High level requirements impact on configuration trade-off analyses in a multidisciplinary integrated conceptual design methodology

High Level Requirements impact on Configuration trade-off analyses in a multidisciplinary integrated conceptual design methodology

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This paper aims at suggesting rational algorithms for the selection of general characteristics of trans-atmospheric vehicles, such as the staging and propulsive strategies, take-off and landing solutions and aero-thermodynamic configurations. The presented selection algorithms exploit different types of high level requirements coming from Stakeholders' Analysis, Market Outlook, Regulatory Framework Analysis and Strategic Plan, to support drivers and criteria definition process for the selection of the optimal solution among the alternatives. The theoretical description of each single algorithm is supported by the results obtained from the application of the methodology to a suborbital vehicle aimed at parabolic flight and to a point-to-point hypersonic transportation system. Eventually, suggestions for on-going software implementation of the algorithms as well as their integration within a complex conceptual and preliminary design workflow are provided.

I. Introduction

This paper aims at suggesting useful algorithms to support the vehicle architecture definition process of innovative aerospace vehicles. It could be very useful to notice that design, besides being an exciting, challenging, satisfying and rewarding activity, it can be considered a more advanced version of problem-solving technique[1]. Differently from the general procedure for solving a mathematical problem, Design is not straightforward, being a much more subjective endeavor where a single "correct" answer is rarely present. Mathematical and science problems are well-posed in a compact form, meaning that the solutions to each problem are unique and compact, and they have an identifiable closure. However, a real-world engineering design problem does not share these characteristics, and it is usually not well-posed, i.e. it has not a unique solution, and open-ended. Following the definition of Engineering Design, proposed by the Accreditation Board of Engineering and Technology (ABET), "Engineering design is the process of devising a system, component, or process to meet desired needs. It is a decision making process (often iterative), in which the basic sciences and mathematics and engineering sciences are applied to convert resources optimally to meet a stated objective. Among the fundamental elements of the design process are the establishment of objectives and criteria, synthesis, analysis, construction, testing, and evaluation."

For this reason, a proper integrated methodology to support the design process with a proper rational, is required, especially in the very preliminary phase, where decisions about the general vehicle configuration should be taken. Furthermore, considering the very high-level of integration and complexity that will characterize future aerospace vehicles, the innovative design methodology should deal with multidisciplinary issues in order to allow proper integration levels and should be supported by a well-structured requirements management. This last aspect is absolutely necessary to target important reductions in the number of design iterations, with consequent time and cost savings[2, 3, 4].

Consequently, an innovative design methodology to support the high-level trade-offs in terms of vehicle configuration is presented in Section II. Then, Section III focuses on the specific topic of architecture definition for

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hypersonic transportation systems. In particular, after collecting and describing the major alternatives, the paper suggests specific trade-off algorithms and related results for the selection of the best staging strategy, propulsive strategy, take-off and landing strategies and aerothermodynamic configurations. Of course, the selection of the configuration from a qualitative standpoint should also be supported by the first high level numerical investigations. This peculiar aspect of the methodology, is presented in Section IV. Eventually conclusions are reported together with some ideas for further methodology enhancements.

II. Overall Design Methodology Overview

This section aims at providing an overview of the overall design process suitable for a very preliminary architecture definition of an innovative and very complex aerospace system. In particular, it focuses on the very first part of an integrated design methodology that aims at deriving Mission Concepts and Architectures starting from the highest level analyses. Starting from a detailed analysis of the Stakeholders (Fig.1) to understand who they are and what are their major needs, the hypothetical scenario is bounded by considering trends of the latest market forecasts and the regulatory framework in which the project is supposed to be operated.

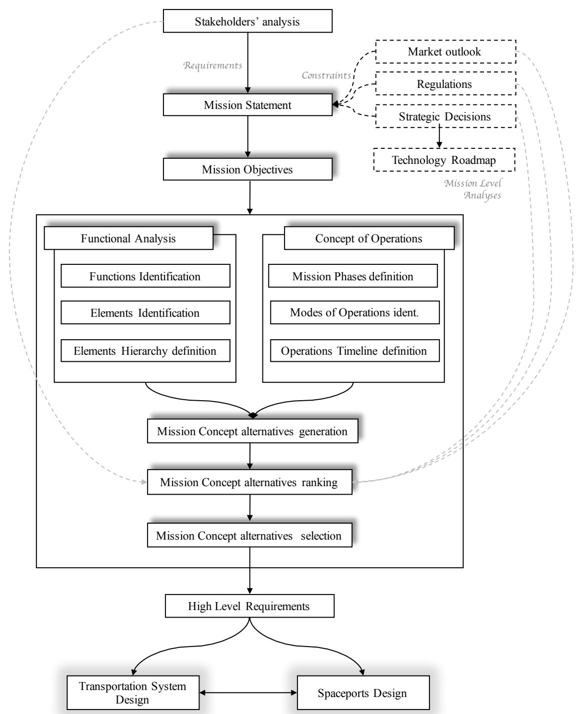


Fig.1 From stakeholder analysis to high level requirements generation

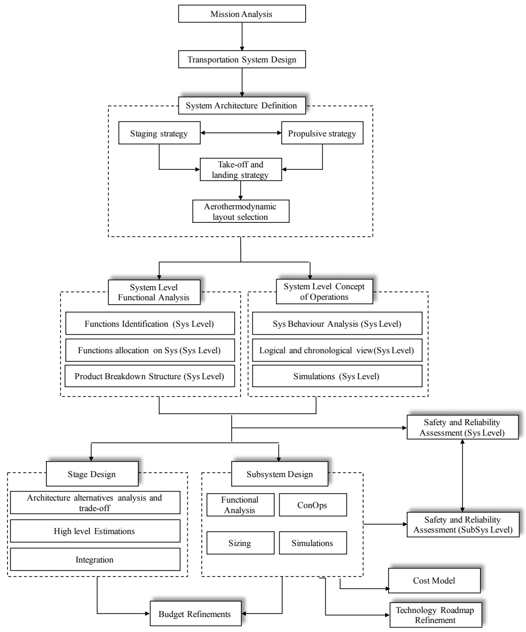


Fig.2 From mission analysis to subsystems design and validation

In addition, in order to define and formalize the purpose of the mission through the Mission Statement, possible constraints coming from high-level strategic decisions should be considered. Then, once the major objectives have been derived, following a Systems Engineering (SE) approach, functional analysis and concept of operation techniques can be exploited to generate a very high number of possible alternatives to accomplish the envisaged objectives. Of course, the feasibility of each concept should be properly investigated with a consequent pruning of the generated alternatives. It is clear that the methodology leads the designer to move from a qualitative to a more quantitative approach, as soon as the first data will become available. For this reason, trade-off analysis with the support of simulations is proposed and integrated within the workflow summarized in Figure 2. This flowchart aims at summarizing the major steps of the process proposed in this chapter, providing also useful elements to understand the major relationships of the activities analyzed in this contest with those that will be carried out following design steps.

