AIRCRAFT MODELING THROUGH BeX & OpenVSP

Final Degree Project in Aerospace Engineering

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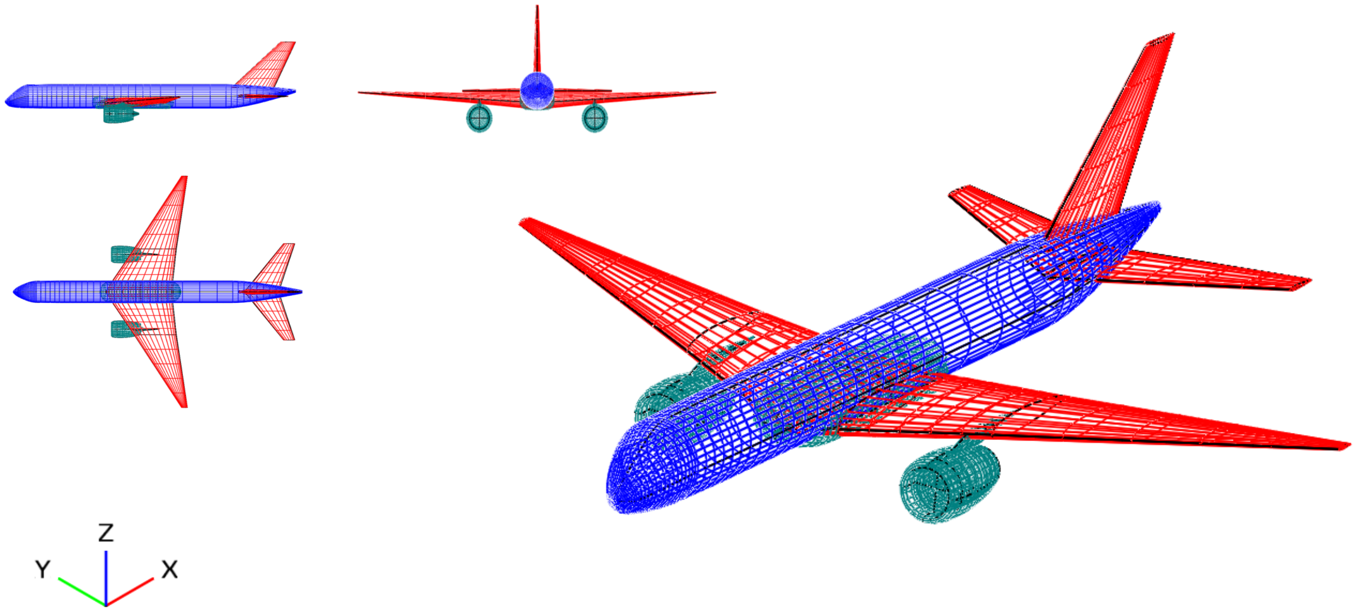

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Abstract

In the field of aircraft conceptual design (ACD), various programs are used to perform the aircraft design process. Through this project, the programs BeX and OpenVSP, commonly used in the conceptual design courses at Linköping University, have been analyzed and compared.

BeX allows to analyze the aircraft in different fields of study (cost, mission, weight and structure, sizing, aerodynamics and aircraft balancing) while OpenVSP works in the aerodynamic and aircraft balancing field. Therefore these two fields of analysis have been compared.

The analysis have shown that BeX does not have accurate results in the aerodynamic calculations due to the methods used are first approximation methods, but develops more practical relations for cruise conditions that OpenVSP. Notwithstanding, OpenVSP uses numerical methods giving precision to the results. Moreover, OpenVSP allows to study the flow around the aircraft which is really relevant in aircraft design.

In the aircraft balancing field, BeX performs a complete and detailed weight estimation while OpenVSP needs reference values to establish the weight of the different components of the aircraft.

Therefore, it is recommended to perform the aircraft design using BeX for all the different fields in which OpenVSP does not work and use OpenVSP parallel to BeX in order to validate the results obtained in the aerodynamic field and expand the aerodynamic knowledge about the aircraft.

Acknowledgements

I would like to express my special thanks of gratitude to Linköping University which gave me the opportunity to extend my period of studies here in Sweden what allowed me to do my final degree project with this fantastic team.

I am also really pleasured to have found a so involved supervisor of my project, Ingo Staack who gave me the chance to perform a study based on what I learned in his lectures during the first semester. It has been really productive to transform what I learned in a real project.

I also want to thank Nour Sanchez Abad, my laboratory mate and friend with whom I designed the aircraft taken as a reference in this project. It cost us effort and sweat but it was worth it.

This experience would not have been the same without all the new friends that I have made in this Erasmus experience: Manel, Anna, Maria 1, Maria 2, Albs, Marts, Mike Cincel, Sebas, Nacho, Raul, Nava and Yuglar. Thank you so much guys, I have enjoyed and laughed a lot at your side.

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Finally, I need to thank my parents all the effort they have done to make me arrive here. They have been a reference of work and perseverance along all my student life. From the beginning to the end chasing dreams and being happy with myself.

Contents

1 Introduction

This document presents the study done about the aircraft design programs BeX and OpenVSP. The aim of this study is to model an aircraft with the same specifications in both programs, compare what kind of information can be extracted from them and investigate about the similarities and differences from the results obtained.

The aircraft selected for this project has been defined and designed in the study done by Marius Fuentes and Nour Sanchez, *Design of a New Mid-Market Aeroplane (NMA)* [1].

Once the aircraft have been selected, it is modeled following the corresponding steps in BeX and OpenVSP. A comparison in the methodology is done in order to see the advantages and disadvantages of the modeling process in both programs.

Moreover, a comparison is performed about the different fields of study that BeX and OpenVSP can offer. This allows to have a global idea of the possible aircraft calculations that can be extracted from both programs. The common fields of study are compared in order to find the discrepancies in the results obtained and try to locate the reasons of these differences between BeX and OpenVSP.

1.1 BeX Description

BeX (Berry Excel for Aircraft Sizing) is an aircraft design program developed by Linköping University [2] through Microsoft Excel [3]. The program covers all the fields involved in the aircraft design: mission requirements, structure, weights, aircraft balancing, sizing, aerodynamics and cost.

All the different domains are directly interconnected. This method tries to mimic the parallel process followed in the aeronautical industry in which a compromise is established e.g.between market requirements, efficiency, comfortability, physics and costs, etc.

1.2 OpenVSP Description

OpenVSP [4] (Vehicle Sketch Pad) is a geometry modeling tool for conceptual aircraft design. The program has been developed by NASA for rapid evaluation of advanced design concepts and aerodynamic study. The software computes aircraft configurations with a low computational cost compared with traditional CAD (Computed Aided Design) programs. The parameterization improves the design optimization by reducing the problem dimensionality and improving descriptive expressiveness.

An aircraft shape is the natural starting point for multidisciplinary analysis and optimization (MDAO). OpenVSP gives good approximations for aerodynamics, mass properties and the physics that impact the vehicle performance.

1.3 Sheared Fields of Study

The aims of BeX and OpenVSP are different. BeX is a tool that offers a complete aircraft design process from the beginning to the end taking into account all the different steps followed in the real industry. In contrary, OpenVSP is a tool designed to study the aerodynamics and the physics involved. Notwithstanding, both programs share several calculations and it is the objective of this project to compare them. Figure 1 shows the different fields of study of both programs and the shared ones.

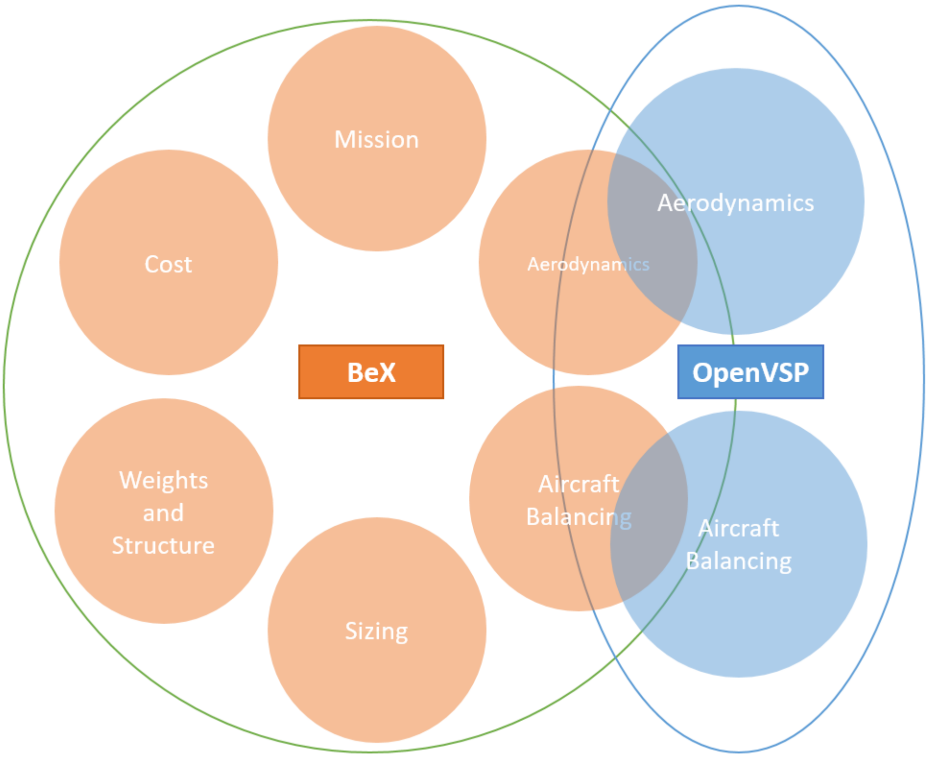


Fig. 1. Fields of study comparison between BeX and OpenVSP.

As it can be seen, both, BeX and OpenVSP study the Aerodynamics and Aircraft Balancing fields. Therefore, these are the fields that are going to be studied and compared in detail.

2 Modeling

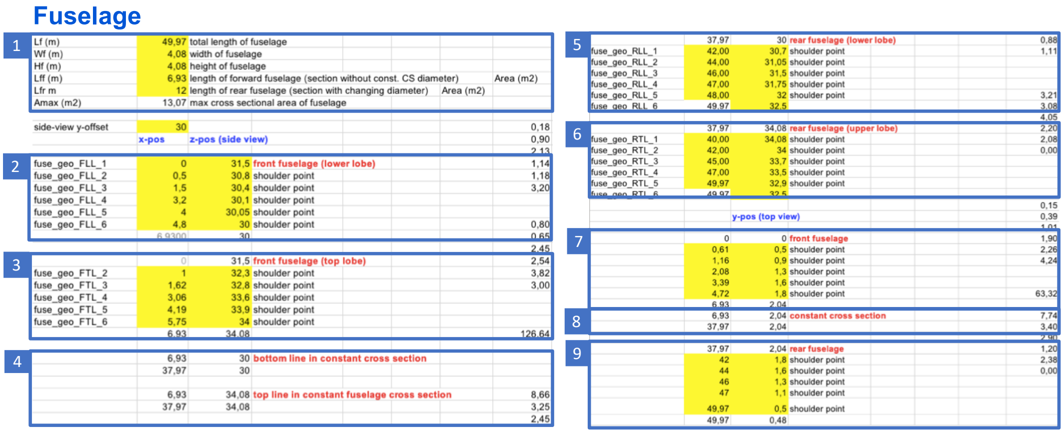
The aircraft selected for this project has been previously defined and developed in the course Aircraft Conceptual Design - TMAL51 at Linköping University [2], by Nour Sanchez Abad and the author of this work. An study of the aviation market was made for the next 10 years. Based on that predictions, a New Middle of the Market Airplane (NMA) was designed. The aircraft specifications can be found in *Design of a New Mid-Market Airplane (NMA)* [1].

In this section, it is explained how BeX and OpenVSP model the different parts of the aircraft. Both programs work in a different way to achieve similar results and the differences are going to be studied.

2.1 Fuselage

2.1.1 Bex

The definition of the fuselage in BeX is executed in the Geometry section. First, the main parameters are set: Total Length, Width, Heigth, Nose Length and Tail Length as it is defined in the 1^{st} group of Fig.2.



Fuselage

1	Lf (m)	49,97	total length of fuselage			
	Wf (m)	4,08	width of fuselage			
	Hf (m)	4,08	height of fuselage			
	Lff (m)	6,93	length of forward fuselage (section without const. CS diameter)		Area (m2)	
	Lfr m	12	length of rear fuselage (section with changing diameter)	Area (m2)		
	Amax (m2)	13,07	max cross sectional area of fuselage			
	side-view y-offset	30				0,18
		x-pos	z-pos (side view)			0,90
						2,13
2	fuse_geo_FLL_1	0	31,5	front fuselage (lower lobe)		1,14
	fuse_geo_FLL_2	0,5	30,8	shoulder point		1,18
	fuse_geo_FLL_3	1,5	30,4	shoulder point		3,20
	fuse_geo_FLL_4	3,2	30,1	shoulder point		
	fuse_geo_FLL_5	4	30,05	shoulder point		
	fuse_geo_FLL_6	4,8	30	shoulder point		0,80
		6,9300	30			0,65
						2,45
3		0	31,5	front fuselage (top lobe)		2,54
	fuse_geo_FTL_2	1	32,3	shoulder point		3,82
	fuse_geo_FTL_3	1,62	32,8	shoulder point		3,00
	fuse_geo_FTL_4	3,06	33,6	shoulder point		
	fuse_geo_FTL_5	4,19	33,9	shoulder point		
	fuse_geo_FTL_6	5,75	34	shoulder point		
		6,93	34,08			126,64
4		6,93	30	bottom line in constant cross section		
		37,97	30			
		6,93	34,08	top line in constant fuselage cross section		8,66
		37,97	34,08			3,25
						2,45

5		37,97	30	rear fuselage (lower lobe)	0,88
	fuse_geo_RLL_1	42,00	30,7	shoulder point	1,11
	fuse_geo_RLL_2	44,00	31,05	shoulder point	
	fuse_geo_RLL_3	46,00	31,5	shoulder point	
	fuse_geo_RLL_4	47,00	31,75	shoulder point	
	fuse_geo_RLL_5	48,00	32	shoulder point	3,21
	fuse_geo_RLL_6	49,97	32,5		3,08
					4,05
6		37,97	34,08	rear fuselage (upper lobe)	2,20
	fuse_geo_RTL_1	40,00	34,08	shoulder point	2,08
	fuse_geo_RTL_2	42,00	34	shoulder point	0,00
	fuse_geo_RTL_3	45,00	33,7	shoulder point	
	fuse_geo_RTL_4	47,00	33,5	shoulder point	
	fuse_geo_RTL_5	49,97	32,9	shoulder point	
	fuse_geo_RTL_6	49,97	32,5		
					0,15
			y-pos (top view)		0,39
					1,01
7		0	0	front fuselage	1,90
		0,61	0,5	shoulder point	2,26
		1,16	0,9	shoulder point	4,24
		2,08	1,3	shoulder point	
		3,39	1,6	shoulder point	
		4,72	1,8	shoulder point	63,32
		6,93	2,04		
8		6,93	2,04	constant cross section	7,74
		37,97	2,04		3,40
					2,90
9		37,97	2,04	rear fuselage	1,20
		42	1,8	shoulder point	2,38
		44	1,6	shoulder point	0,00
		46	1,3	shoulder point	
		47	1,1	shoulder point	
		49,97	0,5	shoulder point	
		49,97	0,48		

Fig. 2. Fuselage modeling in BeX.

