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ORIGINAL PAPER

Conceptual design of a crewed reusable space transportation system aimed at parabolic flights: stakeholder analysis, mission concept selection, and spacecraft architecture definition

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Abstract This paper proposes a methodology to derive architectures and operational concepts for future earth-to-orbit and sub-orbital transportation systems. In particular, at first, it describes the activity flow, methods, and tools leading to the generation of a wide range of alternative solutions to meet the established goal. Subsequently, the methodology allows selecting a small number of feasible options among which the optimal solution can be found. For the sake of clarity, the first part of the paper describes the methodology from a theoretical point of view, while the second part proposes the selection of mission concepts and of a proper transportation system aimed at sub-orbital parabolic flights. Starting from a detailed analysis of the stakeholders and their needs, the major objectives of the mission have been derived. Then, following a system engineering approach, functional analysis tools as well as concept of operations techniques allowed generating a very high number of possible ways to accomplish the envisaged goals. After a preliminary pruning activity, aimed at defining the feasibility of these concepts, more detailed analyses have been carried out. Going on through the procedure, the designer should move from qualitative to quantitative evaluations, and for this reason, to support the trade-off analysis, an ad-hoc built-in mission simulation software has been exploited. This support tool aims at estimating major mission drivers (mass, heat loads, manoeuverability, earth visibility, and volumetric efficiency) as well as proving the feasibility of the concepts. Other crucial and multi-domain mission drivers, such as complexity, innovation level, and safety have been evaluated through the other appropriate analyses. Eventually, one single mission concept has been selected and detailed in terms of layout, systems, and subsystems, highlighting also logistic, safety, and maintainability aspects.

Keywords Conceptual design · Parabolic flights · Trans-atmospheric transportation systems · Mission analysis · Quality functional deployment tool

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1 Introduction

The increasing trend in the development of new advanced technologies, in different engineering fields, is pushing even more the humankind to reach the edge of space. In this context, not only innovative earth-to-orbit transportation systems have been recently developed, but there is also an increasing demand for sub-orbital transportation systems [1]. In fact, the capability of carrying passengers up to a meaningful target altitude is seen as a promising near-future routine service able to guarantee a high level of profits to allow microgravity experience and an amazing view of our planet. From a technical point of view, the development of a sub-orbital transportation system is regarded as an intermediate and necessary step of a longer time vision roadmap aimed at developing reusable earth-to-orbit transportation systems (from a "space" point of view) or at designing a hypersonic spaceplane (from an "aeronautical" point of view).

In this context, it is extremely important to develop an accurate design methodology able to understand and discover the high-level qualitative stakeholders' needs and desirables and to think about all the possible mission concepts able to accomplish these goals. The very fast technological development and the extremely wide number of competitors require the capability of proposing different mission concept options and a proper trade-off strategy to the customers. This paper tries to solve this problem suggesting an innovative conceptual design methodology able to guide the developers from the first stakeholders' analyses to the actual production phase. In particular, after a theoretical description of the proposed methodology and of the selected exploitable tools (Sect. 2), this approach is applied to define, prune, and select a set of mission concepts aimed at providing a sub-orbital flight service (Sect. 3). In particular, in accordance with the stakeholders desires, the mission should guarantee at least a certain number of flight participants at a time to reach a target altitude (100 km), with a spacecraft able to perform vertical take-off and landing. As the reader can easily figure out, this very demanding requirement will strongly affect and lead the development of the vehicle and will impact on the design of the overall mission. At the end of the section, an overview of the reference case study is presented. In this context, some additional details are provided with the help of CAD drawings.

2 Conceptual design methodology

This section deals with the description of a conceptual design methodology allowing engineers to take high-level decisions trying to satisfy the stakeholders' needs in the best way.

In preliminary design phases, where decisions have a deep impact on the mission from several perspectives, it is very important to persuade the customers, clearly showing the technological limits or conflicts among their requirements.

The analysis of the stakeholders' needs is the basic brick of the methodology, which could be roughly divided in two different parts:

- The mission analysis and design,
- The systems design and sizing.

The following sub-sections describe step-by-step the proposed advancements in the conceptual design

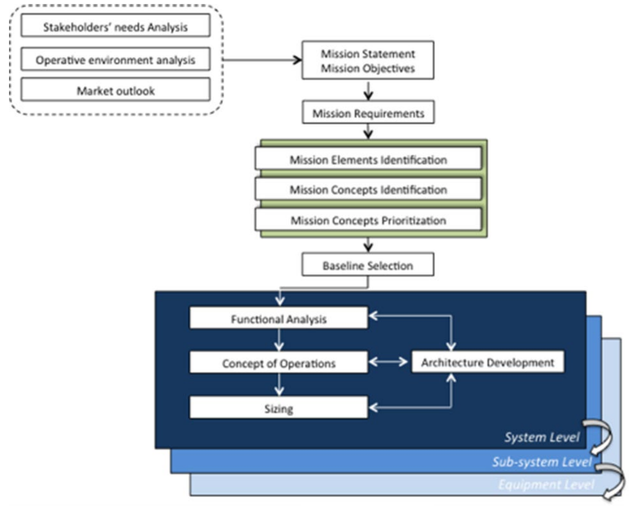


Fig. 1 Conceptual design methodology overview

methodology with respect to previous works of the authors [2, 3]. Moreover, the paper aims at suggesting tools that could be usefully employed to enhance the automation level of the proposed approach.

Figure 1 summarises the fundamental steps of the methodology proposed in this paper.

