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Systematic Approach to Analyze, Evaluate and Select Box Wing Aircraft Configurations from Modified Morphological Matrices

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Abstract

Different configurations of the box wing aircraft have been studied in a systematic way with Morphological Analysis followed by an evaluation based on Cost- Benefit Analysis. Morphological Analysis first breaks down the box wing aircraft into its major basic components: box wing, horizontal tail surface, vertical tail surface, fuselage, engine (position) and landing gear (integration). The box wing is further differentiated with respect to its type of sweep, stagger and vertical position. Sweep type, stagger and vertical position combine to form various box wing configurations. Different box wing configurations are analyzed in steps to find suitable and feasible box wings. Similarly, all the other basic components are analyzed and unpractical outcomes are discarded with valid logical arguments. The classical Morphological Analysis considers all possible combinations and arrives at sometimes unpractical high numbers of solutions. The proposed Modified Morphological Analysis combines parameters and rules out unfeasible partial solutions in steps arriving at final candidate configurations with less overhead. The outcomes from this analysis are 18 feasible box wing aircraft configurations which are subjected to an evaluation based on Cost- Benefit Analysis. In every step the configurations obtained are visualized with OpenVSP for a better understanding. In the Cost Benefit Analysis, criteria are set to measure the strength of the configurations. The criteria are described with these key words: configuration, drag, weight, flight mechanics, operation and development. Each configuration is scored as per the criteria and the total score is the summation of scores obtained for each criteria. The total score for all the configurations are examined and the configuration scoring highest is considered to be the best practical design of a box wing aircraft. Box wing aircraft with unstaggered wing, both wings backward swept, *low-high* box wing vertical position, conventional horizontal tail, conventional fuselage scores the highest and it is concluded to be the most suitable design that could be considered for more detailed box wing aircraft design. Box wing aircraft with unstaggered wings, both wings backward swept, *low-super high* box wing vertical position, conventional horizontal tail and conventional fuselage results to be the second best configuration. If the decision is taken to design a rather unconventional box wing aircraft, box wing aircraft with negative stagger, both wings swept in opposite sense (forming a diamond in the top view), V-tail, conventional fuselage is concluded to be the most feasible to enter more detailed box wing aircraft design.

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List of Abbreviations

=	No Stagger
–_	Positive Stagger
_–	Negative Stagger
<<	Both Wing Backward Swept
>>	Both Wing Forward Swept
< >	Backward and Forward Swept Wing
L – H	Low – High Wing Vertical Position
L – SH	Low – Super High Wing Vertical Position
SL – H	Super Low – High Wing Vertical Position
SL – SH	Super Low – Super High Wing Vertical Position
Can	Horizontal Surface at Fuselage Front
No	Presence of No Horizontal Surface
Aft	Horizontal Surface at Fuselage Aft
Fuse – aft	Engine held at Fuselage Aft
Fuse – mid	Engine held at Fuselage Middle
Wing	Engine held at Wing

Terms and Definitions

Wing Stagger
Wing Stagger is the horizontal positioning of a biplane, triplane, or multiplane's wings in relation to one another. (**Wikipedia 2013b**)

Wing Sweep
A swept wing is a wing planform with a wing root to wingtip direction angled beyond (usually aft ward) the span wise axis, generally used to delay the drag rise caused by fluid compressibility. (**Wikipedia 2013c**)

Wing Vertical Position
The vertical position of the wing with respect to the fuselage, when viewed from the front. (**Raymer 1992**)

Family Concept
An aircraft is chosen as a reference aircraft and different versions of aircraft are made based on the reference aircraft. The common approach is to shorten or lengthen the fuselage section keeping the wing unchanged. (**Schiktanz 2011**)

Zero Lift Drag
For subsonic flight the drag developed because of the skin friction from the wetted area is known as the zero lift drag or parasite drag (**Raymer 1992**)

Induced Drag

> *"Drag forces that are a strong function of lift are known as "induced drag" or "drag-due-to-lift". The induced drag is caused by the circulation about the airfoil that, for a three-dimensional wing, produces vortices in the airflow behind the wing. The energy required to produce these vortices is extracted from the wing as a drag force, and is proportional to the square of the lift."* (**Raymer 1992**)

Ground Handling
Ground Handling is defined as the servicing that the aircraft receives while it's parked on the terminal. Services are mainly: Cabin services, catering, ramp service, passenger service, flight operation service. (**Wikipedia 2013f**)

1 Introduction

1.1 Motivation

The project Airport 2030 concentrates on designing a non planar unconventional aircraft – the box wing aircraft. The project goal is to come up with a suitable box wing design that meets the requirements and to obtain a suitable and efficient aircraft. The concept of box wing to the commercial aircraft is fairly new and development for a risk free box wing aircraft requires capital and time. However, a box wing configuration is advantageous over conventional designs mainly due to the lowered induced drag and less fuel consumption. While the conventional aircraft configuration has achieved its maximum for air transport with its performance and efficiency, a good box wing aircraft configuration could raise it higher. A box wing is explained as a biplane with the presence of horizontal and vertical stagger and both wings connected at the wing tip by extended winglets.

Aircraft design can start with conceptual sketches. Conceptual sketches refer to the different possible configurations of the aircraft. Such sketches of configurations are produced in response to the mission requirements and airport planning. Conceptual sketches provide suitable configurations and indicate the feasibility and conduct of the aircraft, as per the requirements. This report concentrates on a systematic way to find all the possible conceptual sketches of configurations for the box wing aircraft. Study of possibility for feasible configurations is more about arrangement of different parts and is not quantifiable. This project applies Morphological Analysis and Cost Benefit Analysis to find the feasible box wing aircraft configurations for Airport 2030. Application of Morphological Analysis and Cost- Benefit Analysis signifies the merits and demerits of each configuration and help select the best configuration for the next step, the conceptual design.

Findings of this report provides better understanding of the requirements, understand all the drawbacks before entering into detailed design and help design an optimized box wing aircraft. Such an analysis could be adapted when the designer plans to design a non planar unconventional aircraft.

1.2 Objectives

This report opts to study the various possible box wing aircraft configurations that could be achieved, combining major aircraft components, from a systematic approach. To start such an analysis it is important to understand which components are of importance and define a box wing aircraft. In order to maintain the systematic approach it is important to provide logical combination of the aircraft components. The number of combinations obtained could be large and therefore rational way of elimination will be considered. Eliminations consist of logical arguments. The results obtained from the analysis matrix will be verified by cross checking with a cross consistency matrix. This forms a part of the morphological analysis. The configurations resulted from morphological analysis are then subjected to the Cost- Benefit Analysis. Cost- Benefit Analysis places a set of judging factors and configurations for each factor are scored. Finally, an optimized box wing configuration is expected. The scores assigned to different factors require expertise and consistent results. Such consistency in the score has to be verified with the support of reasonable arguments.

1.3 Methodology

The process starts with understanding the potential of the Morphological Analysis and Cost- Benefit Analysis. Study suggests that Morphological Analysis and Cost- Benefit Analysis, combined, synchronizes perfectly as it covers all the aspects and indicates the advantages and disadvantages of the configuration according to the project requirement.

Microsoft Office Excel is used to list all the components and their respective variants for the morphological analysis. Combinations obtained are visualized with the help of OpenVSP. OpenVSP acronym for Open Vehicle Sketch Pad is an open source software by NASA. The figures drawn are only to study the difference in the configurations and are not to scale.

Configurations from Morphological Analysis, visualized in OpenVSP, enter the Cost- Benefit Analysis. Factors set for Cost- Benefit Analysis and a score for each configuration as per the factors are derived from expert's suggestions. The results are tabulated in Microsoft Office Excel. The arguments for the analysis and Cost- Benefit Analysis are supported by the general theories found in all the references quoted.

1.4 Literature

To find the suitable methods and to construct a systematic way to analyze, evaluate and select the optimized box wing aircraft configuration, **Pahl Beitz 2007** was the most important source. **Pahl Beitz 2007** explains all the possible methods that could be applied to design a product. General Morphological Analysis and Cost- Benefit Analysis have been selected after studying all the methods presented in **Pahl Beitz 2007**.

General Morphological Analysis is studied in detail from **Swemorph 2013.** The report explains the main idea of General Morphological Analysis and the process how the method could be utilized to find a solution for non-quantifiable complex problems. Understanding collected from **Swemorph 2013** is implemented to structure the matrix to analyze and form box wing aircraft configurations.

Cost- Benefit Analysis followed after General Morphological Analysis has been selected to evaluate the potential configurations that have been obtained from General Morphological Analysis. The understanding of Cost- Benefit Analysis is mainly gathered from **Pahl Beitz 2007** and **Wikipedia 2013a**. It is then implemented for box wing aircraft configuration evaluation.

In addition to support all the logical reasoning during General Morphological Analysis and Cost-Benefit Analysis mainly **Raymer 1992**, **Sadraey 2013**, **Scholz 2009** and internet survey have been studied.

1.5 Structure of the Report

The report aims to find the most suitable box wing aircraft configuration. It is attempted to clarify the selection of the methods in order to reach the goal and application of the methods. The selection of the configuration is presented in steps.

Chapter 2 mainly studies the different methods that have been listed in **Pahl Beitz 2007** for a product design. All the methods are summarized in this chapter and it is explained why the General Morphological Analysis and Cost- Benefit Analysis have been selected. Suitability of the methods for this particular project has been presented. General Morphological Analysis and Cost- Benefit Analysis have been explained with examples and pros and cons for these methods have been discussed.

Chapter 3 presents the application of General Morphological Analysis to find and analyze the possible box wing aircraft configurations. However, the method has been modified with reasonable arguments to improve the analysis process. The combinations generated have been visualized with OpenVSP figures for better understanding. Feasible and potential configurations have been finalized for evaluation

Chapter 4 evaluates the final outcome from the General Morphological Analysis with Cost- Benefit Analysis. Logical arguments have been presented to support the scoring of the criteria as per the configurations. According to the scoring the most suitable box wing configuration has been selected. However, other potential configurations are also indicated apart from the best one.

2 General Morphological Analysis and Cost-Benefit Analysis

2.1 Selection of General Morphological Analysis and Cost-Benefit Analysis

As stated earlier, the primary intention, of this report is to find a systematic way to find all possible box wing aircraft configurations followed by evaluation and thus obtain the most suitable box wing configuration. This complete process could be divided into two parts:

Analysis – To find all the feasible box wing aircraft configurations from the combination of primary box wing aircraft components.

Evaluation – To evaluate all the configurations obtained from analysis and to select the best box wing aircraft configuration.

To complete the analysis, evaluation and selection it is necessary to find the systematic method/s suitable for the task. Such systematic approaches or methods for engineering design are well documented in **Pahl Beitz 2007**. **Pahl Beitz 2007** presents several analyses, evaluation and selection methods applicable to design a product. Table 2.1 and Figure 2.1 summarize all the analyses, evaluation and selections methods presented in **Pahl Beitz 2007**, respectively. The description provided for the methods are for general engineering design and not subjected to find box wing aircraft configurations. However, it could be imagined to apply different approaches listed in Table 2.1 and Figure 2.1 to find box wing configurations and check if it suits the problem statement for this project or not.

Table 2.1 Summarized explanation of the analysis and evaluation methods for design approach from **Pahl Beitz 2007**

Conventional Methods	**Information Gathering** Gather information about the particular product, system or process to be designed from various literature, publications, presentations of exhibitions and fair catalogues of competitors, patents. Knowledge from gathered information is used to solve and meet the project objective. **Analysis of Natural Systems** Study the biological system from nature that resembles the objectives of the desired projects. Such analogy between biology and technology helps to trigger creative design for the product. **Analysis of Existing Technical Systems** The method explains to study the similar product that exists, observe the modifications performed on the existing product and implement on the product/ system/ process under design. **Analogies** Study another system that is analogous to the design/ product to be designed. **Measurements and Model Tests** Build models and perform experiments to achieve the required data.

Intuitive Methods	**Brainstorming** A group of people is introduced to the objectives and each member is asked to present all the possible solutions each could conceive. Ideas are collected and reviewed within the group to reach the solution. **Method 635** Group of 6 members are asked to suggest 3 solutions. Solutions are passed to the other member and asked to introduce 3 modifications on the solutions. The process is continued until original set of solution of each member has been checked by other 5 members. **Gallery Method** Each member in a group suggests proposals with the help of sketches. All sketches are reviewed by the team for the conclusion. **Delphi Method** A group of experts suggests the starting point to solve the problem. All the suggestions are evaluated and planned after discussion. **Synectics** A group of members generates analogies comparable to the problem statement. Comparison helps generate new ideas. **Combination of Methods** Different methods combine to achieve the required goal which is sometimes not satisfactory from the application of a single method.
Discursive Methods	**Systematic Study of Physical Process** The problem is represented by the equation and the dependent variables are the numerical value of the physical factors that directly affects the solution. Each variable are varied in the experiment and its effect on the solution is recorded and evaluated. **Systematic Search with the help of Classification Schemes** A matrix of row and column is presented filled with the parameters used as classifying criteria. It is possible to present the classifying parameters only in rows if the columns cannot be arranged in order. Such display opens different possibilities for the combination solution. **Use of Design Catalogues** Design catalogues suggest already proven solutions and lists various design problems. It might cover physical effects, working principles, principle solutions, machine elements, standard parts, materials, bought out components, etc. Therefore, design catalogue could be used to match certain design problems and obtain a solution from the catalogue.
Methods for Combining Solutions	**Systematic combination (Morphological Analysis)** The system, product or process is broken down into its basic parameters or factors that build the design or combine all together to reach the solution, respectively. All the parameters are presented in the column and its different variants are listed along the respective column. From each parameter one variant has to be selected and thus combines to form the solution. Therefore it reveals all the possible solutions. **Combining with the help of Mathematical Methods** Uses mathematical models and computer to find the solution/s.

Amongst all the methods listed in Table 2.1, morphological analysis suits the problem statement, i.e, to find all the possible box wing aircraft configurations. Box wing aircraft configuration generation does not resemble any other design problem statement completely. Application of Morphological analysis starts not only by breaking down the problem into its basic components but also systematically combines to present all the possible configurations (including the unfeasible configurations). Use of other methods listed in Table 2.1 doesn't provide any systematic way to combine the parameters.