Once these main parameters are stated, the geometry of the fuselage is represented in a 2D plot (Fig. 3) where the shape is defined. The way in which BeX allows to define the shape of the fuselage is by dividing the geometry represented in the 2D plot in a set of lines and modifying them. In this way, the nose and the tail can take the desired shape in the XY and the XZ plane. This modeling is done in the groups $2^{nd} - 9^{th}$ of Fig.2.

The main problem of this method is that the lines need to be modified by trial and error. BeX does not have the capability to define the fuselage by only introducing the parameters desired so this method is not good when trying to reproduce another aircraft that is set as a reference.

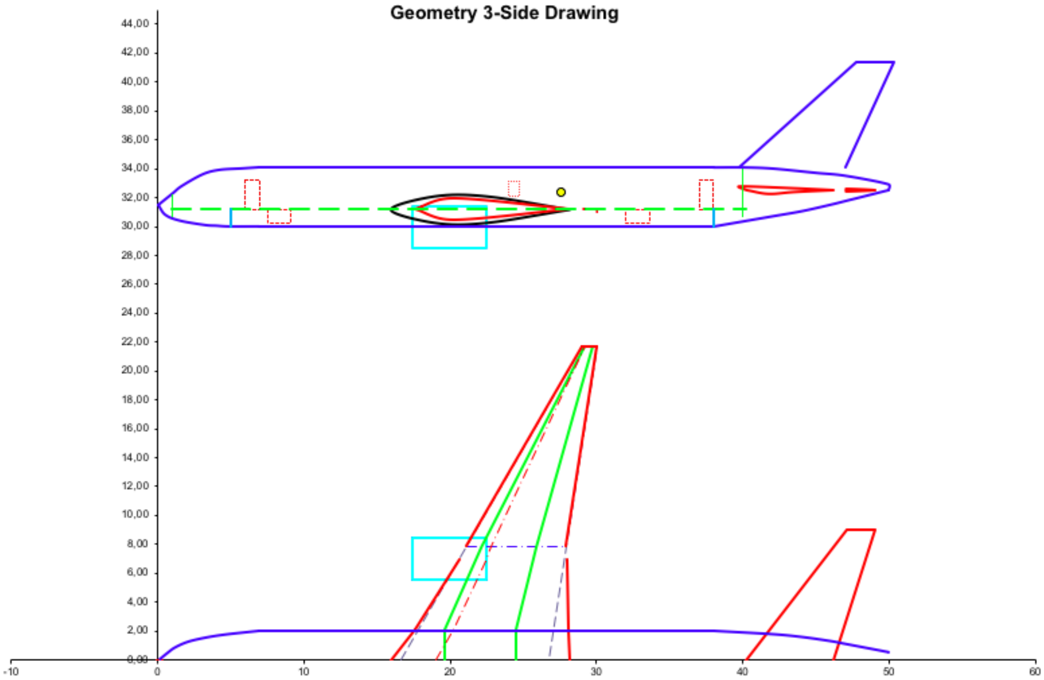


Fig. 3. Aircraft representation in the XY and XZ planes in BeX.

2.1.2 OpenVSP

The geometry definition in OpenVSP has a detailed interface that allows to establish the shape of the fuselage by the introduction of the desired parameters.

The interface is shown in Fig.4. In the *XForm* section, the location of the fuselage is determined. The location is important for further calculations of this program like the center of gravity or the moments of inertia. In the *Design* section, the length of the fuselage is selected. Finally, in the *XSec* section, the cross-sectional shape of the fuselage is defined. The program allows to divide the fuselage in sections and determine for each one its position in the system of coordinates and its diameter. Moreover, the shape of the section can be defined as a circle, ellipse and another geometries.

Coord System: ● Rel ☐ Abs
XLoc 0.000 0.000
YLoc 0.000 0.000
ZLoc 0.000 0.000
XRot 0.000 0.000
YRot 0.000 0.000
ZRot 0.000 0.000
Rot Origin(X) 0.000

Design
Length 49.97000

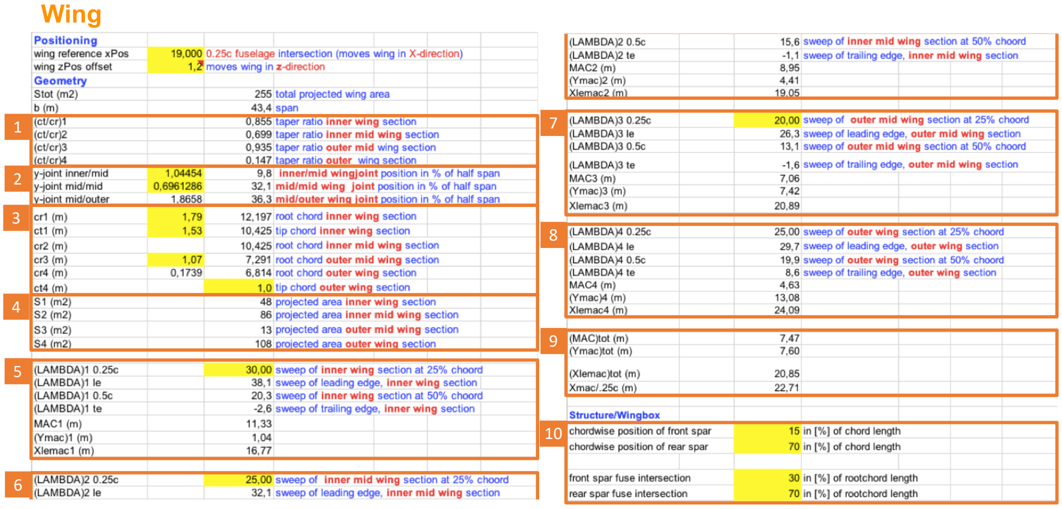
Cross Section 1
Num U 10
X 0.01001 0.50020
Y 0.00000 0.00000
Z -0.01811 -0.90511
Rot X 0.00000
Rot Y 0.00000
Rot Z 0.00000
Spin 0.00000
Choose Type: CIRCLE
Diameter 1.30000

Fig. 4. Interface of the fuselage modeling in OpenVSP.

2.2 Wing

2.2.1 BeX

The wing definition in BeX is done in the Geometry section and follows a similar method than the fuselage definition. First, the main parameters are defined: Wing reference position in X and in Z directions, span and total area.



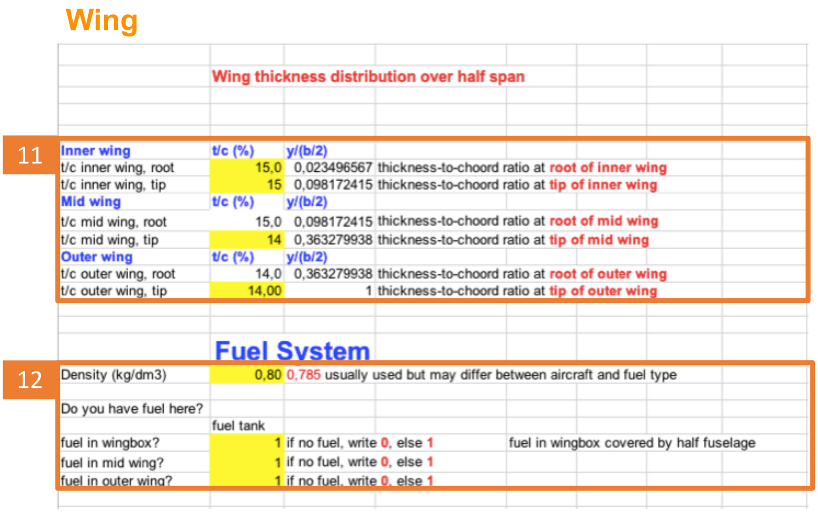
	Positioning			
	wing reference xPos	19,000	0.25c fuselage intersection (moves wing in X-direction)	
	wing zPos offset	1,2	moves wing in z-direction	
	Geometry			
	Stot (m2)		255	total projected wing area
	b (m)		43,4	span
1	(ct/cr)1		0,855	taper ratio inner wing section
	(ct/cr)2		0,699	taper ratio inner mid wing section
	(ct/cr)3		0,935	taper ratio outer mid wing section
	(ct/cr)4		0,147	taper ratio outer wing section
2	y-joint inner/mid	1,04454	9,8	inner/mid wingjoint position in % of half span
	y-joint mid/mid	0,6961286	32,1	mid/mid wing joint position in % of half span
	y-joint mid/outer	1,8658	36,3	mid/outer wing joint position in % of half span
3	cr1 (m)	1,79	12,197	root chord inner wing section
	ct1 (m)	1,53	10,425	tip chord inner wing section
	cr2 (m)		10,425	root chord inner mid wing section
	cr3 (m)	1,07	7,291	root chord outer mid wing section
	cr4 (m)	0,1739	6,814	root chord outer wing section
	ct4 (m)		1,0	tip chord outer wing section
4	S1 (m2)		48	projected area inner wing section
	S2 (m2)		86	projected area inner mid wing section
	S3 (m2)		13	projected area outer mid wing section
	S4 (m2)		108	projected area outer wing section
5	(LAMBDA)1 0.25c		30,00	sweep of inner wing section at 25% choord
	(LAMBDA)1 le		38,1	sweep of leading edge, inner wing section
	(LAMBDA)1 0.5c		20,3	sweep of inner wing section at 50% choord
	(LAMBDA)1 te		-2,6	sweep of trailing edge, inner wing section
	MAC1 (m)		11,33	
	(Ymac)1 (m)		1,04	
	Xlemac1 (m)		16,77	
6	(LAMBDA)2 0.25c		25,00	sweep of inner mid wing section at 25% choord
	(LAMBDA)2 le		32,1	sweep of leading edge, inner mid wing section
	(LAMBDA)2 0.5c		15,6	sweep of inner mid wing section at 50% choord
	(LAMBDA)2 te		-1,1	sweep of trailing edge, inner mid wing section
	MAC2 (m)		8,95	
	(Ymac)2 (m)		4,41	
	Xlemac2 (m)		19,05	
7	(LAMBDA)3 0.25c		20,00	sweep of outer mid wing section at 25% choord
	(LAMBDA)3 le		26,3	sweep of leading edge, outer mid wing section
	(LAMBDA)3 0.5c		13,1	sweep of outer mid wing section at 50% choord
	(LAMBDA)3 te		-1,6	sweep of trailing edge, outer mid wing section
	MAC3 (m)		7,06	
	(Ymac)3 (m)		7,42	
	Xlemac3 (m)		20,89	
8	(LAMBDA)4 0.25c		25,00	sweep of outer wing section at 25% choord
	(LAMBDA)4 le		29,7	sweep of leading edge, outer wing section
	(LAMBDA)4 0.5c		19,9	sweep of outer wing section at 50% choord
	(LAMBDA)4 te		8,6	sweep of trailing edge, outer wing section
	MAC4 (m)		4,63	
	(Ymac)4 (m)		13,08	
	Xlemac4 (m)		24,09	
9	(MAC)tot (m)		7,47	
	(Ymac)tot (m)		7,60	
	(Xlemac)tot (m)		20,85	
	Xmac/.25c (m)		22,71	
	Structure/Wingbox			
10	chordwise position of front spar		15	in [%] of chord length
	chordwise position of rear spar		70	in [%] of chord length
	front spar fuse intersection		30	in [%] of rootchord length
	rear spar fuse intersection		70	in [%] of rootchord length

Fig. 5. Wing modeling in BeX

Once the main parameters are established, the geometry of the wing is defined by a set of sections in which the wing is divided. The sections are: inner wing, inner mid wing, outer mid wing and outer wing. Fig.5 shows the different groups of parameters that determine the shape of the wing. The 1^{st} group defines the taper ratio of each section; 2^{nd} group defines the position of the joint between sections; 3^{rd} group defines the root and tip chord of each section; 4^{th} group defines the projected area of each section; $5^{th} - 9^{th}$ groups define the sweep and the MAC of each section; and the 10^{th} group defines the front and rear spar positions.

One disadvantage in the wing modeling in BeX is the impossibility of any definition of the wing profile e.g. the NACA airfoil of the wing. In BeX this setting is not developed. Instead, the thickness as a percentage of the chord $\left(\frac{t}{c}\right)$ can be defined in each of the four sections, as shown in Fig.6. Another disadvantage is that the dihedral and the twist angle are not taken into account in the wing modeling. This fact and the previous one do not allow to completely define the geometry and the position of the wing.

Finally, BeX allows to determine the amount of fuel that can be stored in the wings as it is shown in Fig.6.