2.1 Stakeholders and other preliminary analysis

The first step of the propose methodology consists in defining and identifying the stakeholders (i.e., all those people that could be interested in the project). It is important to understand their role (funders, users, customers, etc.) their needs and their desirables. It is also important to sense and evaluate the different levels of importance of their requests. In fact, it is a very good practice to distinguish since the beginning, the constraints of the project and the other needs that could be partially satisfied or negotiated in a close cooperation between stakeholders and designers.

Following the NASA guidelines for classification [4], stakeholders can be grouped in:

- Sponsors: those associations or private who establish mission statement and fix bounds on schedule and funds availability;
- Operators: in charge of controlling and maintaining space and ground assets. Typically, they consist of engineering organizations;
- End-users: those people that receive and use space mission's products and capabilities. They are usually scientists or engineers;
- Customers: differ from the previous category, because they are users who pay fees to utilize a specific space mission's product or service.

Moreover, in this preliminary phase, it is also very important to understand the operative environment, in which the mission should be carried out, or the different geographical origins of the stakeholders and of the partners involved in the project. This analysis is focused on identifying the regulatory entities, laws, and suggestions that should be considered as a fundamental source of requirements and constraints. Nowadays, some latest issues of aeronautical regulations are so precise and detailed that can also be considered as good guide and leading methodology for a high-level sizing attempt.

In this top-level design context, it is convenient to take a look at current market trends and future forecasting. In addition to the very useful overview of the main competitors or possible additional or alternative stakeholders, the market analysis gives an overview of past, present, and future projects from which take inspirations.

Once these top-level analyses have been performed, the main objectives of the project could be defined, identifying the main goals of the mission and clearly stating them in a structured and precise way: the mission statement. According to the NASA guidelines, the mission statement is a concise and precise statement able to describe the aim of the mission. From a deep analysis of this statement and of information obtained from the previous analyses, it is possible to write down a preliminary list of top-level mission requirements. Please notice that these steps are the starting point for developing different mission concept options, selecting the best ones and performing a first system and sub-systems sizing.

2.2 Mission concept options generation and prioritization

Once the main objectives of the mission have been clarified, the developers should elaborate different ideas to accomplish the mission. Nowadays, the fast technological evolution and the even higher computational capabilities can allow considering and manage a very high number of options. One of the main benefits of these innovations is the possibility of postponing the trade-off later on in the projects, when more accurate data could be available.

This sub-section gives suggestions on how to manage the very first brainstorming activities, supporting the generation of mission concept alternatives. The proposed methodology starts from a functional view of the mission that allows identifying the different capabilities that the elements of the system of systems should guarantee. Then, looking at the existing reference missions, but also considering possible future near time evolutions, the developers should identify all the possible elements able to accomplish the defined functionalities. To carry out these two steps, typical tools developed and used for the functional analysis can be exploited. In particular, the functional tree can allow defining the main functions the mission shall perform and a function/product matrix could help to structurally define the variety of elements able to accomplish the previously deduced functions (Fig. 2).

2.2.1 Functional tree

A functional tree expresses the functions to be performed for the execution of the mission. The functional tree allows splitting the higher level and complex functions, which stem from the mission objectives, into lower level functions, through a typical breakdown process, eventually allowing the identification of the basic functions that have to be performed by the future product. Therefore, starting from the so-called top-level functions, the functional tree generates various branches, moving from the most complex functions to the basic functions, i.e., those functions at the bottom of the tree that cannot be split any further. The basic functions help defining the functional requirements of the future product, as each basic function can be rewritten as a functional requirement.

2.2.2 Function/product matrix

It allows identifying the elements or building blocks needed to accomplish the functions. Specifically, the matrix's rows contain the basic functions coming from the functional tree, while the columns report the products, i.e., the space mission elements capable of performing those functions. Starting from the analysis of the first basic functions, new elements progressively fill in the columns. Eventually, all basic products are determined. As a result, the elements to be involved in the missions are identified, by mapping all basic functions to products.

Then, it is important to group and combine the elements to derive the different mission concept options. During this process, it is also important to evaluate how well each of the different options of each single function is able to accomplish the function itself and which is its relation to all the other functions of the mission. To increase the level of autonomy of the process, the authors suggest to use the quality function deployment (QFD) tool, also known as house-of-quality.

2.2.3 Quality function deployment tool

The quality function deployment tool is a very useful design method to transform qualitative user demands into quantitative parameters, to deploy the functions forming quality and to deploy methods to achieve the design quality into sub-systems and component parts, and, ultimately, to specific elements of the manufacturing process,