Figure 2.1 presents the comparison between VDI Guideline 2225 and Cost- Benefit Analysis method from **Pahl Beitz 2007.** These are the evaluation and selection methods listen in **Pahl Beitz 2007.**

Step		Cost–Benefit Analysis	VDI Guideline 2225
1	*Identification of objectives* or *evaluation criteria* for the evaluation of concept variants with the aid of the requirements list and a checklist	Construction of a hierarchically related system of design objectives (objectives tree) based on the requirements list and other general requirements	Compilation of important technical characteristics and also of the minimum demands and wishes of the requirements list
2	*Analysis of the evaluation criteria* for the purpose of determining their *weighting* to the overall value of the solution. If necessary, determination of weighting factors	Step-by-step weighting of the objective criteria (evaluation criteria) and if necessary elimination of unimportant criteria	Determination of weighting factors only if evaluation criteria differ markedly in importance
3	*Compilation of parameters* applicable to the concept variants	Construction of an objective parameter matrix	Not generally included
4	*Assessment of the parameter magnitudes* and assignment of values (0–10 or 0–4 points)	Construction of objective value matrix, with the help of a points system or value functions; 0–10 points	Assessment of characteristics by points (0–4 points)
5	*Determination of the overall value* of the individual concept variants, generally by reference to an ideal solution (rating)	Construction of a use-value matrix with due regard to the weightings; determination of overall values by summation	Determination of a technical rating by summation, with or without weightings based on an ideal solution. If necessary determination of an economic rating based on manufacturing costs
6	*Comparison of concept variants*	Comparison of overall use-values	Comparison of the technical and economic ratings. Construction of an s-(strength) diagram
7	*Estimation of evaluation uncertainties*	Estimation of objective parameter scatter and use–value distribution	Not explicitly included
8	*Search for weak spots* for the purpose of improving selected variants	Construction of use-value profiles	Identification of characteristics with a few points only

Figure 2.1 Summarization of individual steps for evaluation methods, Cost- Benefit Analysis and VDI Guideline 2225, and comparison in the steps (**Pahl Beitz 2007**)

For this project Cost- Benefit Analysis is chosen over VDI Guideline 2225. Cost- Benefit Analysis depends only on the weighting factor whereas VDI 2225 requires the construction of the s – (strength) diagram and determination of an economic rating based on the manufacturing costs. Also, Cost- Benefit Analysis could be performed in much simpler way whereas the VDI 225 has to follow the strict guidelines.

2.2 General Morphological Analysis

General Morphological Analysis (GMA) was developed by Fritz Zwicky, the Swiss astrophysicist and aerospace scientist based at the California Institute of Technology (Caltech). Fritz Zwicky explains morphological analysis as a method for structuring and investigating the total set of relationships contained in multi-dimensional, non-quantifiable problem complexes (**Swemorph 2013)**.

2.2.1 Introduction to General Morphological Analysis

Diegm 2013a states:

> *This method breaks down a system, product or process into its essential sub-concepts, each concept representing a dimension in a multi-dimensional matrix. Thus, every product is considered as a bundle of attributes. New ideas are found by searching the matrix for new combination of attributes that do not yet exist. It doesn't provide any specific guidelines for combining the parameters and tends to provide large number of ideas.*

Therefore, morphological analysis is suitable to work on problems which are non quantifiable and require judgmental or logical approach.

According to **Swemorph 2013**, GMA in more generalized form and with broader application identifies and investigates the total set of relationships or configurations in a given problem set.

GMA can be explained in a few steps (**Swemorph 2013**):

- Identify and define the parameters of the problem set to be investigated.
- Each parameter has variants and all the variants are listed under the respective parameters.
- A morphological box or multidimensional matrix is constructed which contains all the parameters and its relevant variants.
- One variant from each parameter is selected and thus combines to form a particular state or configuration of the problem set.
- Similarly other combination sets can be tried to generate other solutions or configurations.
- Product of all the variants from each parameter represents the total set of possible combinations.
- It is not necessary to have similar number of variants for each parameter.

Since there is no restriction in defining the number of parameters and its respective variants for the problem statement, the product of variants can be sometimes too large. Such a large number of solutions turns out to be very difficult to analyze and find out if all the possible combinations are valid or not.

Therefore to reduce the number of solutions and help select only the feasible one, cross consistency assessment is carried out. It is a part of morphological analysis. In cross consistency assessment, all the parameters and its variants are compared with each other, pair wise, and examined in a cross-impact matrix. Such cross check determines up to which extent the pair forms consistent relationship. Also, a computer program has been developed to carry out the reduction of the combination. (**Swemorph 2013**)

To explain GMA more clearly, an example is presented in steps (**Diegm 2013b**)

Step 1: To define the objective

Objective: To improve existing models of cars

Step 2: To list the number of parameters

Parameters:
- Improving element
- Optional equipment
- Internal processes
- Temporary properties

Step 3: Research all the possible solutions to the problem

IMPROVE EXISTING MODELS OF CARS				
	IMPROVING ELEMENTS	OPTIONAL EQUIPMENT	INTERNAL PROCESSES	TEMPORARY PROPERTIES
1	fuel consumption	ABS	automatic	powerful engine
2	breakdowns	air-conditioning	operator-controlled	perfect tyre
3	vibrations	heated seats	random	absence of dust
4	noise	CD player	continuous	cleanness
5	odor	Bluetooth technology	intermittent	new car smell

Figure 2.2 Possible variations for each parameter (**Diegm 2013b**)

Step 4: To select a set or a combination

Step 5: Morphological analysis; Combination:
- odor
- air-conditioning
- operator controlled
- new car smell

Result: Fragrance - control system for cars.
The numbers of possible combinations are 5*5*5*5 which is 625.

IMPROVE EXISTING MODELS OF CARS				
	IMPROVING ELEMENTS	OPTIONAL EQUIPMENT	INTERNAL PROCESSES	TEMPORARY PROPERTIES
1	fuel consumption	ABS	automatic	powerful engine
2	breakdowns	air-conditioning	operator-controlled	perfect tyre
3	vibrations	heated seats	random	absence of dust
4	noise	CD player	continuous	cleanness
5	odor	Bluetooth technology	intermittent	new car smell

Figure 2.3 Variables selected for combination marked in circle (**Diegm 2013b**)

2.2.2 Advantages and Disadvantages of General Morphological Analysis

The advantages of morphological analysis can be discussed as follows (**Diegm 2013a**):

- It has a structured approach and provides all the configurations/ possibilities. New configurations are also discovered which might have been overlooked or never considered.
- Extremes or boundaries are more clearly detected/ displayed and opened for investigation.
- It also has definite advantages for scientific communication and notably for group work.
- Several parameters can be used and yet a clear result is obtained.
- The method is a systematic analysis and also is a way to identify key gaps.

The disadvantages of morphological analysis can be discussed as follows (**Diegm 2013a**):

- One apprehension that has been voiced against morphological analysis is that it is too structured and that this could inhibit free, creative thinking.
- Morphological analysis results in too many possibilities as there are no specific guidelines for making combinations. Human judgments are still needed to direct the outcome.
- Human error- the development of morphological boxes requires critical judgment. If the underlining thought processes are not insightful, the outcomes of this method will be weak.

2.3 Cost- Benefit Analysis

The Cost- Benefit Analysis is also known as Nutzwertanalyse (German), point value method, scoring methods or scoring model and was introduced in the mid-1970s by Zangemeister and Bechmann (**Wikipedia 2013a)**.

2.3.1 Introduction to Cost- Benefit Analysis

Cost- Benefit Analysis can be simply explained as

> *Method that assigns points based on known information to predict an unknown future outcome (**Scoring 2013**)*

To evaluate and select the best box wing configuration, simple Cost- Benefit Analysis will be used. In this simple analysis, the evaluation criteria are placed on x- axis and the configuration/s or problem complexes to be evaluated are placed on y- axis. This forms the evaluation matrix. The problem complex is then scored according to the criteria. This is mainly done with expertise. The difference in points could be according to the decision maker's priority or logical reasoning. Now each criterion for every configuration is analyzed and each configuration as per the criteria is awarded with a weighting factor. The weighting factor is multiplied with the respective point for that particular criterion. This is the final score of that configuration for that criterion. (**Wikipedia 2013a**)

To have a better understanding of simple Cost- Benefit Analysis, an example is presented (**Wikipedia 2013a**).

Step 1:
Decide the scale for the weighting factor. It depends entirely on the decision maker.

- for **"bad"** points **0-2** ,
- for "**medium**" points **3-5**
- for **"good"** points **6-8**
- for "**very good**" points **9**

Step 2:
Set the Table presenting the criteria (x- axis). For this example the evaluation criteria are evaluated for "fulfillment degree candidates". "Fulfillment degree candidates" column is assigned scores as per the criteria. Weighting factor are assigned in another as per decision maker's priority for the criteria or logical reasoning. Product of score in fulfillment degree candidate- problem complex and weighting factor is the final result. The criteria scoring the highest score, i.e. 72- relationship network, is the optimal solution.

Criterion	Fulfillment degree candidates	Weighting	Results / quality
Expertise	5	× weighting factor 9	45
Experience	7	Weighting factor of 6 ×	42
Training readiness	3	× 8 weighting factor	24
Spatial mobility	2	Weighting factor of 7 ×	14
Time flexibility	3	Weighting factor of 5 ×	15
Relationship network	8	× weighting factor 9	72
Leadership	4	Weighting factor of 4 ×	16
Presentation skills	4	Weighting factor of 7 ×	28
Credentials	3	Weighting factor of 4 ×	12
Sympathy	7	Weighting factor of 6 ×	42

Figure 2.4 Simple Cost- Benefit Analysis matrix (**Wikipedia 2013a**)

2.3.2 Advantages and Disadvantages of Cost- Benefit Analysis Method

The advantages and disadvantages of Cost- Benefit Analysis are discussed in this section.

Advantages (**Wikipedia 2013a**)

- Flexibility of the target system
- Adaptation to a large number of special needs
- Direct comparison of each alternative
- Comparable is ensured through common selection criteria

Disadvantages (**Wikipedia 2013a**)

- Comparability of the alternatives because it cannot always be guaranteed that two alternatives are compared in the same respect.
- Problem of agreement when multiple decision makers are available with different preferences
- Problem in the selection of criteria/ weighting factors.

3 Application of General Morphological Analysis to Generate Feasible Box Wing Aircraft Configurations

3.1 Identification of the Parameters for Box Wing Aircraft Configuration Analysis

This report mainly aims to find the most potential box wing aircraft configuration for commercial jet transport. A configuration can be defined as an arrangement of elements or parts in a particular form, figure, combination or shape (**Answers 2013**). Different configurations of box wing aircraft are generated when the basic box wing aircraft components are arranged in different ways. Thus to generate feasible configurations, basic components have to be systematically combined in different arrangements.

A box wing aircraft can be broken down into its basic components like: Fuselage, box wing, vertical stabilizer, horizontal stabilizer, engine, landing gear. Figure 3.1 shows the basic components that combine to form the box wing aircraft. It is aimed to introduce variety in configurations and therefore it has to be scrutinized as to which component offers variations and which do not.

Box wing design is a detailed design and it is the different wing stagger and sweep that combine to generate different shapes of box wings. Wing sweep and stagger are always incorporated in the wing and thus considered as the basic parameters (dimensions) for the analysis. Wing vertical position also contributes to form different configurations.

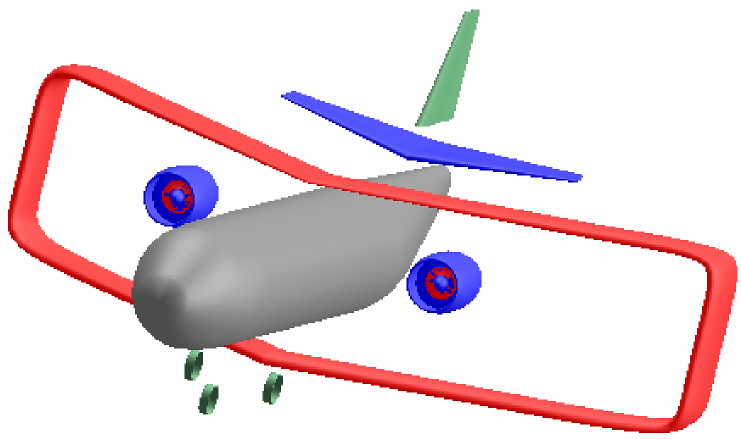


Figure 3.1 Disconnected basic box wing aircraft components

Fuselage is considered constant for all configurations since there is not much variation in fuselage for commercial aircraft. Also, tricycle landing gear is considered for all different configurations to be obtained from analysis. Tricycle landing gear is the most widely used landing gear configuration and could be found frequently equipped in general jet transport aircraft (**Sadraey 2013**). For engine, it is the engine location that is of interest and not the type when it comes to configuration analysis.

Therefore, given that the fuselage and landing gear is fixed, the basic parameters considered for configuration analysis are: wing stagger, wing sweep, wing vertical position, horizontal stabilizer, vertical stabilizer and engine location.

3.2 To Generate Variations in the Parameters Selected for Analysis

The next step in morphological analysis is to define all the discrete conditions or possible variations for each parameter. Variations are mainly the characteristics of these selected parameters that contribute to form different configurations. It is beneficial because it reduces the possibility to miss any valuable option as it lists down all the options.

Following questions help to generate variations for the parameters:

- What are the sweep type and different stagger for a box wing?
- What are the possible wing vertical positions?
- What are the different horizontal tail positions along the fuselage when viewed from top?
- What are the different vertical tail positions and types that could be incorporated in the configuration?
- What are the possible engine positions?

