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Influence of High Level Requirements in Aircraft Design: from scratch to sketch

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This paper suggests an innovative sketch procedure, especially envisaged for very complex and innovative transportation systems. In order to face with the increasing complexity and innovation levels, reducing development schedule and budget, a rational approach is developed and presented. At first, high level requirements, coming from different sources are elicited and then, through a detailed impact analysis, each design parameter used to sketch the vehicle layout is connected to one or more of these requirements. Then, different semi-empirical models, exploiting available statistical data, regulations and best practices, are developed and proper sizing algorithms are suggested to provide a quantitative base to the qualitative sketching procedure. In this approach, special attention is devoted to the evaluation of the impact of the integration of main subsystems (for example, propulsion, propellant, landing gear subsystems) into the final vehicle layout. Eventually, results of the application of the described procedure to an innovative hypersonic transportation system is reported, highlighting the benefit of the increased traceability of requirements into the final product.

I. I. Introduction

THIS paper aims at suggesting useful procedure to carry out the sketch procedure of an aerospace product in a rational way, relating the high level requirements, coming from stakeholders, mission, payload or subsystems integration needs to specific design parameters. This is a very important activity that is currently considered absolutely crucial to reduce development risk, time and costs.

Besides the introduction of more rational methodologies is claimed by universities and research centers, industries continue to be engaged with know-how and experts background, but unlikely these approaches allow innovation. Thus, when dealing with breakthrough configurations or technologies, innovative and rigorous approaches must be pursued. In this context, requirements can play a fundamental role. Indeed, following the introduction of Systems Engineering approach in the aerospace domain, the central role of requirements has emerged, with the need of developing proper methodologies to support the requirements elicitation process[1] and to integrate the requirements management process within the design process[2, 3]. Indeed, once elicited, the requirements should be used and refined all along the design process. They should constitute the main selection criteria in trade-offs but they should also serve as flags in the design and sizing algorithms. A very first attempt has been carried out by Sadrey in [4], but the methodology was not specifically oriented towards innovative aerospace design, besides it was perfectly covering aspects related to traditional architecture.

This paper aims at suggesting a similar approach but specifically focusing on supporting the design of innovative aerospace vehicles, in particular, trans-atmospheric transportation systems.

Moreover, in order to increase the appealing of the suggested method for the industrial contexts, the present work suggests how the approach can be fully automatized, with noticeable advantages from different standpoints. In particular, it may allow to shorten the design activities reducing the number of design iterations as well as to limit the economic risk related to unappropriated design solutions, increasing the confidence level of the high level estimations and postponing as much as possible the freezing of the baseline.

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In order to reach this ambitious objective, the authors investigated different classes of trans-atmospheric vehicles and for each of them, those systems that can have the heaviest impact on the overall vehicle design. For each of these systems, special attention main design parameters have been investigated trying to understand both the way in which they impact the overall vehicle architecture and the list of high level requirements that can impact on the definition of proper values to be used in the conceptual design process.

Consequently, this paper will report the methodology envisaged to tackle wing and fuselage design and major subsystems integration during sketching procedure, with a special focus on hypersonic transportation systems. Fundamental prerequisite to start this activity will be, of course, the first list of requirements mainly coming from the envisaged mission scenario, but also influenced by additional stakeholders needs, special requests from the current market outlook, as well as by applicable regulations and potential strategical decisions pending on the project.

After this brief introduction, Section II presents an overview of the suggested methodology, highlighting major advantages with respect to existing and currently in-use approach. Then, Section III goes into the detail of the algorithm envisaged to support wing design and sizing procedure. Section IV briefly presents the tool-chain envisaged to support the entire process. Section V contains the results of the methodology application, to the design of a suborbital vehicle aimed at parabolic flights. Eventually, major conclusions are drawn and ideas for future improvements are presented.

II. Design Methodology Overview

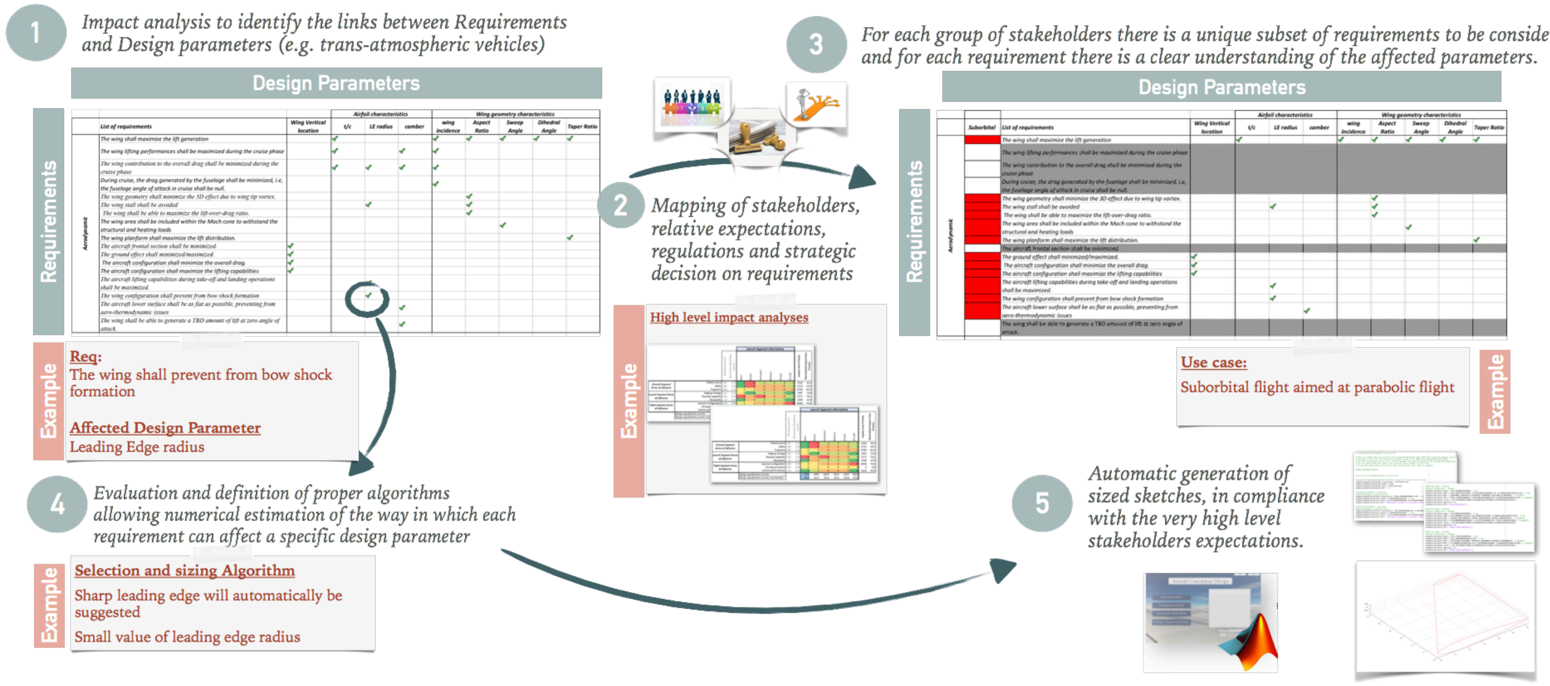
Figure 1 summarizes the major steps of the design methodology that can allow to design and size an aerospace vehicle, starting from a set of well-defined high level requirements. The application of the overall design process can lead to reach a final product in which each design parameter is strictly related to a set of high-level requirements defined at the very beginning of the design process.

Once the high level trade-off for the layout definition have been carried out , and the general aerothermodynamic configuration has been selected, it is important to identify which vehicle systems are the most impacting on the vehicle design. Then for each of these systems (e.g. Wing, Fuselage, Flight Control, Landing Gear, etc…) the procedure schematically sketched in the following Figure can be applied.

The very first step to be performed is the identification of the main deign parameters of the system that is under-investigation. Then, the design parameters should be associated with the high level requirements coming from higher level analysis. The association is not trivial and should be carefully carried out analyzing the impact that each design parameter can have on vehicle and mission performances. The result of this step can be represented through a matrix in which links between requirements and impacted design parameter are evident. This part of the work is absolutely not related to a specific reference mission or vehicle but it is valid for a general aerospace product. The influence of the specific mission to be targeted arrives in Step 2 where stakeholders interested in the specific mission are mapped together with their expectations. Through the exploitation of proper influence matrixes and Quality Functional Deployment tools[3], a subset of the most impacting requirements on the system design process can be identified. This is a crucial point of the methodology and should be carried out considering as stakeholders all those entities that might be interested in the project as well as all the regulatory entities that might imposed important constraints. Then, the results of this second step can be used to prune the matrix obtained at the end of Step 1 to consider only those design parameters that are related to the specific subset of requirements that are important for the specific mission.

It is worth noticing that the identification of which requirements affect a certain design parameter is not sufficient. Indeed, it is important to estimate which can be the numerical value for the design parameter, to comply with those requirements. This is the quantitative estimation reported in Step 4. Then, once that all these rings of the chain have been linked together, an automatic generation of the sketch should be theoretically viable. As it will be highlighted in the following subsections, the exploitation of a combination of commercial and ad-hoc built-in software tools may allow a complete traceability of the high level requirements onto each single design parameters, as it has already been hypothesized in [2, 3].