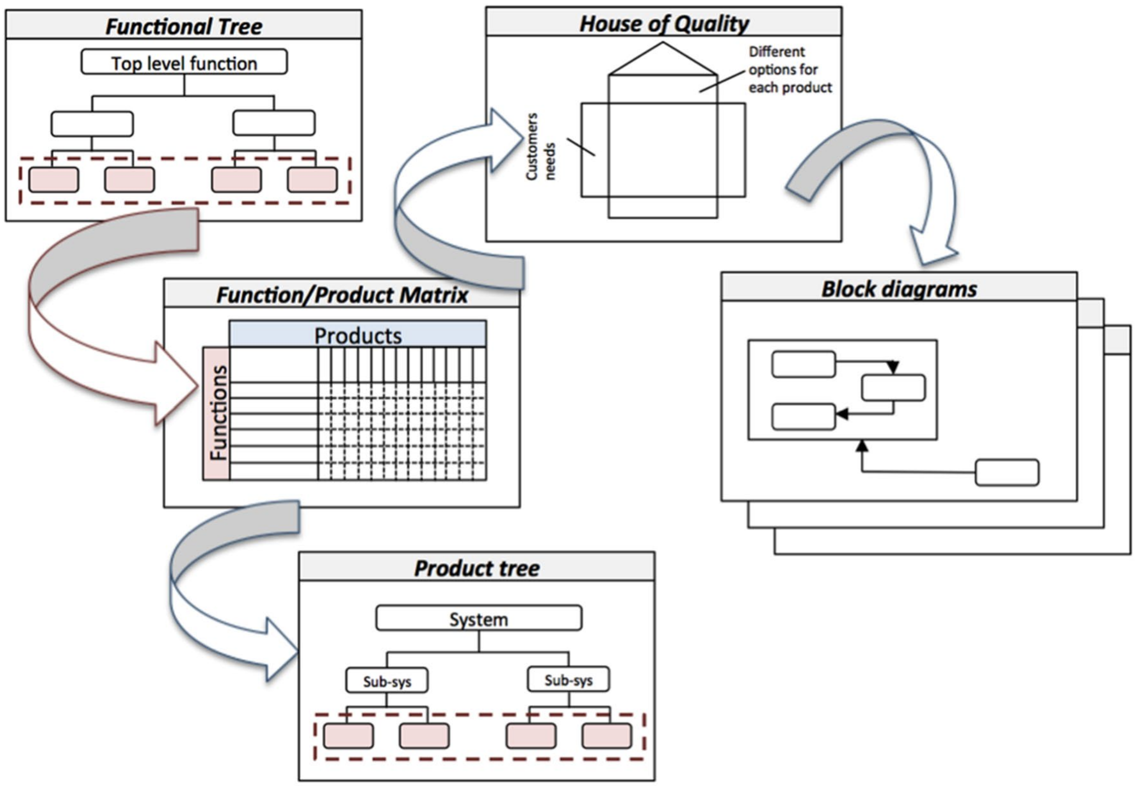


Fig. 2 Sketch of the tools of the functional analysis that can be used to derive mission elements

as described by Akao [5]. From its first theorization, this method has been applied in very different domains [6]. In particular, its become widespread exploited in many design applications, not only at top-level, but also at system and sub-system or equipment levels.

From the graphical point of view, the QFD tool is very similar to a sort of house (in fact, it is very well known has house-of-quality), with external walls, bases, and a roof.

The basic house-of-quality consists of the following parts:

- Rows definitions,
- Rows weighting factors,
- Columns definitions,
- Interaction matrix,
- Relationship matrix,
- Scores or prioritization.

Additional weighting rules or additional compartments to deduce more characteristics could be added.

It is worth to notice that the QFD has not been developed to be used as a stand-alone graphic, but its better exploitation could be obtained within a QFD tool-chain that allows obtaining suggestions for engineering parameters, starting from the top-level market analysis.

The usual sequence of QFDs, covering the overall product life cycle, is reported in Fig. 3.

The tool chain proposed in this paper and described in this and in the following sub-sections aims at providing as main output a series of prioritized mission concept options able to satisfy the top-level mission requirements. It is up to the engineers the definition of the number of options to select for the follow-on of the process. Depending on the number of personnel, budget, and time schedule, it would be convenient to carry on at least two or three different mission concepts. This could be a conservative approach, preserving from unexpected changings at geo-political, management, or economical levels. Moreover, carrying on the procedure, it is possible to obtain a list of enabling technologies from which it is possible to define development roadmaps [7–9].

The first use of the QFD in our methodology aims at discovering the importance of each top-level mission building blocks in an aerospace mission. This result can be obtained using the QFD, as outlined in Fig. 3. The rows contain the list of top-level requirements mainly obtained during the stakeholder analysis (Fig. 4). The columns contain the primary building blocks of the mission, obtained by the joint exploitation of functional tree and functions/products matrix, stopped at first level. The