III. Hypersonic Transportation System: Architecture Definition

Considering all the past and currently under-development projects, it is very difficult to find a unique parameter for the classification of vehicles dealing with hypersonic speed. Indeed, depending on the specific discipline, they can be grouped following different criteria. The easiest categorizations are based on the operative environment[5] or on the maximum achievable Mach number. However, another interesting classification criterion has been proposed by Hirschel in several of his works[6, 7] and also used by other authors [8, 9]. This hybrid categorization mixes together configurational characteristics, propulsive system and mission profiles. In order to include suborbital vehicles within this classification, the following categorization is adopted:

- Re-entry Vehicles (RV)
- Winged re-entry vehicles (W-RV)
- Non winged re-entry vehicles (NW-RV)
- Ascent and re-entry vehicles (ARV)
- Orbital ascent and re-entry vehicles (O-ARV)
- Suborbital ascent and re-entry vehicles(SO-ARV)
- Cruise and acceleration vehicles (CAV)

A. Staging Strategy Definition

The number of stages of a transportation system is a macroscopic element of the layout that can be easily recognized at a first look of the system. Conversely, the staging strategy is more complex to be understood, requiring an integrated view of the vehicle's stages, its main subsystems and the overall mission profile. For this reason, the number of stages is only one of the main parameters to be considered. In addition, the staging strategy is also affected by others factors and one of the most evident is the way in which the propulsive and propellant systems are integrated and exploited along the mission.

1. Staging configuration alternatives

Considering the number of stages, looking at different configurations emerged during the aerospace history, referring to both past and currently under development initiatives, the following categories can be identified:

- Single stage: in this case, the Transportation System consists of a single vehicle that should contain all the subsystems enabling all the capabilities required to reach the mission objectives. The case of a fully reusable single stage vehicle could be considered the “ideal” configuration. It would be very similar to a conventional aircraft, especially from the point of view of the on-ground operations and logistic, avoiding the technical additional complexities related to the integration of more stages and diminishing the risk connected to the separation phase. Conversely, the major drawback of such configuration might be related to the higher take-off gross weight. Rocketplane, for example, is currently trying to overcome this problem with its concept vehicle Pioneer. It aims at diminishing the fuel mass stored on-board, proposing an air-refueling. In this way the maximum take-off gross weight can be drastically reduced as well as the risk of incidents at take-off related to the on-board presence of dangerous propellant. Of course, a proper Technology Readiness Level (TRL) should be reached in the field of air-refueling of liquid hydrogen propellant. Moreover, it is also important to consider that the introduction of additional in-flight operations, is not only affecting the vehicle itself, but it can also have a deep impact of the spaceport design and location selection as it would be explained in the following subsection.
- Two stages: It is considered the best compromise between weight reduction and increase in complexity. In this paper, in case of a Two stages configuration, the authors will refer to the overall integrated vehicle as the Transportation System, consisting of a first stage referred to as carrier and a second stage that is the vehicle that really perform the mission operations and, for this reason, usually referred to as the primary stage. Among all the past and currently under-development initiatives, there are concepts in which the carrier vehicle is a commercial operative aircraft (civil or military). This is a commercial choice aimed at minimizing costs, devoting all the economic and technical efforts at the design and development of the primary stage. This could also be a good solution especially in case of demo or test missions. In a Two Stages transportation system, different propulsive strategies could be envisaged and Fig.3 summarizes the possible alternatives. Some of the configurations, resulting from the direct composition of staging strategy and propulsive strategy, are clearly unfeasible from the technical point of view. In particular, two of them don’t seem to be reasonable alternatives. The first is the Conf. 3.1, that consists of a configuration hosting the propulsion system in the second stage only with the possibility of using it only when attached to the first stage containing the necessary propellant. The only case of application could be the one in which the first stage is a sort of expendable tank and the capability to host the engine in the second stage can allow a great saving in terms of costs (construction and operations). The second not very practical configuration is Conf. 1.2 that proposes a first stage with propulsive element only and a complete second stage. This configuration requires the second stage to host all the amount of propellant required to feed both stages, with undesirable increase in the second stage mass. A part from these configurations, differently from the first stage that could really have different design alternatives, only the second stage could be either an autonomous vehicle (with engines and tanks) or a vehicle without any propulsive capabilities performing an unpowered re-entry (Conf. 2.4). In this case, the first stage should obviously be autonomous providing all the capabilities to allow the vehicle to reach the desired target altitude. This is exactly the case of IXV mission. A similar case is the one (Conf. 3.2) in which the powered first stage is associated to a second that acts as tank. In this case, the optimal strategy should be the one in which before the separation, a propellant transfer should guarantee a re-filling of the tank of the second stage. Another interesting alternative is the one in which both the stages have propulsive capabilities (Conf. 2.2). In this case, in order to save costs and allow services on regular bases, the most convenient case is the one of a fully reusable transportation system. In this case the second stage is really optimized for its peculiar mission. Conf. 3.1 is the one in which the first stage acts as an over-boost for the very first phases of the missions. Please note that in this case, the tanks of the second stage should be sized considering the overall mission profile and not only the trajectory legs following the separation. This has the only advantage of a simplified configuration, as far as the first stage is concerned, limiting the impact in terms of mass related to the additional engines required to fulfil the take off and climb requirements.
- Three stages: This configuration has only few examples of conceptual design activities mainly carried out in the Soviet Union. The increased number of stages implies higher level of complexity and costs but can allow to

increase the maximum altitude and payload capabilities, desirable aspects for the missions devoted to enhance the access to space possibilities but difficult to be implemented in suborbital or a point-to-point mission.