The following Section reports in detail the application of the envisaged methodology to the design of a wing, giving specific suggestions for innovative transportation systems.



1 *Impact analysis to identify the links between Requirements and Design parameters (e.g. trans-atmospheric vehicles)*

Design Parameters

Requirements

			Airfoil characteristics			Wing geometry characteristics				
	List of requirements	Wing Vertical location	t/c	LE radius	camber	wing incidence	Aspect Ratio	Sweep Angle	Dihedral Angle	Taper Ratio
Aerodynamic	The wing shall maximize the lift generation		✓			✓	✓	✓	✓	✓
	The wing lifting performances shall be maximized during the cruise phase		✓		✓	✓				
	The wing contribution to the overall drag shall be minimized during the cruise phase		✓	✓	✓	✓				
	During cruise, the drag generated by the fuselage shall be minimized, i.e, the fuselage angle of attack in cruise shall be null.					✓				
	The wing geometry shall minimize the 3D effect due to wing tip vortex.						✓			
	The wing stall shall be avoided			✓			✓			
	The wing shall be able to maximize the lift-over-drag ratio.						✓			
	The wing area shall be included within the Mach cone to withstand the structural and heating loads							✓		
	The wing planform shall maximize the lift distribution.									✓
	The aircraft frontal section shall be minimized.	✓								
	The ground effect shall minimized/maximized.	✓								
	The aircraft configuration shall minimize the overall drag.	✓								
	The aircraft configuration shall maximize the lifting capabilities	✓								
	The aircraft lifting capabilities during take-off and landing operations shall be maximized.			✓						
	The wing configuration shall prevent from bow shock formation			✓						
	The aircraft lower surface shall be as flat as possible, preventing from aero-thermodynamic issues				✓					
	The wing shall be able to generate a TBD amount of lift at zero angle of attack.				✓					

Example

Req:
The wing shall prevent from bow shock formation

Affected Design Parameter
Leading Edge radius

2 *Mapping of stakeholders, relative expectations, regulations and strategic decision on requirements*

Example

High level impact analyses

3 *For each group of stakeholders there is a unique subset of requirements to be considered and for each requirement there is a clear understanding of the affected parameters.*

Design Parameters

Requirements

				Airfoil characteristics			Wing geometry characteristics				
	Suborbital	List of requirements	Wing Vertical location	t/c	LE radius	camber	wing incidence	Aspect Ratio	Sweep Angle	Dihedral Angle	Taper Ratio
Aerodynamic	🟥	The wing shall maximize the lift generation		✓			✓	✓	✓	✓	✓
		The wing lifting performances shall be maximized during the cruise phase	▨	▨	▨	▨	▨	▨	▨	▨	▨
		The wing contribution to the overall drag shall be minimized during the cruise phase	▨	▨	▨	▨	▨	▨	▨	▨	▨
		During cruise, the drag generated by the fuselage shall be minimized, i.e, the fuselage angle of attack in cruise shall be null.	▨	▨	▨	▨	▨	▨	▨	▨	▨
	🟥	The wing geometry shall minimize the 3D effect due to wing tip vortex.						✓			
	🟥	The wing stall shall be avoided			✓			✓			
	🟥	The wing shall be able to maximize the lift-over-drag ratio.						✓			
	🟥	The wing area shall be included within the Mach cone to withstand the structural and heating loads							✓		
	🟥	The wing planform shall maximize the lift distribution.									✓
		The aircraft frontal section shall be minimized.	▨	▨	▨	▨	▨	▨	▨	▨	▨
	🟥	The ground effect shall minimized/maximized.	✓								
	🟥	The aircraft configuration shall minimize the overall drag.	✓								
	🟥	The aircraft configuration shall maximize the lifting capabilities	✓								
	🟥	The aircraft lifting capabilities during take-off and landing operations shall be maximized.			✓						
	🟥	The wing configuration shall prevent from bow shock formation			✓						
	🟥	The aircraft lower surface shall be as flat as possible, preventing from aero-thermodynamic issues				✓					
		The wing shall be able to generate a TBD amount of lift at zero angle of attack.	▨	▨	▨	▨	▨	▨	▨	▨	▨

Example

Use case:
Suborbital flight aimed at parabolic flight

4 *Evaluation and definition of proper algorithms allowing numerical estimation of the way in which each requirement can affect a specific design parameter*

Example

Selection and sizing Algorithm
Sharp leading edge will automatically be suggested
Small value of leading edge radius

5 *Automatic generation of sized sketches, in compliance with the very high level stakeholders expectations.*

Fig. 1: Overall Design methodology

III. Wing Design procedure

The wing design is usually considered as one of the first activities to be carried out just after the estimation of the high level design characteristics of the overall aerospace vehicle, such as the maximum take-off and landing weights, the fuel mass, the wing surface, etc. and the aircraft architecture definition. Indeed, besides the fact that in the world of very complex and innovative transportation systems, and in particular in the field of hypersonic vehicles, there could be different design architectures in which a wing is not identifiable, the wing remains the central elements as far as the aerodynamic forces generation is concerned, in the majority of the cases. Moreover, the wing should be considered at the beginning of the design process because it has a relevant impact on different other architectural elements and it imposes strict constraint to some on-board systems integration. As it will be clearly described in this chapter, trade-offs, for each of the design parameters, will be required in order to match and satisfy the highest possible number of stakeholder requirements. In particular, trade-off between aerodynamics, structures, on board systems integration, weight and balance, stability and maneuverability, accessibility, maintainability and safety will be reported.

In order to face with the problem of optimizing the definition of a suitable wing for a trans-atmospheric vehicle, in the earliest phase of conceptual design, this paper provides an innovative integrated methodology and a support tool chain, on the basis of a Systems Engineering approach. This will guarantee a complete traceability of the initial requirements (a direct translation of the stakeholders' needs and expectations), onto each design choice.

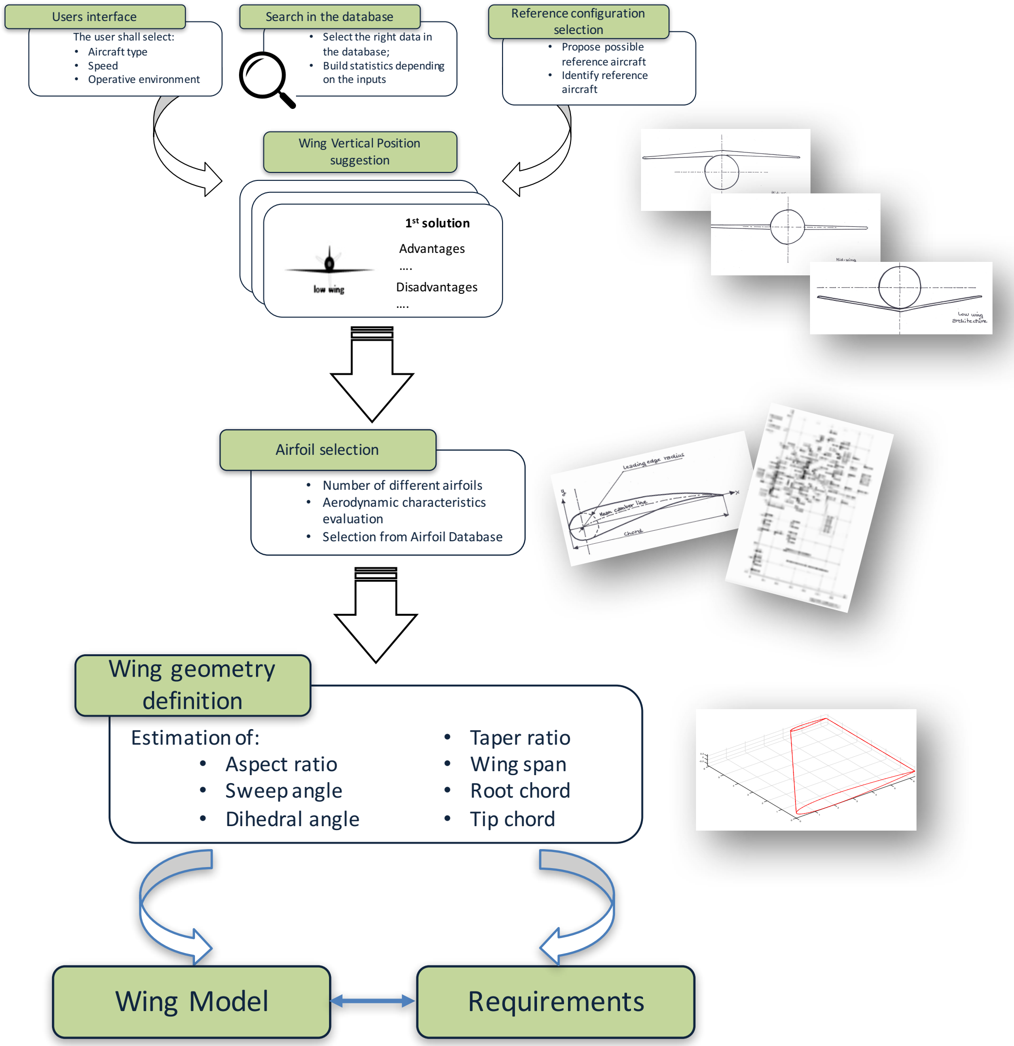


Fig.2: Overall Wing Design methodology

Following the several activities summarized in Fig. 2, the following subsections describes an integrated design methodology to support the definition of the wing layout, applicable to the conceptual design phase. Following the suggested structured approach, the wing design is no more based on the know-how of the chief-designer (with the risk hampering innovation) or of some specialists (with the risk of losing the global perspective on the integrated design), but a multidisciplinary approach is envisaged. This approach will reduce the effort required for refinements in the following design phases, guaranteeing a design closer to the optimal one.