Wing thickness distribution over half span

Inner wing	**t/c (%)**	**y/(b/2)**	
t/c inner wing, root	15,0	0,023496567	thickness-to-choord ratio at **root of inner wing**
t/c inner wing, tip	15	0,098172415	thickness-to-choord ratio at **tip of inner wing**
Mid wing	**t/c (%)**	**y/(b/2)**	
t/c mid wing, root	15,0	0,098172415	thickness-to-choord ratio at **root of mid wing**
t/c mid wing, tip	14	0,363279938	thickness-to-choord ratio at **tip of mid wing**
Outer wing	**t/c (%)**	**y/(b/2)**	
t/c outer wing, root	14,0	0,363279938	thickness-to-choord ratio at **root of outer wing**
t/c outer wing, tip	14,00	1	thickness-to-choord ratio at **tip of outer wing**

Fuel System

Density (kg/dm3)	0,80	0,785 usually used but may differ between aircraft and fuel type	
Do you have fuel here?			
	fuel tank		
fuel in wingbox?	1	if no fuel, write 0, else 1	fuel in wingbox covered by half fuselage
fuel in mid wing?	1	if no fuel, write 0, else 1	
fuel in outer wing?	1	if no fuel, write 0, else 1	

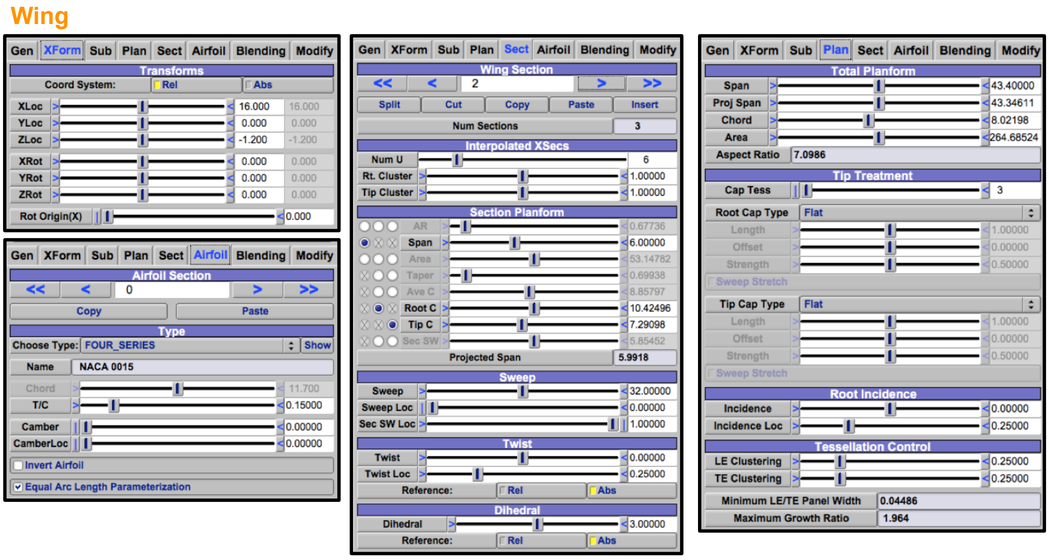
Fig. 6. Wing modeling in BeX

2.2.2 OpenVSP

The geometry definition in OpenVSP has a detailed interface that allows to establish the shape of the wing by the introduction of the desired parameters.

The interface is shown in Fig.7. In the *XForm* section, the position of the wing with respect to the system of coordinates is selected. In the *Plan* section, the main parameters as the span, projected area, chord and and aspect ratio are defined. In order to get a preliminary idea of the wing, this values can be set but when modifying the wing more deeply, these values will change. In the *Sect* Section, the wing is divided into different wing sections. For each wing section, different parameters can be modified (span, root/tip chord, area, taper ratio aspect ratio, sweep angle, twist angle and dihedral angle). Finally, in the *Airfoil* section, the NACA profile of the wing can be chosen. The program allows to chose between the 4-series NACA or the 6-series NACA. This is a good tool in OpenVSP because it allows to perfectly determine the shape of the wing.

As OpenVSP is a computational program whose aim is the aerodynamic study, the fuel storage is not taken into account.



Coord System: ● Rel ☐ Abs
XLoc 16.000 16.000
YLoc 0.000 0.000
ZLoc -1.200 -1.200
XRot 0.000 0.000
YRot 0.000 0.000
ZRot 0.000 0.000
Rot Origin(X) 0.000

Airfoil Section: 0
Choose Type: FOUR_SERIES
Name NACA 0015
Chord 11.700
T/C 0.15000
Camber 0.00000
CamberLoc 0.00000
☐ Invert Airfoil
☑ Equal Arc Length Parameterization

Wing Section: 2
Num Sections 3
Num U 6
Rt. Cluster 1.00000
Tip Cluster 1.00000
AR 0.67736
Span 6.00000
Area 53.14782
Taper 0.69938
Ave C 8.85797
Root C 10.42496
Tip C 7.29098
Sec SW 5.85452
Projected Span 5.9918
Sweep 32.00000
Sweep Loc 0.00000
Sec SW Loc 1.00000
Twist 0.00000
Twist Loc 0.25000
Reference: ☐ Rel ● Abs
Dihedral 3.00000
Reference: ☐ Rel ● Abs

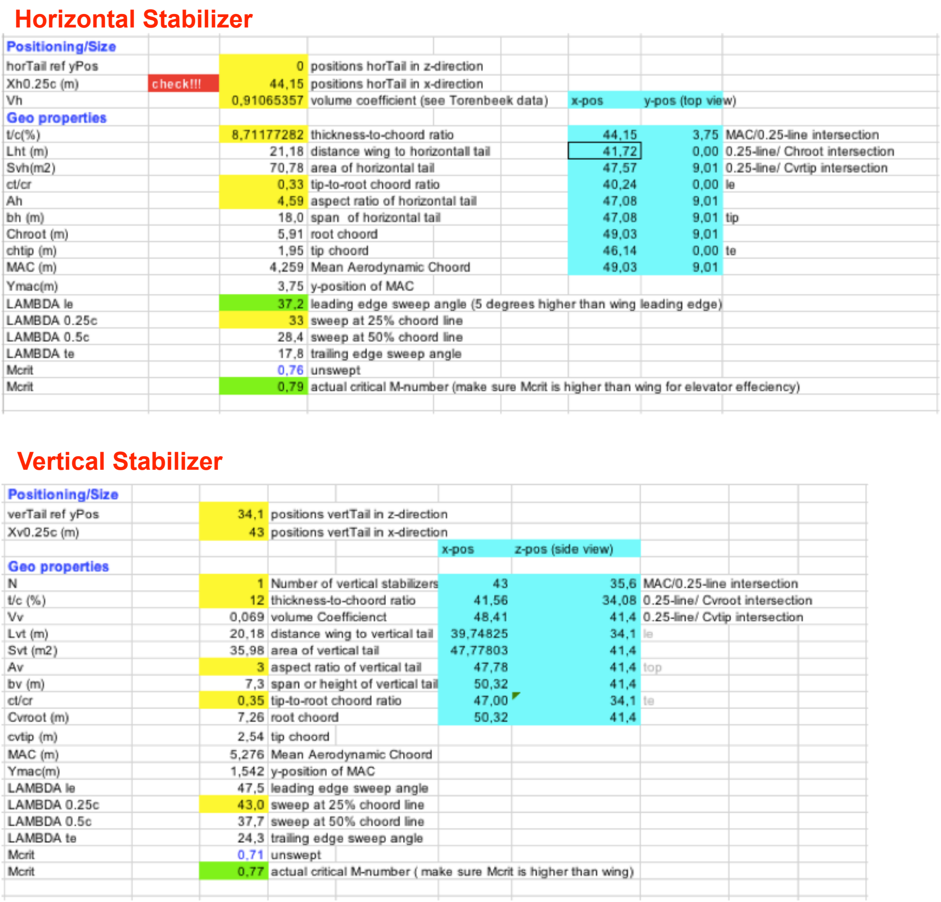
Span 43.40000
Proj Span 43.34611
Chord 8.02198
Area 264.68524
Aspect Ratio 7.0986
Cap Tess 3
Root Cap Type Flat
Length 1.00000
Offset 0.00000
Strength 0.50000
☐ Sweep Stretch
Tip Cap Type Flat
Length 1.00000
Offset 0.00000
Strength 0.50000
☐ Sweep Stretch
Incidence 0.00000
Incidence Loc 0.25000
LE Clustering 0.25000
TE Clustering 0.25000
Minimum LE/TE Panel Width 0.04486
Maximum Growth Ratio 1.964

Fig. 7. Interface of the wing modeling in OpenVSP.

2.3 Vertical & Horizontal Stabilizer

2.3.1 BeX

The vertical and horizontal stabilizer definition in BeX is done in the Geometry section. In this case, for simplicity, there is not a section division so the only inputs, as shown in Fig.8, are the main parameters: position in the Z and X direction, thickness to chord ratio, tip to chord ratio, aspect ratio and sweep angle.



Horizontal Stabilizer

Positioning/Size						
horTail ref yPos		0	positions horTail in z-direction			
Xh0.25c (m)	check!!!	44,15	positions horTail in x-direction			
Vh		0,91065357	volume coefficient (see Torenbeek data)	x-pos	y-pos (top view)	
Geo properties						
t/c(%)		8,71177282	thickness-to-choord ratio	44,15	3,75	MAC/0.25-line intersection
Lht (m)		21,18	distance wing to horizontall tail	41,72	0,00	0.25-line/ Chroot intersection
Svh(m2)		70,78	area of horizontal tail	47,57	9,01	0.25-line/ Cvrtip intersection
ct/cr		0,33	tip-to-root choord ratio	40,24	0,00	le
Ah		4,59	aspect ratio of horizontal tail	47,08	9,01	
bh (m)		18,0	span of horizontal tail	47,08	9,01	tip
Chroot (m)		5,91	root choord	49,03	9,01	
chtip (m)		1,95	tip choord	46,14	0,00	te
MAC (m)		4,259	Mean Aerodynamic Choord	49,03	9,01	
Ymac(m)		3,75	y-position of MAC			
LAMBDA le		37,2	leading edge sweep angle (5 degrees higher than wing leading edge)			
LAMBDA 0.25c		33	sweep at 25% choord line			
LAMBDA 0.5c		28,4	sweep at 50% choord line			
LAMBDA te		17,8	trailing edge sweep angle			
Mcrit		0,76	unswept			
Mcrit		0,79	actual critical M-number (make sure Mcrit is higher than wing for elevator effeciency)			

Vertical Stabilizer

Positioning/Size						
verTail ref yPos		34,1	positions vertTail in z-direction			
Xv0.25c (m)		43	positions vertTail in x-direction			
				x-pos	z-pos (side view)	
Geo properties						
N		1	Number of vertical stabilizers	43	35,6	MAC/0.25-line intersection
t/c (%)		12	thickness-to-choord ratio	41,56	34,08	0.25-line/ Cvroot intersection
Vv		0,069	volume Coefficienct	48,41	41,4	0.25-line/ Cvtip intersection
Lvt (m)		20,18	distance wing to vertical tail	39,74825	34,1	le
Svt (m2)		35,98	area of vertical tail	47,77803	41,4	
Av		3	aspect ratio of vertical tail	47,78	41,4	top
bv (m)		7,3	span or height of vertical tail	50,32	41,4	
ct/cr		0,35	tip-to-root choord ratio	47,00	34,1	te
Cvroot (m)		7,26	root choord	50,32	41,4	
cvtip (m)		2,54	tip choord			
MAC (m)		5,276	Mean Aerodynamic Choord			
Ymac(m)		1,542	y-position of MAC			
LAMBDA le		47,5	leading edge sweep angle			
LAMBDA 0.25c		43,0	sweep at 25% choord line			
LAMBDA 0.5c		37,7	sweep at 50% choord line			
LAMBDA te		24,3	trailing edge sweep angle			
Mcrit		0,71	unswept			
Mcrit		0,77	actual critical M-number (make sure Mcrit is higher than wing)			

Fig. 8. Vertical and horizontal stabilizer modeling in BeX

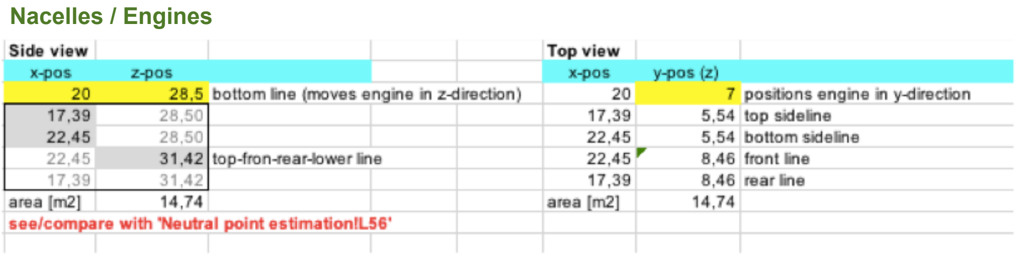
2.3.2 OpenVSP

In OpenVSP, the vertical and horizontal stabilizers are treated as a wing, so the procedure is exactly the same followed for the main wing modeling.

2.4 Nacelles

2.4.1 BeX

The engine definition in BeX is done through a database in the program in which there are several types of engines available. Depending on the specifications, an engine is selected and a scale factor is introduced to match the requirements. Apart from this selection, the position along the wing can be selected in the X, Y and Z positions as shown in Fig.9.



Nacelles / Engines

Side view			Top view		
x-pos	z-pos		x-pos	y-pos (z)	
20	28,5	bottom line (moves engine in z-direction)	20	7	positions engine in y-direction
17,39	28,50		17,39	5,54	top sideline
22,45	28,50		22,45	5,54	bottom sideline
22,45	31,42	top-fron-rear-lower line	22,45	8,46	front line
17,39	31,42		17,39	8,46	rear line
area [m2]	14,74		area [m2]	14,74	
see/compare with 'Neutral point estimation!L56'					

Fig. 9. Engine definition in BeX

2.4.2 OpenVSP

In OpenVSP there is not engines database because this program does not study the performance of the aircraft but the aerodynamics so it only takes into account the shape of the nacelle of the engine. In OpenVSP there is not a nacelle interface for the modeling so the nacelle is considered as a body. The definition procedure is the same followed in the fuselage modeling.

3 Parasitic Drag Coefficient Cd0 Calculation

In this section the calculations of the Parasitic Drag Coefficient (Cd0) are analyzed and compared for BeX and OpenVSP. The different dissimilarities are explained and a reasonable explanation is given to this discrepancies in the results. Moreover, a solution for further versions of the BeX program is motivated.

The information presented below about the calculation of the parasitic drag coefficient has been extracted from *Civil Jet Aircraft Design* [5] and the *OpenVSP NASA Documentation* [6].

3.1 Simplifications for the Cd0 Calculation

In order to establish the maximum similarity in the calculation of the Cd0, some simplifications are done in the OpenVSP aircraft to adapt it to BeX. The different structural parts taken into account in BeX and OpenVSP are presented in Table 1.