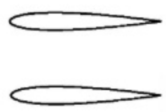
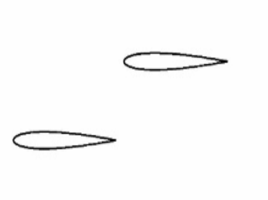
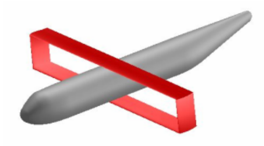
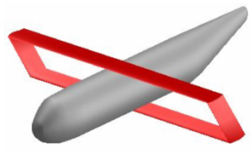
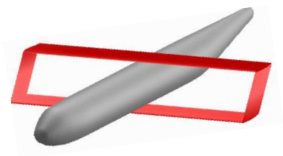
3.2.1 Variations of Wing Stagger

Different possibilities for wing stagger, in case of box wing are (**Wikipedia 2013b**):

- Unstaggered – When both wing are positioned directly above each other
- Positive stagger – When the upper wing is placed forward to the lower wing
- Negative stagger – When the upper wing is placed behind the lower wing

Table 3.1 shows only the box wing with different stagger with reference to the fuselage. The third row presents abbreviations which are created to easily represent the wing stagger variations. Such abbreviations are used to represent other variations for other parameters as well. This is mainly because it is easier to use the symbols rather than the figures for the analysis later where the repetitions for the figures are several times.

Table 3.1 Box wing with unstaggered, positive stagger and negative stagger

	Unstaggered	Positive stagger	Negative stagger
Sketche of side view			
OpenVSP 3-D figure			
Abbreviation	=	‾_	_‾

3.2.2 Variations of Wing Sweep

Different sweep types (**Wikipedia 2013c**) that could be addressed in box wing are:

- No sweep
- Positive sweep
- Negative sweep
- Positive and negative sweep

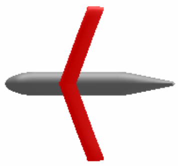
Nevertheless, it is reasonable to eliminate the “no sweep” option since the commercial jet aims to fly at sufficiently high Mach number and requires sweep. So, swept wing benefits over “no sweep” wing because it makes the aircraft capable of flying at high Mach number as actual relative air speed is at an angle to the wing leading surface and therefore the air component perpendicular to the wing leading edge is less, and hence the wing senses less speed than actual. Thus, the aircraft can fly to high Mach number (**Huenecke 1987**).

Therefore, the different sweep types that could be addressed to box wing are:

- Positive sweep
- Negative sweep
- Positive and negative sweep

Table 3.2 helps in visualizing the wing sweep type in box wing configurations.

Table 3.2 Box wing with no sweep, positive sweep, negative sweep and positive and negative sweep.

	Backward sweep	Forward sweep	Forward and Backward sweep
OpenVSP top view figure			
Abbreviation	<<	>>	< >

The top views presented in the table indicate the box wing where both the wings are parallel and on top of each other. It is more concentrated to show the different sweep type. In case of forward and backward sweep, in Table 3.2 it is shown that the top wing is forward swept and bottom wing is backward swept. However, it is possible to have the opposite condition, i.e., top wing – backward swept, and bottom wing – forward swept. It will be later discussed which sweep type should the wings have in case of forward and backward swept box wing.

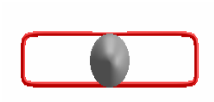
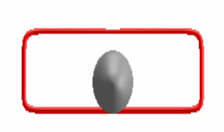
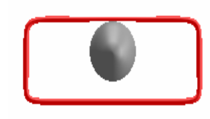
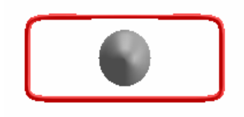
3.2.3 Variations of Wing Vertical Position

Wing vertical position when viewed from front, locates the wing position with reference to the fuselage. Since the box wing has two wings, it is required to mention the vertical positions of both the wings. The different wing vertical positions possible for box wing are:

- Low – High position
- Low – Super high position
- Super low – High position
- Super low – Super high position

Table 3.3 shows the front view of all the different wing vertical position

Table 3.3 Box wing with different wing vertical position

	Low – High Position	Low – Super High Position	Super Low – High Position	Super Low – Super High Position
OpenVSP front view figure				
Abbreviation	L – H	L – SH	SL – H	SL – SH

As stated earlier, such variation study helps present all the options. However, the possible box wing vertical positions demonstrated in Table 3.3 could be investigated further and the very extreme and improbable options could be eliminated before entering the table into the morphological analysis matrix. It is only sensible to investigate because some solutions clearly illustrate more disadvantages than any benefit.

Super low – super high and Super low – high positions are unlikely features. Though, Super low – super high position has a significant vertical gap and therefore reduces induced drag greatly, the demerits exceed the benefit. In case of Super low – high position, one could argue it is a similar solution as Low – super high position. However, it does not achieve any additional advantage than Low – super high position and serves more disadvantages. Therefore, from all box wing vertical positions it is reasonable to eliminate Super low – High and Super low – Super high positions. The explanations to support the elimination are either logical or cited from **Sadraey 2013**. They are:

- This can be visualized as a combination of parasol and inverse parasol. That means the wings are held by struts from above and below the fuselage. Presence of struts is the increase of wetted area of the aircraft, thus more parasite drag is the result.
- Aircraft structure is heavier when struts are employed. This causes empty weight to be heavy.
- Since the fuselage will be held higher from ground than usual, the nose gear length will be longer and therefore becomes heavy. Aircraft structure again becomes heavier in this case.
- Long nose gear will consume more space in the fuselage when in retracted position. To compromise space for both nose gear and payload or cargo, the designer might consider stretching the fuselage thus increasing the wetted area, parasite drag and weight.
- High fuselage is highly unsuitable for loading and unloading of cargo.
- Ground handling is a major factor that might add a stop to this configuration. All the ground-handling vehicles of airports are of standard height and size which are compatible with the aircraft size. Such a configuration leads to change the entire ground handling plan and vehicles. Such a big change involves enormous investment of capital and so not feasible. It is thus extremely unlikely.
- Maintenance is very difficult as the wing and fuselage is held in such a high position.
- Since the drag and weight increases, more fuel consumption increases and so does the operating cost.

The points addressed above are similar for the Super Low – high position also. Therefore, these two positions are eliminated from the design solution.

Low – high and Low – super high are the two box wing vertical positions selected for further analysis.

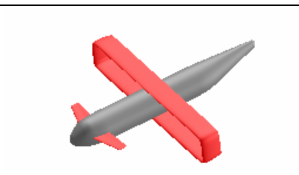
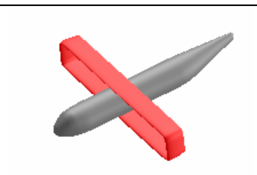
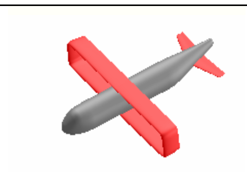
3.2.4 Variations of Horizontal Tail Position along the Fuselage Length

Horizontal tail or surface planform involves detailed design. However, the position of the horizontal tail along the fuselage generates different configurations. Therefore, the possible variations are:

- Horizontal surface at the front – canard
- Horizontal surface at the rear – horizontal tail
- Presence of no horizontal surface

Table 3.4 presents the figures and symbols for different horizontal surface positions along the fuselage length.

Table 3.4 Horizontal tail surface position along the fuselage length

	Canard	No Horizontal tail	Horizontal surface
OpenVSP 3-D figure			
Abbreviation	Can	No	Aft

3.2.5 Variations of Vertical Tail Positions and Type

In case of the vertical stabilizer, its location along the fuselage length, similar to horizontal length, is not considered because it is destabilizing as it moves towards the nose along the fuselage length, when viewed from top (**Scholz 2009**). Vertical tail at the aft is the only suitable solution. For the analysis matrix it is only the vertical stabilizer position, i.e., the aft position will be considered for simplicity. However, variations in types of aft vertical stabilizer could be studied. Once the best configuration is selected, different tail types, finalized tail type from this section, could be fitted to the configuration to help conceptual design better.

Vertical tail type in this case is mainly investigated as per number of vertical surfaces and more concentrated only on the vertical surface and not the horizontal surface. Different types of vertical tail are investigated mainly from **Raymer 1992** and categorized as per the number of vertical surfaces. They are:

Single surface combines with horizontal surface mainly to form:

- Conventional Tail

- Cruciform Tail
- T – Tail

Double surface vertical tails are:

- V – Tail
- Inverted V – Tail
- H – Tail
- Twin Tail

With triple surface, different vertical tails are:

- Triple Tail
- Y – Tail

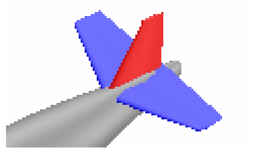
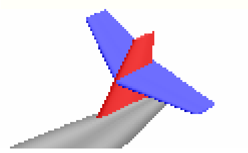
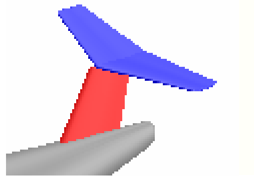
Unconventional vertical tail:

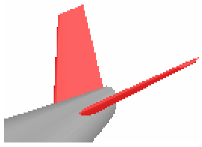
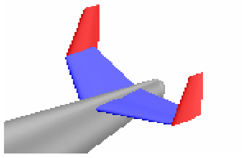
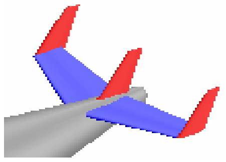
- Ring tail

Amongst all the vertical tail configurations listed above, Inverted V – Tail and Y – Tail are eliminated because it is not a convenient feature for commercial jet while take-off. Both inverted V – Tail and Y – Tail have surfaces below the fuselage cone and it would hit the ground during take-off unless the surface below the fuselage cone is reasonably small or the fuselage cone is at a significantly high angle. Also, ring tail is eliminated because it is only an unconventional design and it has no aerodynamic advantage (**EAA 2013**).

Therefore, as stated before, only considering vertical tail position at the fuselage aft, these are the different vertical tail types possible (Table 3.5). It is only the vertical tail position, i.e. fuselage aft, will be presented in the morphological analysis matrix.

Table 3.5 Different vertical tail types possible at the fuselage aft

Number of Surfaces	Tail Type	OpenVSP figure
Single Surface Vertical Stabilizer	Conventional Tail	
	Cruciform Tail	
	T- Tail	

Double Surface Vertical Stabilizer	V - Tail	
	H - Tail	
	Twin Tail	
Triple Surface Vertical Stabilizer	Triple Tail	

3.2.6 Variations of Engine Position

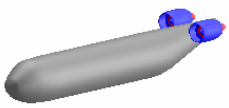
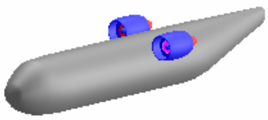
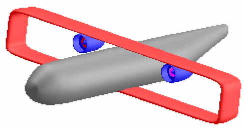
For box wing aircraft configuration, three engine positions are considered to be well suited and basic. In later stages of design, detailed design could be introduced in these suggested positions. The considered engine positions are:

- Fuselage aft
- Fuselage middle
- On the wing

Fuselage front is out of option since it is near the cockpit and first class, it is noisier and is not preferred (**Scholz 2009**). Also it obstructs the view for the first class passengers. For the engine position on the wing it is considered that only the top wing supports the engine.

Table 3.6 demonstrates the possible engine positions

Table 3.6 Engine positions for box wing aircraft

	Fuselage Aft	Fuselage Middle	On the wing
OpenVSP 3-D figure			
Abbreviation	Fuse - aft	Fuse - mid	Wing

With the discussion of variation of engine positions the study of parameter variation ends. Next step is to form the analysis matrix with all the parameters, and its respective variants, and discuss the combinations.

3.3 Formation and Modification of Morphological Analysis Matrices

The parameters, and its respective variations, discussed in Chapter 3.2 will be presented in an analysis matrix in this chapter. The parameters will be presented in a row and its variations in the respective columns. The variations in the columns will be presented with abbreviations, introduced in Chapter 3.2. Table 3.7 presents the morphological analysis matrix with all the basic parameters for a basic box wing aircraft. The variations of parameters are listed in abbreviations. For the descriptions of the abbreviations it is suggested to refer to Chapter 3.2.

Table 3.7 Morphological Analysis Matrix created in Microsoft Excel

Stagger	Sweep	Box Wing Vertical Position	Horizontal Stabilizer Position	Vertical Stabilizer Position	Engine Position
=	<<	L – H	Can	Aft	Fuse – aft
–_	>>	L – SH	No		Fuse – mid
_–	< >		Aft		Wing

To form a particular box wing aircraft configuration it is necessary to select one variation from each parameter and combine the variations.

For an example, a combination of Negative Stagger (_–), Backward and forward sweep (< >), Low – high position (L – H), Aft horizontal stabilizer position (Aft), Aft vertical tail position (Aft) and Engines located at the middle of the fuselage (Fuse – mid) will form a box wing aircraft as shown in Figure 3.2.

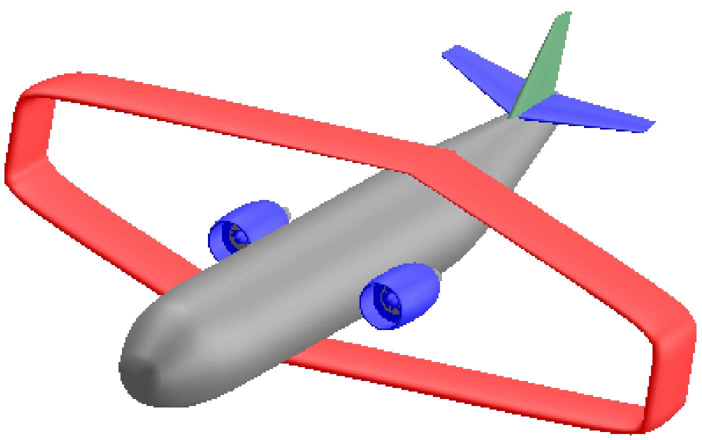


Figure 3.2 Configuration generated from combination of randomly selected variations and visualized in OpenVSP

Therefore, the total number of combinations that could be achieved from this analysis matrix (see Table 3.7) is: 3*3*2*3*1*3 = 162. These 162 combinations are 162 feasible box wing aircraft configurations. Without prior elimination in Chapter 3.2.3 and 3.2.5 the respective number would be even as high as: 3*3*4*3*7*3 = 2268. This number is clearly too high and down selection would become unnecessary complicated.