A. Functions identification

As it has been already mentioned before, a Systems Engineering approach has been used and it is mainly for this reason that the first step consisted in the identification of primary and secondary functions that a wing should perform.

- Primary Functions:
    - To generate sufficient lift force
    - To minimize the drag force
    - To minimize the pitching moment
    - To maximize the L/D ratio
- Secondary Functions:
    - To host fuel tanks
    - To host landing gear and relative actuation system
    - To host propulsive group
    - To host high lift devices
    - To host flight control surfaces and relative actuation system
    - To host Thermal Protection System
    - To guarantee a floating surface in case of splash down

Looking at this list of functions, it is clear that among the secondary functions, only a small subset should be guaranteed depending on the type of aircraft under design, thus, depending on the stakeholders' needs, the list should be properly pruning. In particular, there are some typical aspects that should be taken into account when the designer is dealing with hypersonic transportation system, such as the capability of hosting Thermal Protection Systems or the need of maximizing the L/D ratio.

Once the list of initial requirements has been fixed, before moving to the wing geometry definition, its location in the vertical plane with respect to the fuselage should be properly investigated.

B. Wing Vertical Location

The wing vertical location (Fig.3), a major characteristic of the wing, that is deeply affected by the environment in which the aircraft will be operated, by its role and also by the speed regime. In view of this fact, the aircraft can be categorized depending on Role: (Civil transportation, Military transportation, Fighter, Monitoring), Speed regime (Subsonic, Supersonic, Hypersonic) and the operative environment (Lower atmosphere, Upper atmosphere, Inner space, Outer space).

In-depth studying the possible impact of the different stakeholders on the selection of the most suitable wing vertical location, a list of requirements has been elicited. From the requirements list, the most interesting areas of impact for the selection of the wing vertical location is enlisted. Then, an in depth analysis of each identified area of impact is performed for each of the existing alternative configuration (high, medium or low wing). An example of investigation for the high wing configuration is reported in Table I.

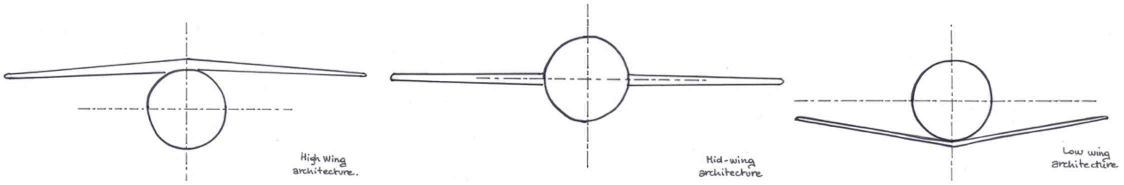


Fig. 3: Wing Vertical Location with respect to the fuselage

Table I: Identification and analysis of the areas of interest for the selection of the Wing Vertical Location

Wing Vertical Location *(with respect to the fuselage section)*	**Areas of Impact**	**Comments**
High	Payload Accommodation	• Enhanced volume for payload; both cargo and passengers would be easily accommodated.
	Structure	• Shorter and Lighter landing gear • Lighter wing in case of external struts. • Lighter fuselage due to the lower number of cuts and relative stiffened.
	Logistic and Maintenance	• Easy loading and unloading especially of cargo, because of the closest location of the fuselage to the ground. • Enhanced engine clearance (in case of wing-mounted engines) • Ground support infrastructure required to access to the engines (in case of wing-mounted engines) and to do the refueling.
	Aerodynamics	• Higher aerodynamic drag due to the enlarged frontal area and fairings. • Ground Effect reduced
	Stability and Control	• No special benefits
	Safety and Operations	• Larger wing flaps are required to guarantee STOL capability • Possibility of performing take-off from un-prepared fields • Limited pilot's visibility in case of small aircraft.

From this analysis, the following list of ***technical characteristics*** related to the several areas of impact previously analysed have been derived:

- Payload accommodation:
  - Volume available for payload
- Structure:
  - Wing weight and complexity
  - Fuselage weight and complexity
  - Landing Gear weight and complexity
- Logistic:
  - Passengers loading and unloading
  - Cargo loading and unloading
- Maintenance:
  - Systems accessibility
- Stability and Control:
  - Handling qualities in take-off

- Handling qualities in climb
- Handling qualities in cruise
- Handling qualities in re-entry
- Handling qualities in landing

Other considerations such as the aerodynamic characteristics or the impact on safety and operations are hardly quantifiable at this high level of design and for this reason, they are not part of the trade-off criteria but they are evaluated and linked to the selected configuration a-posteriori. It is clear that in order to carry out a rational trade-off to properly select the best wing positioning for a wing, it is necessary to evaluate:

1. The impact of the technical and operational features on the wing vertical position (L_i, M_i, H_i). These evaluations are independent from the type of aircraft under investigation.
2. The relationship of the technical characteristics with the different aircraft categories. At this purpose, simple FoMs have been built, making use of statistical data easily derived by a Database.

Focusing on the impact of the technical and operational features on the wing vertical position (L_i, M_i, H_i), a voting process have been used on the basis of a 1 to 10 scale. Table II summarizes the results of this process proposing possible values for the high wing configuration. Of course, the numerical values can be furtherly investigated through sensitivity analysis, tuning the models trying to reproduce existing case studies.

Complementary, the above report table shows possible mathematical formulations that could be adopted for the evaluation of the weight to be assigned to each technical feature. As it is possible to notice from the table, the values reported in Table III are not directly influenced by the type of mission to be performed or by specific stakeholders' needs but they are only related to considerations with general validity, that could be applied to all those aircraft configurations in which a clear distinction between fuselage and wing is identifiable. On the contrary, the weighting factors, whose suggestions for evaluation are reported in Table IV, are strictly related to the different type of aircraft and mission and thus, to the stakeholders' expectations. For this reason, a proper database should be used in support to these evaluations, properly pruned in the basis of the stakeholders' needs, already identified and analyzed at the beginning of the design process. Then, following the activity flow briefly highlighted in Fig. 2, Table II can be completed, allowing a prioritization of the configurations under analysis. The alternative with the highest score would be the one offering the best compromise considering all the stakeholders' expectations.

Table II: Identification of technical features impacting on High Wing location

	Importance of the characteristic for	**Low wing**	**Mid wing**	**High wing**
Technical Feature 1	w_1	L_1	M_1	H_1
Technical Feature 2	w_2	L_2	M_2	H_2
Technical Feature 3	w_3	L_3	M_3	H_3
…..	…..	……	……	……
		L	M	H

Table III: Identification of technical features impacting on High Wing location

Technical Feature	**Importance for a High Wing configuration (h_i)**	**Comments**
Volume available for payload	10 (8)	The highest value is related to the configuration with external structure. In case of internal carrythrough box, the volume available for payload can be moderately lower.
Wing weight and complexity	10 (7)	In case of external structure, the wing is light and with a low level of complexity. Complementary, in case of internal carrythrough box, the wing has a higher weight and complexity.
Fuselage weight and complexity	6 (5)	In case of external wing and the fuselage structure should not be interrupted, the fuselage increment in weight is only due to the presence of a heavier landing gear and of the aerodynamic fairings. Complementary, in case of internal carrythrough box, the fuselage weight is increased.
Landing gear weight and complexity	7	Medium weight and complexity landing gear can be envisaged in case of high wing configuration, mainly due to the possible wing installation.
Passengers Loading and Unloading	7	The high wing configuration allows passenger to access the aircraft without special problems. However, in case of internal carrythrough box, some comfort issues may arise.
Cargo Loading and Unloading	10	The high wing configuration is the best alternative from the logistic point of view. Indeed, the fuselage is closer to the terrain and the loading and unloading operations, for cargo is optimized.
System accessibility	8	This configuration diminishes the distance of the fuselage to the ground and this would facilitate the accessibility to many on-board systems. It is worth noticing that an intermediate weight as been assigned because there are also additional systems installed within the wing and thus, in this configuration, special on-ground equipment should be envisaged.
Handling qualities in take-off	7	The high wing configuration, both in case of internal and external mounting, can obstruct the pilot visibility during take-off phase.
Handling qualities in climb	4	The problem of pilot visibility is even more critical in climbing phase.
Handling qualities in cruise	5-8	The range of suggested values will strongly depend on the type of mountings. Indeed, this weighting factor is strictly related to the cross section area.
Handling qualities in re-entry	5	This configuration may suffer from serious injuries during due to the heating loads and the difficulties in providing an efficient Thermal Protection System. Of course, in case of vehicles that should be able to perform an orbit re-entry, external structures should not be considered.
Handling qualities in landing	10	The high wing configuration guarantees optimal controllability characteristics. Moreover, precision landing capabilities are increased thanks to the reduction of ground effect.