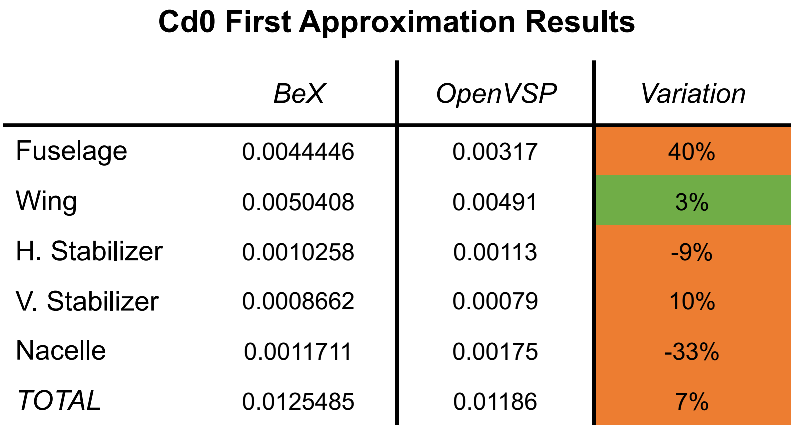
	Cd0 Calculation		**Cd0 Comparison**	
	BeX	*OpenVSP*	*BeX*	*OpenVSP*
Fuselage	✓	✓	✓	✓
Wing	✓	✓	✓	✓
H. Stabilizer	✓	✓	✓	✓
V. Stabilizer	✓	✓	✓	✓
Pylon	⊗	✓	⊗	⊗
Nacelle	✓	✓	✓	✓
Power Face	⊗	✓	⊗	⊗
Wheel Well	⊗	✓	⊗	⊗

Table 1. Parts of the model taken into account by Bex and OpenVSP predefined (left). Parts of the model taken into account in the comparison done between both programs (right).

In Table 1 it can be seen that the pylon, the power face and the wheel well (landing gear compartment) have been removed in the OpenVSP model to take into account the same components than the BeX model.

3.2 Cd0 First Approximation

The results obtained of the Cd0 for BeX and OpenVSP after the simplifications done are presented in Table 2.



Cd0 First Approximation Results

	BeX	*OpenVSP*	*Variation*
Fuselage	0.0044446	0.00317	40%
Wing	0.0050408	0.00491	3%
H. Stabilizer	0.0010258	0.00113	-9%
V. Stabilizer	0.0008662	0.00079	10%
Nacelle	0.0011711	0.00175	-33%
TOTAL	0.0125485	0.01186	7%

Table 2. First approximation of the Cd0 in BeX and OpenVSP with the predefined methods of calculation.

As it can be seen in Table **??**, the results obtained differ considerably between the different programs being extremely different in the Fuselage and the Nacelle calculation. The total difference of 7% makes necessary to investigate thoughtfully these differences. To do so, the way in which the Cd0 is calculated is going to be examinated in the following section.

3.3 Calculation Background

The theoretical way in which the programs calculate the parasitic drag, is detailed in this subsection.

3.3.1 Parasitic Drag Coefficient, Cd0

The formula used in both programs for the Cd0 is:

$$Cd0 = FF \cdot C_f \cdot S_w \tag{1}$$

where FF is the Form Factor, C_f the friction coefficient, S_w is the wetted surface, for each component of the model.

3.3.2 Form Factor, FF

In the form factor calculation, BeX is not flexible in the method selected as it only uses one method predefined for each component. Against, OpenVSP allows to select the method for calculating the form factor for each component of the model independently.

Fuselage

BeX uses the *Jenkinson Fuselage Method*:

$$FF_{Fuselage} = 1 + \frac{2.2}{\Lambda^{1.5}} - \frac{0.9}{\Lambda^{3}} \qquad \Lambda = \frac{l_f}{\left(\frac{4}{\pi} A_x\right)^{0.5}} \tag{2}$$

where l_f is the fuselage length and A_x is the cross sectional fuselage area.

OpenVSP uses the *Hoerner Streamlined Body Method*:

$$FF_{Fuselage} = 1 + \frac{1.5}{\left(\frac{l_f}{d_f}\right)^{1.5}} + \frac{7}{\left(\frac{l_f}{d_f}\right)^{1.5}} \tag{3}$$

where l_f is the fuselage length and d_f is the fuselage diameter.

Wing, Vertical and Horizontal Stabilizer

BeX uses the *Jenkinson Wing Method*:

$$FF_{Wing} = \left(3.3\left(\frac{t}{c}\right) - 0.008\left(\frac{t}{c}\right)^2 + 27\left(\frac{t}{c}\right)^3\right) Cos^2\left(\Lambda_{\frac{c}{2}}\right) + 1 \tag{4}$$

$$FF_{H\&VTail} = \left(3.52\left(\frac{t}{c}\right)\right) Cos^2\left(\Lambda_{\frac{c}{2}}\right) + 1 \tag{5}$$

where $\frac{t}{c}$ is the thickness to chord ratio.

OpenVSP uses the *Hoerner Method*:

$$FF_{Wing,H\&VTail} = 1 + 2\left(\frac{t}{c}\right) + 60\left(\frac{t}{c}\right)^4 \tag{6}$$

where $\frac{t}{c}$ is the thickness to chord ratio.

Nacelles

The form factor of the nacelles in BeX and OpenVSP is based on the *Jenkinson Wing Nacelle Method* that suggests a constant form factor for typical nacelles on wings:

$$FF_{Nacelles} = 1.25 \tag{7}$$

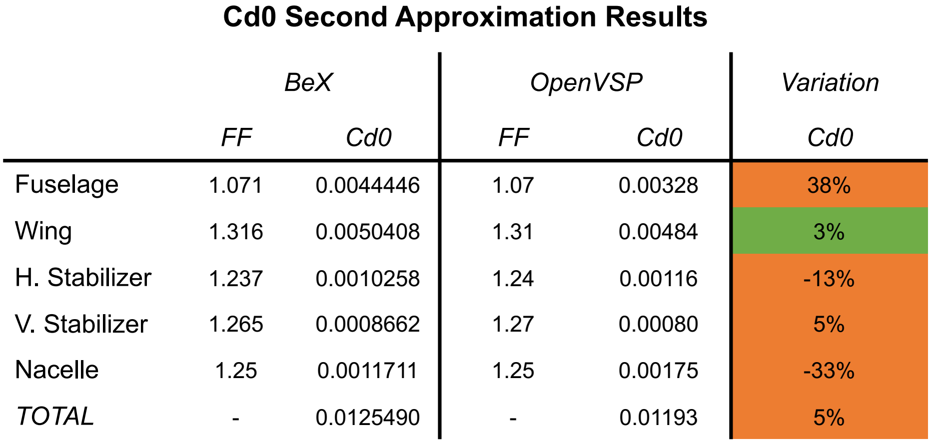
For the form factor calculations, discrepancies exist between both programs but both of them follow a valid method for each component so the differences in the parasitic drag coefficient should be negligible. Table 3 show the results obtained for the BeX and the OpenVSP, using in this last program the same methods followed in BeX.

Form Factor Comparison

	BeX	*OpenVSP*	*OpenVSP modified*
Fuselage	1.051	1.04	1.05
Wing	1.316	1.33	1.31
H. Stabilizer	1.237	1.21	1.24
V. Stabilizer	1.265	1.25	1.27
Nacelle	1.25	1.25	1.25

Table 3. Comparison of the form factor values between BeX (left) with the predefined method in OpenVSP (center) and the method followed by BeX in OpenVSP (right)

As it can be observed, all the form factors match perfectly. Once the form factor is equal in both programs, the parasitic drag coefficient is recalculated. The results are shown in Table 4



Cd0 Second Approximation Results

	BeX		*OpenVSP*		*Variation*
	FF	*Cd0*	*FF*	*Cd0*	*Cd0*
Fuselage	1.071	0.0044446	1.07	0.00328	38%
Wing	1.316	0.0050408	1.31	0.00484	3%
H. Stabilizer	1.237	0.0010258	1.24	0.00116	-13%
V. Stabilizer	1.265	0.0008662	1.27	0.00080	5%
Nacelle	1.25	0.0011711	1.25	0.00175	-33%
TOTAL	-	0.0125490	-	0.01193	5%

Table 4. Second approximation of the Cd0 in BeX and OpenVSP with the same form factor for each component.

As it can be seen, the changes are significant. Now the form factor is well calculated and these differences have affected the parasitic drag coefficient. In the fuselage, the wing and the horizontal stabilizer this correction has decreased the variation in Cd0 but has increased for the vertical stabilizer. The total Cd0 variation has decreased considerably but the differences between each component continue being high. The investigation now will be centered in the next parameters of the Cd0.

3.3.3 Friction Coefficient, C_f

In the calculation of the friction coefficient, BeX is again restrictive because it uses a unique method based on the *Schlichting equation*. Otherwise, OpenVSP works with different possible methods but not the one used with BeX. In order to approximate the value as much as possible, it has been selected the *Schlichting-Prandtl equation* that is an improvement of the *Schlichting equation*.

Schlichting equation:

$$C_f = \frac{0.455}{(log_{10}(Re))^{2.58} + (1 - 0.144M^2)^{0.65}} \tag{8}$$

Schlichting-Prandtl equation:

$$C_f = \frac{1}{(2 \cdot log_{10}(Re) - 0.65)^{2.3}} \tag{9}$$

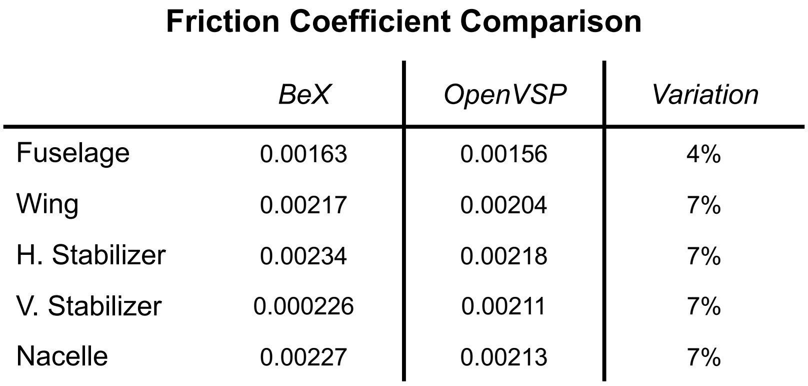
where M is the Mach number and Re is the Reynolds number in cruise conditions.

The Reynolds number has been calculated for cruise conditions:

$$Re = \frac{V_{cruise} \cdot L_{ref}}{\nu} \qquad V_{cruise} = 272 \; [m/s] \tag{10}$$

where ν is the kinematic viscosity of the air at 30000 ft. stated by *The U.S. standard atmosphere, 1976* [7] and L_{ref} is the characteristic length of each component. As the model in OpenVSP has been designed based on the BeX model, the characteristic lengths match.

The results obtained for the frction coefficient are shown in Table 5:



Friction Coefficient Comparison

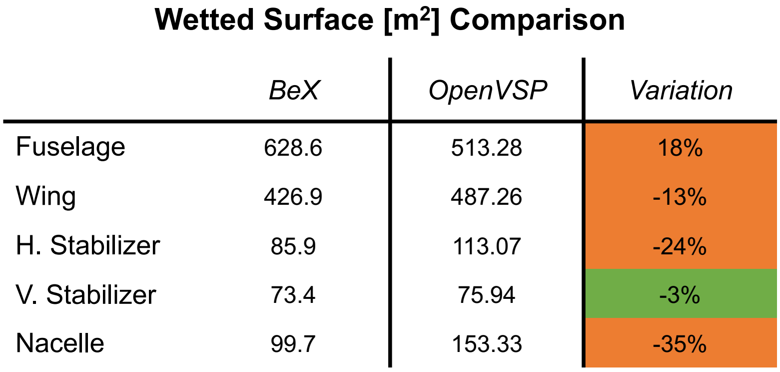
	BeX	*OpenVSP*	*Variation*
Fuselage	0.00163	0.00156	4%
Wing	0.00217	0.00204	7%
H. Stabilizer	0.00234	0.00218	7%
V. Stabilizer	0.000226	0.00211	7%
Nacelle	0.00227	0.00213	7%

Table 5. Friction coefficient comparison between BeX and OpenVSP.

As it can be seen in Table 5, the constant error between the *Schlichting* and *Schlichting-Prandtl* formulations is not significant to explain the high deviation in the parasitic drag coefficient between both programs. Moreover, this constant error in the friction coefficient is not reflected in the Cd0 results so the deviation between BeX and OpenVSP in the C_f is explained by the modification done in the formulation.

3.3.4 Wetted Surface, S_{wet}

Another important component in the parasitic drag coefficient calculation is the wetted surface. Each program calculates the wet surface for each component of the model. The values are compared in Table 6.



Wetted Surface [m²] Comparison

	BeX	*OpenVSP*	*Variation*
Fuselage	628.6	513.28	18%
Wing	426.9	487.26	-13%
H. Stabilizer	85.9	113.07	-24%
V. Stabilizer	73.4	75.94	-3%
Nacelle	99.7	153.33	-35%

Table 6. Wetted Surface comparison between BeX and OpenVSP.

From Table 6 it can be extracted that something is not working well in the calculation of the wetted surface. These high deviations could explain the differences in the parasitic drag coefficient (Table 4).

In order to do this investigation, it is going to be studied the wetted surface calculation method for each component of the model in BeX and OpenVSP.

Fuselage

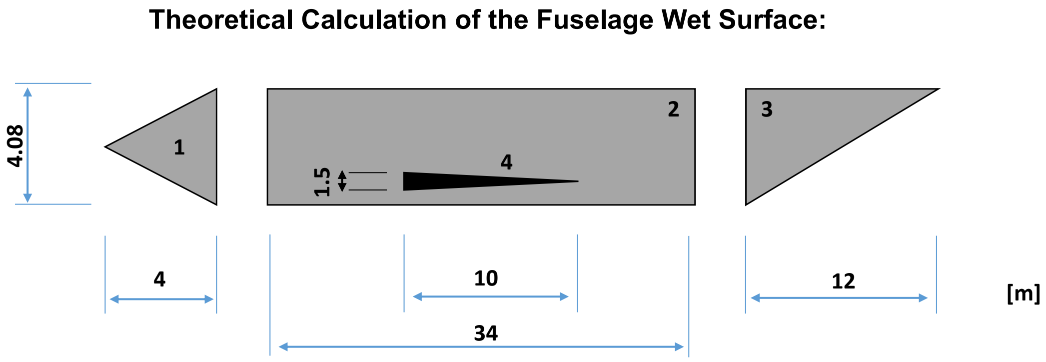
OpenVSP calculates the wetted surface of the fuselage by creating first a mesh along all the body and then integrating numerically the surface obtaining the result shown in Table 6. The fidelity level of OpenVSP in this type of calculation is Level-2, because of this method recreates a detailed geometrical representation as states the study *Collaborative understanding of disciplinary correlations using a low-fidelity physics based aerospace toolkit* [8].

BeX uses the following method to calculate the fuselage wetted surface:

$$S_{wet} = \frac{3.479 \cdot A_T \cdot A_S}{2} \tag{11}$$

where A_T is the area of the top view of the fuselage and A_S is is the area of the side view of the fuselage. BeX does not provide information or the authorship of this formula and after some research, the method followed remains to the study *Simulation of Wetted Surface Area* [9] in which the formula is used as a first approximation to the wetted surface.