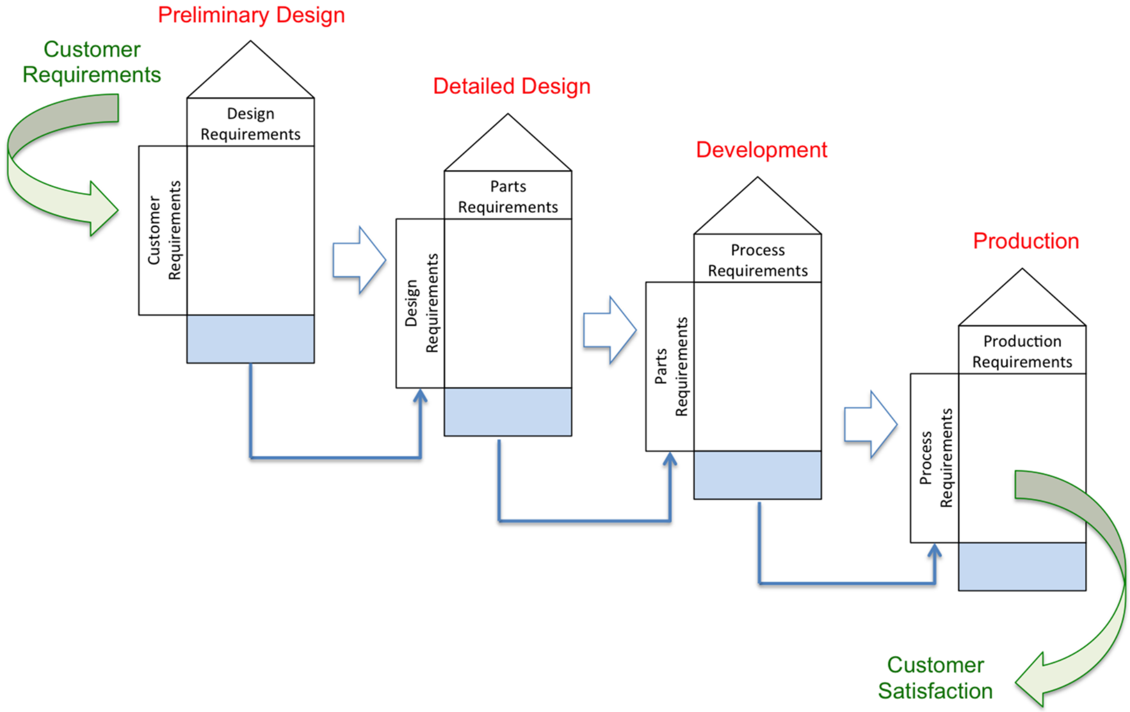
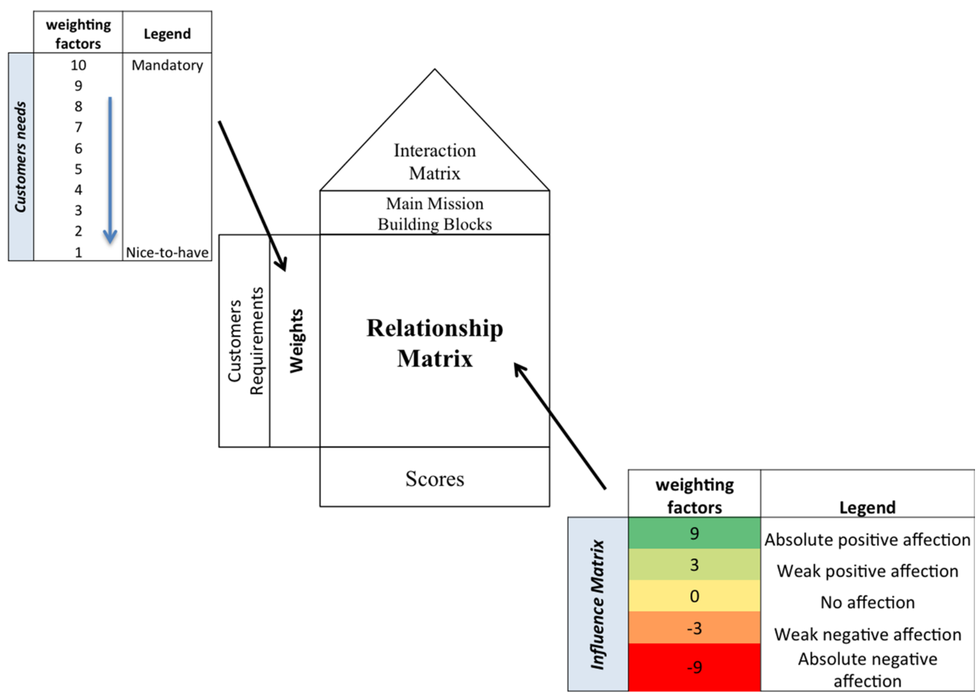


Fig. 3 QFD typical tool chain covering all the development and production phases

Fig. 4 QFD initialization



scores obtained in output give the designer an overview of the relative importance of each building block for the considered mission. This is very important not only from a pure technical point of view, but also from a managerial perspective. In fact, the building block with the highest score should be in-depth analysed, and additional efforts should be devoted to its development, in terms of personnel, resources, or budget, because it is the mission component, on which the customer requirements will have the major impact.