Table IV: Wing Vertical Location: weights definition

Technical Feature	Mathematical formulation	Comments
Volume available for payload	$w_1 = \frac{V_{payload}}{L_{fus}\,A_{fus}}$	where $V_{payload}$ is the volume available for passengers and cargo [m^3]. L_{fus} is the length of the fuselage [m]. A_{fus} is the fuselage section area [m^2] This formula allows to estimate the available the volume efficiency for the different aircraft.
Wing weight and complexity	$w_2 = \frac{m_{wing}}{MTOM}$	m_{wing} is the wing mass estimation [kg]. $MTOM$ is the Maximum Take-Off Mass [kg] This formula allows estimating the relevance in terms of mass and complexity of the wing on the overall vehicle architecture.
Fuselage weight and complexity	$w_3 = \frac{m_{fus}}{MTOM}$	m_{fus} is the fuselage mass estimation [kg]. $MTOM$ is the Maximum Take-Off Mass [kg] This formula allows estimating the relevance in terms of mass and complexity of the fuselage on the overall vehicle architecture.
Landing gear weight and complexity	$w_4 = \frac{m_{lg}}{MTOM}$	m_{lg} is the landing gear mass estimation [kg]. $MTOM$ is the Maximum Take-Off Mass [kg] This formula allows estimating the relevance in terms of mass and complexity of the landing gear on the overall vehicle architecture.
Passengers Loading and Unloading	$w_5 = \frac{m_{pax} \cdot t_{load}}{MTOM \cdot TAT}$	$m_{pax}$is the passengers mass [kg]. t_{load} is the time estimated to perform the boarding/unboarding of passengers [s]. $MTOM$ is the Maximum Take-Off Mass [kg] TAT is the Turn Around Time [s] This formula allows estimating the impact of passengers loading and un-loading operations on the overall mission.
Cargo Loading and Unloading	$w_6 = \frac{m_{cargo} \cdot t_{load}}{MTOM \cdot TAT}$	$m_{cargo}$is the payload mass [kg]. t_{load} is the time estimated to perform the boarding/unboarding of cargo [s]. $MTOM$ is the Maximum Take-Off Mass [kg] TAT is the Turn Around Time [s] This formula allows estimating the impact of cargo loading and un-loading operations on the overall mission.
System accessibility	$w_7 = \frac{m_{sys} \cdot MTTR}{MTOM \cdot TAT}$	$m_{sys}$is the on-board systems mass [kg]. $MTTR$ is the time estimated to perform the maintenance actions after each single mission[s]. $MTOM$ is the Maximum Take-Off Mass [kg] TAT is the Turn Around Time [s] This formula allows estimating the impact of systems on the overall accessibility and maintenance characteristics of the aircraft.

Handling qualities in take-off	$w_8 = \frac{t_{TO} \cdot T_{TO}}{t_{mission} \cdot T_{max}}$	$t_{TO}$is the duration of the take-off maneuver [s] T_{TO} is the thrust required to perform the take-off [N].. $t_{mission}$ is the overall mission duration [s] $T_{max}$is the maximum available thrust [N]. This formula allows estimating the importance of take-off phase on the overall mission.
Handling qualities in climb	$w_9 = \frac{t_{climb} \cdot T_{climb}}{t_{mission} \cdot T_{max}}$	$t_{climb}$is the duration of the climb maneuver [s] T_{climb} is the thrust required to perform the climb phase [N].. $t_{mission}$ is the overall mission duration [s] $T_{max}$is the maximum available thrust [N]. It has to be noticed that in case of multi staged climb, performed with different propulsion systems, the overall FoM values should be evaluated as a $\sum_i \; w_{9_i}$. This formula allows estimating the importance of climb phase on the overall mission.
Handling qualities in cruise	$w_{10} = \frac{t_{climb} \cdot T_{climb}}{t_{mission} \cdot T_{max}}$	$t_{climb}$is the duration of the cruise maneuver [s] T_{climb} is the thrust required to perform the cruise phase [N].. $t_{mission}$ is the overall mission duration [s] $T_{max}$is the maximum available thrust [N]. This formula allows estimating the importance of cruise phase on the overall mission.
Handling qualities in re-entry	$w_{11} = \frac{t_{re} \cdot T_{re}}{t_{mission} \cdot T_{max}}$	$t_{climb}$is the duration of the re-entry maneuver [s] T_{climb} is the thrust required to perform the re-entry phase [N].. $t_{mission}$ is the overall mission duration [s] $T_{max}$is the maximum available thrust [N]. This formula allows estimating the importance of re-entry phase on the overall mission.
Handling qualities in landing	$w_{12} = \frac{t_{land} \cdot T_{land}}{t_{mission} \cdot T_{max}}$	$t_{climb}$is the duration of the land maneuver [s] T_{climb} is the thrust required to perform the land phase [N].. $t_{mission}$ is the overall mission duration [s] $T_{max}$is the maximum available thrust [N]. This formula allows estimating the importance of re-entry phase on the overall mission.

C. Airfoil Selection

Once that the vertical relative position of the wing with respect to a hypothetical fuselage has been assessed, before moving to the definition of the wing geometry, it is important to define the 2D wing section profile. Always taking into account that during conceptual design phase, there would not be the possibility to carry out specific aerodynamic investigations, proper algorithms have been studied in order to guide the designer towards the selection of a suitable airfoil, able to comply with the expected performances.

Two different approaches may be envisaged at this high level of design: from one side, a new airfoil can be design from scratch, investigating the main design parameters, such as the Leading Edge Radius, the camber and so on and then, the new airfoil aerodynamics characteristics should be investigated in order to verify the compliance with the requirements. On the opposite, another approach, starting from requirements and leading to the selection of an existing airfoil for which the main aerodynamic performances are known. This approach is the most suitable at this design level, and it is perfectly in line with the basic idea of this paper, i.e. to guarantee a complete traceability of the stakeholders' needs and thus the high level requirements onto the design choice. Table IV together with Fig.3 aim at summarizing this approach.

Table V: Airfoil selection procedure

Step	Formulas	Comments
Calculate the aircraft ideal cruise lift coefficient	$C_{L_C} = \frac{2W_{mean}}{\rho V_C^2 S}$ *Where:* C_{L_C} is the aircraft ideal cruise lift coefficient; ρ is the air density (at cruise altitude) [kg/m^3]; $S$is wing surface [m^2].	This first step allows estimating a first value for the requirements of the overall aircraft in an intermediate point of the cruise.
Calculate the wing lift coefficient	$C_{L_{C_W}} = \frac{C_{L_C}}{k_w}$ Where: $C_{L_{C_W}}$ is the wing cruise lift coefficient; k_w is the wing contribution percentage to the overall aircraft lifting characteristics.	This step allows the designer to move from aircraft-level to the wing-level. Considering that the wing is usually the solely responsible for the generation of the lift, k_w can be set at 0.95 for traditional configuration [4] It is clear that in case of configuration on which tail/canard surfaces or the fuselage are more strongly contributing to the overall aircraft lifting capacity, this value should be properly reduced.
Calculate the wing airfoil ideal lift coefficient	$C_{L_i} = \frac{C_{L_{C_W}}}{k_a}$ C_{L_i} is the wing cruise lift coefficient; k_a is the wing airfoil lifting contribution to the wing lifting coefficient.	This step allows moving from a 3D problem at wing level, to a 2D investigation, focusing on the airfoil. The parametric coefficient k_a present in this equation can be set at 0.9 in conceptual and preliminary design evaluation. This allows considering the fact that the wing span is limited, and the possible presence of sweep angle and non-constant chord.
Calculate the aircraft maximum lift coefficient	$C_{L_{max}} = \frac{2W_{TO}}{\rho_0 V_S^2 S}$ *Where:* $C_{L_{max}}$ is the aircraft maximum lift coefficient; ρ_0 is the air density (at sea level) [kg/m^3]; $S$is wing surface [m^2]. $W_{TO}$is the maximum take-off weight; V_S is the stall speed [m/s]	This step is absolutely similar to the very first one, but allows deriving the maximum aircraft lift coefficient. Following the same top-down approach it will be possible to estimate the wing airfoil maximum lift coefficient.

Calculate the wing maximum lift coefficient	$C_{L_{max_W}} = \frac{C_{L_{max}}}{k_w}$ Where: $C_{L_{max_W}}$ is the maximum wing lift coefficient; k_w is the wing contribution percentage to the overall aircraft lifting characteristics.	
Calculate the wing airfoil gross maximum lift coefficient	$C_{l_{max-gross}} = \frac{C_{L_{max_W}}}{k_a}$ $C_{L_{max-gross}}$ is the wing airfoil gross maximum lift coefficient ; k_a is the wing airfoil lifting contribution to the wing lifting coefficient.	The effect of High Lift Devices (HLD) is included
Calculate the wing airfoil net maximum lift coefficient	$c_{l_{max}} = C_{l_{max-gross}} - \Delta C_{l_{HLD}}$	Where the contribution to the to the wing maximum lift coefficient depends on the geometry, type and maximum deflection of the selected HLD.

