methods

Weight estimation are often based on empirical methods based on existing aircraft as described. Theses methods, however, are not adapted for studies of unconventional aircraft concept. Two main reasons can be found; first since the weight estimating formulas are based on existing aircraft their application on unconventional configuration is uncertain. Second the impact of advanced technologies and material are hard to integrate.

The classic plate theory is limited to wings and may not be applied for the fuselage, this method is therefore not of interest for the complete aircraft configuration.

Almost all weight estimation methods are based on sizes and loads but not on the structural volume.

Extension of CAD tools and integration of finite element method in major CAD software permit a new approach to weight estimation and offer new possibilities for conceptual design.

4 Present method

The present model presents an approach based on the use of 3D models to determine the structural weight and at the same time determine the fuel volume and fuel weight in the wing. In the same time the CAD model provides extra information to the designer and possibility to communicate with other calculation methods such as computational fluid dynamics for the aerodynamic prediction, the present method data flow is illustrated in Figure 1.

4.1 Overview

Modern sizing methods in conceptual design provide a good view of the geometrical layout of the current aircraft. CAD tools such as CATIA and Pro/Engineer can be linked to the sizing program and allows interactive parameter exchange. The present method will generate a preliminary structure layout from the sizing inputs and simple load analyses. Similar approach has been presented by Airbus [5] but limited to commercial aircraft.

All major CAD software provide the possibility of parameterize all main component of an aircraft in conceptual design. A well-determined and parameterized model can be suitable for commercial aircraft as well as for military aircraft. In the present work only the wing is parameterized, with a particular attention on the wing box structure.

4.2 Parameterization

The parameterization has been done in order to provide the maximum flexibility to the model. From the simple external geometry the structure layout can be set to a two-cell box or multi-spars design. This allow the designer to use the same ground layout to design a transport or a fighter, the input to the CAD program are set from the sizing program where the type of aircraft will be chosen. The main parameters for the external geometry are shown in figure 2. The wing has been divided into 5 sections where the local wingspan and chord can be set. In the present case each section can be set to different NACA 4 series airfoil, the section can be changed to the actual airfoil geometry if available. The number of sections can be increased or changed in order to fit the real geometry of the wing if desired.

The external geometry parameters inputs are for each section:

- Leading edge sweep angle
- Dihedral angle
- Chord length
- Twist angle

The main inputs for the structure are for each section:

- Beam thickness
- Rib thickness
- Rib spacing
- Beam location
- Number of beams (to allow multi-spar structure)
- Rib angle

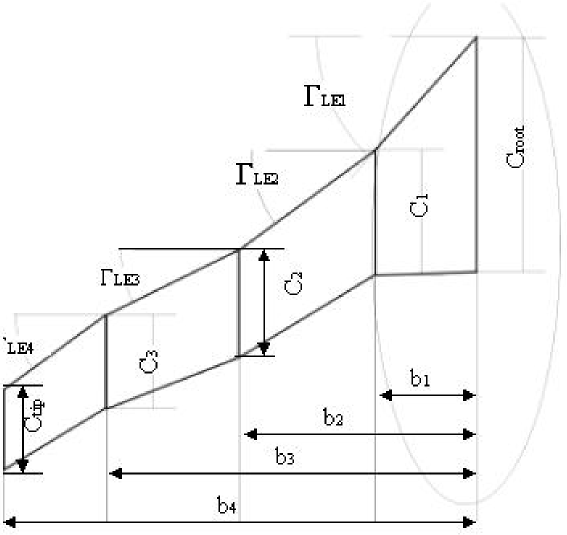

Figure 2. External geometry parameters

The preliminary structural layout is defined by a simple load analyses in the sizing program, providing preliminary beam size, beam placement, ribs displacement and dimension. The CAD model of the structural layout is then automatically generated. The internal structure is limited to spars, ribs and cover. The representation is in a first approach limited to rectangular cross sections.

The CAD model assembly consists of four components; wing surface; wing structure; fuel volume and analysis.