This formula has a fidelity Level-0 due to is based on empirical design rules and only allows exploration of the conventional design space, as is stated in the study mentioned previously [8]. In order to probe the accuracy of this formula, the fuselage wetted surface is going to be validated with a theoretical calculation presented in Fig.10



$$S_1 = \pi \cdot r \cdot g_1 = \pi \cdot \sqrt{h_1^2 + r^2} = \pi \cdot \sqrt{4^2 + 4.08^2} = 28 \; [m^2]$$

$$S_2 = 2\pi \cdot r \cdot h_2 = 2\pi \cdot 4.08 \cdot 34 = 427 \; [m^2]$$

$$S_3 = \pi \cdot r \cdot g_3 = \pi \cdot \sqrt{h_3^2 + r^2} = \pi \cdot \sqrt{12^2 + 4.08^2} = 76 \; [m^2]$$

$$S_4 = 2 \cdot (b \cdot h)/2 = 2 \cdot (10 \cdot 1.5)/2 = 15 \; [m^2]$$

$$S_{Fuselage} = S_1 + S_2 + S_3 - S_4 = 516 \;\; [m^2]$$

Fig. 10. Theoretical fuselage wet surface calculation.

In Fig.10, each part represent a simplification of the geometry of the fuselage. The nose and the tail have been simplified as a cone, the central part of the fuselage as a cylinder and the wing intersection as a triangle, where it has been selected the chord and the maximum thickness at the intersection.

Finally, the three results are compared:

$$BeX: \;\; S_{wet} = 629 \; [m^2]$$

$$OpenVSP: \;\; S_{wet} = 513.28 \; [m^2]$$

$$Theoretical: \;\; S_{wet} = 516 \; [m^2]$$

With the support of the theoretical calculation, taking into account the deviations in the result due to the simplification made in the theoretical calculation, the OpenVSP value is validated and the BeX calculation is considered as invalid to define the wet surface of the fuselage of this project.

Wing, Vertical and Horizontal Stabilizer

For the calculation of the wing wetted surface, BeX first calculates the projected area of the three main sections in which the wing has been divided during the modeling process. Once the projected areas are calculated, the wing wetted surface is calculated using the formula based on the study made in *Simulation of Wetted Surface Area* [9]. The process is done as follows:

Projected Section Area:

$$A_P = C_{root} \left(\frac{Y_{tip} - Y_{root}}{100} \frac{b}{2} \right) (1 + \lambda)$$

where C_{root} is the chord at the root of the wing section, Y_{tip}, Y_{root} is the position in the Y axis of the tip/root of the wing of the section, b is the span and λ is the tapper ratio of the wing section.

Wing Section Wetted Surface:

$$S_{wet} = A_P \left[1.977 + 0.52 \left(\frac{\left(\frac{t}{c}\right)_{root} + \left(\frac{t}{c}\right)_{tip}}{2} \frac{1}{100} \right) \right]$$

where $\left(\frac{t}{c}\right)_{root}$, $\left(\frac{t}{c}\right)_{tip}$ is the thickness to chord ratio in percentage [%] of the root/tip of each section in which the wing is divided. The total wetted surface is calculated as the addition of the three section wet surfaces.

The described method is the same used for the calculation of the wetted surface for both vertical and horizontal stabilizer.

The calculation of the projected area and the wetted surface is an approximation based on the geometry of the wing but does not represent the actual projection. The parameters that these formulas depend on have been revised and match with the parameters set in OpenVSP.

OpenVSP calculates the wing wetted surface by creating first a mesh along all the body and then integrating numerically the surface obtaining the result shown in Table 6.

The fidelity level of the BeX calculation according to the study of low-fidelity physics [8] is Level-0 of accuracy as the fuselage wetted surface calculation. In contrary, OpenVSP uses a Level-2 of fidelity. For this reason, the OpenVSP results are considered to be more accurate than the BeX results.

Nacelles

The nacelles wetted surface is the one that presents more deviation (35%) in its calculation when comparing them between BeX and OpenVSP. This huge variation is due to the way in with each program calculates it.

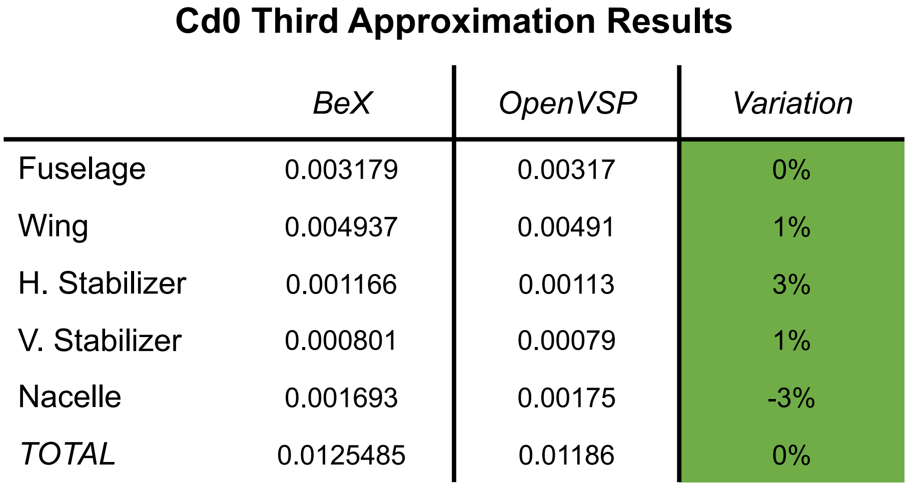
BeX calculates the wetted surface as a simple external surface of a cylinder:

$$S_{wet} = N_{engines} \cdot (2 \cdot \pi \cdot r \cdot L) = 2 \cdot (2 \cdot \pi \cdot 3.14 \cdot 5.06) = 99.7 \; [m^2]$$

where r is the external radius of the nacelle and L is the longitudinal length of the nacelle.

OpenVSP takes into account both external and internal surfaces when the mesh interpolation is done to calculate the wetted surface and this is the reason why there is a difference of 35%.

Once all the parts of the model have been investigated, a last calculation of the Cd0 is done setting the wetted surface calculated in OpenVSP in both programs in order to see the influence of the wetted surface in the Cd0 calculation. The other parameters as the form factor FF, the friction coefficient C_f are calculated independently by each program in their respective predefined methods. The results are presented in Table 7.



Cd0 Third Approximation Results

	BeX	*OpenVSP*	*Variation*
Fuselage	0.003179	0.00317	0%
Wing	0.004937	0.00491	1%
H. Stabilizer	0.001166	0.00113	3%
V. Stabilizer	0.000801	0.00079	1%
Nacelle	0.001693	0.00175	-3%
TOTAL	0.0125485	0.01186	0%

Table 7. Third approximation of the Cd0 in BeX and OpenVSP with the same wet surface for each component.

3.4 Cd0 Comparison Conclusion

As a conclusion, it has been demonstrated that each parameter has a singular importance in the total Cd0 but due to its high order of magnitude, the wetted surface is the most sensitive parameter. Table 7 shows the relevance of this parameter in the final result. The variation comes from the different methods followed by each program with different fidelity levels (Level-0 in BeX and Level-2 in OpenVSP) that highly influences the parasitic drag coefficient.

Notwithstanding, the approximation done in BeX is completely valid as a first approximation due to the method followed is approved by the study *Simulation of Wetted Surface Area* [9]. It is necessary to take into account that BeX is not a CFD program and its aim goes further than the aerodynamic study.

4 Aerodynamic Relations

The aerodynamic field of both BeX and OpenVSP goes further than the parasitic drag coefficient calculation. In this section different important relations between aerodynamic parameters, usually used in the aerodynamic sector due to its usefulness, are going to be calculated and compared between BeX and OpenVSP. The different dissimilarities are explained and a reasonable explanation is given to this discrepancies in the results.

4.1 Lift Coefficient versus Angle of Attack

The first relation that is going to be studied is the lift coefficient versus the angle of attack. The higher the angle of attack the higher the pressure difference between the lower and the upper part of the wing so the higher the lift coefficient. But the increase of the angle of attack also brings forward the detachment of the boundary layer. So for a determined high angle of attack, the stall of the airfoil will be produced.

In this case, both BeX and OpenVSP do not take into account the critical angle of attack so the programs only give information about the tendency of the lift coefficient. Therefore, this relation is valid for moderated angles of attack. Figure 11 shows the relation.

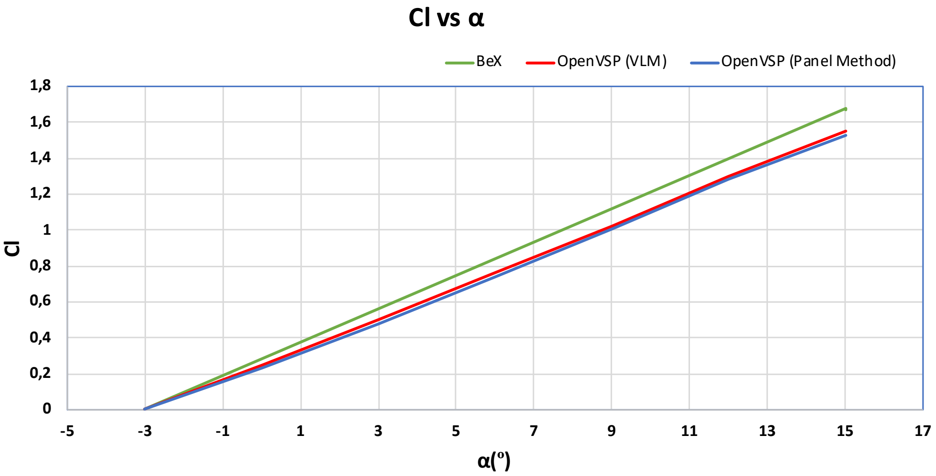


Fig. 11. Comparison of the relation between the lift coefficient and the angle of attack for BeX and OpenVSP. (BeX model trimmed).

As it can be seen if Fig.11, both solutions have a really good approximation. Starting from the negative angles of attack, the zero lift angle is achieved for $\alpha = -3^o$.

This coincidence reinforces the wing model recreated in OpenVSP from the information available in the BeX model. Nevertheless, there is an increasing error that is propagated along the dependence between the lift coefficient and the angle of attack from 0% ($\alpha = -3^o$) to 7% ($\alpha = 15^o$). It is necessary to take into account that BeX does not allow to define the NACA airfoil that can be directly defined in OpenVSP.

BeX first defines the zero lift angle of attack and then calculates the tendency using the following formula:

$$C_L(\alpha) = C_{L_\alpha} \left(\alpha_{C_L=0} - \alpha\right) \tag{12}$$

where C_{L_α} is the relation between the lift coefficient and the angle of attack and $\alpha_{C_L=0}$ is the zero lift angle of attack.

The fidelity level of the method followed by BeX is Level-1 according to the study of low-fidelity physics [8] because the method is based on a linear behavior simplification of the physics involved .

OpenVSP works in this field with a sub-program called VSPAERO. This sub-program calculates the aerodynamic parameters and the relation between them. VSPAERO allows two different methods of calculation, *The Vortex Lattice Method* and *The Panel Method*.

The *Vortex Lattice Method (VLM)*, is a numerical method used in computational fluid dynamics, mainly in the early stages of aircraft design. This method models the lifting surfaces, such as a wing, of the aircraft as an infinitely thin sheet of discrete vortices to compute lift and induced drag. The influence of the thickness, viscosity is neglected. By simulating the flow field, *The Vortex lattice method* can extract the force distribution around the simulated body. This knowledge is then used to compute the aerodynamic coefficients and their derivatives that are important for assessing the aircraft's handling qualities in the conceptual design phase.

The *Panel Method* models the flow past an airfoil as the summation of a uniform flow (same speed and direction everywhere) and a series of vortex 'panels' arranged to form a closed polygon with a shape that approximates the airfoil geometry. *The Panel Method* is ideal for concepts of design analysis due to the low time calculation and the relatively easy surface modeling. Notwithstanding, this method does not predict the boundary layer and the flow separation.

The *Vortex Lattice Method* and the *Panel Method* have a Level-2 of fidelity due to these tools are based on accurate physical representations of the disciplines involved as is stated in the study of low-fidelity physics [8].

4.2 Lift/Drag versus Mach Number

The second relation presented is the Lift to Drag ratio versus the Mach number. This relation is one of the most significant ones because determines the cruise speed of the aircraft in terms of the efficiency. Thought this relation, it can be extracted the speed that optimizes the Lift for the Drag created. Figure 12 shows the comparison between both programs.

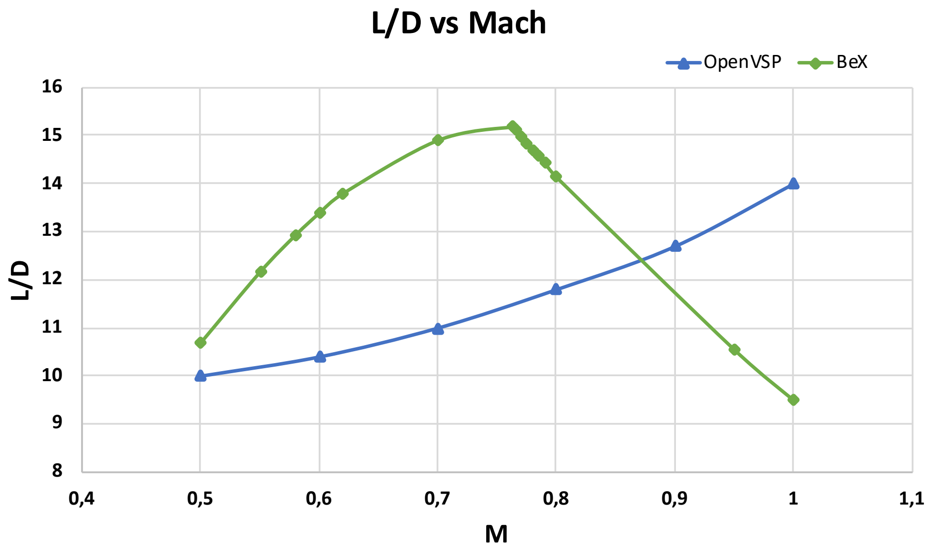


Fig. 12. Comparison of the relation between the L/D and the Mach number for BeX and OpenVSP. (OpenVSP at constant angle of attack of 0^o). (BeX model trimmed).

As it can be observed, the solutions do not approximate each other. This is due to the reason that BeX and OpenVSP are not exactly calculating the same type of relation.

BeX, calculates this relation from the point of view of the mission of the aircraft and therefore looks for a relation that gives information of the efficiency. In order to do it, BeX calculates this relation in cruise conditions, fixing the Lift of the aircraft as a constant value:

$$L = m \cdot g \tag{13}$$

where m is the mass of the aircraft. Once the Lift is fixed, the total drag is calculated for each Mach number.