2. Staging strategy trade-off

Considering all the identified feasible configurations, a trade-off analysis can be carried out in order to properly select the best design alternative with respect to the mission that these vehicles should perform together with the major stakeholders' expectations. To perform a valuable trade-off, it is fundamental to identify the major elements that may impact on the selection of the optimal staging strategy. In addition, to evaluate the best option, three Figures of Merit (FoMs) have been combined together: Complexity, Cost and Safety.

Then, for each of the identified FoMs, an impact analysis has been carried out, trying to understand the impact of the design parameters on them. This qualitative approach helped the authors in mapping the impact of the design parameters on each FoM, paving the way for the derivation of a hypothetical mathematical formulation of the FoM.

For the sake of clarity, Table I reports an example of the impact analysis carried out for the Complexity FoM.

		First Stage			
		Propulsive System only	**Propulsive Sys and Propellant Sys(existing carrier)**	**Propulsive Sys and Propellant Sys (To be developed)**	**Propellant System only**
Second Stage	**Propulsive System only**	Unfeasible	Unfeasible	Unfeasible	Conf. 3.1
	Propulsive Sys and Propellant Sys	Conf. 1.2	Conf. 2.2 (a)	Conf. 2.2 (b)	Conf. 3.2
	Propellant System only	Unfeasible	Unfeasible	Unfeasible	Unfeasible
	No Propulsive and No Propellant systems	Unfeasible	Conf. 2.4 (a)	Conf. 2.4 (b)	Unfeasible

Fig.3 Staging strategies

Table I. Impact analysis of Design parameters on the staging strategy selection

Figure of Merit	**Design Parameters impacting on the FoM evaluation**	**Comments**
Complexity	Number of stages	The number of stages deeply affect the complexity of the transportation system with an impact that is proportional to the number of stages that should be ad-hoc designed and built.
	Presence of propulsive system on each stage	The propulsive subsystem is one of the most complex in a hypersonic transportation system and it is a key factor for the definition of the complexity of the spaceplane. The presence of engines in a stage is also impacting on the maintenance and logistic activities required and on the related turn-around time.

	Presence of propellant tanks on each stage	The presence of propellant requires the construction and integration of tanks in the stage. The impact on the complexity is relevant even if lower wrt the propulsive system.
	Presence of cross-feed between stages	In case of a multi-stages vehicle, the presence of tank in both stages can require the construction of proper cross-feed subsystems. This could be very impacting on the complexity of the overall transportation system.
	Exploitation of existing first stage	The exploitation existing stages diminishes the complexity of the design and the development of the vehicle.
Cost	Number of stages	The cost is proportional to the number of stages that should be ad-hoc developed.
	Presence of propulsive system on each stage	The propulsive system is one the major component of cost for a vehicle. Different costs should be taken into and they are related in various ways to all the design phases and to the different maintenance and logistic activities to be carried out on ground.
	Presence of propellant tanks on each stage	The presence of propellant tanks on each stages can enhance the cost due to the need of cross-feed and the deep impact on the additional maintenance activities that are required to the subsystems after each mission.
	Exploitation of existing first stage	The exploitation of already existing vehicles able to act as first stage can drastically reduce the cost of design and development of the transportation system. Considering the costs related to the operations of an existing first stage, the impact can be both positive or negative depending on the exploitation of a commercial aircraft or an expendable rocket.
Safety	Number of stages	The number of stages impacts on the safety, guaranteeing the possibility for the passenger compartment or the payload bay, to be separated from the rest of the transportation system. In reality, as it is detailed in Chapter 6, the single stage configuration can also be improved from the point of view of the safety, in different ways and the most promising one seems to be the design of a cabin escape system.
	Presence of propulsive system on each stage	The presence of a propulsive system in a stage guarantees additional manoeuvrability, enhancing the capability of surviving in case of emergency.
	Presence of propellant tanks on each stage	On the contrary with respect to the presence of a propulsive system, the on-board propellant is always considered a risk element for the passengers.

Following the same approach for all the FoMs, the following mathematical formulations have been conceived.

$$Complexity = C_{b1} n_{stages} \cdot \left[1 - (1 - j)\left(\frac{1}{n_{stages}}\right)\right] + k_e \left(\sum_{i=1}^{n_{stages}} j_i e_i\right) + k_{t1}\left(\sum_{i=1}^{n_{stages}} t_i\right) + jk_{t2}\left(1 - \prod_{i=1}^{n_{stages}} t_i\right)$$

where:

C_{b1} is the basic level of complexity;

n_{stages} is the overall number of stages of the configuration;

i is an index representing each single stage;

e_i is a variable that indicates the presence of the propulsive system in the *i*-esim stage.

$e_i = 1$ means that the i-esim stage hosts a propulsive system
$e_i = 0$ means that the i-esim stage has not got a propulsive system
t_i is a variable that indicates the presence of the propellant system in *i*-esim stage.
$t_i = 1$ means that the i-esim stage hosts a propellant system
$t_i = 0$ means that the i-esim stage has not got a propellant system
k_e is a weighting factor that shows the impact of the propulsive system on the complexity FoM.
k_{t1} is a weighting factor that shows the impact of the propellant system on the complexity FoM.
k_{t2} is a weighting factor that shows the impact of the presence of cross-feed on the complexity FoM.
j is a *"switching"* variable that indicates the presence of already developed stages.
$j = 1$ means that all the stages should be properly designed and developed.
$j = 0$ means that the first stage is already existing.
j_i is a *"switching"* variable that indicates the presence of propulsion systems in already developed stages.
j_2 is always equal to 1 meaning that the second stage propulsion system should bead-hoc developed.
$j_1 = j = 0$ means that the propulsion system is related to an existing first stage.
$j_1 = j = 1$ means that the propulsion system is related to a first stage that should be developed yet.

$$Cost = C_{b2} n_{stages} \cdot \left[1 - (1-j)\left(\frac{1}{n_{stages}}\right)\right] + k_e\left(\sum_{i=1}^{n_{stages}} e_i\right) + k_{t1}\left(\sum_{i=1}^{n_{stages}} t_i\right)$$

where:

C_{b2} is the basic level of cost;
n_{stages} is the overall number of stages of the configuration;
i is an index representing each single stage;
e_i is a variable that indicates the presence of the propulsive system in the *i*-esim stage.
$e_i = 1$ means that the i-esim stage hosts a propulsive system
$e_i = 0$ means that the i-esim stage has not got a propulsive system
t_i is a variable that indicates the presence of the propellant system in *i*-esim stage.
$t_i = 1$ means that the i-esim stage hosts a propellant system
$t_i = 0$ means that the i-esim stage has not got a propellant system
k_e is a weighting factor that shows the impact of the propulsive system on the cost FoM.
k_{t1} is a weighting factor that shows the impact of the propellant system on the cost FoM.
j is a *"switching"* variable that indicates the presence of already developed stages.
$j = 1$ means that all the stages should be properly designed and developed.
$j = 0$ means that the first stage is already existing.

$$Safety = S_b + \left(\sum_{i=1}^{n_{stages}} k_{ei} e_i\right) - k_{t1}\left(\sum_{i=1}^{n_{stages}} t_i\right)$$

S_b is the basic level of cost;
n_{stages} is the overall number of stages of the configuration;
i is an index representing each single stage;
e_i is a variable that indicates the presence of the propulsive system in the *i*-esim stage.
$e_i = 1$ means that the i-esim stage hosts a propulsive system
$e_i = 0$ means that the i-esim stage has not got a propulsive system
t_i is a variable that indicates the presence of the propellant system in *i*-esim stage.
$t_i = 1$ means that the i-esim stage hosts a propellant system
$t_i = 0$ means that the i-esim stage has not got a propellant system
k_{ei} is a weighting factor that shows the impact of the propulsive system of each single stage on the cost FoM.
k_{t1} is a weighting factor that shows the impact of the propellant system on the cost FoM.

The trade-off is carried out considering that all the three FoMs play a significant role in determining the optimal staging strategy. In particular, the following formulation can be adopted:

$$T.O. = \frac{K_1 \cdot safety}{K_2 \cdot complexity + K_3 \cdot cost}$$

Depending on the need or the performances expected by the stakeholders, the three FoMs can have a different impact on the selection of the optimal staging strategy. For this reason, the following table provides the results obtained for the basic case in which all the FoMs are supposed to have the same impact on the selection of the optimal solution. Moreover, in order to evaluate the consistency of the results with the variation of the weighting factors, different test cases have been carried out. The hypotheses about the weighting factors and the results are reported in Table 2. As it is possible to notice, the variation of weighting factors is not affecting the ordered list of the configuration, suggesting the two stages configuration exploiting an existing vehicle as first stage as the optimal staging strategy.

Table II Trade-off results for the staging strategy selection

	Weighting Factor			Single Stage	Two Stages				
	K_1	K_2	K_3		Conf. 2.2 (a)	Conf. 2.2 (b)	Conf. 2.4 (a)	Conf. 2.4 (b)	Conf. 3.2
Case 1	*0,33*	*0,33*	*0,33*	0,51	0,43	0,23	0,45	0,23	0,23
Case 2	*0,5*	*0,25*	*0,25*	1,03	0,87	0,46	0,91	0,45	0,47
Case 3	*0,25*	*0,5*	*0,25*	0,35	0,29	0,15	0,31	0,15	0,16
Case 4	*0,25*	*0,25*	*0,5*	0,34	0,29	0,15	0,3	0,15	0,16

B. Propulsive strategy

Referring to the observation done by H. J. Allen in 1958[10] ,it is easy to be understood that the propulsive strategy shall be properly investigated as soon as the mission profile has been defined. It is crystal clear that the selection of the most suitable propulsive system is strictly related to two major aspects of the mission profile: the operative environments and the maximum expected Mach number. In particular, in case of hypersonic and trans-atmospheric vehicles, due to wide range of speed regimes and the different operative environments that shall be considered within each single mission, an integrated propulsive strategy may be adopted, combining together different propulsive technologies to be exploited to operate the vehicle during the different mission phases. Taking a look at the current status of the propulsive technologies that could be exploited in the field of hypersonic and trans-atmospheric vehicles, it is possible to notice that both rocket and air-breathing propulsion systems may be exploited.

1. Propulsive configuration alternatives

As far as rocket-based propulsion is concerned, liquid, hybrid and solid rocket may be employed. Complementary, looking at the more various world of air-breathing propulsion, both turbojet and turbofan can be theoretically exploited at the beginning of the mission profile, but they need to be supported by additional propulsion subsystems in order to reach the desired Mach numbers. In particular, Ramjet and Scramjet will be adopted. It is easy to be understood that depending on the Maximum achievable Mach number and the altitude at which a certain Mach number shall be reached, different propulsion subsystems will be exploited together. Figure 4 summarizes the major propulsive strategy alternatives.
It is worth noting that many currently under-development research activities in the field of hypersonic speed propulsion are focused on integrating within single components different propulsive technologies. Some of them have a long historical path coming back up to the Second World War. They are known as combined cycle or composite engines. Among the most relevant initiatives, it is useful to remember

- The Air Turbo Ramjet (ATR) a composite engine that behaves like a turbojet at very low speeds and as a rocket engine at higher speeds. Depending on the different applications, several variations on the theme have been developed, like:
    - the turbo ramjet rocket
    - the supercharged ejector ramjet (SERJ)
- The Dual Mode Ramjet (DMR)[12] is a ramjet engine which can operate in both subsonic and supersonic combustion mode.
- Rocket Based Combined Cycle (RBCC)
- Turbine Based Combined Cycle (TBCC)

Other entirely separate classes of air-breathing engines specifically developed for the hypersonic application are the Liquid Air Cycle Engine (LACE) and the Inverse Cycle Engine. However, due to the relatively very low technology maturation. However, future technological developments will provide the designer to include these propulsion systems within the set of eligible technologies.
The definition of the propulsion system shall be carried out properly selecting the best alternative for the different mission phases and trying to exploit the lowest number of different propulsive subsystems that can allow to fulfil all the mission requirements maximizing some Figures of Merit, such as the cost, the complexity and the overall vehicle mass (both dry and wet). Indeed, different types of combined propulsive cycles are currently under investigations. It is clear that the selection of the proper propulsion system architecture can not only be perform on the basis of some qualitative considerations, but it is important to include some high level performances within the selection process. In particular, the minim and the maximum achievable Mach number, the specific impulse, the thrust level and the current TRL shall be properly considered