The wing surface is a robust model capable of vast parameter variation. Virtually no user interaction in the CAD system is necessary to change between stored wing layouts or import new ones. Figure 3 gives an example of the possibilities of the model.

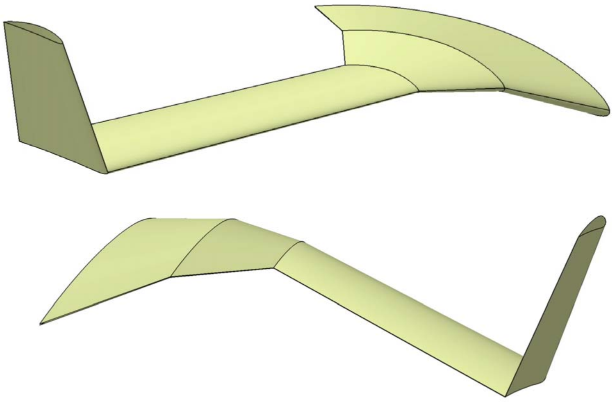

Figure 3. Wing surface model

The wing structure model builds the structure in accordance with the wing surface and the given parameters. Minor actions in the CAD model might be required; in particular after major changes in the wing surface, examples of possible structure layouts are illustrated in figure 5. The steering parameters for the structural layout are represented in figure 4; all parameters can be changed in each section. If spars are used, the same types of parameters are also applied to drive them.

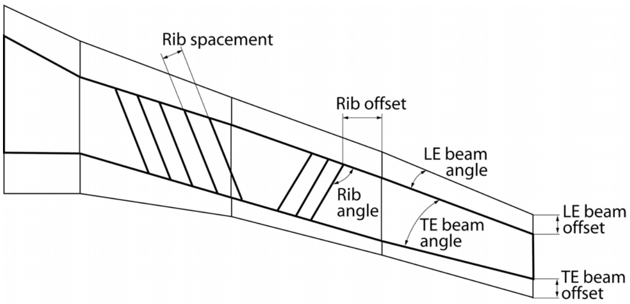

Figure 4. Structure parameters

The fuel model fills up the resultant empty space inside the structure with fuel. It is divided in four fuel compartements. Any combination of “empty/filled” is possible.

The analysis model contains the loads and restraints. The loads can be changed to the one of the predefined cases or to a new set. The model also defines the connections between all the other three models. If wing mounted engines are desired the mass of one or two motors, or any desired number, and relevant connections to the structure is added. These connections are virtual and possess no mass in the present version of the model.

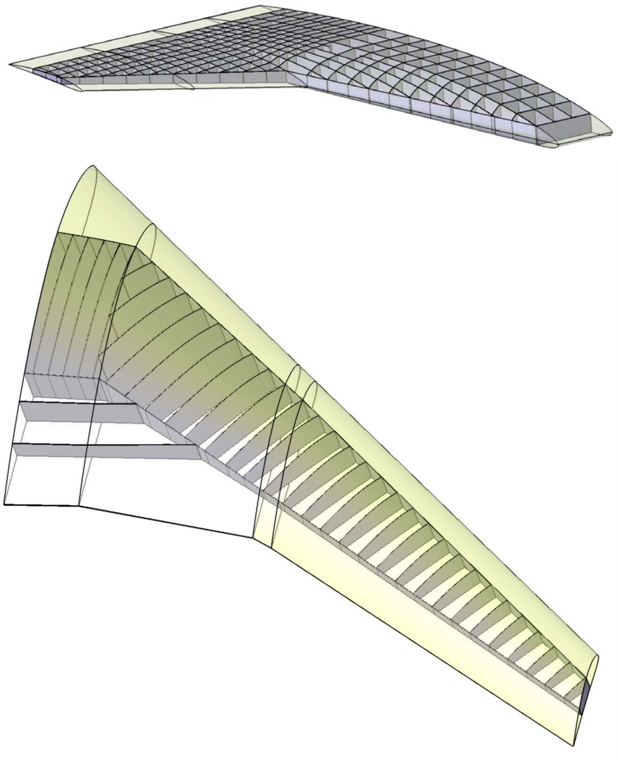

Figure 5. Structure layout examples

The parameterization of the wing allows complete control over the structure layout, by coupling finite element analyses to optimization the structure layout can be globally optimized with respect to the constrained fixed by the designer or by manufacturing aspect. In the present case all useful parameters are available in an Excel spreadsheet, directly linked to a sizing program. The designer only has to focus on the overall design.