This relation is only useful for performance and efficiency fields in the aircraft design. This is the reason why BeX directly calculates this relation. But OpenVSP does not directly allow to represent this type of relation. So in order to extract it from OpenVSP, it is necessary to proceed with the same procedure.

In order to do it in OpenVSP, the following steps have been performed:

- Calculate for each Mach number the relation of C_L over the AoA.
- Calculate for each Mach number the relation of C_D over the AoA.
- Calculate for each Mach number the C_L fixing the Lift.
- Extract the AoA for the C_L obtained for each Mach Number.
- Extract the C_D for the same values of the AoA for each Mach number.
- Divide the C_L over the C_D for each Mach number.

The result obtained from the modification of the OpenVSP procedure is presented in Fig.13.

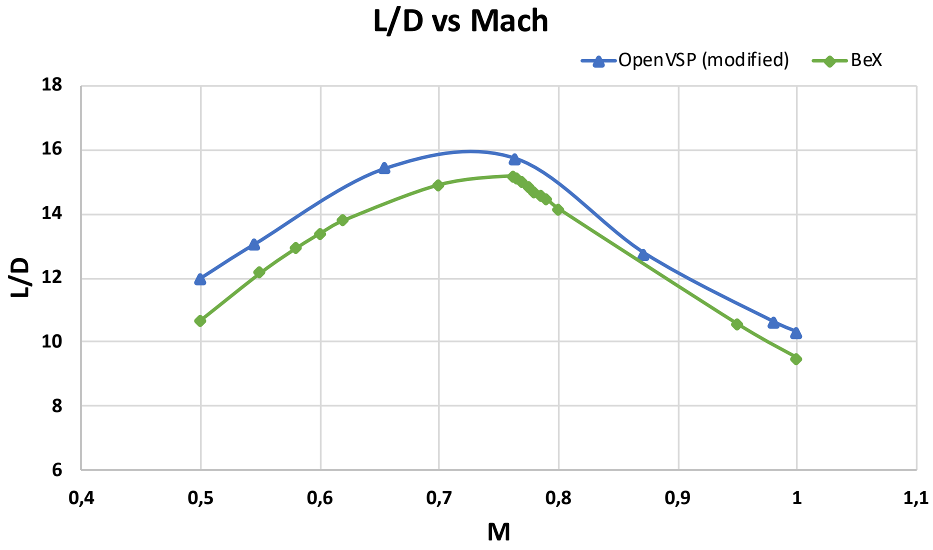


Fig. 13. Comparison of the relation between the L/D and the Mach number for BeX and OpenVSP (modified). (BeX model trimmed).

As it can be observed, now the behavior of both programs is exactly the same. First the L/D relation increases due to the Drag reduction with the increase of the Mach number, until the optimum speed reached around 0.7M. After this point, the Drag starts increasing again reducing the relation L/D. In Fig.13 it can also be seen an underestimation in the BeX result. This is due to BeX overestimates the parasitic drag due to a problem in the wet surface calculation as has been explained in Section 3 *Parasitic Drag Coefficient Cd0 Calculation.* This overestimation of the Drag reduces the L/D relation. Therefore, this relation reaches a good approximation between both programs.

5 Aircraft Balancing

In this section, it is studied how both programs calculate the weight distribution of the aircraft. Some discrepancies appear in this calculation due to the different aims that each program has. Once the weight is compared, the center of gravity is also studied in order to prove if the balance done in both programs coincide.

5.1 Weight

The treatment of the weight is completely different in both programs. BeX is a program centered in the real development of a aircraft so it takes into account step by step all the different components that define the weight of the aircraft: structure, systems, fuel, furniture, cabin equipment... On the other hand, OpenVSP is not centered in the real weight distribution and does not take into account the different components that define the entire aircraft. For that reason, the weight in OpenVSP only depends on the shape of the aircraft defined. The first comparison of the Operational Empty Weight (OEW) in both programs is presented in Table 8.

First Comparison of the Weight Distribution (Kg)

	BeX	*OpenVSP*
Fuselage	13956	494
Wing	12557	193
H. Stabilizer	1735	20
V. Stabilizer	812	16
Nacelles	641	21
Propulsion	13498	
Systems	20553	0
Fluids	637	
Op. Items	1392	
OEW	65781	744

Table 8. First Comparison of the weight distribution in of the aircraft. Only taken into account the OEW.

The first thing to highlight is that the OEW distribution in BeX takes into account in the engines section both the nacelles and the propulsion but OpenVSP only considers the nacelles because they already define the engines shape. For the Equipment section, BeX takes into account the systems, the fluids and the operational items but OpenVSP does not define it because nothing has to do with the shape and hence with the aerodynamics.

Now, centering the attention in the results of Table 8, it can be seen that the results offered by OpenVSP do not represent a real weight distribution of an aircraft so the way in which OpenVSP works is going to be investigated.

OpenVSP works with a sub-program called Mass-Prop to do the calculation of the mass. This sub-program does not offer a weight breakdown of all the different components, it only allows to calculate the weight of one shape that can be one component or a set of components. Mass-Prop divides this shape studied in different slices along the X axis to reduce the computational cost of the operation. Figure 14 shows the slice division done in OpenVSP of the studied model. Then, the weight is calculated as an interpolation between slices, only taking into account the density of each component and the volume interpolated. The higher the number of slices, the higher the accuracy will be.

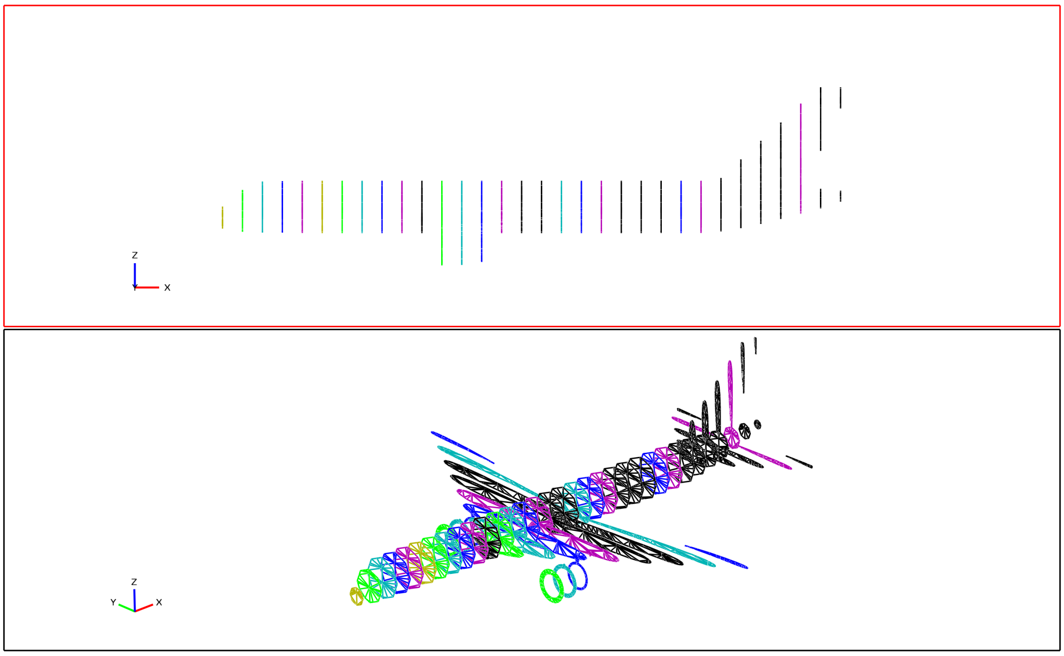
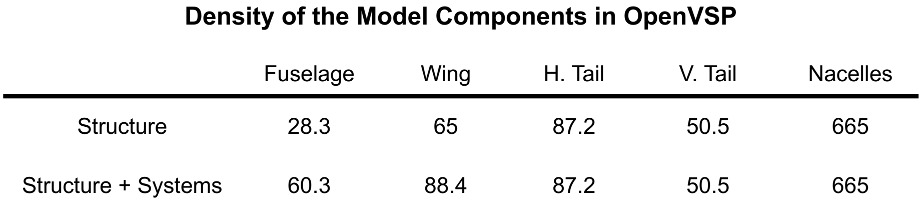


Fig. 14. Slice division of the aircraft in the Mass-Prop subprogram in OpenVSP.

Therefore the only way to set a real weight values is to adjust the density of each component but always with a reference value of the desired weight. In order words, the weight needs to be imposed by the user. In this case of study, it has been defined the density values of the components using as reference the BeX weight values. Table 9 shows the obtained density values.



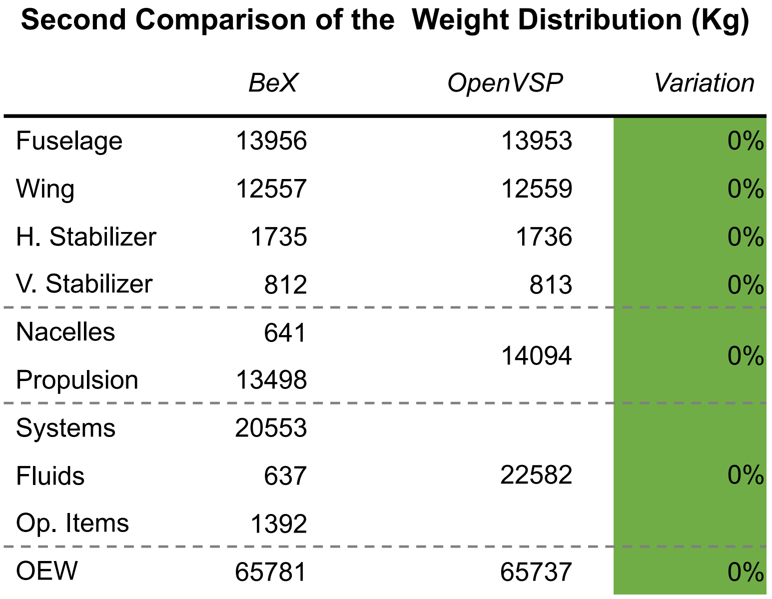
Density of the Model Components in OpenVSP

	Fuselage	Wing	H. Tail	V. Tail	Nacelles
Structure	28.3	65	87.2	50.5	665
Structure + Systems	60.3	88.4	87.2	50.5	665

Table 9. Density of the aircraft parts for accomplish the BeX weights.

As it can be seen in Table 9, it has been included a Systems field. This is due to in OpenVSP the equipment is not taken into account but represents a really significant part of the OEW of the aircraft. The systems weight has been divided between the fuselage carrying the 77% and the wing carrying the 23% of the weight as shows the distribution done in BeX in Table 11. The density of the Systems component is a modification of the Fuselage density from 28.3 to 60.3 and the Wing density from 65 to 88.4, to assume the total equipment weight. This decision will be discussed in Subsection 5.2 *Center of Gravity, CG.*

Once the new density values are set, the weight distribution is computed again in OpenVSP. The new comparison is presented in Table 10.



Second Comparison of the Weight Distribution (Kg)

	BeX	*OpenVSP*	*Variation*
Fuselage	13956	13953	0%
Wing	12557	12559	0%
H. Stabilizer	1735	1736	0%
V. Stabilizer	812	813	0%
Nacelles	641	14094	0%
Propulsion	13498		
Systems	20553	22582	0%
Fluids	637		
Op. Items	1392		
OEW	65781	65737	0%

Table 10. Second Comparison of the weights between BeX and OpenVSP.

The new values present a really good approximation of the weight distribution. This means that the density tool is capable to define correctly the weight of the aircraft components when reference values are available.

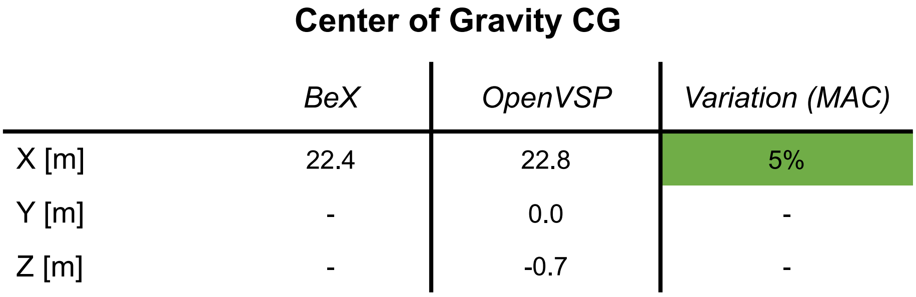
DISTRIBUTION OF THE SYSTEMS WEIGHT [Kg]

	FUSELAGE	*WING*
ATA 21 Air conditioning	1138	-
ATA 22 Auto flight	0	-
ATA 23 Communication	236	-
ATA 24 Electrical power	1759	-
ATA 25 Furnishing	6311	-
ATA 26 Fire protection	-	379
ATA 27 Flight controls	-	1436
ATA28 Fuel system	374	-
ATA 29 Hydraulics	-	1282
ATA 30 Ice & rain protection	-	467
ATA 31 Indicating/recording	364	-
ATA 32 Landing gear	4625	-
ATA 33 Lights	-	210
ATA 34 Navigation	820	-
ATA 35 Oxygen	277	-
ATA 36 Pneumatic	-	400
ATA 38 Water/waste	10	-
ATA49 APU	464	-
Percentage of Total Weight	77%	23%

Table 11. Distribution of the system weights in BeX for the calculation of the OEW.

5.2 Center of Gravity, CG

Once the weight is calculated, the center of gravity can be determined in both programs. BeX has a really complete aircraft balancing field of study that can calculate the excursion of the center of gravity from the OEW to the MTOW. Nevertheless, OpenVSP only allows to calculate the center of gravity position for one component or a set of components. Table 12 shows the comparison of the center of gravity with the adjusted weights in both programs.



Center of Gravity CG

	BeX	*OpenVSP*	*Variation (MAC)*
X [m]	22.4	22.8	5%
Y [m]	-	0.0	-
Z [m]	-	-0.7	-

Table 12. Center of gravity comparison of the aircraft for the OEW in BeX and OpenVSP.

As it can be observed, the center of gravity position in the X direction practically coincides with a deviation of 5% with respect to the MAC (Mean Aerodynamic Chord). This is a really good approximation but some points have to be explained.

OpenVSP does not allow to include extra weight for equipment, as it has been explained in Subsection 5.1, this extra weight has been included in the fuselage and wing weight. This simplification in OpenVSP is not done in BeX. The equipment weight included in the BeX model, is distributed in the different components depending on their real position on the aircraft. The decision of including the whole equipment weight in the fuselage and the wings is because these are the main structure parts of the aircraft in which are located most of the systems.