Identify the airfoil selection alternatives that deliver the desired C_{l_i} and C_{lmax}

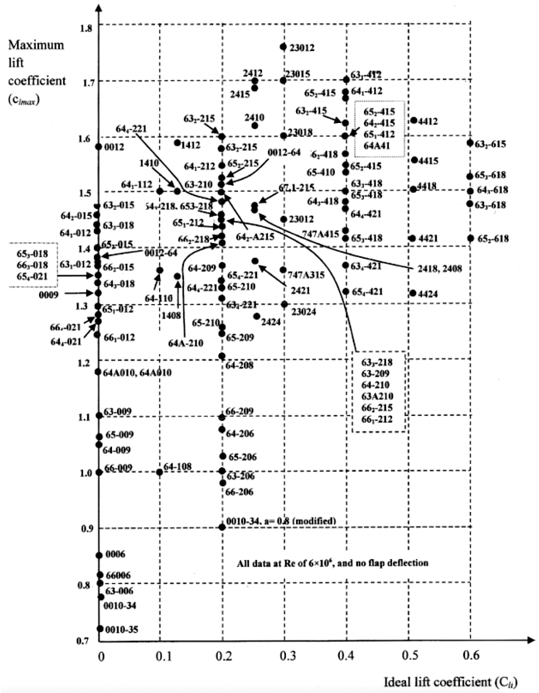


Fig. 4: Wing profile selection

D. Wing Geometry definition

This section aims at providing algorithms for the selection or evaluation of the main wing geometry parameters: wing incidence, aspect ratio, wing sweep and dihedral angles and taper ratio. A common procedure that starts from the identification of the requirements having the greatest impact on the design parameter under investigation proper mathematical equations can be built in order to having a first evaluation of the parameter for different aircraft configuration. It is worth noticing that depending on the type of mission and again on the stakeholders' needs, only a subset of requirements can be meaningful for the selection process.

1. Wing Incidence

One of the first parameters that should be selected at the beginning of the wing geometry definition procedure is the wing incidence. Referring to the literature, this parameter could be defined as the angle between the fuselage centre line and the wing root chord. In literature, this angle is also referred to wing settling angle (α_{set}).

Two different architecture alternatives can be envisaged: a variable wing incidence and a fixed one. Possible pros and cons for both these options from different perspectives, have been evaluated and at the end, it was possible to convene that a fixed wing incidence is the best option to reduce weight and to avoid possible huge safety and operational constraints. This is even more true if hypersonic transportation systems are concerned. Indeed, the possibility of changing the incidence of very big surfaces at very high speed would require a too huge amount of power in front of a very limited aerodynamic and stability advantage.

Hypothesizing that a fixed wing incidence has strategy has been selected, in order to understand how to select the best value of α_{set}, it is important to start listing which high level requirements can have a deeper impact on this parameter:

Aerodynamic

1. The wing shall maximize the lift generation.
2. The wing lifting performances shall be maximized during the cruise phase.
3. The wing contribution to the overall drag shall be minimized during the cruise phase
4. During cruise, the drag generated by the fuselage shall be minimized, i.e, the fuselage angle of attack in cruise shall be null.

Operations

5. The available excursion of angle of attack during take-off operation shall be maximized.
6. During cruise phase, the fuselage angle of attack in cruise shall be null in order to guarantee the maximum comfort level.
7. The aircraft landing distance shall be minimized.

Taking into account all these requirements, a first way to select the best value of α_{set} is to exploit, if available, the airfoil lifting curve coefficient. In this case the wing settling angle shall correspond to that angle for which the selected airfoil is able to generate the ideal lift coefficient.

In case the confidence level in the airfoil aerodynamic data would be limited, a statistical approach may be implied. In particular, it would be possible to estimate α_{set} using the following equation:

$$\alpha_{set} = (\alpha_{set})_0 - \Delta i_w$$

where:

$(\alpha_{set})_0$ can be identified following a statistical approach and it is strictly related to the type of aircraft. Please notice that some useful first value attempts are reported in Table VI.

Table VI: Wing incidence suggestions

Aircraft Type	**Wing Incidence**
Supersonic fighters	0 – 1 deg
Hypersonic Transportation Systems	0 – 1 deg
General Aviation	2 – 4 deg
Jet transportation	3 – 5 deg

2. *Aspect Ratio*

In order to define the best Aspect Ratio (AR), this paragraph summarizes the impact of AR on the different design areas. In particular, for each area, a list of requirements that will impact on the selection of the best value of AR has been derived. In this section, the results of the investigation for the safety area of interest are reported (see Tab.VII)

List of requirements that can have an impact on the selection of the AR.

1. The wing shall maximize the lift generation
2. The wing geometry shall minimize the 3D effect due to wing tip vortex.
3. The wing stall shall be avoided.
4. The wing shall be able to maximize the lift-over-drag ratio.
5. The wing stall shall be postponed.
6. The tail stall shall be postponed after wing stall
7. The wing weight shall be reduced.
8. The wing production cost shall be reduced
9. The wing geometry shall maximize the effectiveness of wing control surfaces.
10. Gliding performances shall be maximized.

Table VII: AR impact on safety

Safety performance	**Effect of the increment of AR**	
	Pros	**Cons**
Gliding range	The gliding performances are improved with the adoption of a higher AR wing. This allows increasing safety in case of engine failures.	
α_S		Stall angle decreases in view of the wing effective angle of attack reduction. In particular, for safety recovery requirements it is convenient to set: $(AR)_{canard} > (AR)_{wing} > (AR)_{tail}$

Table VIII: AR evaluation suggestions

Type of aircraft	**Aspect Ratio estimation**[5]	**Suggestion**[4]
Sailplane	$0.19\left(best\frac{L}{D}\right)^{\frac{1}{3}}$	20 – 40
Jet trainer	$4.737\,(M_{max})^{-0.979}$	4 - 8
Jet fighter	$4.110\,(M_{max})^{-0.0622}$	2 - 4
Military Cargo	$5.570\,(M_{max})^{-1.075}$	6 – 12
Low subsonic Transport		6 - 9
High subsonic Transport		8 – 12
Supersonic transport		2 - 4
Hypersonic transport		1 - 3

In the basis of statistical analysis, Raymer[5] tried to express the Aspect Ratio as function of the aircraft type and of the maximum Mach number. For hypersonic vehicles, considering the very limited number of projects and programs, estimation based on[4] is here proposed.

3. *Wing Sweep Angle*

The wing sweep angle is defined as the angle between a constant percentage chord line along the semi-span of the wing and the lateral axis perpendicular to the aircraft centre line (y-axis). In particular, to be more precise, this is the definition of the Leading Edge sweep angle. In the same way, it is possible to define the Trailing Edge sweep angle as the angle between the wing trailing edge and the longitudinal axis of the aircraft, the quarter chord sweep as the angle between the wing quarter chord line and the longitudinal axis and finally the 50% chord sweep as the angle between the wing 50% chord line and the aircraft longitudinal axis.

Conventionally, in literature, a sweep angle is considered positive (aft sweep) whether the wing is inclined towards the tail; otherwise, it is referred to as forward sweep (negative).

Two different architectural alternatives should be evaluated:

- fixed wing sweep angle
- variable wing sweep angle.

Pro and cons of the two options have been in-depth analysed. In particular, it has to be noticed that the variable geometry has been deeply investigated in the late 1980s especially because it offers the best compromise among very different mission phases. However, the high level of complexity, risk and costs related to this innovative and technologically advanced solution, forced the engineers to focus on different design architectures.

Moreover, as far as the wing configuration is concerned, it is possible to classify the alternatives as Single wing sweep angle or Double sweep angle.

Considering these alternatives, a double wing can be used to compensate variations for aerodynamic in low and high speed regimes and it would be very useful for single stage hypersonic vehicles that should face with flight phases with a wide range of speed and altitudes.

This is the list of requirements having the major impact on the selection of the proper wing sweep angle.

1. The wing area shall be included within the Mach cone to withstand the structural and heating loads.
2. The wing shall maximize the lift generation
3. The stall speed shall be increased.
4. Lateral stability shall be enhanced.
5. Lateral manoeuvrability shall be enhanced.
6. The aircraft controllability in turbulence shall be enhanced.

Considering the case of hypersonic vehicles, the maximum Mach number, and the related requirements, is the most affecting parameters for the selection of the most suitable LE sweep angle. In particular, from the theoretical point of view, the semi-aperture of the Mach cone (μ) can be defined as

$$\mu = \sin^{-1}\left(\frac{1}{M}\right)$$

and the relative sweep angle can be usually defined as

$$\Lambda = k_{\Lambda}(90 - \mu)$$

where k_{Λ} is a factor that will be used to diminish the wave drag in supersonic and hypersonic speed. Considering some results provided by literature, a factor of 1.2 will guarantee the lowest wave drag, avoiding the shock wave to be very closed to the wing leading edge, generating high temperature due to a serious increment of the aerodynamic heating. Following this approach, this trend of Fig. 5 have been derived and could be exploited as a first attempt of wing sweep angle estimation.