4.3 Load analyses

In the present case a simple pull up manoeuvre is used for dimensioning. No particular attention is given on aero-elasticity constraints. Such aspect can be implemented later in the present approach.

The load analyses are based on Ardema et al.[6] and Howe[7]. The lift distribution is a Schrenk distribution, illustrated in figure 6. Only 20% percent of the fuel is present in the wing for the calculation and is spread out over the all tank span. The rib spacing is fixed along the wingspan.

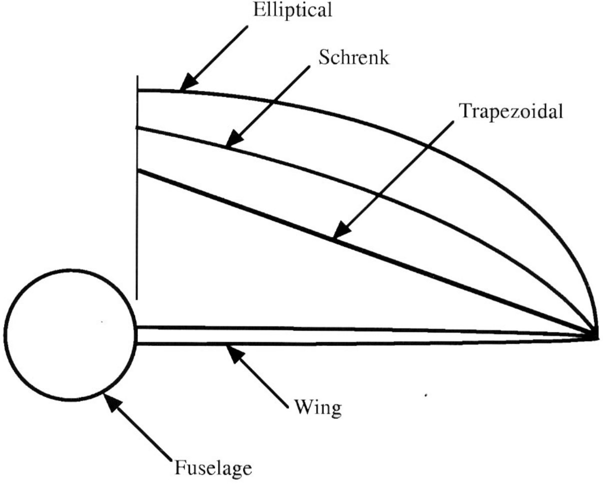

Figure 6. Lift distribution

The shear forces are determined by:

$$F_S(y) = n \cdot K_S \cdot [\frac{W}{S} \cdot A - W_{FT}(y) - \sum_{i=1}^{n_e} h_e \cdot (y_{ei} - y) \cdot W_{ei} - \sum_{i=1}^{n_{\lg}} h_{\lg} \cdot (y_{\lg i-y}) \cdot W_{\lg i}] \quad (1)$$

Where, n_e and n_{lg} are the number engines and landing gear mounted on the semispan, respectively; W_{ei} and W_{lgi} are the weights of the

i^{th} engine and landing gear. The location of the I^{th} engine and the I^{th} landing gear are y_{ei} and y_{lgi}, respectively.

And :

$$h_e \cdot (y_{ei} - y) = \begin{Bmatrix} 1 & y_{ei} > y \\ 0 & y_{ei} < y \end{Bmatrix} \tag{2}$$

$$h_{lg} \cdot (y_{lg\,i-y}) = \begin{Bmatrix} 1 & y_{lg\,i} > y \\ 0 & y_{lg\,i} < y \end{Bmatrix} \tag{3}$$

The bending moment is determined by:

$$M(y) = n \cdot K_S \cdot [\frac{W}{S} \cdot A \cdot C_P - W_{FT}(y) \cdot C_P - \sum_{i=1}^{n_e} h_e \cdot (y_{ei} - y) \cdot W_{ei} \cdot (y_{ei} - y) - \sum_{i=1}^{n_{lg}} h_{lg} \cdot (y_{lg\,i-y}) \cdot W_{lg\,i} \cdot (y_{ei} - y)] \tag{4}$$