Besides, BeX takes into account the trim of the aircraft. The trimming is directly related with the center of gravity. Any force acting at some distance from the the CG will create a torque about the CG that will produce the rotation of the aircraft. During cruise conditions, if there is not rotation about the CG, the aircraft is said to be trimmed. The center of gravity is located near the center of pressure of the wing to reduce the torque created by the lift force about the CG. The lift produced by the horizontal stabilizer also creates a torque about the CG. In order to trim the aircraft, it is necessary to balance the torques produced by the wing and the horizontal stabilizer. As BeX performs a complete study of cruise conditions and its performace, this balance to trim the aircraft is executed in BeX. But OpenVSP does not take into account the torques created in the designed aircraft.

Coming back to Table 12, it can be seen that OpenVSP also calculates the center of gravity in the other two components (Y,Z) while BeX only calculates it in the X component. This is due to OpenVSP uses this center of gravity position (X,Y,Z) to calculate the moments of inertia in the three components.

In order to see the sensibility of the center of gravity in OpenVSP, the density of the different components have been modified from their original value of 1. The results are presented in Table 13.

Center of Gravity Sensibility in OpenVSP

	Density 1	*Density 2*	*Density 3*	*Density 4*
Fuselage	1	1	1	1
Wing	1	1	1	1
H. Stabilizer	1	2	2	1
V. Stabilizer	1	1	2	1
Nacelle	1	1	1	10
X [m]	23.910	24.325	24.739	22.844
Y [m]	0.000	0.000	0.000	0.000
Z [m]	-0.173	-0.169	-0.075	-0.778

Table 13. Sensibility study of the center of gravity of the aircraft in OpenVSP.

As it can be seen, when modifying the density of the horizontal stabilizer doubling its weight (case 2), the center of gravity moves backwards in the X direction. In the Z direction, there is not practically change because the horizontal stabilizer is located at $Z = 0$ $[m]$. Moreover, if the density of the vertical stabilizer is also doubled (case 3), the center of gravity in the X direction moves backward again because more weight is located in the tail. In this case, the center of gravity in the Z direction considerably goes upwards because the vertical stabilizer is approximately located at $Z = 2$ $[m]$ and hence separated from the origin. Finally, if the density of the nacelles is modified to ten times its original value (case 4), the center of gravity in X direction moves forward and in the Z direction moves downwards due to the negative position of the nacelles in the Z coordinate. In none of the 4 cases, the center of gravity in the Y direction is modified from the origin. This is due to the plane is completely symmetric in the XZ plane. In a real aircraft, the center of gravity in Y direction can be slightly moved from the origin despite of the systems and the equipment are located as symmetric as possible.

6 BeX Extra Calculations

In this section, it is going to be explained the different calculations that Bex can offer apart from the previous compared with OpenVSP seen in the past sections. The comparison between BeX and OpenVSP is really limited compared with the whole design calculations that BeX can extract from the aircraft studied. Therefore, the most important findings are going to be shown.

6.1 Center of Gravity Excursion

The first calculation is the center of gravity excursion. BeX takes into account along the design of the aircraft, all the different weights that take part of the MTOW (Maximum Take Off Weight). The weight variation along the different steps of the flight modifies the center of gravity. This variation is studied in BeX as it is shown in Fig.15. The green line represents the modification of the center of gravity of the aircraft from the initial point at $X = 22.4\,m$ where the aircraft only carries the OEW (Operational Empty Weight). After introducing the payload and the fuel in the aircraft, the CG moves backwards to $X = 23.3\,m$. This point represents the take off conditions. During the flight the fuel waste modifies again the CG to $X = 22.9\,m$.

This variation is really important in the aircraft design because it determines the stability of the aircraft, it allows to know what is the difference between the CG and the aerodynamic center (where the Lift is applied) at each flight step and hence the moment induced by the Lift. For this reason, the center of gravity excursion has been remarked as one of the important BeX calculations. Moreover, the CG excursion comes from a really detailed weight study also remarkable.

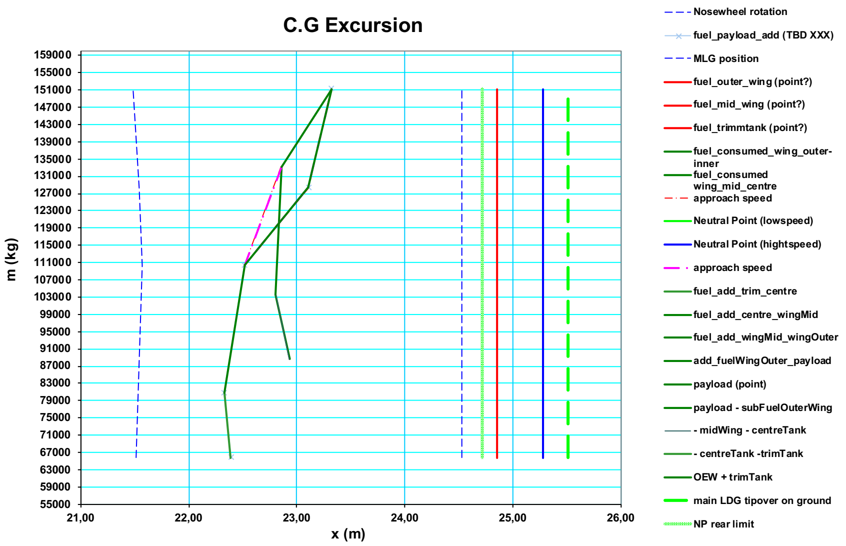


Fig. 15. Center of gracity excursion of the aircraft in BeX.

6.2 Constraint Diagram

The following calculation highlighted is the constraint diagram. BeX calculates it taking into account the MTOW and the thrust available for the engines selected in the design process. The wing loading it is also taken into account.

The constraint diagram in Fig.16 shows the different limitations of minimum thrust that the aircraft needs depending on the wing loading to safely perform the different flight phases (take off, climb, cruise, approach and landing). In Fig.16 it is also shown the design point for the wing loading selected and the optimum design point at which both the thrust to weight ratio and the wing loading are minimized within the feasible area.

This calculation gives a lot of crucial information for the engine selection of the aircraft.

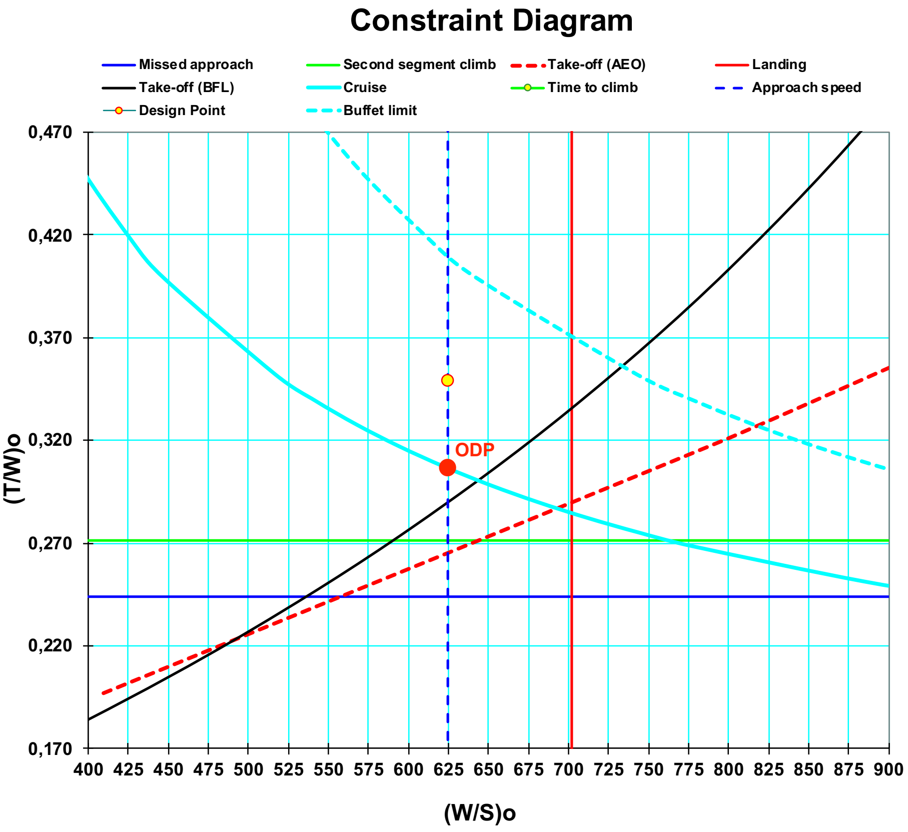


Fig. 16. Constraint Diagram of the aircraft in Bex.

6.3 Bending Moment & Shear Load

The bending moment and the shear load distribution are also going to be commented. BeX offers the possibility to calculate both distributions along the fuselage and the half of the wing as shown in Fig.17 and Fig.18 respectively.

The bending moment along the fuselage calculated gives an idea of the distribution. It is practically concentrated in the wing position. The same occurs in the shear stress distribution. This is an important fact to consider in the structure design of the aircraft and is the reason why BeX takes it into consideration.

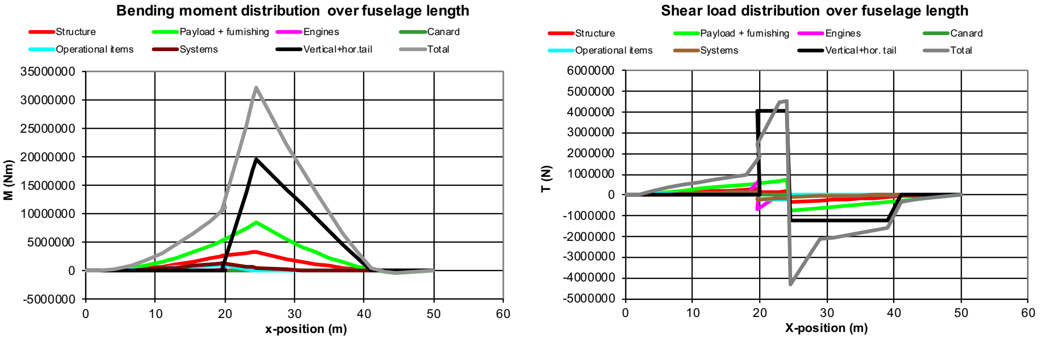


Fig. 17. Bending moment (left) and shear stress (right) distribution over the fuselage length of the aircraft in BeX.

The bending moment calculated along the half of the wing allows to analyze the factors that take part in it. As it can be seen the weight and the lift are opposed and BeX takes into account this behavior in order to approximate as much as possible to the real value that the aircraft would experiment. The same method is followed in the shear load distribution along half of the wing.

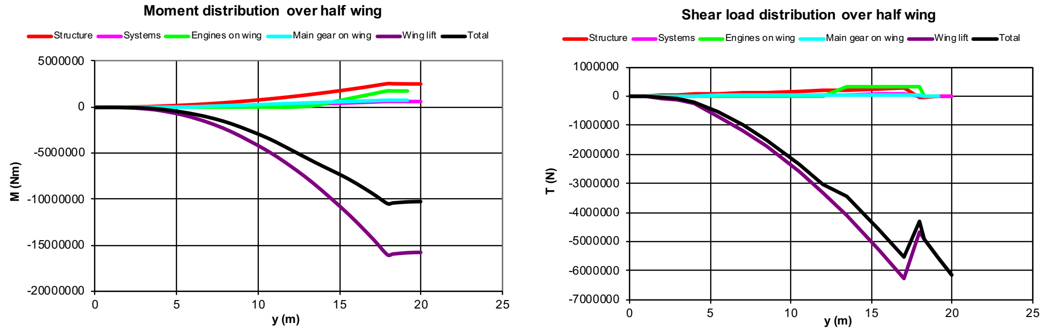


Fig. 18. Bending moment (left) and shear stress (right) distribution over half of the wing length of the aircraft in BeX.

6.4 Thrust & Drag versus Mach Number

Finally, the relation of thrust and drag versus the Mach number is also considered. BeX calculates the total drag and thrust available at cruise conditions and represents both versus the Mach Number. Through this representation, in Fig.19, it can be observed the region in which the aircraft can operate being the thrust available higher than the drag created.

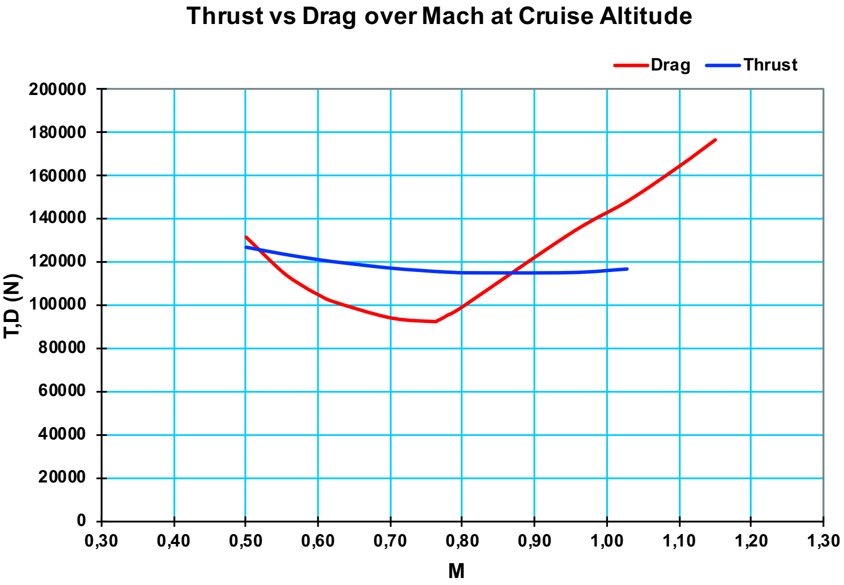


Fig. 19. Comparison of the Thrust and the Drag over the Mach number at cruise altitude in BeX.

As it has been shown in this section, BeX works in all the fields involved in the aircraft design extracting relevant information that would be useful as a preliminary design of a new aircraft.

7 OpenVSP Extra Calculations

In this section, OpenVSP is going to be studied deeply and the most important calculations that the software can run are going to be explained apart from the ones compared with BeX.

7.1 Span-wise Lift Distribution

OpenVSP is a program focused in the aerodynamics of the aircraft and develops a really good approximations of the aerodynamic coefficients as it has been seen with the parasitic drag coefficient CD_0 in Section 3. Figure 20 represents the lift coefficient C_L distribution along the span of the wing and the horizontal stabilizer of the studied aircraft calculated in the subprogram VSPAERO. The graph shows different angle of attack distribution for the same cruise Mach number ($M = 0.8$).