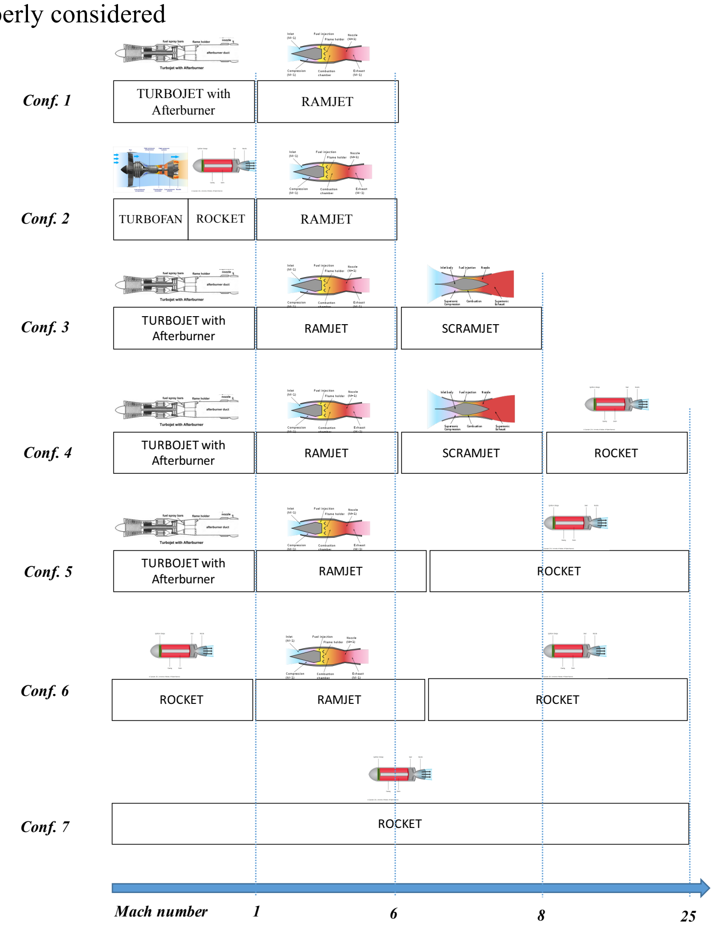


Fig.4 Propulsive architecture alternatives

2. *Propulsive configuration trade-off*

The trade-off methodology here suggested for the selection of the optimal propulsive configuration, is a little bit different from the one used for the staging strategy. In particular, in order to rationalize the selection process, the following logical steps have been followed:

1. Elicitation of the requirements with the highest impact on the propulsive strategy selection
2. Definition of the technical areas and technical aspects that will impact on the selection process. (See Table III)
3. Definition of the weighting criteria (See Table IV)
4. Alternatives scoring process (See Table IV)
5. Trade-Off (See Table V)

Table III. Impact analysis of Design parameters on the propulsive strategy selection

Areas of Interest	Drivers	Impact on the propulsive strategy selection
Weight and Balance	• Number of different propulsion systems	The highest is the number of different propulsion systems, the highest the dry mass associated to the overall dry mass. In case of different propulsion systems fully integrated within a single propulsive element, a reduction factor may be considered.
	• Wall temperature	The wall temperature is an optimal indicator of the mass increase due to the need of active cooling and thermal protection systems.
	• Presence of rotating machinery	The presence of rotating machinery is undoubtedly contributing to increase the mass and the complexity of the overall vehicle.
	• Presence of oxidizer	The need of carrying proper oxidizer on-board, increases the overall mass of the vehicle, affecting both the dry and the wet mass.
Operations	• Re-start capability	The possibility for a propulsion system to be restarted allows to enlarge the operative scenarios.
	• Throttling capability	The possibility of playing with the thrust module allows to enlarge the ranges of application of this propulsive system
	• Maximum Operative Mach number	The maximum operative Mach Number defines the possibility of exploiting a certain propulsive system in each single mission phases.
	• Thrust Vectoring capability	The possibility of guaranteeing a Thrust Vectoring allows perform vertical/short take-off and landing
Maintenance	• Number of different propulsion systems	The highest is the number of different propulsion systems, the highest will be the maintenance actions required. In case of a highly integrated solutions, this value can also be increased. In addition, it increases the need of additional specialized technicians to carry out the maintenance actions.
	• Wall Temperature	The wall temperature is an indicator of the criticalities that characterize propulsion system structure and material. Indeed, the highest is the wall temperature, the heaviest will be the required maintenance actions.
	• Presence of rotating machinery	The presence of rotating machinery increases diminishes the reliability of the system, theoretically. In order to keep it constant, additional maintenance actions will be required.
	• Propellant type	The type of propellant used by the several different types of engines increases the need of additional specialized technicians to carry out the maintenance actions. Moreover, the maintenance actions will be required more frequently. However, this is a more detailed choice that could be perform later on in the design process.
	• Presence of Oxidizer	The presence of on-board oxidizer will require additional maintenance actions

Table IV Drivers evaluation for the different propulsive configurations

	Drivers	C1	C2	C3	C4	C5	C6	C7
		TJ with AB Rocket	*TF Rocket Ramjet*	*TJ with AB Ramjet Scramjet*	*TJ with AB Ramjet Scramjet Rocket*	*TJ with AB Ramjet Rocket*	*Rocket Ramjet Rocket*	*Rocket*
Weight and Balance	[A1] Number of different propulsion systems	2	3	3	4	3	3	1
	[A2] Wall temperature	M(5)	H(10)	H(10)	H(10)	M(5)	M(5)	M(5)
	[A3] Presence of rotating machinery	1/2	1/3	1/3	1/4	1/3	0	0
	[A4] Presence of oxidizer	1/2	1/3	0	1/4	1/3	2/3	1/1
Operations	[B1] Re-start capability	M(5)	L(3)	M(5)	M(5)	M(5)	L(3)	V(1)
	[B2] Throttling capability	M(5)	L(3)	M(5)	M(5)	M(5)	L(3)	V(1)
	[B3] Maximum Operative Mach number	6	6	8	25	25	25	25
	[B4] Thrust Vectoring capability	Y(1)	N(0)	Y(1)	Y(1)	Y(1)	N(0)	N(0)
Maintenance	[C1] Number of different propulsion systems	2	3	3	4	3	3	1
	[C2] Wall Temperature	M(5)	H(10)	H(10)	H(10)	M(5)	M(5)	M(5)
	[C3] Presence of rotating machinery	1/2	1/3	1/3	1/4	1/3	0	0
	[C4] Presence of Oxidizer	1/2	1/3	0	1/4	1/3	2/3	1/1

In order to evaluate the best alternative in terms of propulsive strategy, the different Figures of Merit listed in the previous table have been combined as follows:

$$TO = -K_A * \sum (A_i)_n + K_B * (B_i)_n - K_C * \sum (C_i)_n$$

where

TO is the global FoM

K_A is the weighting factor taking into account the impact of weight & balance area of interest on the selection of the propulsive strategy. The minus sign is due to the fact that the characteristics afferent to this area of interest are playing against it.