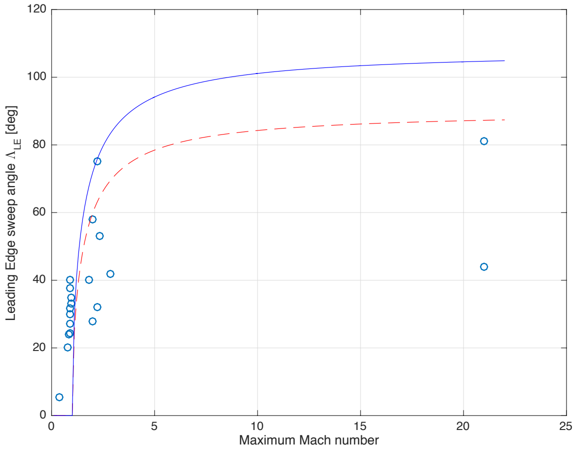


Fig. 5: Leading Edge Sweep Angle vs Mach number

4. *Dihedral Angle*

Looking at existing aircraft configurations it is also important to notice that there is a close relationship between wing vertical location and the dihedral effect and this is mainly due to lateral stability and control requirements. As it is possible to be noticed in Tab. IX, the presence of a high wing it is usually associated with a negative dihedral angle. Conversely, the presence of positive dihedral angles is mainly associated with a low wing configuration. In addition, for the same reasons, there is a strict relation with the sweep angle too. Referring to the practical suggestions provided in [5], 10 deg of sweep provides about 1 deg of effective dihedral. In particular, in case of a forward swept wing, a negative dihedral angle will be required. Table IX [4] reports some useful ranges for dihedral angle values, allowing to carry out a first high level estimation of this peculiar wing characteristics on the bases of wing vertical location and sweep angle.

Table IX: Sweep Angle and Wing, Vertical Wing Location and Dihedral Angle mutual influence

	Low Wing	**Mid Wing**	**High Wing**
Un-swept	5 to 10 deg	3 to 6 deg	-4 to -10 deg
Low-subsonic swept	2 to 5 deg	-3 to 3 deg	-3 to -6 deg
High subsonic swept	3 to 8 deg	-4 to 2 deg	-5 to -10 deg
Supersonic swept	0 to -3 deg	1 to -4 deg	0 to -5 deg
Hypersonic swept	1 to 0 deg	0 to -1 deg	-1 to -2 deg

5. *Taper Ratio*

In order to select a suitable wing planform and so, to hypothesize a proper value of taper ratio, the most useful and simple approach, applicable during the conceptual design phase, is to evaluate the variations in terms of lifting capabilities of a family of wing geometries having the same airfoil, and equal geometrical features except for the wing taper ratio. This approach can be carried out in conceptual design phases, exploiting the so called lifting-line theory proposed by Prandtl. With the same approach, it is also possible to evaluate the effect of aspect ratios and wing surface on the lift distribution.

E. Wing Design Traceability Matrix

The following table (Tab.8) can be considered one of the main output of the performed investigations to create a methodology able to support and innovate the wing design process in conceptual design. As it is shown in the following section, this table can become the reference document to understand the major impact of each requirements on the design parameter. Please notice that this table has been built to support the wing design of a generic aircraft, thus, depending on the specific case study, only a subset of these requirements should be considered.

Table X: Wing traceability Matrix

			Airfoil characteristics			Wing geometry characteristics				
	List of requirements	Wing Vertical location	t/c	LE radius	camber	wing incidence	Aspect Ratio	Sweep Angle	Dihedral Angle	Taper Ratio
Aerodynamic	The wing shall maximize the lift generation		✓			✓	✓	✓	✓	✓
	The wing lifting performances shall be maximized during the cruise phase		✓		✓	✓				
	The wing contribution to the overall drag shall be minimized during the cruise phase		✓	✓	✓	✓				
	During cruise, the drag generated by the fuselage shall be minimized, i.e, the fuselage angle of attack in cruise shall be null.					✓				
	The wing geometry shall minimize the 3D effect due to wing tip vortex.						✓			
	The wing stall shall be avoided			✓			✓			
	The wing shall be able to maximize the lift-over-drag ratio.						✓			
	The wing area shall be included within the Mach cone to withstand the structural and heating loads							✓		
	The wing planform shall maximize the lift distribution.									✓
	The aircraft frontal section shall be minimized.	✓								
	The ground effect shall minimized/maximized.	✓								
	The aircraft configuration shall minimize the overall drag.	✓								
	The aircraft configuration shall maximize the lifting capabilities	✓								
	The aircraft lifting capabilities during take-off and landing operations shall be maximized.			✓						
	The wing configuration shall prevent from bow shock formation			✓						
	The aircraft lower surface shall be as flat as possible, preventing from aero-thermodynamic issues				✓					
	The wing shall be able to generate a TBD amount of lift at zero angle of attack.				✓					
Operations	The available excursion of angle of attack during take-off operation shall be maximized					✓				
	During cruise phase, the fuselage angle of attack in cruise shall be null in order to guarantee the maximum comfort level.					✓				
	The aircraft landing distance shall be minimized.					✓				
	The wing architecture shall guarantee proper clearance to ground and water.								✓	
	The landing gear length shall be minimized	✓								
	The aircraft configuration shall facilitate the loading and unloading operations	✓								
	The aircraft configuration shall guarantee the proper on-ground clearance to the ground	✓								
	The aircraft configuration shall facilitate the refuelling operations	✓								
	The aircraft configuration shall enhance STOL capabilities	✓								
	The aircraft shall be operated from un-prepared fields	✓								
	The aircraft configuration shall guarantee a proper pilot visibility	✓								
	The aircraft configuration shall allow proper floating capabilities in case of emergency landing on waters.	✓								
	The aircraft should be able to operate at high angle of attacks.			✓						
Stability and Control	The wing geometry shall maximize the effectiveness of wing control						✓			
	Lateral stability shall be enhanced.							✓	✓	✓
	Lateral manoeuvrability shall be enhanced							✓		
	The aircraft controllability in turbulence shall be enhanced.									✓
	The aircraft lateral control shall be improved									
	The aircraft pitching moment shall me maximized				✓					
Safety	Gliding performances shall be maximized.						✓			
	The wing stall shall be postponed with respect to the canard stall.						✓			
	The wing stall shall be anticipated with respect to the tail stall.						✓			
	The stall speed shall be increased							✓		
Logistic and maintainance	The aircraft shall be easy to be maintained.								✓	
	Logistic on-ground infrastructures required to perform maintenance shall be reduced.								✓	
Costs	The wing manufacturing costs shall be minimized.									✓
Weight and Balance	The wing weight shall be minimized	✓								✓
	The fuselage weight shall be minimized.	✓								
	The landing gear weight shall be minimized	✓								
Payload and Systems	The volume available to host passengers shall be maximized.	✓								
	The volume available to accommodate payload shall be maximized	✓								
	The volume available to accommodate payload shall be maximized		✓							
Structure	The number of cuts in the fuselage structure shall be reduced	✓								

IV. Suborbital Vehicle wing design

A. Reference vehicle and missions

The reference case study presented in this work deals with the design of trans-atmospheric vehicle aims at performing suborbital parabolic flights. The initial idea of this project as well as the high-level requirements belong to have been developed within the framework of a collaboration of Politecnico di Torino, Altec S.p.A. and Thales Alenia Space Italy, for private Malaysian stakeholders. Since 2014, several works, covering different aspects of this vehicle and the related mission have already been presented and published [6, 7, 8, 9, 10].

Considering the constraints coming from the need to operate the vehicle from a wider range of worldwide locations, the special capability to perform a vertical take-off and landing (VTOL) have been considered. This and other requests from the stakeholders are clear examples of how requirements can deeply affect the design of the overall mission and related systems and subsystems.

For the sake of clarity, this is the mission statement describing the main goals of the vehicle and of its mission.

> "*The mission shall allow regular flight services to enable 4 flight participants at a time to reach 100 km to experience a period of microgravity and an amazing view of the Earth. The spacecraft shall perform a vertical take-off from a sea-based or land-based platform and a vertical landing on the same site. Moreover, the additional capability to perform an un-crewed mission shall be considered*"

Starting from these high level considerations and exploiting the results of in-depth investigations, the requirement matrix presented in the previous section, has been properly pruned. In the following subsections, a summary of the major results obtained applying the methodology presented in this paper to the design of the wing of a vehicle able to perform parabolic missions.

B. 2D Airfoil Profile Definition

Considering the wing airfoil definition, before selecting a proper airfoil, it is important to have an idea of the leading edge radius, camber and thickness that can be selected.

Following the methodology described in the previous paragraphs and thanks to the support of the ad-hoc built-in Matlab® tool that will be described in the following Section, the main airfoil parameters have been estimated. In particular, the following table summarizes the results obtained for this case study, with relative comments about the proposed solutions.