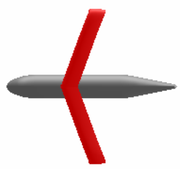
Though General Morphological Analysis presents all the possible solutions there is no specific guideline on how to combine the parameters or choose the variation from each parameter systematically to form the configurations. It is necessary for this particular report that all the possible combinations are visualized. So, such random selection may cause overlap in outcome. Also, since it is aimed to find the best configurations, a systematic way of combining the parameters reveals the incompatible combinations at the early stages. To combine the variations in a logical fashion a systematic way of few steps has been developed which is suitable for this project. Even 162 configurations are quite a large number of configurations and to generate each configuration it is necessary to find a systematic way to combine the parameters. For such systematic combinations, steps are developed which are suitable to get the box wing aircraft configurations.

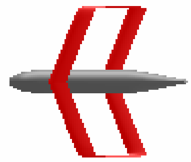
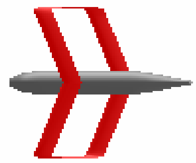
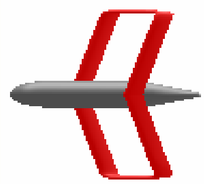
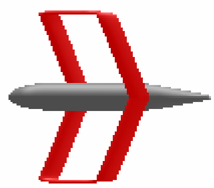
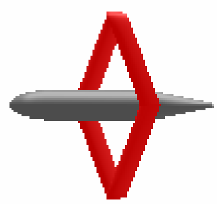
Usually cross consistency or the computer program will be the next step to eliminate the unwanted solution. As mentioned before in Chapter 2.2, in cross consistency every parameter is cross checked with each other to find if each variation of a particular parameter is compatible with another or not.

The point made here in this report is that it is advantages to combine in a systematic way only what works instead of producing many combination with difficult to comprehend down selection afterwards. For systematic combination it is the sequence of logical parameter combinations which is of importance. In case of the box wing, stagger, sweep and vertical location combine to define the wing; vertical stabilizer and horizontal stabilizer combine to form the empennage; and the engine position completes the basic box wing aircraft configuration. If different parameters (like: stagger and horizontal stabilizer) are combined, the process is inefficient as the combinations are inconsistent and thus results in complications after a few steps. A sequence on combinations that seemed to work well for the box wing is:

Step 1:
Combination of stagger and sweep parameters. For each stagger wing sweep is varied and Table 3.8 shows the top view of the outcome.

Table 3.8 Outcome from the combination of Stagger and Sweep

Stagger	Sweep	Outcome	OpenVSP Figure	Remark
=	<<	= and <<		**Selected**

=	>>	= and >>		**Selected**
=	< >	= and < >		Eliminated
–_	<<	–_ and <<		Eliminated
–_	>>	–_ and >>		Eliminated
–_	< >	–_ and < >		**Selected**
_–	<<	_– and <<		Eliminated
_–	>>	_– and >>		Eliminated
_–	< >	_– and < >		**Selected**

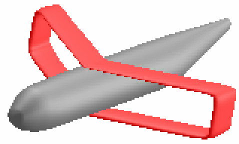
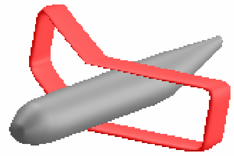
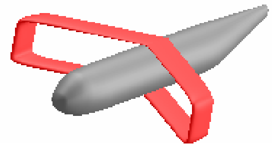
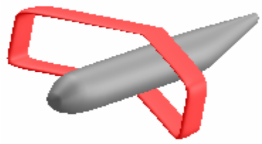
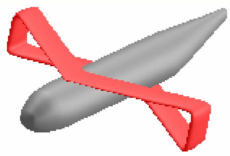
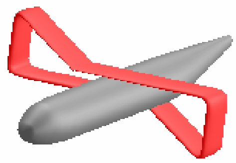
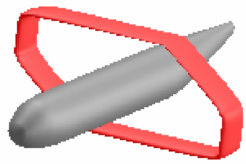
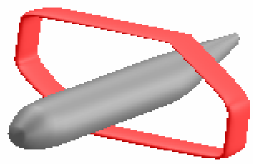
From the outcome of stagger and sweep, 5 combinations are eliminated. This is mainly because the combinations result in long winglets. Combinations selected have optimum winglets. Of course the winglets could be adjusted according to the design requirements. However, the eliminated combinations will always result in long winglets which in turn will result in more parasite drag and structural weight. If the sweep is in the same direction, it does not make sense to stagger, because it takes more space away from ground handling. Stagger should also not only be introduced to achieve longitudinal control without a tail, because introducing a tail causes less trouble and is not too bad on additional drag. It should also be noted that in case of the combinations '–_ and < >' the upper wing and the lower wing always has to be backward swept and forward swept, respectively. For combination '_– ' and '< >' the upper wing and lower wing always have to be forward swept and backward swept, respectively. OpenVSP figures for these two combinations can be seen in Table 3.8. Therefore the selected combination for stagger and sweep are listed in Table 3.9 and marked in boldface in Table 3.8.

Table 3.9 Selected combination for stagger and sweep

Stagger	Sweep	Selected Outcome
=	<<	= and <<
=	>>	= and >>
–_	< >	–_ and < >
_–	< >	_– and < >

Step 2: Combining the selected outcome of Stagger and Sweep (from Table 3.9) to Box Wing Vertical Location. Table 3.10 presents the outcome.

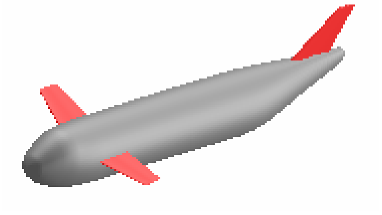
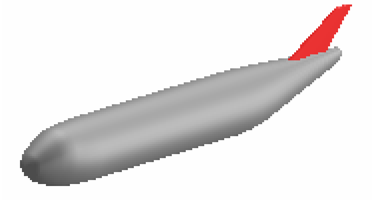
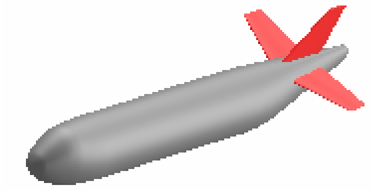
Table 3.10 Outcome from the combination of the stagger and sweep, and box wing vertical position

Stagger and Sweep	Box Wing Vertical Position	Outcome	OpenVSP figures
= and <<	L- H	=, << and L-H	
= and <<	L-SH	=, << and L-SH	
= and >>	L- H	=, >> and L-H	
= and >>	L-SH	=, >> and L- SH	
–_ and < >	L- H	–_ , < > and L-H	
–_ and < >	L-SH	–_ , < > and L-SH	
_– and < >	L- H	_– , < > and L-H	
_– and < >	L-SH	_– , < > and L-SH	

All the eight combinations are selected. In case of Low – Super high position, the upper wing could be held either by struts or by the vertical stabilizer. In the figures on Table 3.10, for the combinations with Low – Super high the gap is kept blank and not filled by struts or vertical stabilizer.

Step 3:
In Steps 1 and 2 the combination of the parameters defined the possible box wing type. Now, combination of Horizontal stabilizer position and Vertical tail position results in the formation of the type of empennage or indicates the control surface positions. Table 3.11 presents the outcome. The vertical stabilizer in the figures from Table 3.11, to indicate the position, is indicated with a single surface to form the basic configuration. However, it will be explained later once the most suitable configuration is selected, how the different types of vertical stabilizer could be fitted.

Table 3.11 Outcome from the combination of horizontal and vertical stabilizer

Horizontal Stabilizer Position	Vertical Stabilizer Position	Outcome	OpenVSP Figure
Can	Aft	Can - Aft	
No	Aft	No - Aft	
Aft	Aft	Aft - Aft	

Step 4:
In this step, the outcome from Tables 3.10 and 3.11 will be combined. This results in the most basic box wing aircraft configurations without the engine.

Table 3.12 Outcome from the combination of Stagger, Sweep, Box Wing Vertical position, Horizontal Stabilizer Position and Vertical Stabilizer Position.

Stagger, Sweep and Box Wing Vertical Position	Horizontal and Vertical Stabilizer Position	Outcome	Figure No
=, << and L-H	Can - Aft	=, <<, L-H and Can - Aft	Figure 3.3
=, << and L-H	No - Aft	=, <<, L-H and No - Aft	Figure 3.4
=, << and L-H	Aft - Aft	=, <<, L-H and Aft - Aft	Figure 3.5
=, << and L-SH	Can - Aft	=, <<, L-SH and Can - Aft	Figure 3.6
=, << and L-SH	No - Aft	=, <<, L-SH and No - Aft	Figure 3.7
=, << and L-SH	Aft - Aft	=, <<, L-SH and Aft - Aft	Figure 3.8
=, >> and L-H	Can - Aft	=, >>, L-H and Can - Aft	Figure 3.9
=, >> and L-H	No - Aft	=, >>, L-H and No - Aft	Figure 3.10
=, >> and L-H	Aft - Aft	=, >>, L-H and Aft - Aft	Figure 3.11
=, >> and L- SH	Can - Aft	=, >>, L-SH and Can - Aft	Figure 3.12
=, >> and L- SH	No - Aft	=, >>, L-SH and No - Aft	Figure 3.13
=, >> and L- SH	Aft - Aft	=, >>, L-SH and Aft - Aft	Figure 3.14
–_ , < > and L-H	Can - Aft	–_ , < >, L-H and Can- Aft	Figure 3.15
–_ , < > and L-H	No - Aft	–_ , < >, L-H and No- Aft	Figure 3.16
–_ , < > and L-H	Aft - Aft	–_ , < >, L-H and Aft- Aft	Figure 3.17
–_ , < > and L-SH	Can - Aft	–_ , < >, L-SH and Can- Aft	Figure 3.18
–_ , < > and L-SH	No - Aft	–_ , < >, L-SH and No- Aft	Figure 3.19
–_ , < > and L-SH	Aft - Aft	–_ , < >, L-SH and Aft- Aft	Figure 3.20
_– , < > and L-H	Can - Aft	_– , < >, L-H and Can- Aft	Figure 3.21
_– , < > and L-H	No - Aft	_– , < >, L-H and No- Aft	Figure 3.22
_– , < > and L-H	Aft - Aft	_– , < >, L-H and Aft- Aft	Figure 3.23
_– , < > and L-SH	Can - Aft	_– , < >, L-SH and Can- Aft	Figure 3.24
_– , < > and L-SH	No - Aft	_– , < >, L-SH and No- Aft	Figure 3.25
_– , < > and L-SH	Aft - Aft	_– , < >, L-SH and Aft- Aft	Figure 3.26

Table 3.12 presents the outcome from the combination of Stagger, Sweep, Box Wing Vertical position, Horizontal Stabilizer Position and Vertical Stabilizer Position.

The total number of outcomes is 24. All the outcomes are visualized in OpenVSP and the figures as per the combination are presented from Figure 3.3 to Figure 3.26. The figures present the very basic configurations. The horizontal tail and vertical tail geometry and shape could be obtained in detailed design. Note that equal sweep (<< or >>) and no horizontal tail only works, because for the vertical tail a V-tail can be chosen in detail design. Longitudinal stability from the wing alone is not intended.