The Structure main dimensions are obtained from the following equation [8], where all dimension are depending on the bending moment:

$$t_w = t(y) \cdot \sqrt{\cdot \left(\frac{M(y)}{Z_S(y) \cdot t(y) \cdot E} \right)^{\left(2 - \frac{1}{e_c}\right)} \cdot \left(\frac{\varepsilon_c \cdot d_w}{t(y)} \right)^{\frac{1}{e_c}} \cdot \frac{2}{\varepsilon_w}} \tag{5}$$

$$t_c = d_w(y) \cdot \left(\frac{M(y)}{Z_S(y) \cdot t(y) \cdot E \cdot \varepsilon_c \cdot d_w} \right)^{\frac{1}{e_c}} \tag{6}$$

The parameters in the above equation are summarized in Table 1, all value comes from Ardema et. al.[6].

Table 1 Wing structure coefficients and exponents.

Cover	Webs	ε	e	ε_c	e_c	ε_w	K_{gc}	K_{gw}
Unstiff.	Truss	2.25	0.556	3.62	3	0.605	1	0.407
Unstiff.	Unflange	2.21	0.556	3.62	3	0.656	1	0.505
Unstiff.	Z-stiffened	2.05	0.556	3.62	3	0.911	1	0.405
Truss	Truss	2.44	0.6	1.108	3	0.605	0.546	0.407
Truss	Unflange	2.40	0.6	1.108	3	0.656	0.546	0.505
Truss	Z-stiffened	2.25	0.6	1.108	3	0.911	0.546	0.405

In the present case finite element analyses have not been fully implemented. Simple calculations have been performed in order to check the feasibility of structure optimization and finite element analyses with regard to the computational time. The preliminary result indicates that finite element analyses can be computed on a standard personal computer in a short and feasible period of time.

5 Results

The present method has been compared with different methods and published weight data from different aircraft. The present method has been applied on two commercial aircraft, Boeing 747 and on a MD-11. No comparisons with military aircraft are presented due to the lack of published data on military aircraft weights. Two different results are presented, in the first case only the load carrying structure is considered, in the second case a total weight is determined, the total weight includes high-lift device mechanism. The load carrying structure and the skin of the total wing area defines the weight estimated from the CAD model, in the case of the total wing weight. The weight obtain is therefore expected to be lower.
Table 2 presents the weight estimations for the load carrying structure.

Table 2. Load carrying structure weights

	Present [kg]	Ardema et. al [6] [kg]
Boeing 747	22544* 26456$^+$	22858
MD-11	15124 16928	15947

The weight estimation for all 3 models is closely related to the structural layout, small changes in the governing dimension result in large weight changes.

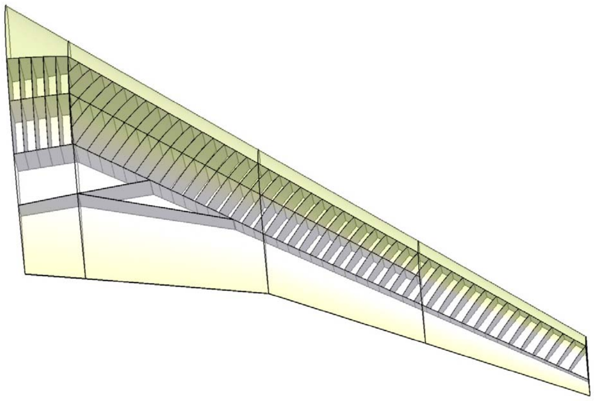

Figure 7. Structure layout for the Boeing 747 including landing gear beam.

The different weights obtained in Table 2 for the present model are dependent on the inclusion or not of the landing gear beam structure, differences illustrated in figure 7 and figure 8. In the case of the Boeing 747 a third beam as been added between the fuselage and the location of the second engine, figure 7, accounting for some extra weight compared to the structure layout in figure 8.