K_B is the weighting factor taking into account the impact of maintenance area of interest on the selection of the propulsive strategy.

K_C is the weighting factor taking into account the impact of operations area of interest on the selection of the propulsive strategy. The minus sign is due to the fact that the characteristics afferent to this area of interest are playing against it.

$(A_i)_n$ is the normalized estimation obtained as $\frac{A_i}{\max(A_i)}$.

$(B_i)_n$ is the normalized estimation obtained as $\frac{B_i}{\max(B_i)}$.

$(C_i)_n$ is the normalized estimation obtained as $\frac{C_i}{\max(C_i)}$.

As it is possible to notice in Table V, different weighting strategy have been tested, performing a sort of sensitivity analysis of the results. The solution provides to be robust enough. Indeed, the configuration with the highest scoring results is always the configuration that will exploits in series: a Turbojet with afterburner, a ramjet and a rocket technology. Depending on the weighting strategy adopted, the second and the third suggested strategies may vary.

It is clear that, depending on the specific case study, some tuning of the inserted value should be performed. In particular, as it will be clearly demonstrated with the help of the case-study, some high level stakeholders' requirements or other high level mission constraints can prevent the designer to consider one or more of the proposed configurations.

Table V Trade-off results for the selection of the propulsive strategy

Weighting Factor			**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**
K_A	**K_B**	**K_C**	*TJ with AB Rocket*	*TF Rocket Ramjet*	*TJ with AB Ramjet Scramjet*	*TJ with AB Ramjet Scramjet Rocket*	*TJ with AB Ramjet Rocket*	*Rocket Ramjet Rocket*	*Rocket*
1/3	*1/3*	*1/3*	-0,59	-1,35	-0,64	-0,63	-0,17	-0,54	-0,70
1/2	*1/4*	*1/4*	-1,07	-1,70	-1,08	-1,16	-0,69	-0,89	-0,96
1/4	*1/2*	*1/4*	0,37	-0,66	0,25	0,43	0,88	0,14	-0,18
1/4	*1/4*	*1/2*	-1,07	-1,70	-1,08	-1,16	-0,69	-0,89	-0,96

C. Take-off and landing strategy

As far as take-off and landing strategy is concerned, it has to be noticed that two main option can be available: traditional horizontal take-off and landing of vertical take-off and landing. In particular, in this section, the results (Tab. VI) of the application of an approach very similar to the one suggested in the previous sections, are presented, focusing on the selection of different strategies for the vertical take-off, because these are the most impacting on the vehicle architecture. In the following Table, the trade-off results are summarized. Please, notice that:

K_A is the weighting factor taking into account the impact of accommodation area of interest;

K_B is the weighting factor taking into account the impact of aerodynamic and aero-thermo-dynamic;

K_C is the weighting factor taking into account the impact of structure;

K_D is the weighting factor taking into account the impact of operations;

K_E is the weighting factor taking into account the impact of stability and control;

K_F is the weighting factor taking into account the impact of logistics and maintenance.

Table VI Trade-off results for the selection of the take-off and landing strategy

Weighting Factor						C1	C2	C3	C4	C5	C6	C7	C8	C9
K_A	K_B	K_C	K_D	K_E	K_F	*Tail Sitting*	*Vectored Trust at CG*	*Tilt Nacelle at CG*	*Un-augmented flow*	*Tip driven fan*	*Ejectors*	*Separate Lift Engines*	*L+L/C vectored*	*L+L/C tilt nacelles*
1/6	***1/6***	***1/6***	***1/6***	***1/6***	***1/6***	-0,59	-0,33	-0,57	-0,43	-0,38	-0,48	-0,17	-0,33	-0,57
1/12	***1/2***	***1/12***	***1/12***	***1/12***	***1/12***	-0,04	0,42	0,30	0,37	0,64	0,34	0,75	0,08	-0,03
1/12	***1/12***	***1/2***	***1/12***	***1/12***	***1/12***	-0,71	-1,04	-1,28	-0,76	-1,03	-1,08	-0,63	-0,83	-1,41
1/12	***1/12***	***1/12***	***1/2***	***1/12***	***1/12***	-0,29	-0,17	-0,58	-0,51	-0,61	-0,53	-0,50	-0,58	-0,70
1/12	***1/12***	***1/12***	***1/12***	***1/2***	***1/12***	-1,31	-1,13	-1,41	-1,34	-1,03	-1,37	-0,79	-0,88	-1,12
1/12	***1/12***	***1/12***	***1/12***	***1/12***	***1/2***	0,25	0,67	0,55	0,49	0,64	0,63	0,75	0,96	0,97

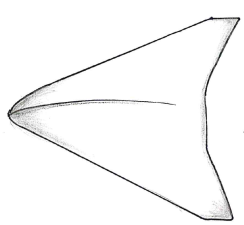
Taking a look at the results, it is possible to notice that the best option in terms of take-off and landing strategy, is strictly relate to the design aspect that the stakeholders would like to privilege. In particular, if operations would be facilitated, vectored thrust at CG seems to be the best option, while, in case the impact on maintenance would be reduced, the configuration with L+L/C with tilt Nacelles is suggested. In all the other cases, separate Lift engines appear to be the best solution, ensuring the minimum additional mass and costs, guaranteeing safety and operations.