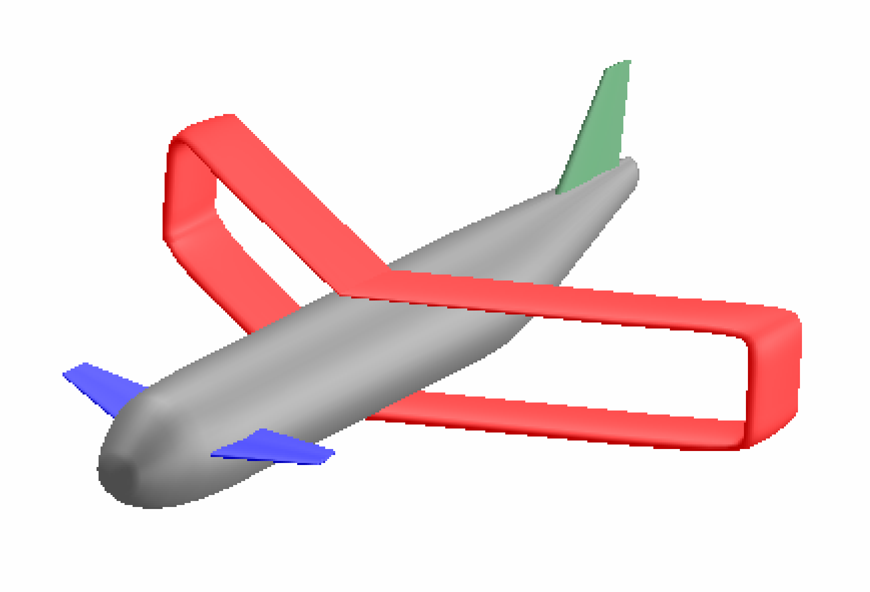


Figure 3.3 "**=, <<, L-H and Can – Aft**" Box wing aircraft configuration

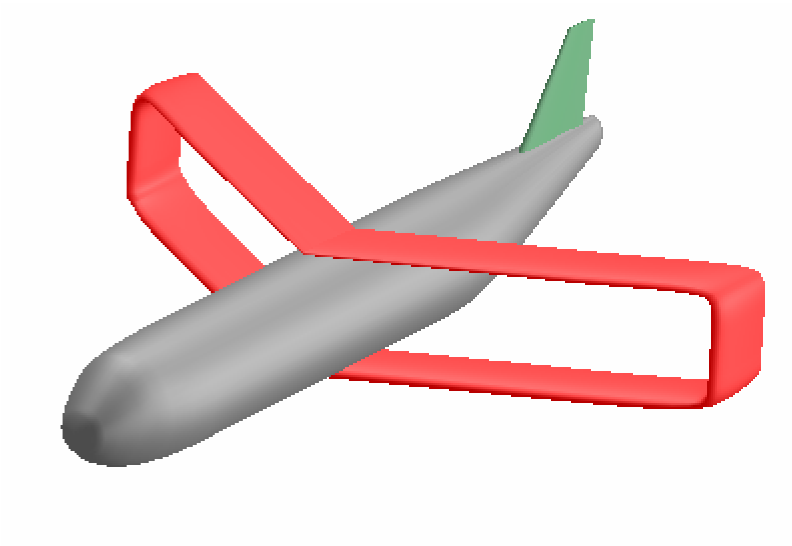


Figure 3.4 "**=, <<, L-H and No – Aft"** Box wing aircraft configuration

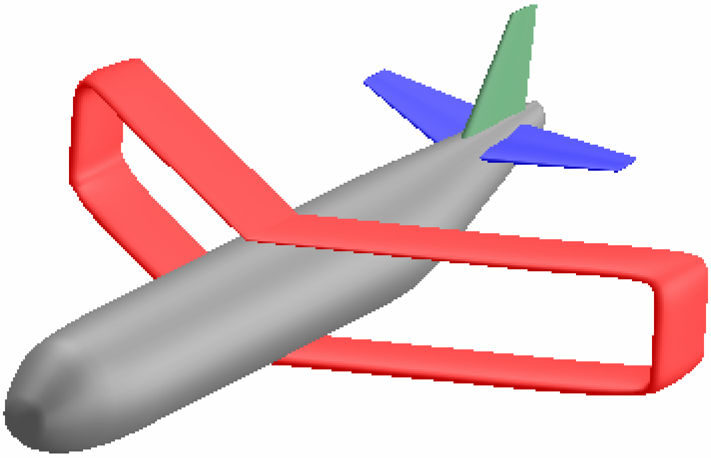


Figure 3.5 “**=, <<, L-H and Aft - Aft**” Box wing aircraft configuration

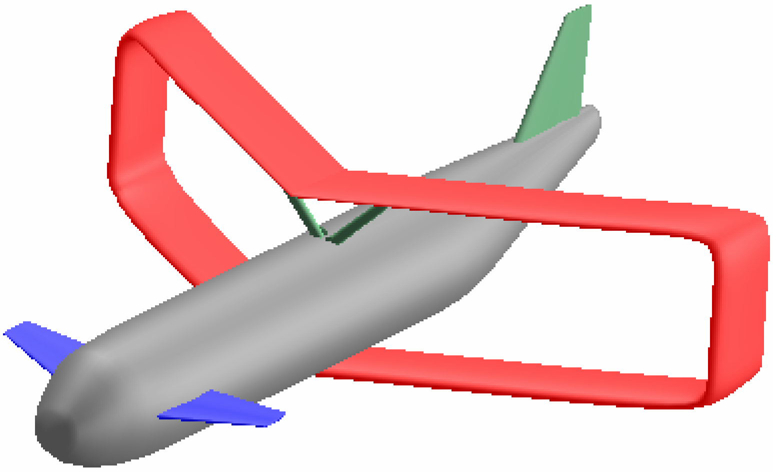


Figure 3.6 “**=, <<, L-SH and Can – Aft**” Box wing aircraft configuration

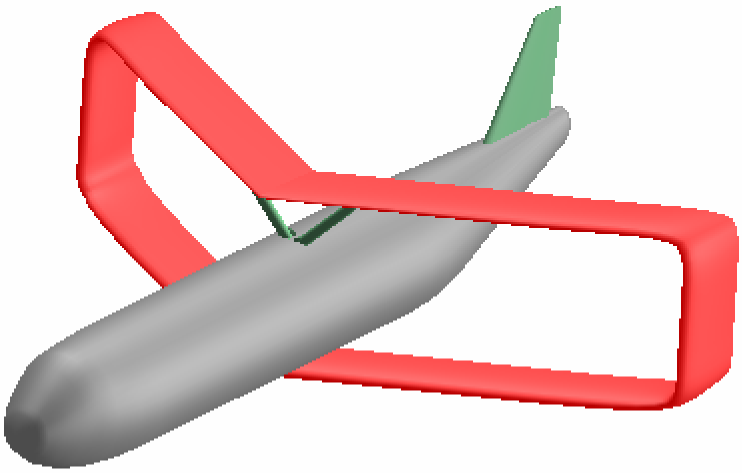


Figure 3.7 “**=, <<, L-SH and No – Aft**” Box wing aircraft configuration

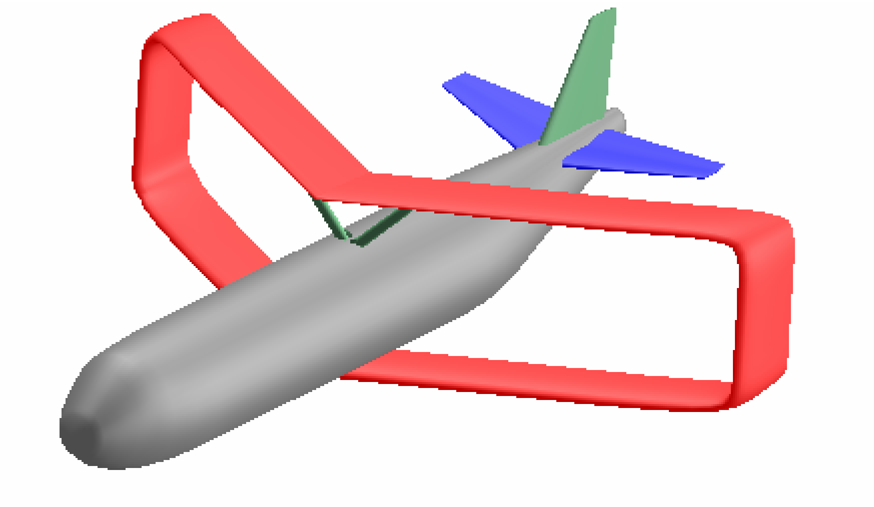


Figure 3.10 "**=, <<, L-SH and Aft – Aft**" Box wing aircraft configuration

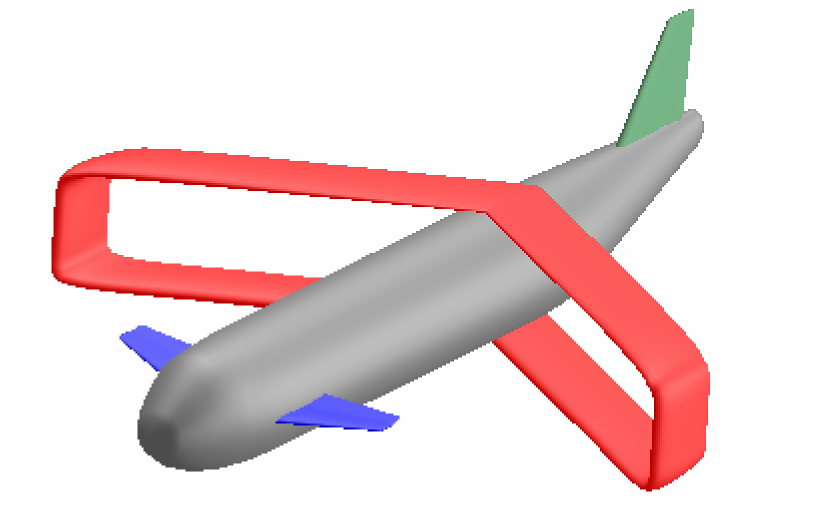


Figure 3.11 "**=, >>, L-H and Can – Aft**" Box wing aircraft configuration

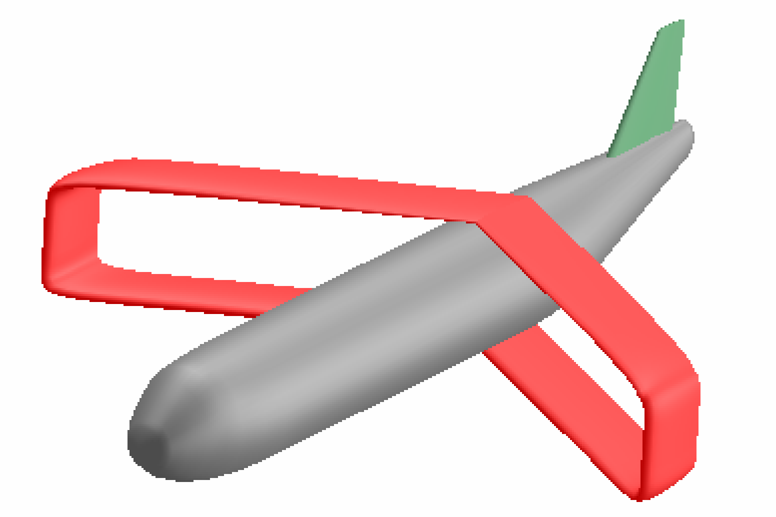


Figure 3.12 "**=, >>, L-H and No – Aft**" Box wing aircraft configuration

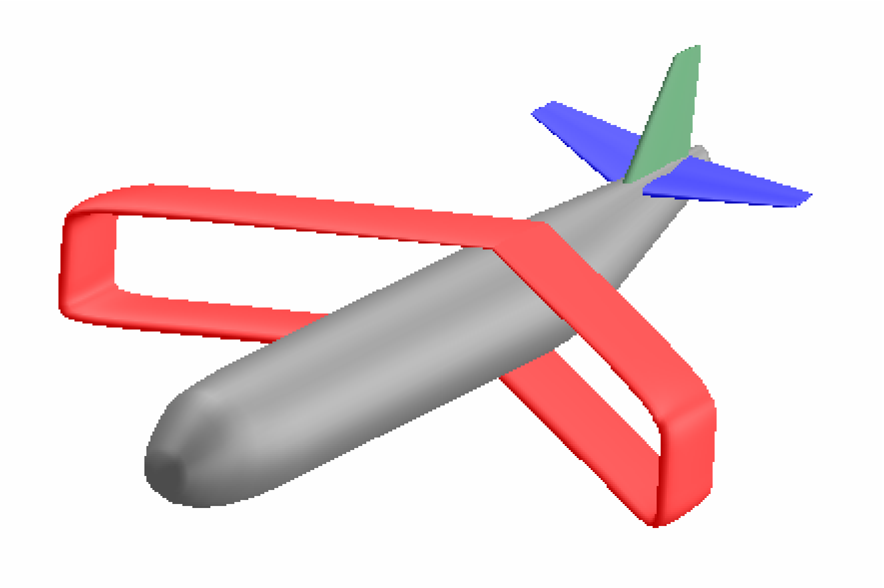


Figure 3.13 “**=, >>, L-H and Aft – Aft**” Box wing aircraft configuration

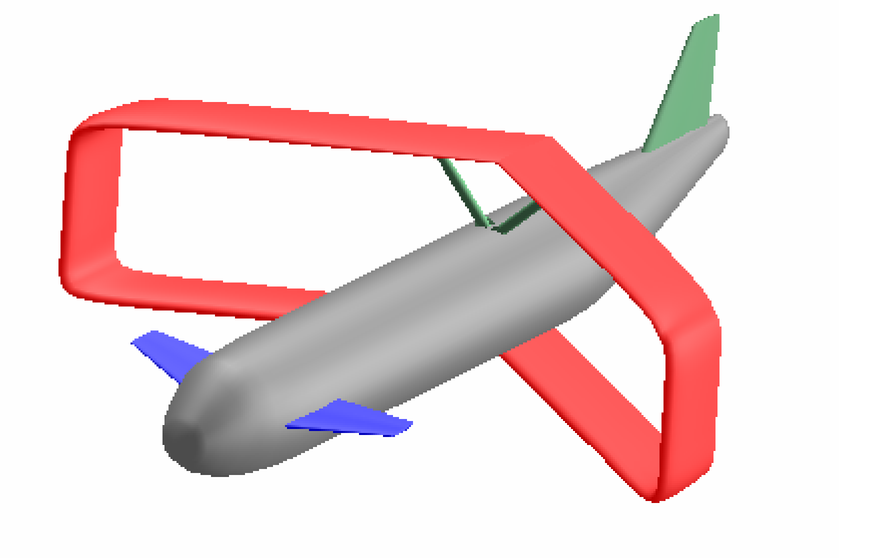


Figure 3.14 “**=, >>, L-SH and Can – Aft**” Box wing aircraft configuration

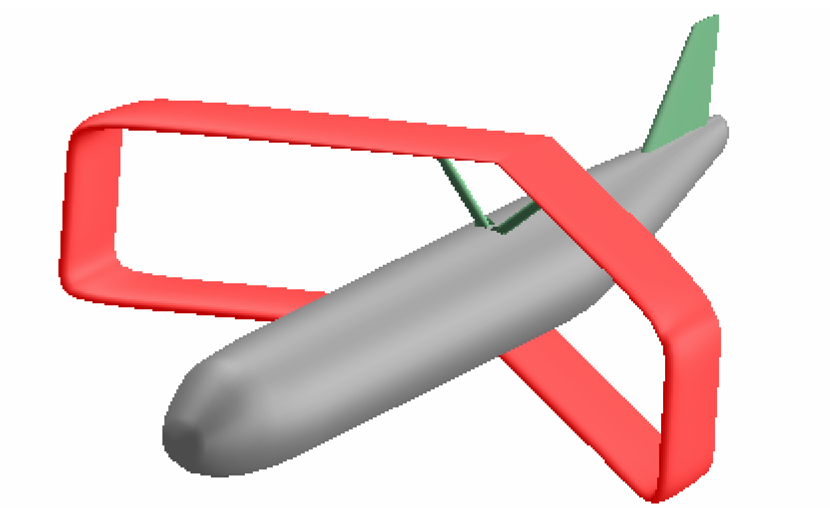


Figure 3.15 “**=, >>, L-SH and No – Aft**” Box wing aircraft configuration

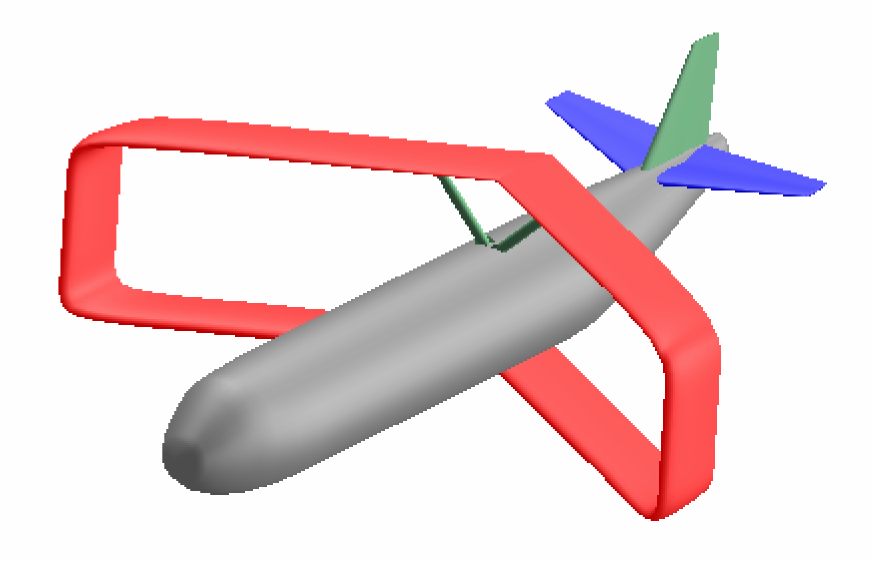


Figure 3.16 “**=, >>, L-SH and Aft – Aft**” Box wing aircraft configuration

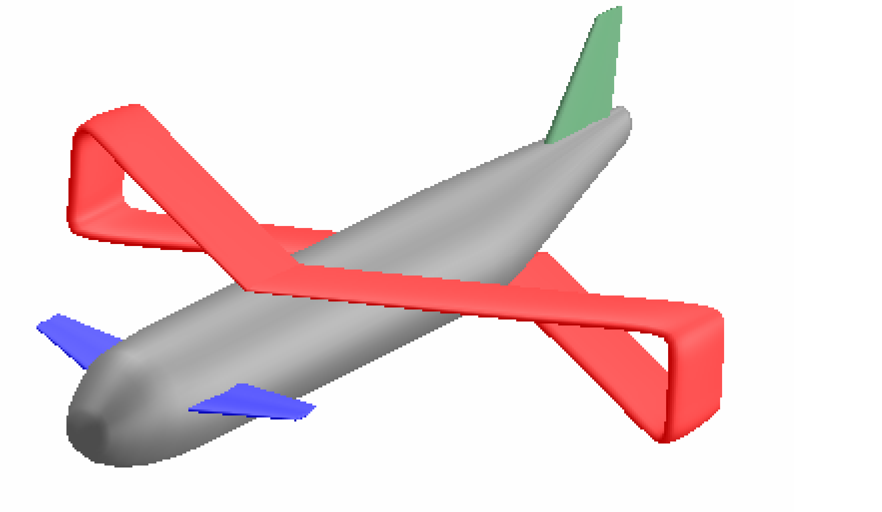


Figure 3.17 “**–_ , < >, L-H and Can- Aft**” Box wing aircraft configuration

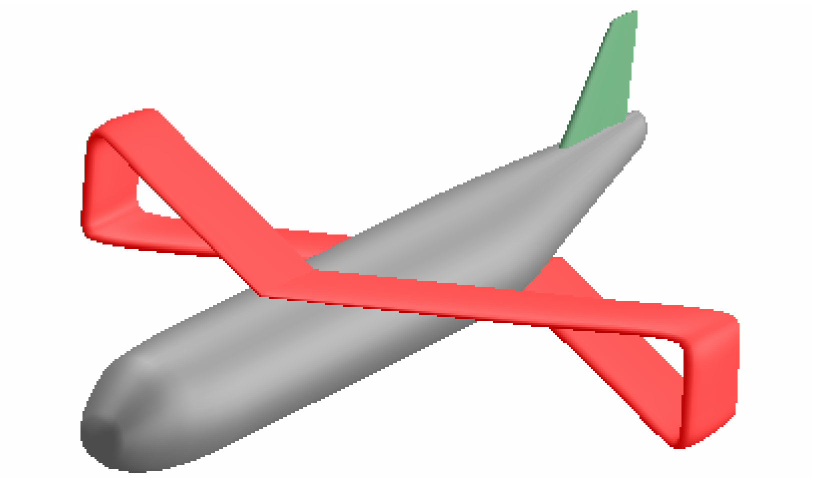


Figure 3.18 “**–_ , < >, L-H and No- Aft**” Box wing aircraft configuration

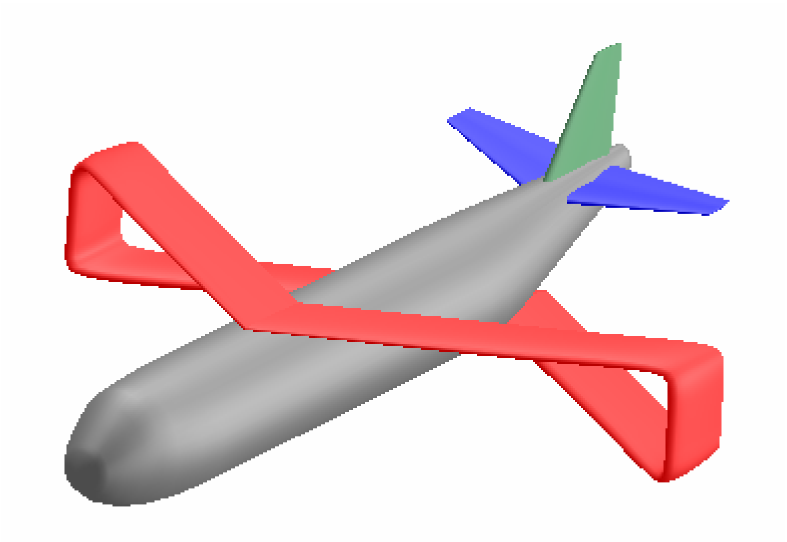


Figure 3.19 "**–_ , < >, L-H and Aft- Aft**" Box wing aircraft configuration

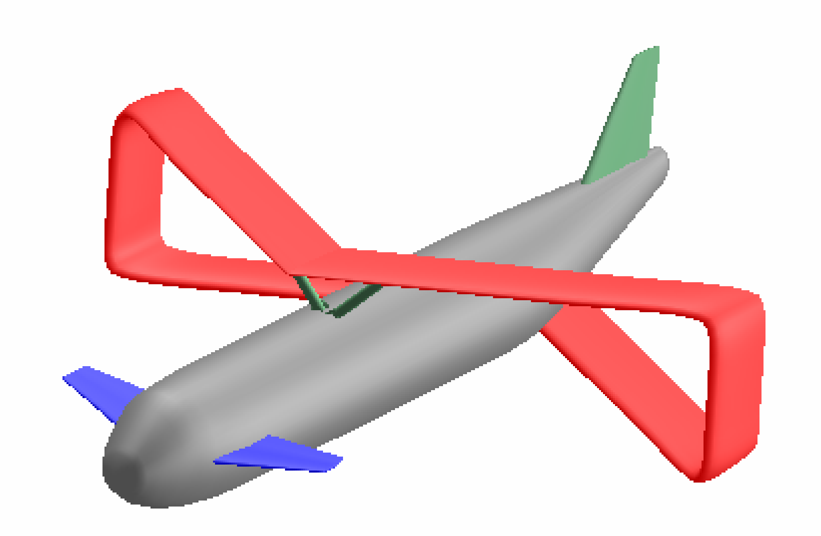


Figure 3.20 "**–_ , < >, L-SH and Can- Aft**" Box wing aircraft configuration

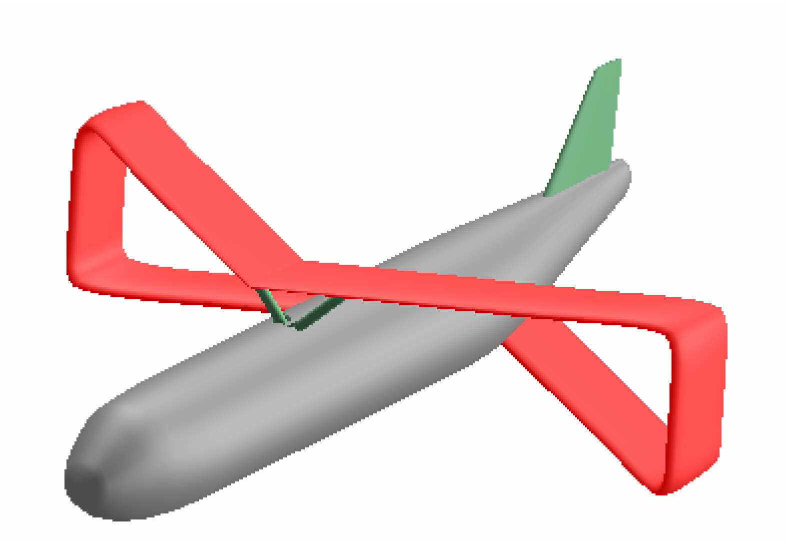


Figure 3.21 "**–_ , < >, L-SH and No- Aft**" Box wing aircraft configuration

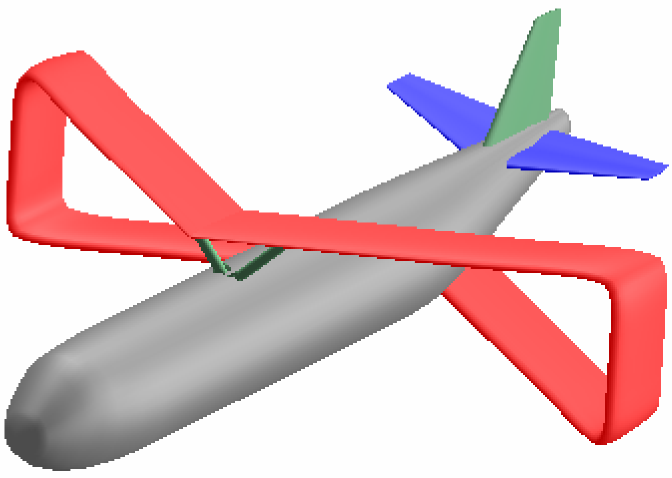


Figure 3.22 “**–_ , < >, L-SH and Aft- Aft**” Box wing aircraft configuration

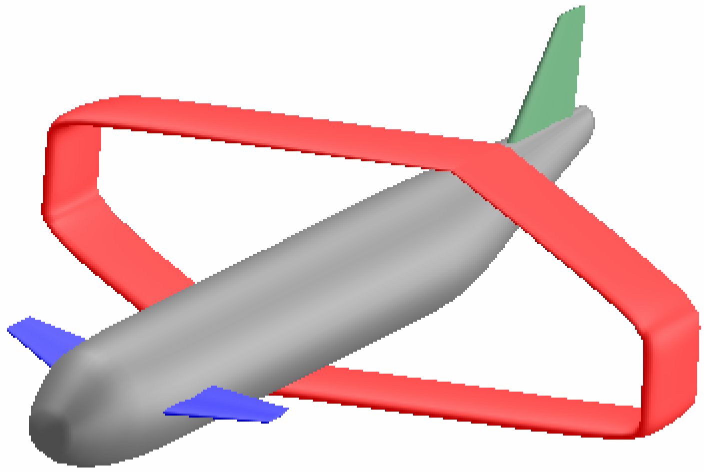


Figure 3.23 “**_– , < >, L-H and Can- Aft**” Box wing aircraft configuration

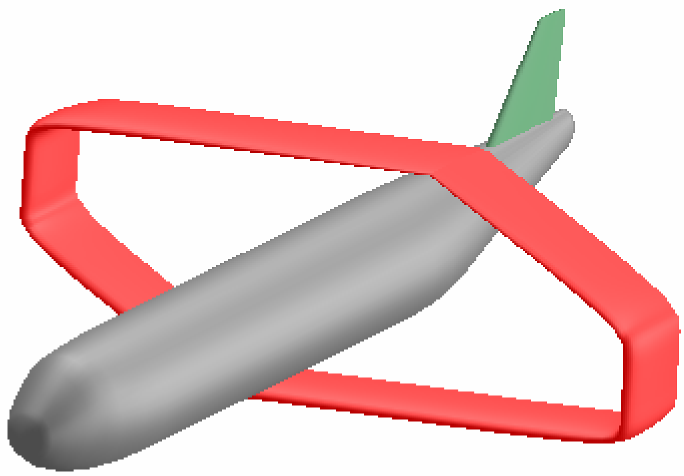


Figure 3.24 “**_– , < >, L-H and No- Aft**” Box wing aircraft configuration

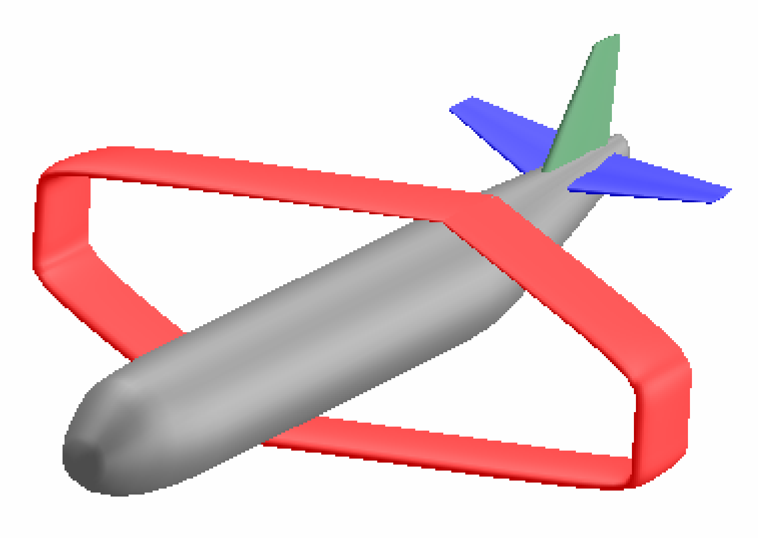


Figure 3.25 **“_– , < >, L-H and No- Aft”** Box wing aircraft configuration

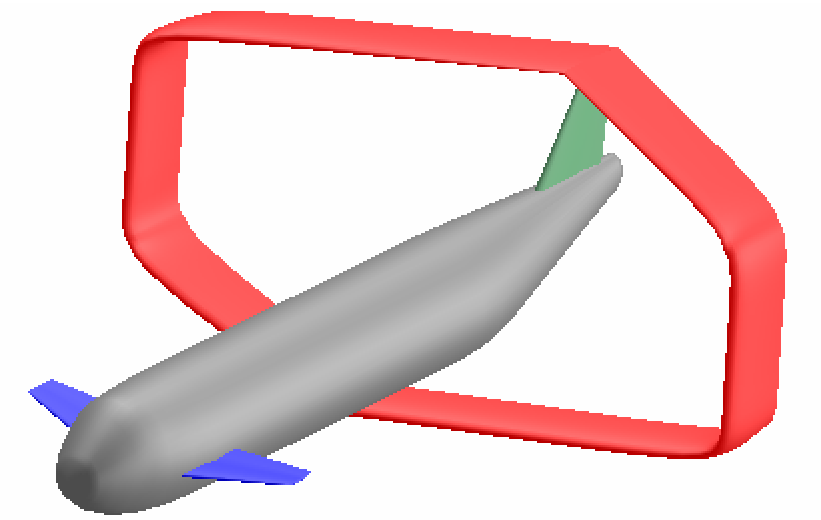


Figure 3.26 **“_– , < >, L-SH and Can- Aft”** Box wing aircraft configuration

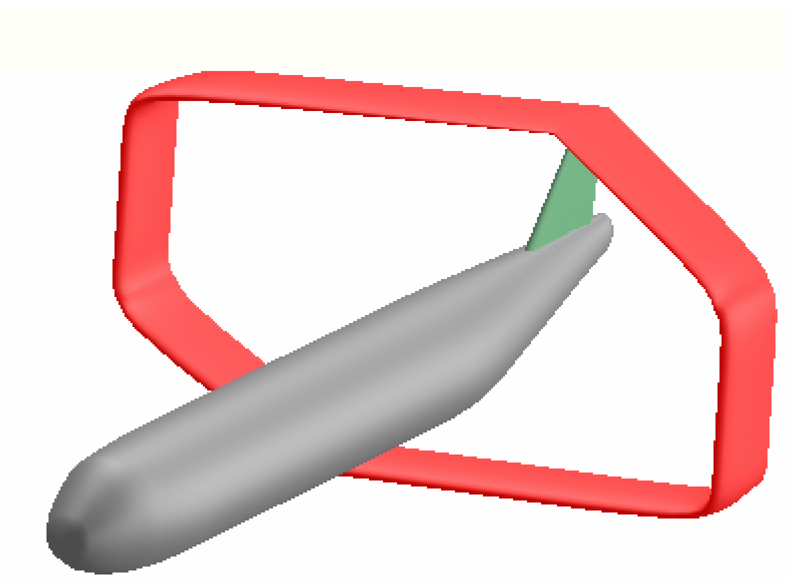


Figure 3.27 **“_– , < >, L-SH and No- Aft”** Box wing aircraft configuration

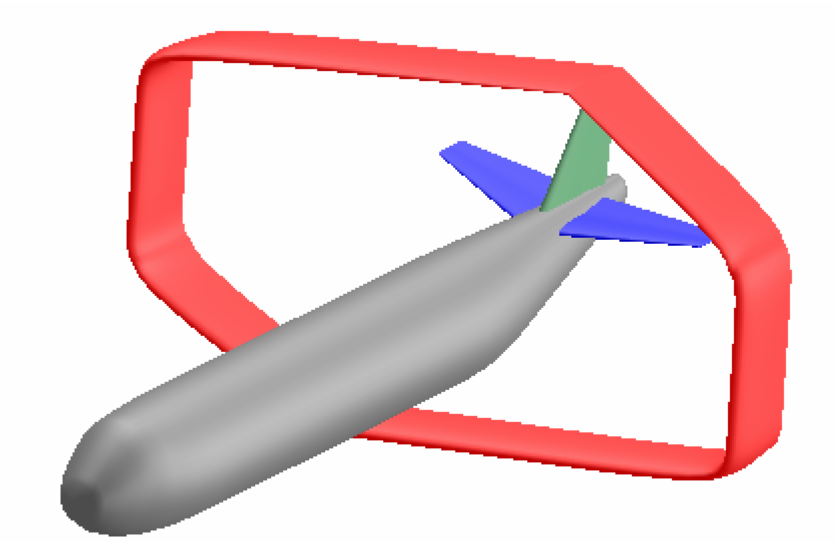


Figure 3.28 "**_– , < >, L-SH and Aft- Aft**" Box wing aircraft configuration

Step 5: Final selection of configurations.

The number of combinations from Table 3.12 is still a little high for evaluation. The figures illustrating Table 3.12 show that configurations containing both wings forward swept may be eliminated. The arguments for having both wings forward swept are basically the same as having one wing forward swept and history was in favor of the aft swept wing. Forward swept wings have advantages in terms of maneuverability and stall (stalls at the wing base and thus delays wing stall) (**Wikipedia 2013d**). The advantages from forward swept wing could be of importance mainly for combat aircraft. The disadvantages associated with forward swept wing are (**Desktop 2013**):