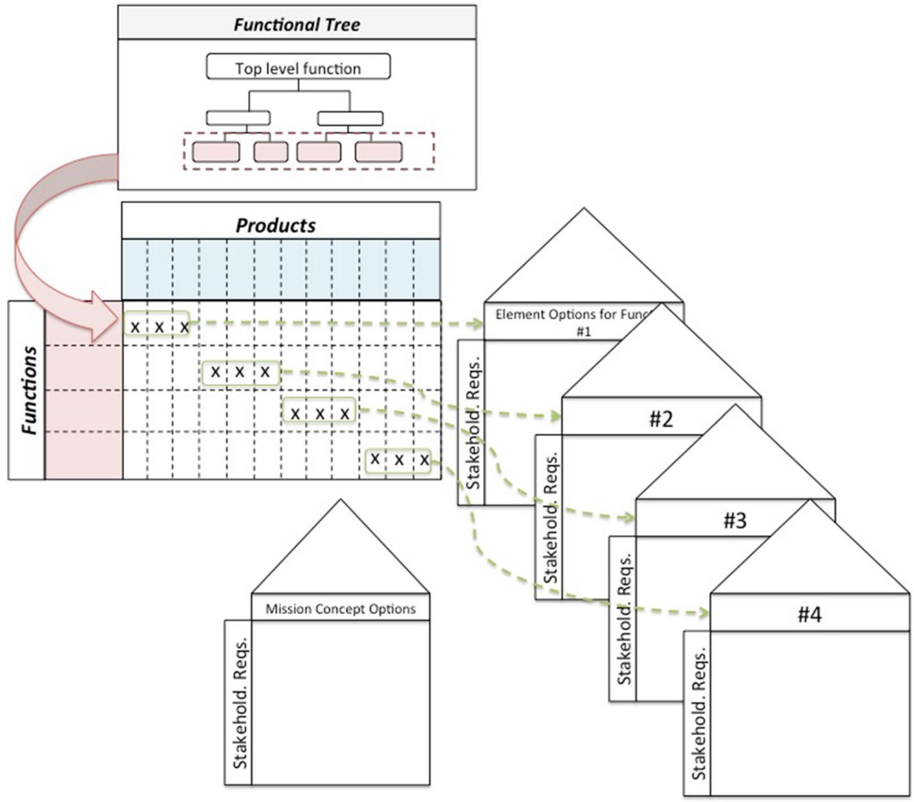


Fig. 5 From the functions identification to the mission elements prioritization

The starting point is the requirement weighting process. This activity is a direct consequence of the analyses carried out at the very beginning allowing the elicitation of the first draft list of mission requirements. Depending on the wishes of the stakeholders, the deduced requirements can have different levels of importance. In this paper, the authors suggested to weight the requirements from 1 to 10, where the maximum score is assigned to constraints and the minimum is related to low impact nice-to-have. Besides the foreseeable negligible impact of some requirements, it is useful to take them into account, because of their direct impact on some mission elements or on the overall configuration. The same reasoning is also valid for the other top-level requirements coming from other sources, such as regulations or geo-political aspects.

The following step is the definition of the impact of the building blocks on the requirements satisfaction (i.e.: “How well this element is able to fulfil the requirement?”). Several strategies could be used at this purpose. In this case, the authors propose a modified version of the classical QFD tool that, in the original version, suggested filling in the matrix customer needs/products with:

- “0” in case, the requirement is not affecting the product design,
- “3” in case, the requirement is moderately affecting the product design,
- “9” in case, the requirement is strongly affecting the product design.

The authors suggest an extension of the ranking rules embracing the possibility that a one or more defined mission elements could be in contrast with some requirements. To take it into account, the authors propose to add:

- “−3” in case, the requirement is moderately against the product design,
- “−9” in case, the requirement is strongly against the product design.

Moreover, a requirement with a weight greater or equal to 8 cannot admit elements with negative influence score on it. If it happens, the related element should unavoidably be erased from the list of options. Once the scoring process has been concluded, it is possible to rank the elements inserted in the columns. This is obtained applying the following equation:

$$S_{\mathrm{BB}_j} = \sum_{i=1}^{n_{\mathrm{req}}} \left[(w_{\mathrm{req}})_i \times (w_{\mathrm{rel}})_{ij} \right]$$