D. Aerothermodynamic configuration

1. *Aerothermodynamic configuration alternatives*

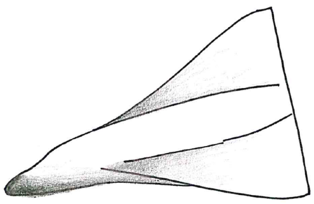
The following table aims at summarizing possible aero-thermodynamic design alternatives.

Table VII Overview of the principal aerothermodynamic architectures

Possible aero-thermodynamic	L/D	Description
Winged Vehicle (Flying Wing) *Conf. 1* 		This configuration is characterized by a high lifting surface. The fuselage is not clearly distinct with respect to the fuselage. This configuration maximizes the range in (powered or unpowered) gliding phases. This configuration is preferable in case a high number of passengers should be hosted. In this case, bubble structures can be exploited to maximize the volumetric efficiency minimizing the impact on weight. NASA is currently focusing on this kind of configuration, with the idea of resuming the heritage of some X-series projects such as the X-33. This configuration can be theoretically exploited for RVs, ,O-ARVs, SO-ARVs and CAVs.

Winged-Re-entry Vehicle (Fuselage + wing)

Conf. 2

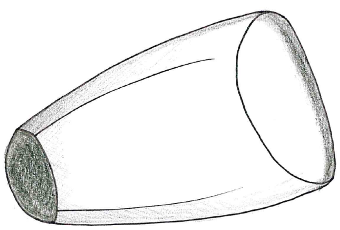


L/D > 1.4

The winged vehicle is the most traditional configuration, where fuselage and wing are clearly distinct. In this case, the passengers compartment is host within the available room in the conical section, while the wing surface is the major responsible for the aerodynamic lift generation. This configuration can be a good compromise among several mission needs. X-38, Phoenix and Hope demonstrators are examples of implementation of a winged configuration for a re-entry mission. This configuration can be theoretically exploited for RVs, O-ARVs, SO-ARVs and CAVs.

Non -Winged-Re-entry Vehicle (Lifting Body)

Conf. 3

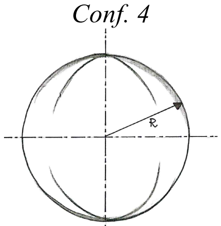


L/D = 1 – 1.4

The lifting body configuration can be considered optimal as far as the capability of withstanding the thermal loads during re-entry is concerned. On the contrary, special Guidance Navigation and Control systems should be envisaged in order to enhance the controllability of this object. In addition, it is worth noting that this configuration is more suitable in case a limited amount of payload should be transported. This configuration has been exploited for the ESA IXV project and will it is a candidate for the Space Rider vehicle. In addition to orbital re-entry, this aero-thermodynamic configuration could be envisaged for O-ARVs and SO-ARVs. Due to its aerodynamic characteristics, this configuration can hardly be exploited to perform an autonomous ascent or cruise phase.

Spherical Capsule

Conf. 4

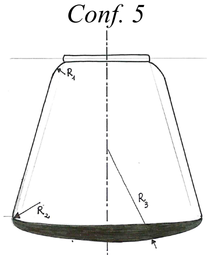


L/D = 0

The spherical shape is the simplest configuration that can be envisaged to perform a re-entry. Considering the impossibility of including flight control systems within this configuration, the spherical shape is the worst in terms of controllability and manoeuvrability. On the opposite, it can provide high volumetric efficiency with optimal weight distribution. Suitable for small number of passengers. This type of configuration, as well as all the other capsule-like configurations, is suitable for re-entry missions only.

Blunt Cone Capsule

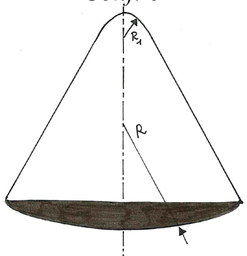
Conf. 5



L/D = 0.35 – 0.45

The blunt cone capsule is the best compromise among the aero-thermodynamic efficiency, simplicity and the volumetric efficiency. Indeed, the shape allows to make a clear division of the available volume, in a lower part, in which the major subsystems could be located and the upper part for the passengers.
This shape has been exploited by the Russian since the 1965 and they have been exploited especially for Low Earth Orbit missions. SOYUZ capsules are a clear example of blunt cone shape capsules.

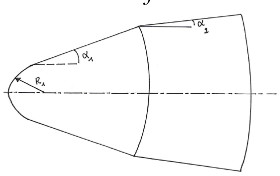
Conic Capsule
Conf. 6



L/D = 0.35 – 0.4

The conic capsule could be considered as the most aerodynamically efficient capsule and this is mainly due to the differences in the radius of the upper and lower part. From the stability point of view, this configuration has the advantages of an axisymmetric shape.
Several vehicles have been developed and manufactured in the USA. In particular, during the APOLLO project, different models flown during 1966 – 1973 period.

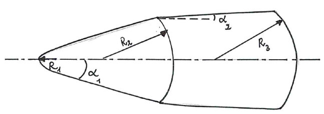
Bluff Bi-conic Capsule
Conf. 7



L/D = 0.55 – 0.7

The bluff bi-conic capsule is a shape envisaged by some German studies, in the frame of the European Crew Rescue Vehicle project.

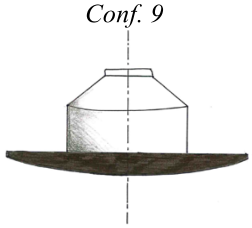
Slender Bi-conic Capsule
Conf. 8



L/D = 0.8 – 1.2

The slender bi-conic capsule has been envisaged by Russians to carry out re-entry missions from Low Earth Orbits. In addition, some Mars Lander concepts have exploited this shape.

Heatshield with Afterbody
Conf. 9



L/D = 0.2 – 0.4

This configuration allows to guarantee the capability of withstanding extreme thermal loads to non-non winged configuration. With respect to the other proposed configurations, the heatshield is not part of the main body but it is a sort of external element. Depending on the specific application, it is also possible to envisage a detachable heatshield to be operated in specific mission phases. An example of implementation of this configuration is the Viking Mars probe.