Then, it should be necessary to find out if an existing airfoil could be selected for this application. Considering the peculiarities in terms of wide speed and altitude ranges, it is convenient to look at some existing ad-hoc developed airfoil for similar applications and verify that the aerodynamic characteristics could match the designer expectations. In particular, an airfoil similar to the designed for the Space Shuttle can be exploited [11]. Considering the difference in terms of maximum speed, the analysis of the lifting coefficient variations are here limited to the speed range of interest.

Table XI: Selection of airfoil characteristics for the reference case study

Characteristic		Comments
Leading Edge radius	Large-to-intermediate	Considering the specific mission profile, the most important requirement affecting this selection is the need of guaranteeing the capability of flying and performing maneuvers at high angles of attack.
Camber	Double cambered	This solution allows the airfoil to guarantee a certain amount of lift. This is extremely useful in this case in which the aircraft should be able to perform a vertical take-off. The lower surface will be only moderated cambered in order to withstand to the aero-thermo-dynamic loads.
Thickness	$(t/c)_{max}<0.09$	A thin airfoil has been proposed taking into account the speed regime that the aircraft shall guarantee. However,

considering the range of numerical values proposed for the supersonic speed regime, the highest estimation has been considered in order to partially satisfy the need of free room to install systems within the wing.

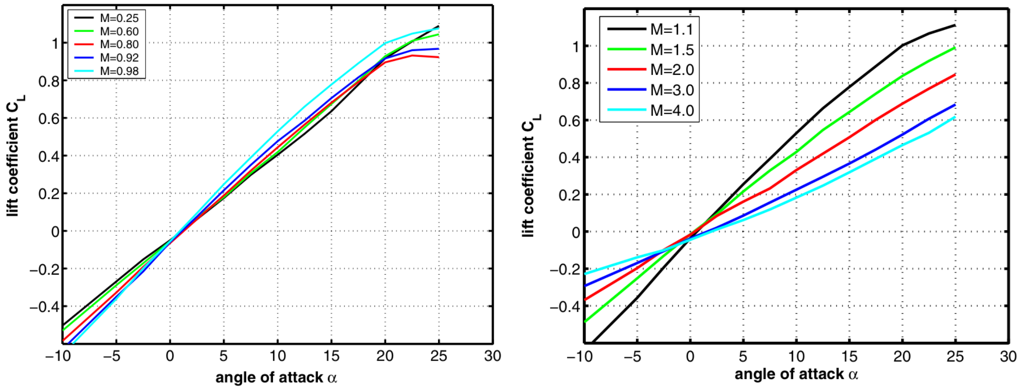


Fig. 6: Example of lift coefficient trends at different Mach numbers for a simple reference airfoil selected in conceptual design.

C. 3D Wing Geometry Definition

Once the 2D airfoil has been selected, it is possible to finalize the 3D wing design defining all the other geometrical characteristics of the wing.
In the following table, the major results are reported.

Table XII: Selection of wing characteristics for the reference case study

	Characteristic	Comments
Wing incidence	α_{set} = 1 deg (fixed)	A fixed incidence will be adopted in order to avoid higher maintenance costs and increasing risk. The numerical value is the results of the application of the statistical approach .
Aspect Ratio	AR = 3	The selected aspect ratio is relatively low considering the typical aeronautical scenario. However, it is perfectly compliant with the AR values of existing suborbital vehicles. In particular, besides the fact that this choice may not be the optimal one from the aerodynamic point of view, it has several other benefits. Indeed, as far as stability and control is concerned, this value moves away the risk of aileron reversal. Moreover, the CG shift due to the fuel consumption results to be reduced.
Wing Sweep Angle	Λ = 79.7 deg (fixed)	Considering that the envisaged mission profile has not so wide speed ranges to be faced with, because the aircraft will not reach hypersonic Mach numbers, a single wing sweep strategy can be suitable. The numerical values obtained by the estimation guarantees the overall wing surface to stay within the Mach cone.
Dihedral Angle	Γ = 1; (positive)	A small positive dihedral angle is suggested to take into account the low wing selected configuration and the supersonic flight regime, enhancing the lateral stability and the on ground clearance. However, higher values cannot be

		adopted to allow vertical take-off in not tail-sitting position.
Taper Ratio	$\lambda = 0.15$ (quasi Delta wing)	Delta wing configuration provides the aircraft optimal lateral control and spiral stability, allowing a weight reduction, due to an optimized material distribution. However, as it shown in Figures 9 and 10, this solution is not providing the designer with the best lifting distribution. This problem is here accepted considering that a proper design of the fuselage and of the interface between wing and fuselage can be properly pursued in next design steps.

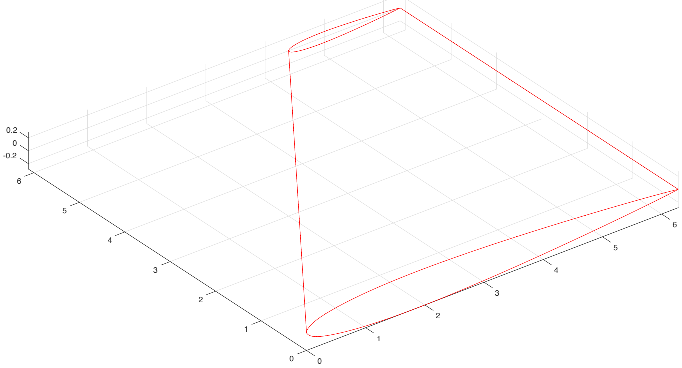


Fig. 7: Simple graphical representation of the under-development 3D wing in the Matlab® GUI

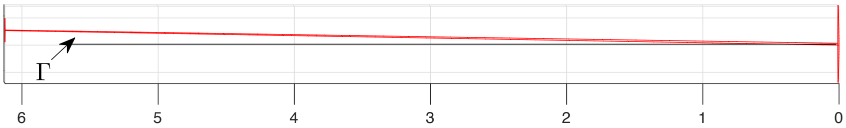


Fig. 8: Front view of under-development 3D wing in the Matlab® GUI

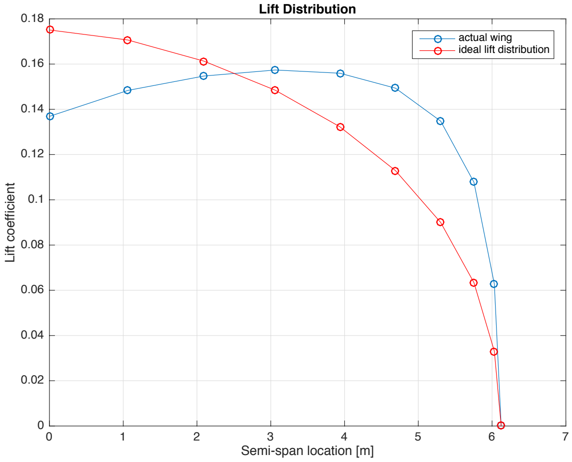


Figure 9: Lift distribution for the case-study wing

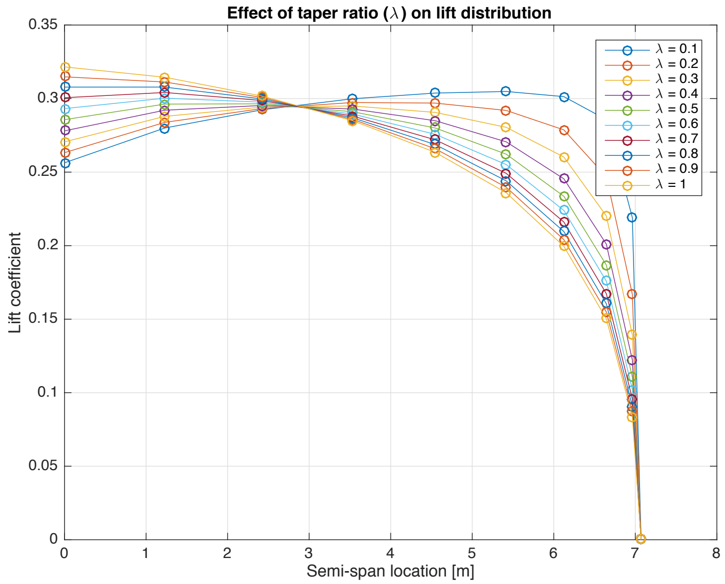


Fig.10: Effect of taper ratio on lift distribution for the case-study wing

It is clear that this is only the very first step in the definition of a wing, especially for hypersonic vehicles. However, it is the fundamental step toward further investigations, in the different specialist disciplines. Furthermore, the tool chain presented in the following Section, consisting of both commercial and under development tools, is a very useful support for the conceptual design phase..

V. Vehicle Validation and Support Tool Chain

In order to support the wing design activity as well as the design of the fuselage and of the most impacting subsystems, a proper Matlab® code is currently under-development by Politecnico di Torino. However, this is only one software of a more complex tool-chain that consists of different commercial and under-development tools. The aim of this tools collection is to provide a valuable support to the designer, speeding up the conceptual design phase, targeting a complete traceability of requirements onto the design products. Thus, considering the fact that this design step is a mixed of both sketching and sizing activity, proper interfaces between Matlab® code and other development environments such as Solidworks® and Simulink®, as well as with requirements management such as IBM Doors® or configuration management such as IBM Rapsody® have been in-depth analysed, providing a complete tool chain to the final user. The user workload has been reduced thanks to the creation of a Graphical User Interface, that eases the overall process. This GUI has been developed in a Matlab environment with the aim of supporting the user during the overall process. In particular, this the GUI allows to:

- Ease the process of problem definition.
- The management of the overall wing design process.
- Ease design iterations.
- Allowing track changes.