As it can be seen in Fig.20, the fuselage affects negatively to the lift creation due to a decrease in the C_L in the center of the aircraft. The engines also have a negative effect in the C_L as it can be observed in their position $Y = \pm 8\ m$.

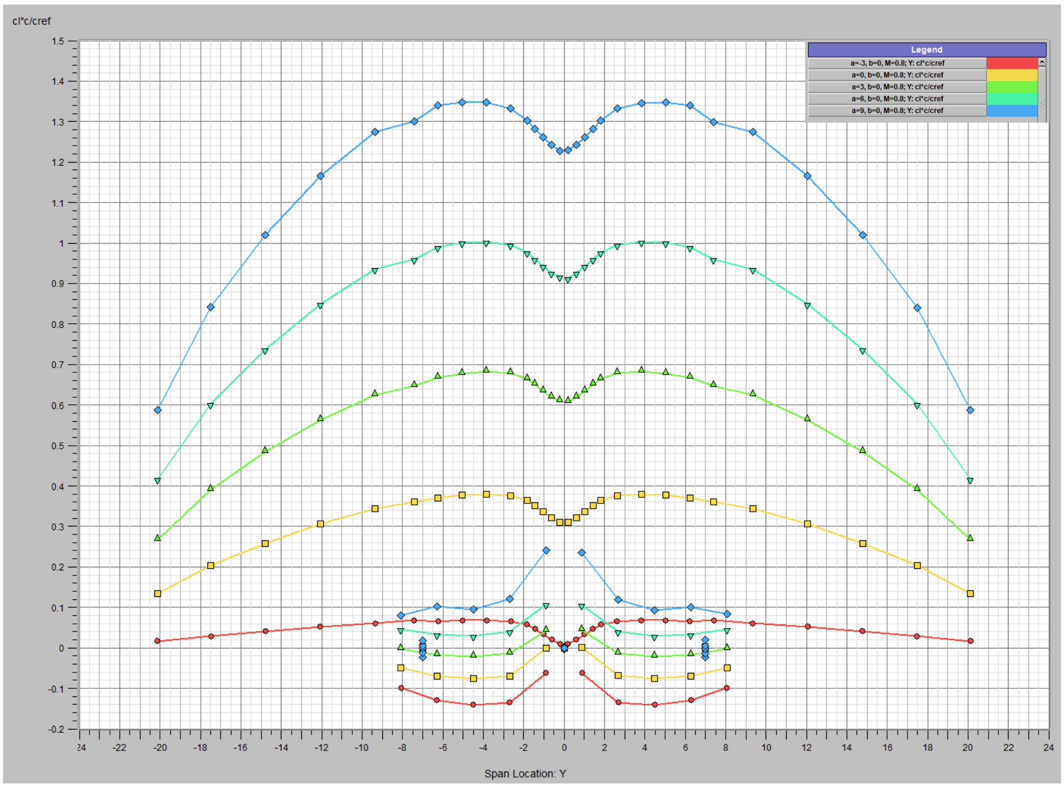


Fig. 20. Lift distribution along the span of the wing and the horizontal stabilizer for different angles of attack for cruise Mach number ($M = 0.8$) in OpenVSP.

Observing more in detail the distribution created at $\alpha = -3^o$, it can be seen that the C_L created is practically null. This is because $\alpha = -3^o$ is the zero lift angle of attack as was described in Subsection 4.2 Fig.11.

This is a really useful tool to know where the Lift is created along the span and gives a lot of information as the negative influence of the elements as it has been explained. Notwithstanding, these type of calculations need a *Vortex Lattice Method* or a *Panel Method* requiring high computational cost for programs not designed to this aim like BeX. It is true that BeX takes into account the Lift created in the wing to perform the bending moment distribution along half of the wing (Fig.18) but considering a constant lift distribution along the span. This is a good approximation for the BeX usage that is to have an idea of the loads and moments experimented by the wing during flight. But from the point of view of the aerodynamics it is not a valid approximation because does not take into account the real behavior of the flow over the wing.

7.2 Pressure Coefficient Distribution

The following tool to be remarked in the subprogram VSPAERO of OpenVSP is the pressure coefficient C_P distribution along the aircraft surface. Figure 21 shows the C_P distribution for different angles of attack at cruise Mach number ($M = 0.8$).

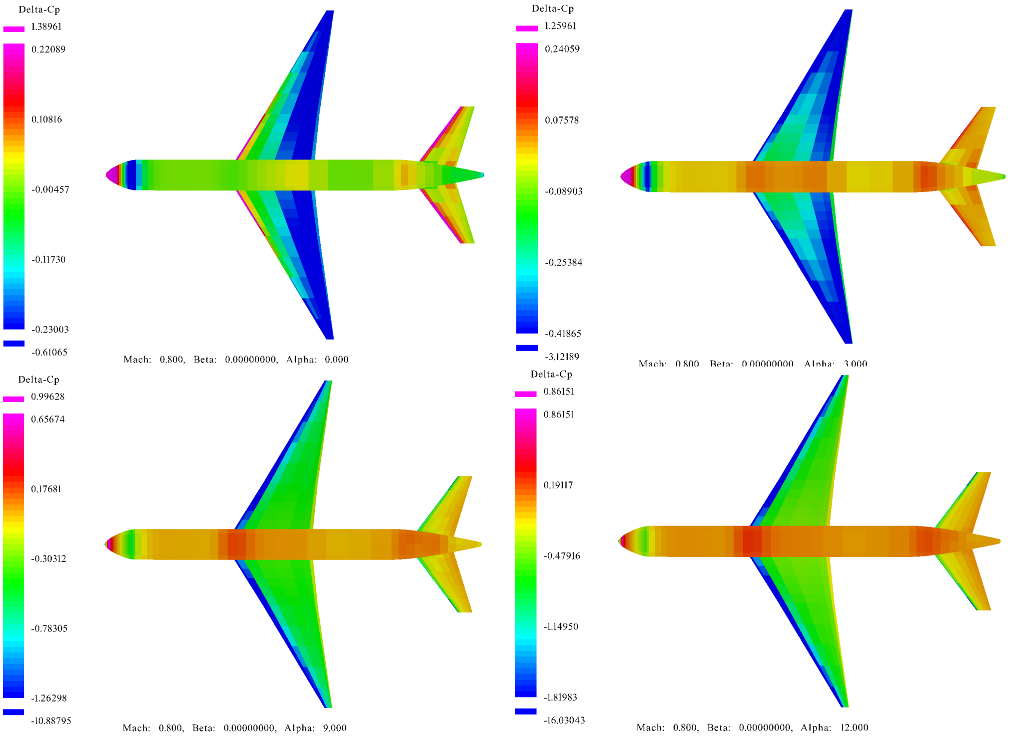


Fig. 21. Comparison of pressure coefficient distribution along the aircraft surface for different angles of attack at cruise Mach number (M=0.8) in OpenVSP. The range of the legend changes for each case.

As it can be observed, the higher the angle of attack the lower the pressure coefficient on the upper part of the wing. It can also be observed that for the angles of attack $\alpha = 9^o$ and $\alpha = 12^o$ the low pressure coefficients values are concentrated in the leading edge of the wing and the rest of the wing presents the same pressure coefficient. This tool can give useful information about the detachment of the boundary layer. The aircrafts are designed to operate in a certain range of angles of attack but BeX does not contemplate this fact. Therefore, OpenVSP would be a good tool to complete these requirements.

Moreover, the VSPAERO subprogram also offers to represent together with the pressure coefficient, the streamlines that pass through and leave the aircraft. Figure 22 shows the streamlines for different angles of attack for cruise Mach number ($M = 0.8$).

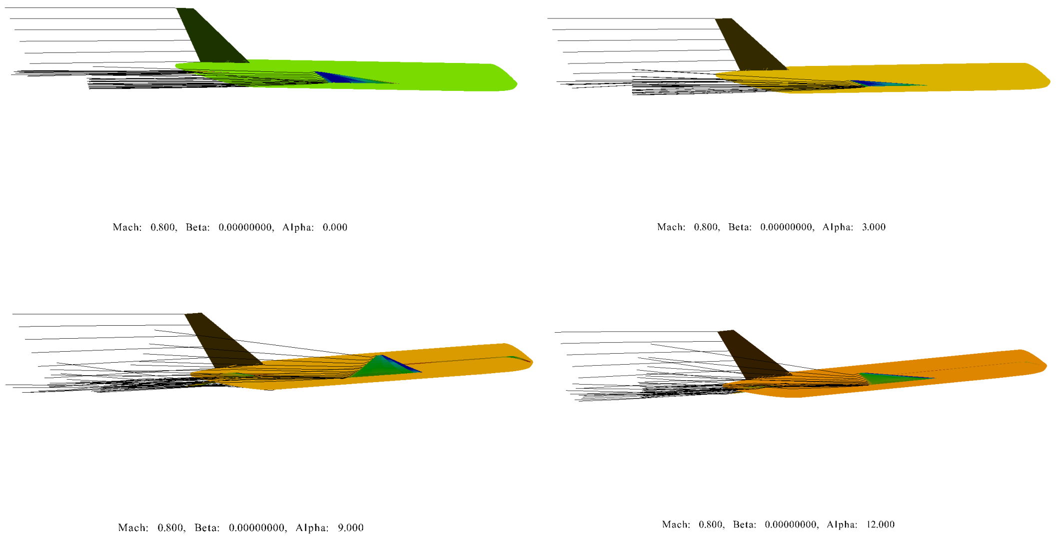


Fig. 22. Comparison of streamlines that leave the aircraft for different angles of attack at cruise Mach number (M=0.8) in OpenVSP.

This graph complements the pressure coefficient graph of Fig.21 and more information can be extracted about the behavior of the flow over the wing. It can be perfectly observed how for high angles of attack $\alpha = 9^o$ and $\alpha = 12^o$ the flow detaches earlier.

OpenVSP offers in VSPAERO really useful information that can support the design created in BeX so both programs can work together in the aerodynamic design of the aircraft.

8 Discussion

After performing the comparative study between BeX and OpenVSP about aircraft design some aspects are going to be highlighted.

Concerning the modeling of the aircraft, OpenVSP provides a precise and intuitive interface to create a really detailed aircraft structure in which each part can be easily designed. Specially in the wing design, in which parameters as the twist angle, the dihedral angle and the NACA airfoil can be determined. Nonetheless, BeX does not offer a practical way to define the external structure of the aircraft since the geometric definition of the fuselage, the wing and the stabilizers is done by trial and error in a 2D (XY and XZ planes) representation of the aircraft. Moreover, the parameters mentioned above are not available in the program. From the point of view of the modeling, this fact limits the design done in BeX. But this lack of parameters is solved in BeX by introducing the expected performance of the wing as the Lift force generated or the zero lift angle of attack. The geometry tool of BeX does not offer the flexibility of OpenVSP but as the aim of BeX is extracting information fron the geometry in order to calculate the performance of the aircraft, parameters with difficult impact calculation have been replaced by the results desired in the aircraft performance.

Regarding the comparison of the parasitic drag coefficient, OpenVSP offers a powerful tool VSPAERO that calculates the CD0 through numerical methods (*VLM* and *Panel Method*) with a Level-2 of fidelity, giving accuracy to the results obtained. As it has been explained in Section 3, both programs work with the same formulas to calculate the CD0 except for the wetted surface. As it has been demonstrated, this parameter has a high influence in the CD0 calculation. While OpenVSP uses an interpolation method with Level-1 of fidelity to calculate this parameter, BeX uses a first approximation method (*Simulation of Wetted Surface Area* [9]) with Level-0 of fidelity that results in a bad approximation of the wetted surface. This has been the only failure detected in the calculation of the CD0, because the other parameters involved do not differ from the OpenVSP results. For future versions of BeX, it is proposed through this work to change the wetted surface calculation method and introduce approximations following the method done in Fig.10 in Subsubsection 3.3.4, that has shown good approximations to OpenVSP results.

In respect of the comparison of the aerodynamic relations, BeX offers a compete set of representations that gives useful information about the performance in cruise conditions (e.g. Cl vs AOA, L/D vs M, T vs D, etc). On the other hand, OpenVSP also offers a lot of combinations of parameters to represent but has limitations to fix variables in the relations performed like the Lift force (as in the L/D vs M), useful for cruise conditions studies. In the representation of the Lift coefficient versus the angle of attack, the results have shown a slight difference between both programs attributed to the different way in which the wing is modeled and the level of fidelity of the calculations done (Level-1 in BeX and Level-2 in OpenVSP) as it has been explained in Subsection 4.1.

About the weight calculation, BeX presents a strong tool to exhaustively define the weight. It takes into account all the different components distributed along the aircraft (structure, systems, furniture, etc), in order to get a good approximation of the real center of gravity. Nevertheless, spite the fact that OpenVSP has the possibility to calculate the weight through Mass-Prop, this tool is not designed to establish in a practical way the weight of each part of the aircraft. Moreover, the tool needs reference values to define the mass of the different parts of the aircraft. It seems clear that the tool has been designed to strictly calculate the center of gravity.

Finally, it is going to be discussed the center of gravity calculation. The results have shown a variation between both results of a 5% with respect to the MAC that is a good approximation. Despite of this fact, OpenVSP do not represent a real approximation of the value, because as it does not consider the weight of the systems, this weight has been distributed homogeneously along the fuselage and the wing, neglecting their real position in the aircraft. However, BeX calculates the center of gravity considering the real position of the systems. Besides, BeX performs the balance of the torques created by the wing and the horizontal stabilizer about the CG, therefore the aircraft is trimmed, giving a complete calculation of the aircraft balancing.

9 Conclusions

The study done has allowed to know more deeply the capabilities of BeX and OpenVSP and which methods follows each program in the sheared fields of study in the Aircraft Conceptual Design (ACD).

Depending on the objective followed by the user, one program can be selected. If the aims of the study are only the aerodynamic effects of the desired aircraft, the most complete program is OpenVSP. However, if an aircraft is going to be designed taking into account more fields of study (mission requirements, structure, weights, aircraft balancing, sizing, aerodynamics and cost), BeX is recommended to be used taking in consideration the limitations in the aerodynamic field explained through this work.

Finally, it is concluded that BeX and OpenVSP should be used together in the ACD process, taking advantage of the strengths of each program. It seams clear that an aircraft can not be designed with only one program because this type of designs require precision in really different fields of study. Therefore, it is recommended to work in parallel with both programs and validate the aerodynamic study done in BeX with the results obtained in OpenVSP, as well as expand the aerodynamic knowledge about the aircraft.

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