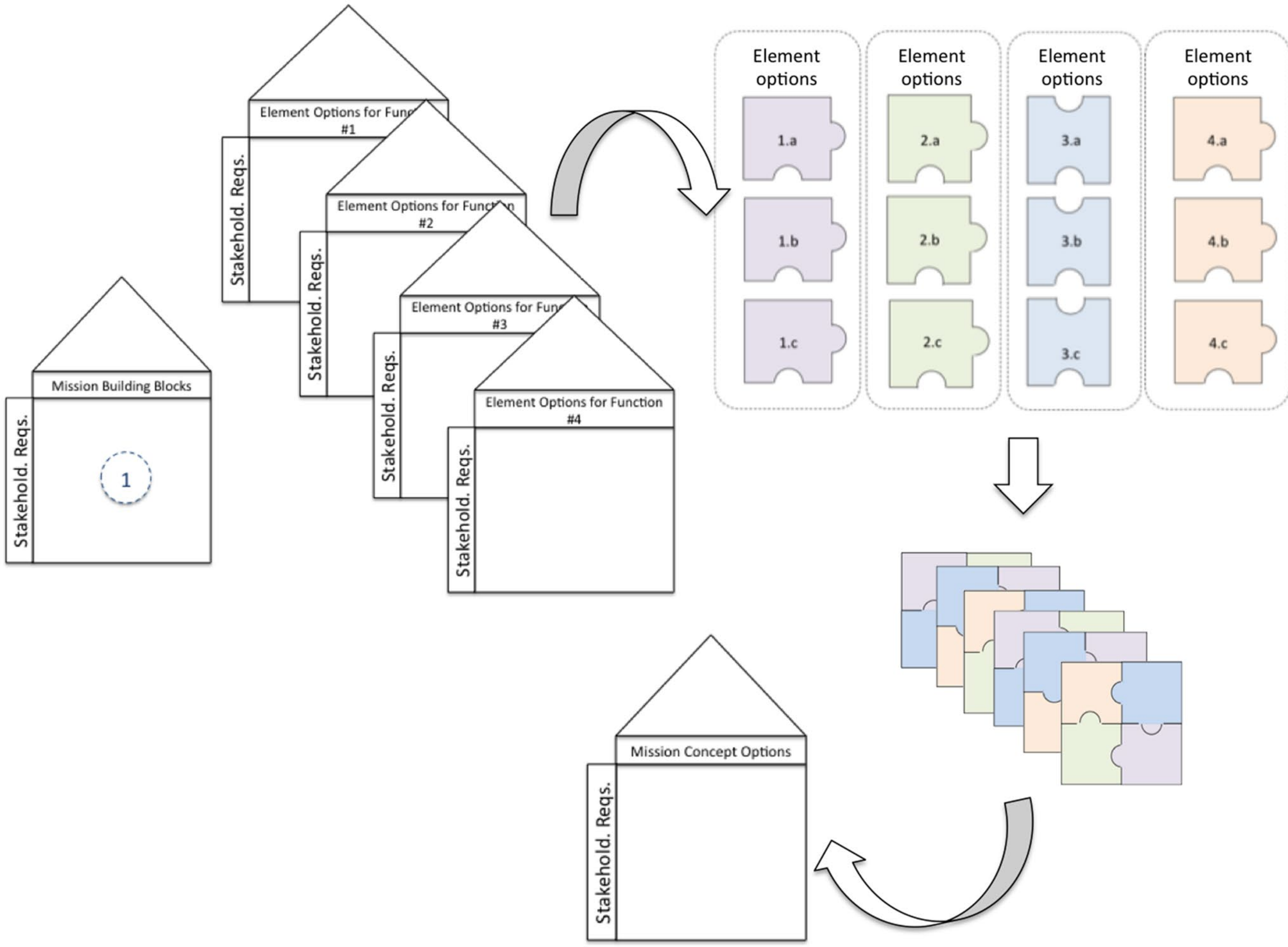


Fig. 6 From the mission elements prioritization to the mission concept proposal

where: i is the requirements index; j is the building blocks index; S_{BB_j} represents the score related to the j-th building block; $(w_{\mathrm{req}})_i$ is the weighting factor assigned to the i-th requirement; and $(w_{\mathrm{rel}})_{ij}$ is the weighting factor assigned within the relation matrix.

Then, a second QFD matrix could be used to prioritize the mission elements options. Indeed, each building block has to be considered as a collection of interconnected elements. At top level, it is important to consider all the possible options for the elements of a mission. To this purpose, the methodology has been applied to prioritize the mission elements. To perform this activity in a logical and structured way, the authors propose to build several QFDs, one per each original function of the functional tree and use a combination algorithm later on, to generate the different mission concept options.

Applying the same above-described methodology, the mission elements prioritization could be obtained applying the following equation:

$$(S_{\mathrm{EO}})_{lm} = \sum_{i=1}^{n_{\mathrm{req}}} \left[(w_{\mathrm{req}})_i \times (w_{\mathrm{rel}})_{il} \right]$$

where: i is the requirements index; l is the element options index; $(S_{\mathrm{EO}})_{lm}$ represents the score related to the l-th element option able to accomplish the m-th mission function; $(w_{\mathrm{req}})_i$ is the weighting factor assigned to the i-th requirement; and $(w_{\mathrm{rel}})_{il}$ is the weighting factor assigned within the relation matrix.

The values obtained could be used to prioritize the options for each element. If the process is carried out for each function that the mission shall perform, the engineers can have several rankings, one for each function. The following step implies the combination of the elements to create mission concept options. This activity can be automatically performed making all the existing combinations, sorting one element per list.