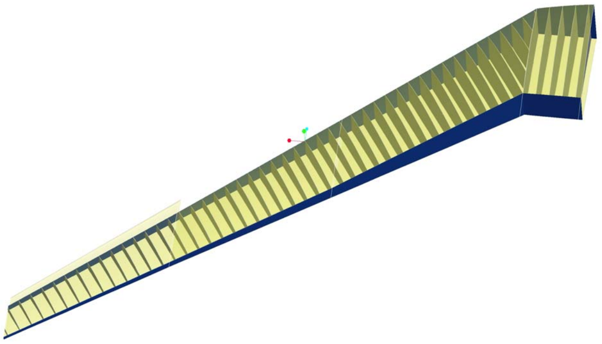

Figure 8. Load carrying structure without landing gear beam for the Boeing 747

Table 3 present the total wing weight estimates.

Table 3. Total structural wing weight

	Present	Ardema et. al[6]
Boeing 747	36800	40007
MD-11	25194	28569

The estimated total wing weight is as expected lower than the real total wing weight. The total weight presented by Ardema[8] includes the load carrying structure, high lift devices, control surface and access items; the present weight estimation model does not include high lift devices and control surface. The total weight extracted from the present model is based on the load carrying structure and the skin covering the entire wing. Kelm et. al. realized that [5] in order to augment the reliability and confidence, all major items in the wing must be parameterized in the same way. Parameterization of all major items allows large flexibility and extended possibilities for the present model. By allowing multi-spar structure and large flexibility in the wing shape, the presented model coupled with parameterization of all major items on the wing allows investigation of any kind of design.

Table 4 summarizes the fuel volume obtained, note that the fuel volume is dependent on the number of compartment and the percent of wing span covered by the fuel tanks.

Table 4. Fuel volume estimation

	Present	Manufacturer data
Boeing 747	298 m^3	216m^3
MD-11	152m^3	117.3m^3

The present values are presented to illustrate the possibility of obtaining the internal fuel volume in the wing. The results cannot be compared directly with real data, the main differences being the percent of wingspan filled with fuel. Figure 9 illustrates a possible fuel distribution in a wing.

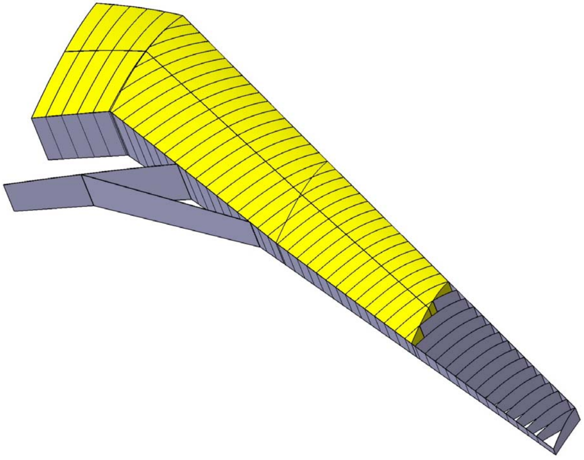

Figure 9. Structure and fuel tank on Boeing 747

6 Discussion

Several different weight estimation methods can be used in conceptual design. Some of them, Torenbeek[3], density theories [9], equivalent plate theories and the method describe by Ardema et. al[6] are showing good agreement with real weight. The method presented by Ardema [8] being one of the most flexible among the one cited previously. Despite their good estimation they are limited to certain configuration and material choices, except for Ardema et al. The present method can be used on any kind of design.