2. *Aerothermodynamic configuration trade-off*

Table VIII Trade-off results for the selection of the best Aerothermodynamic configuration

Weighting Factor				**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**
K_A	**K_B**	**K_C**	**KD**	*Flying Wing*	*Fuselage + Wing*	*Lifting Body*	*Spherical Capsule*	*Blunt Cone Capsule*	*Conic Capsule*	*Bluff bi-conic capsule*	*Slender bi-conic capsule*	*Heatshield with afterbody*
1/4	***1/4***	***1/4***	***1/4***	*1,58*	*1,58*	*1,23*	*0,63*	*0,80*	*0,80*	*0,80*	*0,98*	*0,80*
1/2	***1/6***	***1/6***	***1/6***	*1,48*	*1,48*	*1,28*	*0,75*	*0,97*	*0,97*	*0,97*	*1,08*	*0,97*
1/6	***1/2***	***1/6***	***1/6***	*1,62*	*1,62*	*1,05*	*0,28*	*0,40*	*0,40*	*0,40*	*0,62*	*0,40*
1/6	***1/6***	***1/2***	***1/6***	*1,72*	*1,72*	*1,28*	*0,62*	*0,87*	*0,87*	*0,87*	*1,12*	*0,87*
1/6	***1/6***	***1/6***	***1/2***	*1,48*	*1,48*	*1,28*	*0,85*	*0,97*	*0,97*	*0,97*	*1,08*	*0,97*

Considering the results (see Table VIII) of the trade-off analysis carried out taking into account all the drivers listed above, it is clear that from a technical perspective, the exploitation of a more traditional transportation system configuration appears to be the most promising. However, mission and vehicle concept validation should be carried out in order to verify the compliance of the selected architectures with regulations, especially with safety ones.

E. Guidelines for preliminary numerical estimations

Once that the main trade-off analyses have been completed, it is important to start a first cycle of numerical evaluations, in order to obtain the very first estimation of the most important design parameters. The flow-chart reported in Figure 5 summarizes this high level estimation process. In particular, it is possible to notice that the very first estimations are based on statistical data. They are mainly related to the high level mass estimations such as MTOM (Maximum Take-Off Mass), Fuel Mass, Empty Mass, and the first allocation in terms of fuselage, wing, landing gear and on-board systems masses. All these mass estimations will be furtherly refined. However, for some of them, especially for the fuel mass estimation (with a direct impact on both the MTOM and the empty mass), the exploitation of mission simulation will allow iteratively moving towards the most realistic value. In the following Figures, an example of statistical data elaboration is proposed. Data used can both derive from existing mathematical formulations or from continuously updated Databases like HYDAT[5]. In addition, it has to be noticed that in this phase, mission simulation has a crucial role in validating and refining results[13], allowing integrated design loops.

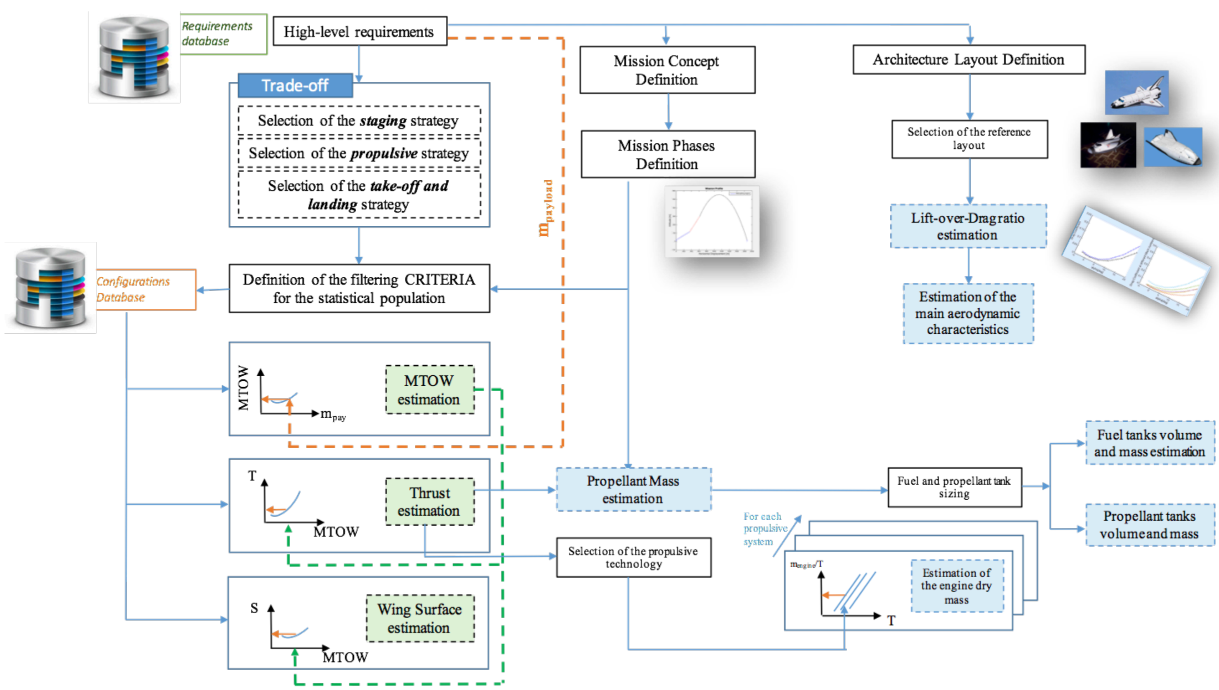


Fig.5 Preliminary numerical workflow

1. Conclusion and future works

This paper aims at suggesting the readers a proper methodology to face with the very first design step of an innovative aerospace products like a hypersonic transportation system. In particular, the authors describe algorithm to support the vehicle layout definition process, a very complex but crucial design step characterized by qualitative parameters. In this case, the suggested mathematical approach will guarantee a rationalization of the entire process, with many benefits such as the enhanced requirements traceability, design time reduction, results closer to the optimal solution and possibility of applying a multidisciplinary approach since the beginning of the conceptual design. This guarantees to reduce the design efforts and diminish the risk of selecting unfeasible mission and vehicle concepts. Moreover, in the full-length paper, a critical analysis of the results of the application of the presented methodology will be presented.

Eventually, a matrix summarizing the impact of the various high level requirements onto the different selection criteria will be presented.
In future works, the application of the methodology to the design of a suborbital vehicles aimed at parabolic flights and of a point-to-point transportation system will be presented, highlighting the flexibility of the tool, as well as validating the overall methodology.

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