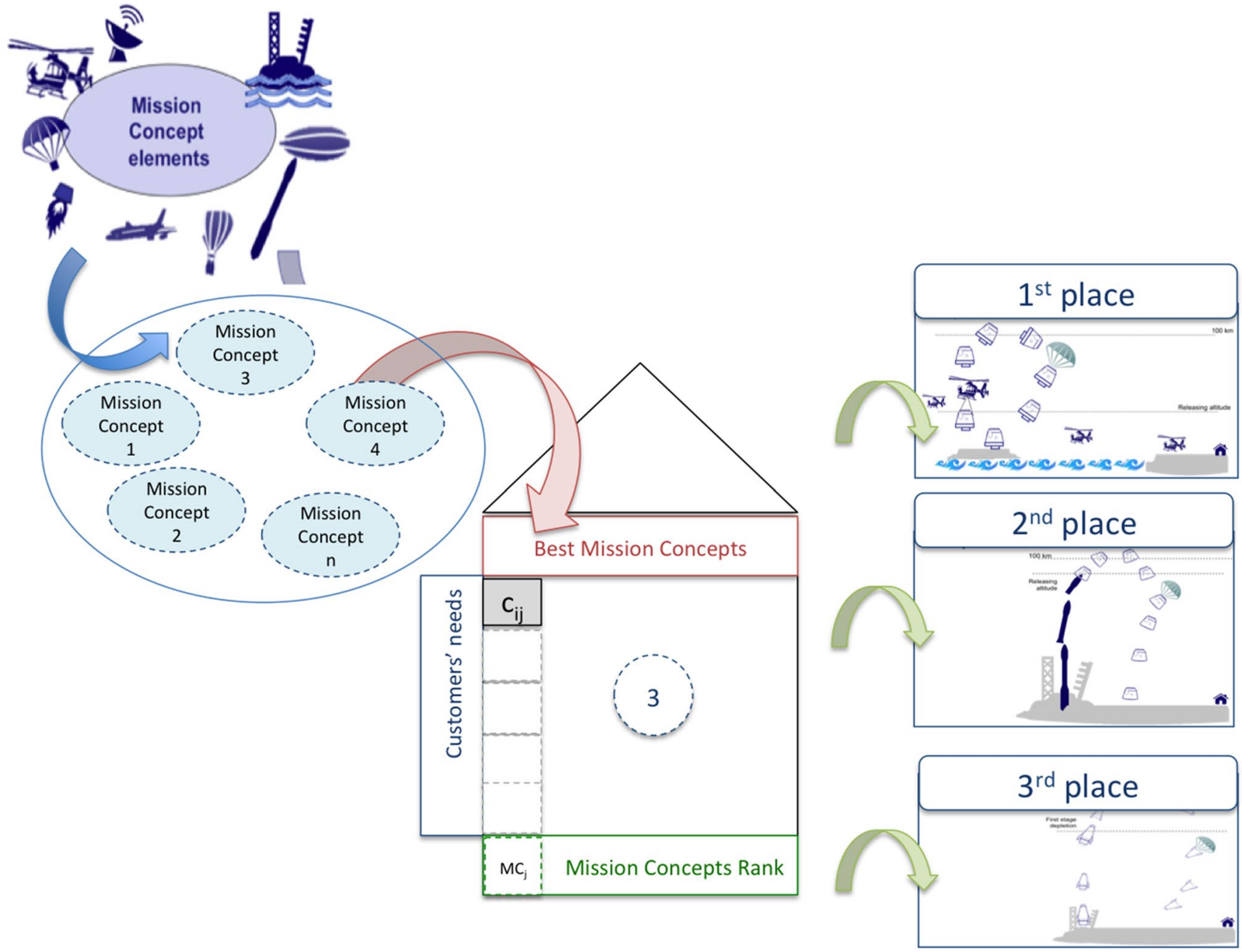


Fig. 7 Mission concept options prioritization

Remembering that each element has been previously scored, the score related to each derived mission concept is a linear combination of the scores obtained in the previous steps, as stated by the following equation:

$$(\mathrm{MC})_k = \sum_{p=1}^{n_{\mathrm{ele}}} \left[(S_{\mathrm{EO}})_p \right]$$

where: k is the mission concept index; p is the element options index; and $(S_{\mathrm{EO}})_p$ represents the score related to the l-th element option able to accomplish the m-th mission function;

The number of possible combination will be exactly foreseen, since the beginning using the following equation:

$$n_{\mathrm{MC}} = \prod_{q=1}^{n_{\mathrm{fun}}} (n_{\mathrm{eo}})_q$$

where: n_{MC} is the maximum number of mission concept options; n_{eo} is the overall number of element options; and n_{fun} is the number of functions (i.e., the groups from which element options should be taken) (Figs. 5, 6, 7).

2.3 Mission concept characterization

The mission concepts derived exploiting the QFD technique are simple combinations of elements like puzzles. It is clear that an additional characterization is required, because a system is not only defined by the elements themselves, but also by their mutual connections. In particular, to discover the relationships among the elements, the authors propose to start from a functional point of view to reach a physical and operative perspective. At this purpose, several tools of the functional analysis could be employed. In particular, the product tree, block diagrams, and functional flow block diagrams are suggested. Please notice that is convenient to apply this and the following steps of the methodology, only at the mission concept options selected as baselines because this approach can avoid worthless waste of time and money.

2.3.1 Product tree

Product tree can be obtained grouping together the elements identified in the function/product matrix. Unlike the functional tree, which has a typical top-down approach, the development of the product tree follows a straightforward bottom-up process. Like in the functional tree, also in this case, it is extremely important to clearly define the level of decomposition at which each product belongs to.

2.3.2 Block diagrams

Block diagrams represent the building blocks linked through point-to-point connections. The block diagram provides the designer with further information, if compared to the connection matrix, about the links' directionality. Moreover, it gives evidence of the type of connection (e.g., mechanical, electrical, etc.). From these diagrams, configuration requirements can be refined and interface requirements can be derived.

2.3.3 Functional flow block diagrams

Functional flow block diagrams (FFBD) allow defining the different operations, the system shall perform, and the different phases and operative modes. FFBDs specifically depict each functional event (represented by a block) occurring, following the preceding function. Some functions may be performed in parallel, or alternative paths may be taken. The FFBD network shows the logical sequence of "what" must happen; it does not ascribe time duration to functions or between functions. The FFBDs are function oriented, not equipment oriented.

Moreover, it is convenient to sketch the so-called concept of operations.

2.3.4 Concept of operations

Complementary, to derive possible mission concepts, it is also important to describe the systems from an operative point of view. At this first level, the concept of operations consists in hypothesizing the general way of working of the systems, including evaluations of mission phases, operation timelines, operational scenarios, end-to-end communications strategy, command and data architecture, operational facilities, integrated logistic support, and critical events. In fact, according to NASA Handbook [4], the ConOps is an important component in capturing stakeholder expectations, requirements, and the architecture of the project. It stimulates the development of the requirements and architecture related to the user elements of the system. It serves as the basis for subsequent definition documents, such as the operations plan, launch and early orbit plan, and operations handbook, and provides the foundation for the long-range operational planning activities, such as operational facilities, staffing, and network scheduling.

It is clear that an extremely high level of uncertainty characterizes this preliminary design stage. To mitigate this problem, an ad-hoc tool has been built to simulate the mission, starting from a limited set of inputs. The results, although characterized by a high degree of approximation, can allow estimating the very first quantitative data, and they can be exploited to evaluate figures of merit in the trade-off analysis.

2.4 Systems and sub-systems design

Once the best mission concept has been selected, each segment, i.e., elements playing a role in the system of systems, should be analysed in detail.

To select a design baseline for the following stages of the design and development activities, it is necessary to consider each system identified with the previous analysis and perform a first sizing attempt. Considering the peculiarity of a mission involving trans-atmospheric trajectories, flight segment should be in-depth analysed and a special attention should be devoted to the on-ground infrastructures required to support the operations. In this way, it is possible to make comparisons among different mission concepts and architecture on quantitative bases. These evaluations shall be repeated all along the design process at different levels until the design of each single piece that shall be built or bought. It is clear that a continuous updating of requirements, constraints, and design specifications shall support this activity. In particular, new branch of model based system engineering (MBSE) [10] developed tools able to automatically keep all the specifications updated during the overall lifecycle. This is considered a powerful capability, because it guarantees the traceability of products and requirements and also a full historical background of all the changes performed during the project.