- Aeroelastic divergence or additional wing mass penalty to avoid it
- Lower effective dihedral
- Lower yaw stability
- Bad for winglets
- Large pitching moment coefficient with flaps
- Reduced pitch stability due to additional lift and fuselage interference

For configurations containing both backward and forward sweep, '< >', the disadvantages could be compensated up to some point with the one backward swept wing.

The final configurations obtained from General Morphological Analysis are listed in Table 3.13. The total number of configurations selected from General Morphological Analysis is 18. All these 18 configurations will be now subjected to Cost- Benefit Analysis and the elimination with Morphological analysis ends. With Cost- Benefit Analysis the configurations will be studied a bit more with specific parameters and thus the best configurations can be obtained.

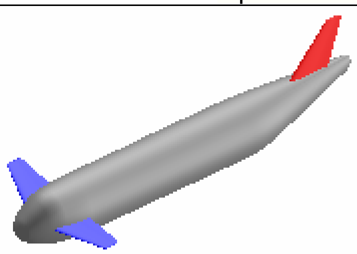
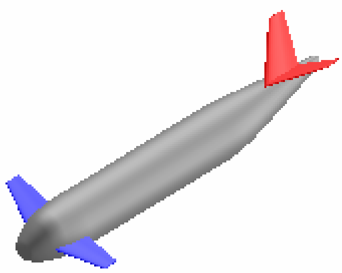
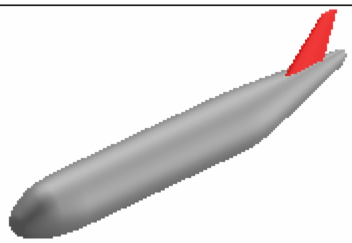
Before proceeding to Cost- Benefit Analysis, it is intended to explain the possible combinations for horizontal stabilizer position and vertical stabilizer type. Table 3.13 presents the different vertical stabilizer type that could be incorporated with different horizontal stabilizer positions. After the final configuration is selected, the possible control surface types (outcome from Table 3.13) and different engine locations (Table 3.6) will be equipped with the final configuration to present it for detailed design.

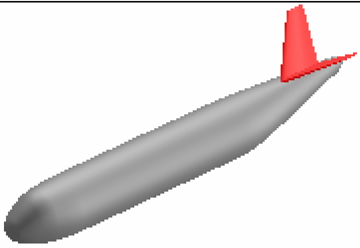
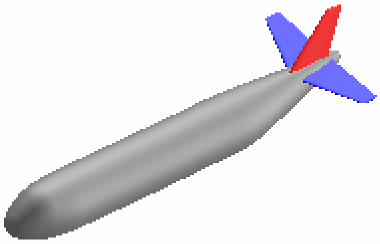
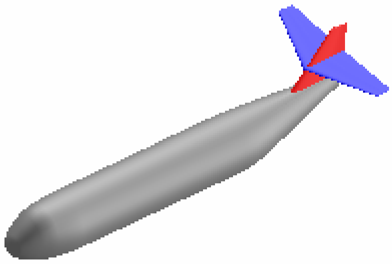
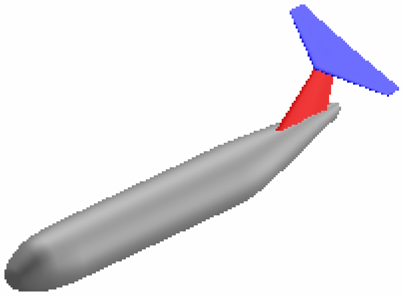
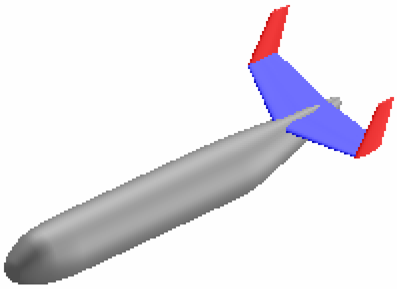
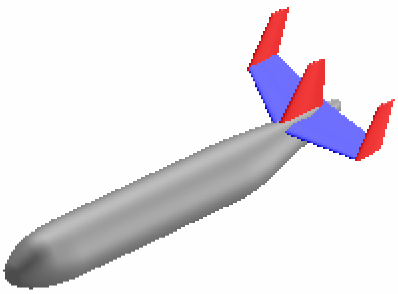
Table 3.13 Final basic box wing aircraft (without engine) configurations obtained from General Morphological Analysis

=, <<, L-H and Can - Aft
=, <<, L-H and No - Aft
=, <<, L-H and Aft - Aft
=, <<, L-SH and Can - Aft
=, <<, L-SH and No - Aft
=, <<, L-SH and Aft - Aft
–_ , < >, L-H and Can- Aft
–_ , < >, L-H and No- Aft
–_ , < >, L-H and Aft- Aft
–_ , < >, L-SH and Can- Aft
–_ , < >, L-SH and No- Aft
–_ , < >, L-SH and Aft- Aft
_– , < >, L-H and Can- Aft
_– , < >, L-H and No- Aft
_– , < >, L-H and Aft- Aft
_– , < >, L-SH and Can- Aft
_– , < >, L-SH and No- Aft
_– , < >, L-SH and Aft- Aft

Not all the horizontal stabilizer positions can combine with all vertical stabilizer types. Canard can only combine with single aft vertical surface, V- tail and Twin tail. No horizontal stabilizer can combine with single aft vertical surface, V- tail and Twin tail. Aft horizontal stabilizer can combine with single aft vertical surface to form conventional tail, T- tail, cruciform, H- tail and triple tail.

Table 3.14 Outcome from combination of Horizontal Stabilizer Position and different Vertical Stabilizer Type

Outcome	OpenVSP Figure
Can- Single surface vertical stabilizer	
Can- V- Tail	
No- Single surface vertical Stabilizer	

No- V Tail	
Conventional Tail	
Cruciform Tail	
T- Tail	
H - Tail	
Triple Tail	

4 Application of Cost- Benefit Analysis on the Configurations Selected from General Morphological Analysis

4.1 Criteria Set for Cost- Benefit Analysis

The criteria to be considered for Cost- Benefit Analysis have to cover all the general aspects before the design could be set for the manufacturing and production stages. When evaluated, the configurations based on these criteria, help to indicate the possibility to get the design accepted for detailed design and production.