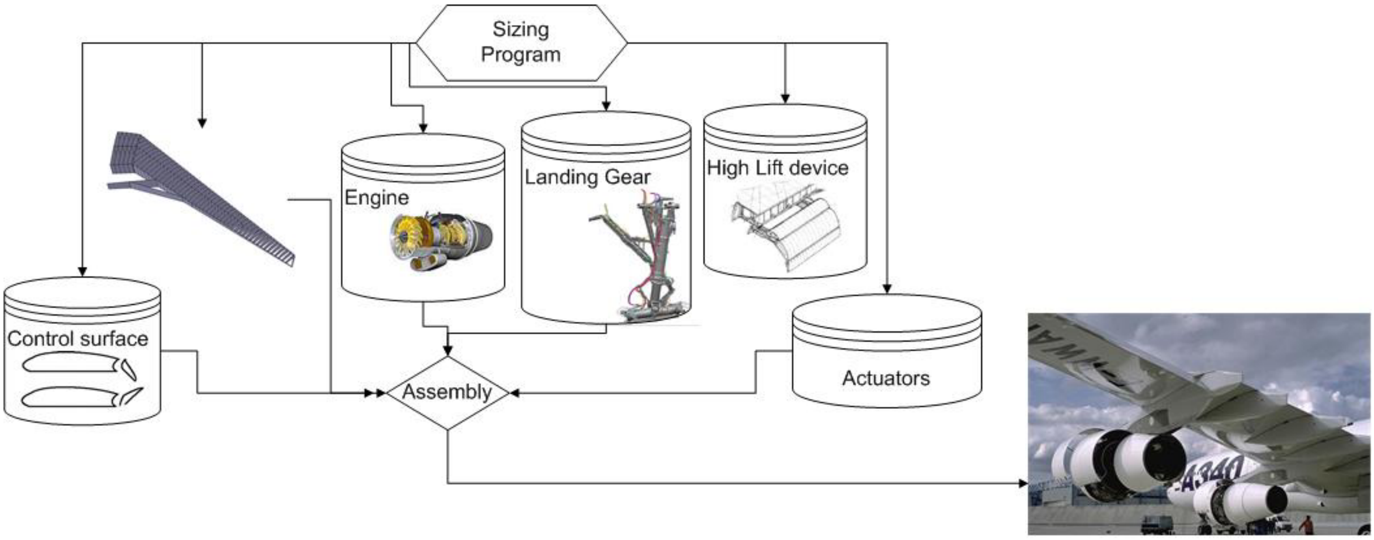

Figure 10 Flow diagram for wing design process

The result presented here shows the large influences of the structure layout on the weight estimation. And the need for parameterization of all major wing items in order to provide reliable weight estimation.

In the present status the influences of parameter changes such as new layout, new airfoil profile or new beam location can provide trend analyses and influences on the carrying load structure weight.

Besides providing weight data and fuel volumes, 3D CAD model also provide inertia prediction, system fitting and visual support for analyses among other.

The present results are the start of a larger parameterization of different items to allow the designer to "assemble" an aircraft in the same way "lego[3]" are assembled. Figure 10 resumes the future design process. Kemp [10] proposed the same approach in the middle eighties.

Modern aircraft and future design include in some extent structure in composite materials; due to the nature and the behaviour of such materials finite element analyses are not always applicable. A method presented by Henson et. al. [11] can be implement in conceptual design. Progress in finite element analyses indicates that full analyses of composite structure are not mature yet, but may be in a near future.

The sizing program provides the main dimension and location for the different parts, in the case of engine and actuators it is either based on manufacturer data, or a parametric model to describe the external dimension. The process describes for the wing can easily be implemented on tail surface. The same build up principle can be used on the fuselage, where the main difficulty is the parameterization of unconventional bodies and interaction between the wing and the body. This approach is quit similar to ASCYNT [12], but offering the profit of modern CAD software and the benefit of full control on the sizing program, given that the data ex-changed from the sizing to the CAD software is carried out in an Excel spreadsheet.

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[3] Lego is a copyright name from LEGO A/S

7 Conclusion

The present method shows encouraging possibility for weight estimation from 3D CAD models. The weight estimation is directly related to the structure layout, the structure layout is automatically generated from the input parameters from the sizing program. Finite element analyses are useable in conceptual design due to the reduced computational time, opening new perspective to structure optimization in earlier design. By introducing 3D CAD models in conceptual design the designer can integrate some analyses previously done later in the design on some chosen concept. The overall analysis time in conceptual design can be reduced on each concept allowing more concepts to be evaluated.

Weight estimation from CAD model does not required statistic on similar aircraft and allows evaluation of unconventional design.

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