The Matlab® code is currently related to a spreadsheet generated in MS Excel environment that contains inputs and outputs of the design process. Moreover, the Matlab tool has been developed to be able to be connected with HyDat, a Database of Hypersonic initiatives [REF] currently under-development by Politecnico di Torino. The Excel file format has also been selected because it can also provide the link between the Matlab code and the IBM Doors. Indeed, in order to ease the requirements managing process, Excel files are used to create interfaces between Matlab and Doors and vice versa.
The developed Matlab® code implements the overall approach previously described. In particular, the user, interacting with the GUI, performing the first selections, such as the type of mission required, the role and the

maximum achievable mach number. In this case, the user is simply doing selections on the screen but these are precious information to start the overall design process. In particular, thanks to these high level choices, the tool is able to generate a high list of requirements, belonging to different categories, from aerodynamic to operation, from safety to maintenance, simply automatically selecting the most impacting ones from the main matrix.

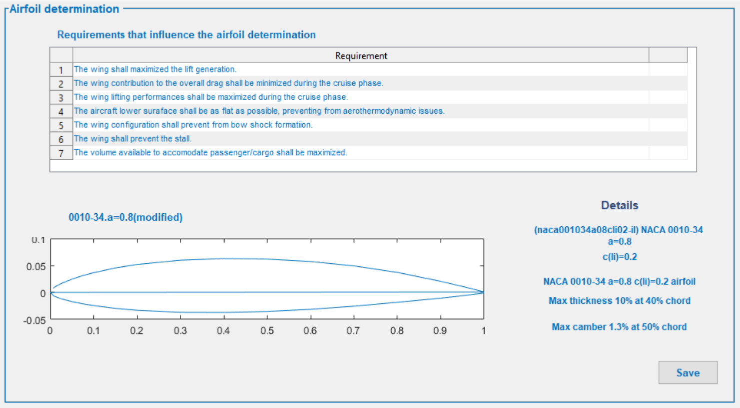
Once the major inputs have been inserted, the Matlab® tool is able to provide the user with the suggestion of the most convenient wing vertical location. In particular, the tool will provide the user with a series of ordered sheets, each one presenting a pictorial view of the vertical location and the related list of pros and cons. Considering the crucial role of this selection, the user can decide to accept the suggestion of the tool and proceed in the wing design process with the first ranked configuration. Otherwise, the user can navigate through the other options and select a different one, accepting related pros and cons. This degree of freedom is required because this tool-chain is not intended to force the designer to a frozen solution but supporting in a rational way the creative process of aircraft design.

Then, once the vertical location of the wing with respect to the fuselage has been fixed, the user shall insert some numerical high level estimations that are closely related to what has been done in previous steps, when the aircraft configuration has been selected and the first numerical estimation have been carried out. In this way, the tool can suggest a proper airfoil (or a family of airfoil) suitable for the envisaged application. Also in this case, as in the previous step, the designer is not forced to use the suggested airfoil but he/she can decide to move to the next step of the design process directly importing the geometry of the airfoil and the some aerodynamic and geometrical characteristics.

At this stage it is possible to go on with the definition of the optimal geometry for the wing. The results of these evaluations can be accessed by the users in several ways. First of all, a new process of requirements refinement/generation starts, providing an update list of requirements, properly stored. Then, a proper routine provides the designer with a wing sketch. Moreover, the same data are used to update a 3D parametric CAD model. Using a proper interface between the code (in Matlab environment) and the 3D model, the user can also add some changes in the parametric model and these changes have a direct impact on the requirements. In this way, there is complete traceability between model and requirements. Moreover, the 3D model can be exported to be used in other higher fidelity tools, to perform more detailed analyses such as the aerodynamic and structural ones. In particular, the possibility of importing the CAD model in Simulink® exploiting the SimScape® library that allows to simulate the way of working of the imported 3D components. In particular, this tools connection demonstrated to be very useful in order to test and solve some issues related to the integration of components and equipment within a system. In the case of wing, the simulation of the actuation of movable surfaces or the retraction and extraction of landing gear, can be directly simulated. Like in the case of Solidworks®, also for the Simulink® model there is the possibility of connecting each element or variable to one or more requirements. In case of requirements containing numerical information, there would also be the possibility of verify them directly during the simulation.

This tool chain has been envisaged at first and here described thinking to the specific case of supporting an aircraft wing design. However, it is crystal clear that this is a general approach that could be implemented for all the other different design areas. Moreover, the possibility of maintaining the traceability of the overall process shows is major benefits with respect to the traditional approach, in case of complex systems.

Furthermore, the introduction of a Flight Simulator, like X-Plane, has been envisaged in order to test and verify additional characteristics such as the handling qualities or different flying performances, that are hardly quantifiable at this high level of design.



Airfoil determination

Requirements that influence the airfoil determination

	Requirement	
1	The wing shall maximized the lift generation.	
2	The wing contribution to the overall drag shall be minimized during the cruise phase.	
3	The wing lifting performances shall be maximized during the cruise phase.	
4	The aircraft lower suraface shall be as flat as possible, preventing from aerothermodynamic issues.	
5	The wing configuration shall prevent from bow shock formatiion.	
6	The wing shall prevent the stall.	
7	The volume available to accomodate passenger/cargo shall be maximized.	

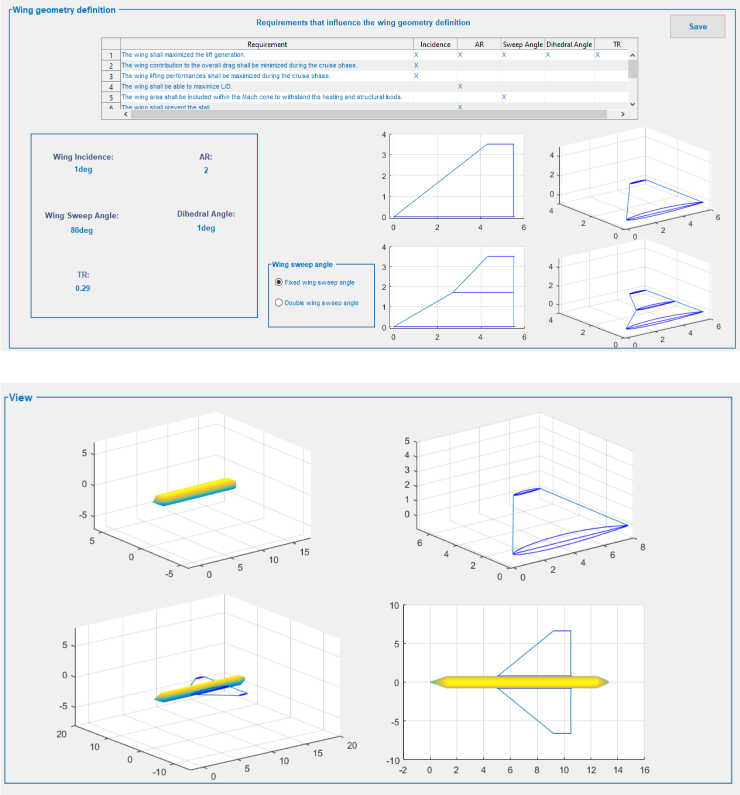
Details

(naca001034a08cli02-il) NACA 0010-34
a=0.8
c(li)=0.2

NACA 0010-34 a=0.8 c(li)=0.2 airfoil

Max thickness 10% at 40% chord

Max camber 1.3% at 50% chord



Wing geometry definition

Requirements that influence the wing geometry definition

	Requirement	Incidence	AR	Sweep Angle	Dihedral Angle	TR
1	The wing shall maximized the lift generation.	X	X	X	X	X
2	The wing contribution to the overall drag shall be minimized during the cruise phase.	X				
3	The wing lifting performances shall be maximized during the cruise phase.	X				
4	The wing shall be able to maximize L/D.		X			
5	The wing area shall be included within the Mach cone to withstand the heating and structural loods.			X		
6	The wing shall prevent the stall		X			

Wing Incidence: 1deg

AR: 2

Wing Sweep Angle: 80deg

Dihedral Angle: 1deg

TR: 0.29

Wing sweep angle

● Fixed wing sweep angle

○ Double wing sweep angle

Fig. 11: Example of Matlab GUI interface

VI. Conclusion

This work demonstrates that it is possible to carry out the conceptual design of an innovative transportation system, developing new vehicles from scratch, within a modern environment in which a complete traceability of requirements onto the design parameters is guaranteed. In particular, this paper suggests practical solutions to carry out the design of new vehicles including breakthrough innovative technologies, with a possible high impact on the overall vehicle architecture.

The analysis of the presented results reveals that if high level requirements, coming from stakeholders, mission, payload or subsystems integration needs can be directly associated to specific design parameters, design risk and development time and costs will be dramatically reduced. A quantification of the advantages will be further analyzed.

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