The major criteria considered for evaluation are:

- Configuration
- Drag
- Weight
- Flight Mechanics
- Operation
- Development

Table 4.1 Sub criteria from major criteria for Cost- Benefit Analysis

Major Criteria	Sub Criteria
Configuration	Better horizontal Stabilizer Position Force Fighting Destabilizing Forward Struts Family Concept
Drag	Zero Lift Drag/ Parasite Drag Induced Drag
Weight	Empty Weight
Flight Mechanics	Mainly Longitudinal Stability and CG Range
Operation	Ground Handling
Development	Development Time and Cost Risk

These major criteria are broken down into sub criteria and finalized for the evaluation. This is mainly done to obtain better and understandable evaluation. The breakdown of major criteria to sub criteria are presented in Table 4.1

Therefore, the total number of evaluation criteria is 11. In this case all the sub criteria/ factors for evaluation are assigned equal amount of weighting factor. It is mainly because all the listed sub criteria are equally important to determine the potential of the configurations. So the determining factor will be the points that will be assigned by an expert or a group of people or with logical reasoning to all the configurations according to the sub criteria.

4.2 Cost- Benefit Analysis Evaluation Matrix and Selection of Box Wing Aircraft Configuration

As explained in Chapter 2.3, the criteria are set in the columns and the problem complex or configurations obtained from the morphological analysis are set in rows. As per the criteria, each configuration will be scored. The score in this case is decided based on logical explanation. The scale of the score is set as such:

Score “0” – Bad
Score “1” – Average
Score “2” – Good

Figure 4.1 presents the Cost- Benefit Analysis evaluation matrix. The highest score achievable in theory is 11*2 = 22. The highest score that was obtained is 19. Two configurations have achieved this score: “=, <<, L – H, Aft – Aft” and “=, <<, L – H, No – Aft” (with V-tail). Finally, box wing aircraft configuration “=, <<, L – H, Aft – Aft” is considered to be the best because “=, <<, L – H, No – Aft” configuration the V-tail seems not to be an overall optimum as aviation history seems to indicate. V-tails cause greater stress on the rear fuselage when pitching or yawing (**Wikipedia 2013e**). Second highest score is 17 and there are again two configurations that scored 17. They are: “=, <<, L – SH, Aft – Aft” and “=, <<, L – SH, No – Aft”. Configuration “=, <<, L – SH, Aft – Aft” is more suited for the second position because of the tail arrangement, as explained for the winner (avoidance of V-tail). The lowest point scored is 8 and by “–_, < >, L-SH, Can-Aft”. The winner is a box wing aircraft that is almost similar to a conventional aircraft design that results to be the suitable design configuration. However, when opted for unconventional configuration “_–, < >, L-SH, No-Aft” results to be the best option with a score of 14.

It is essential to discuss the classification of the criteria according to the scoring scale. It is suggested to refer to Figure 4.1 along with reading the discussions to get a better understanding.

In “configuration”, for “better horizontal stabilizer position” the aft horizontal stabilizer is considered to be better than the canard and the canard is better than no horizontal stabilizer. Therefore configurations to be evaluated which have aft horizontal stabilizer, canard and no horizontal stabilizer are scored with 2, 1 and 0, respectively.

Long Fuselage _–,< >,L-H, Aft-Aft	Long Fuselage _–,< >,L-H, Can-Aft	_–,< >,L-H, No-Aft	Long Fuselage _–,< >,L-SH, Aft- Aft	Long Fuselage _–,< >,L-SH, Can-Aft	_–,< >,L-SH, No-Aft
2	1	1	2	1	1
1	2	2	1	2	2
2	2	2	2	2	2
1	1	1	1	1	1
1	1	2	0	1	2
1	1	1	2	2	2
1	1	2	0	0	2
2	1	0	2	1	0
0	0	0	0	0	0
1	0	1	1	0	1
1	1	1	1	1	1
13	11	13	12	11	14

=,<<,L-SH, Can-Aft	V-Tail =,<<,L-SH, No-Aft	Long Fuselage −_ ,< >,L-H, Aft-Aft	Long Fuselage −_,< >,L-H, Can-Aft	−_ ,< >,L-H, No-Aft	Long Fuselage −_,< >,L-SH,Aft-Aft	Long Fuselage −_,< >,L-SH, Can-Aft	−_ ,< >,L-SH, No-Aft
1	1	2	1	1	2	1	1
2	2	1	2	2	1	2	2
1	1	2	2	2	0	0	0
2	2	1	1	1	1	1	1
0	1	1	1	2	0	0	1
2	2	1	1	1	2	2	2
0	1	1	1	2	0	0	1
0	1	2	1	0	2	1	0
1	2	0	0	0	0	0	0
1	2	1	0	1	1	0	1
1	2	1	1	1	1	1	1
11	17	13	11	13	10	8	10

				V-Tail	
		=,<<,L-H, Aft-Aft	=,<<,L-H, Can-Aft	=,<<,L-H, No-Aft	=,<<,L-SH,Aft-Aft
Configuration	Better Horizontal Stabilizer Position	2	1	1	2
	Force Fighting	2	2	2	2
	Destabalizing Forward Struts	2	2	2	1
	Family Concept	2	2	2	2
Drag	Zero Lift Drag/ Parasite drag	1	1	2	0
	Induced Drag	1	1	1	2
Weight	Weight	1	1	2	0
Flight Mechanics	Mainly Longitudinal stability and CG range	2	0	1	2
Operation	Ground handling	2	1	2	2
Development	Development Time and Cost	2	1	2	2
	Risk	2	1	2	2
	total	19	13	19	17

Figure 4.2 Cost Benefit Analysis Matrix

"Force fighting" occurs maximum where the box wing, when swept and staggered, is close enough to the horizontal stabilizer. No configuration has been awarded zero since there is always some amount of force fighting involved. Force fighting is mainly the interaction of the force generated by the wing (lift) and the horizontal stabilizer to maintain the balance (downward force). Force fighting occurs if there is no lever arm between wing and tail (or only a very short lever arm).

Struts are used to support the upper wing in super high position. Such a case is noticed in the parallel box wing and when the box wing has upper wing backward sweep. So, the more the struts move forward toward the fuselage nose, the more destabilizing it is. So box wing with upper wing in super high position receives score of "0", parallel box wing and no stagger with super high scores "1" and the box wing with high position or in case of super high when held with vertical stabilizer receives score "2".

"Family Concept" is easier for conventional aircraft design. In this case the box wing aircraft with parallel wings and no stagger are much easier for family concept rather than the staggered and swept box wing. Staggered box wing combined with sweep results in unconventional configurations. Therefore, it is more difficult to achieve. No configuration is scored "0" because family concept is possible to achieve in all 18 configurations.

For all the configurations "Zero Lift Drag/ Parasite Drag" definitely exists. The amount of zero lift drag in this case is thought to be indicated with the number of surfaces. This is mainly to get the easy and simple logical indication without any detailed calculation. The higher the number of surfaces, the higher the zero lift drag and the lower the score. The configurations with most number of surfaces get "0", less than that score "1" and the configurations with least number of surfaces score "2".

"Induced Drag" is reduced as the vertical gap within the box wing is increased. So the aircraft configurations with Low-Super high position score "2" and the configurations with Low – High position score "1". Score "0" is not assigned to any configurations since all the box wing configurations, when compared to single wing aircraft have a reduction of "Induced Drag".

"Empty Weight" is analogous to "Zero lift Drag" in this case because it is reasonable to consider that a high number of surfaces results in more weight and mass. Weight of the surfaces will add to the empty weight of the aircraft. Hence, the higher the number of surfaces, the higher is the "Empty Weight" and the less is the score.

"Longitudinal Stability and CG range" in case of configurations with parallel and unstaggered wings is more stable with horizontal stabilizer position at the aft than the no horizontal stabilizer than canard. In case of no horizontal stabilizer the vertical surface could be a V- tail (Table 3.13) and V- tail could be used as ruddervators (**Wikipedia 2013e**). In Figure 4.1, V-tail is mentioned in the name of the configuration to remind the reader that a V-tail needs to be incorporated. In case of stagger and swept box wing configurations, the stability and cg range increases in presence of the aft horizontal stabilizer than canard than no horizontal stabilizer, given that the fuselage is long enough to provide a noticeable lever arm. In Figure 4.1, it is mentioned above the configurations "Long fuselage" indicating that the scoring holds true only if the fuselage is long enough. The long fuselage is also necessary to avoid force fighting (see above).

"Ground Handling" is better in case of parallel and unstaggered box wing configurations and therefore scores "2". However, parallel and unstaggered box wing configurations with canard causes more obstruction for vehicle operating during ground handling. So, such configurations receive “1” since the ground handling is least effective with the box wing configurations which have both wings swept and staggered and hence scored “0”. Such configurations obstruct a large area due to its swept and staggered wing.

“Development Time and Cost” – amongst all the aircraft to be evaluated, the box wing aircraft configuration with parallel and unstaggered wing with an aft horizontal stabilizer is similar up to an extent to a conventional aircraft. Therefore, it takes less development time and less cost and is scored “2”. However, such configurations that consist of a canard instead of an aft horizontal stabilizer take more development time and cost and therefore they are scored “1”. In case of configuration with stagger and swept box wing, development time and cost is more and thus scored as “1”. Staggered and swept wing with canard takes the most development time and cost and hence is scored “0”.

“Risk” is also listed under development and means “Development Risk”. Development risk is always avoided by the aircraft manufacturer. It stands for a degree of unpredictability of the outcome of the aircraft development. Unforeseen problems could arise during development or during flight testing. This can considerably lengthen development time and costs, but (in contrast to the above paragraph) in an unpredictable way. No configuration has been scored zero because all configurations are considered to be feasible. The configurations with a swept and staggered box wing and no tail are considered to have more risk since they are unconventional in design and encounter stability problems (**Schiktanz 2011**) and hence scored “1”. The unstaggered and parallel box wing configurations with aft horizontal stabilizer position result in least risk and scored “2”. The unstaggered and parallel box wing configurations with canard are also risky and hence scored “1” (**Raymer 1992**).

Figure 4.2 presents the best configuration obtained after performing morphological analysis and cost benefit analysis. Figure 4.3 and 4.4 present the second suitable option and the configuration to score the highest with unconventional design. To make the unconventional design better, it is conceived that the aft tail would be a V–tail (tail type discussed in Table 3.14). Such V–tail supports the wing more rigid and reduces tendencies of the box towards flutter. There is a reduction in surfaces in case of V–tail compared with unconventional design though there are problems attaining stability (**Schiktanz 2013**). Overall, for unconventional design Figure 4.4 could be the ideal configuration and warrens further work on conceptual design.

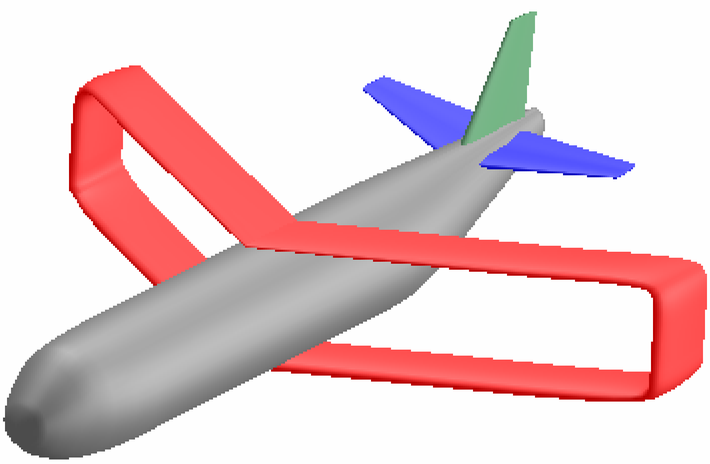


Figure 4.2 Box wing aircraft configuration with highest score

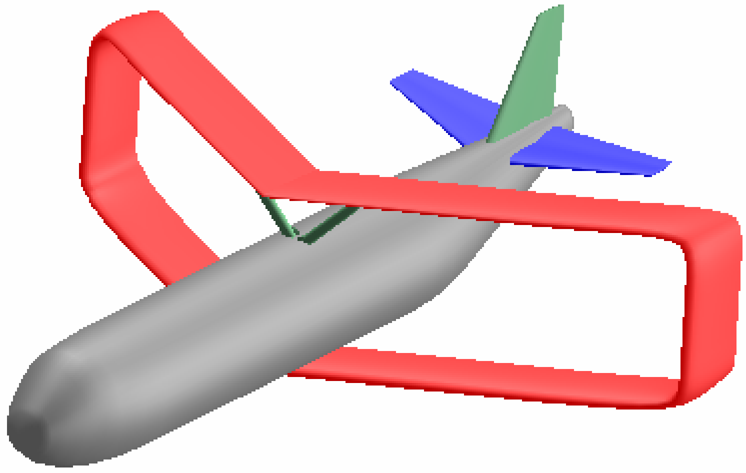


Figure 4.3 Box wing aircraft configuration with second highest score.

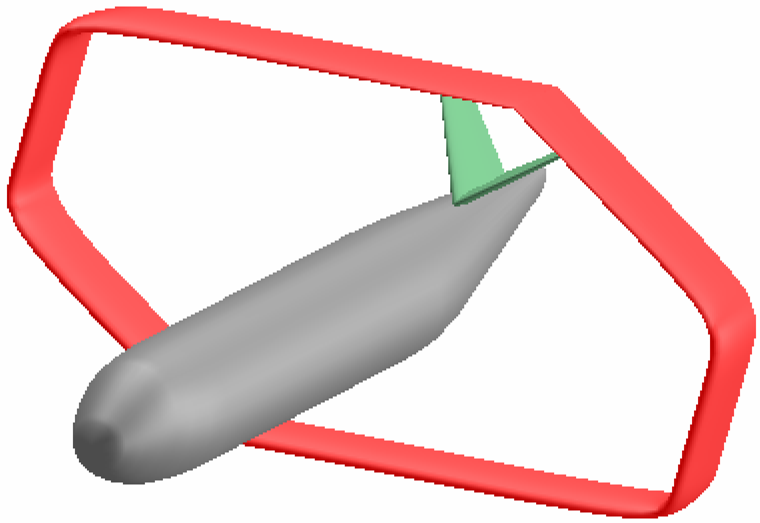


Figure 4.4 Unconventional box wing aircraft configuration with highest score.

5 Conclusion

Analysis methods were studied and it was decided that General Morphological Analysis and Cost-Benefit Analysis are the best suited methods to generate and study the box wing aircraft configurations. In this report the basic components of box wing aircraft are considered to combine and form the box wing aircraft. No detailed design or calculation has been performed. However, the arguments are based on logic, references and expert opinion.

Morphological Analysis forms the basic foundation of the box wing aircraft configuration analysis. Morphological analysis helps display all the possibilities in a matrix including both the possible and impractical solutions. Morphological Analysis matrix results in 162 outcomes. Such high number is difficult to handle and also the General Morphological Analysis does not provide any particular guideline to combine the components systematically to form the box wing aircraft configurations. Therefore, it is in this report the systematic way to combine the components has been achieved. It is discussed in several steps and clear arguments to support the findings, elimination and selection are presented. So, the Morphological Analysis matrix has been modified in several steps and presented in matrices to result in the outcome. It is therefore called *modified morphological analysis*. Also, during the systematic analysis the impractical solutions are discarded and in this way the number of outcome were reasonable at the end. A total of 18 potential configurations were selected after the systematic component combination in steps. These 18 configurations were then subjected to Cost- Benefit Analysis and reasonable criterions were set. Each configuration was scored as per the criteria and finally all the configurations total score were compared. The score were assigned as per reasonable explanations.

The box wing aircraft configuration with unstaggered, both wings aft swept, low – high box wing vertical position, conventional tail and conventional fuselage achieved the highest score (19). The box wing aircraft with unstaggered, both wing backward swept, low – super high box wing vertical position, conventional achieved the second highest score (17), which is not significantly less from the highest score. Therefore, the configuration with second highest score could also be a potential conceptual sketch. Also, the unconventional box wing aircraft with negative stagger, both wing swept, low – super high box wing vertical position, V–tail, conventional fuselage scores 14 which is the highest score amongst all the unconventional configurations. So, this unconventional configuration could be considered for further studies if the aim is an unconventional design with the best aerodynamic potential.

6 Future Work

All the analysis has been studied and the General Morphological Analysis has been selected based on arguments presented. However, it is possible to study all the analysis methods in more detail and implement other method to check if it results in the same outcome or any different configuration is formed which is not listed in this report.

The systematic approach with General Morphological Analysis could be done in different ways. So, other possibilities to systematically combine the components could be studied. The box wing aircraft configuration study for this report has been performed with very basic box wing aircraft components. It is possible to study the components in details and perform the Morphological Analysis. In that way the conceptual sketches could be more specific. Addition, removal or replacement of parameters could be performed in the Morphological Analysis matrix to study the changes. Also, though the cross- consistency has been mentioned in this report it is not performed for the box wing aircraft analysis, since this report concentrates more on systematic component combination. Cross- consistency matrix could be performed to check if the eliminations are valid.

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