3 Conceptual design of a crewed space transportation system

This section deals the application of the previously defined methodology to a peculiar reference case study, in which Politecnico di Torino has been involved with Thales Alenia Space Italy, leaded by Altec Space. In particular, the

Table 1 Stakeholders identification

Stakeholder category	Stakeholder identification	Stakeholder's needs
Sponsors	Malaysian private enterprise	To develop, produce, and commercialize a transportation system able to perform parabolic flights To provide a routine flight service of parabolic flight with an ad-hoc transportation system To demonstrate national capabilities
Operators	Italian and Malaysian companies	To provide a routine flight service of parabolic flight with an ad-hoc transportation system To design, develop, and manage spaceports and related logistic infrastructures
End users	Malaysian private enterprise, Malaysian ministry, and Scientific community	To receive, analyse, and exploit data coming from the mission or from scientific experiments carried out To enhance public consensus about commercial flight initiatives
Customers	Passengers	To experience microgravity To experience an amazing view of the earth To carry out scientific experiments

methodology sketched in Sect. 2 is here detailed and well explained, thanks to the help of a real application.

3.1 Mission statement and mission objectives

The reference case study proposed in this paper deals with the conceptual design of a spacecraft aimed at parabolic flights with the special capability of being able to perform a vertical take-off and landing (VTOL). As it can be seen in the following sub-section, dedicated at the stakeholder analysis, VTOL capabilities and other peculiar requests directly come from a certain group of people and will deeply affect the design of the overall mission and related systems and sub-systems.

For the sake of clarity, the mission statement, a concise and precise phrase, describing the objectives of the mission, its principal goals proposing a way to fulfil the aim of the mission, is here reported.

> "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"

Please, notice that within the statement, there is a clear indication about the minimum number of flight participant to accommodate. To be conservative, the designers considered:

- 1 pilot,
- 1 co-pilot (or scientist devoted to carry out experiments), and
- 2 passengers.

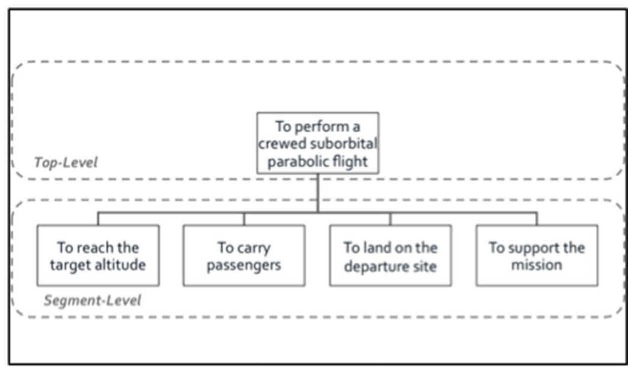


Fig. 8 Top-level functional tree for the reference parabolic mission

Considering the results of the very preliminary sizing, the reader will see that the consistent margins considered during the first design activities will allow accommodating two more passengers within the hypothesized cabin envelope, with negligible impact on the overall architecture.

A list of top-level mission requirements has been derived. It is important to notice that proper ID codes associated to each requirement have been introduced allowing tracing them all along the project. Moreover, the requirement ID will permit to find out the source (or in this case the stakeholder) to which it is related.

3.2 Stakeholders' analysis

As it has been stated in Sect. 2.1, the main goal of the project was to find a way to accomplish the needs expressed by a group of identified interested people. Table 1 summarises the results of the stakeholders' analysis carried

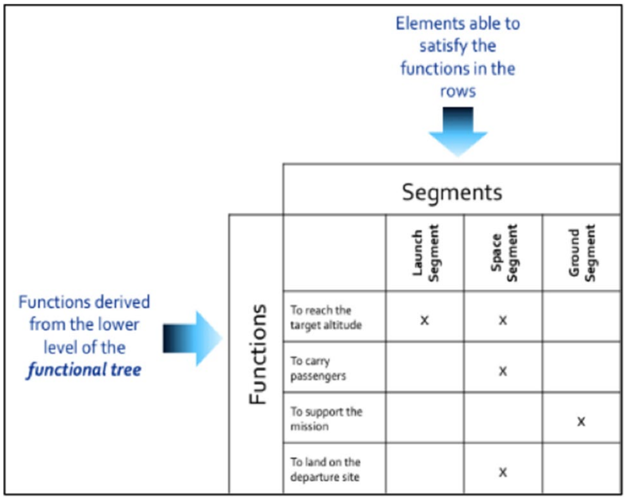


Fig. 9 Functions/products matrix for the reference parabolic mission

out following the procedure suggested in [4] and indicates a series of desirables. It is clear that the main goal of the designers will be the proposal of mission concept options able to make a limited number of passengers to enjoy parabolic flights.

As it could be easily understood, the main difficulties of the project are related to the constraints about the take-off and landing strategies.

Moreover, as it has been expressed previously, a detailed analysis of the geo-political aspects, in which the mission is supposed to be carried out, is mandatory to consider pressing constraints or to foresee additional hidden positive consequences of the mission. In this specific case, stakeholders came from Malaysia and their desirables are strongly supported by the government and ministerial entities. An overview of the current political and economical situation has been performed, and a list of technological topics, on which they are focusing on, has been obtained. This is the reason for which topics, such as electric propulsion or high-tech cabin design, have been selected for further evaluations, and have been considered during the system design phase. In particular, the possibility of exploiting electric propulsion has been considered for attitude controls at higher attitudes.

From the point of view of the market, it is important to look at similar initiatives aimed at providing parabolic flight capabilities all around the world. US, for example, accounts several projects at different development phases for human transportation systems. It is also important to

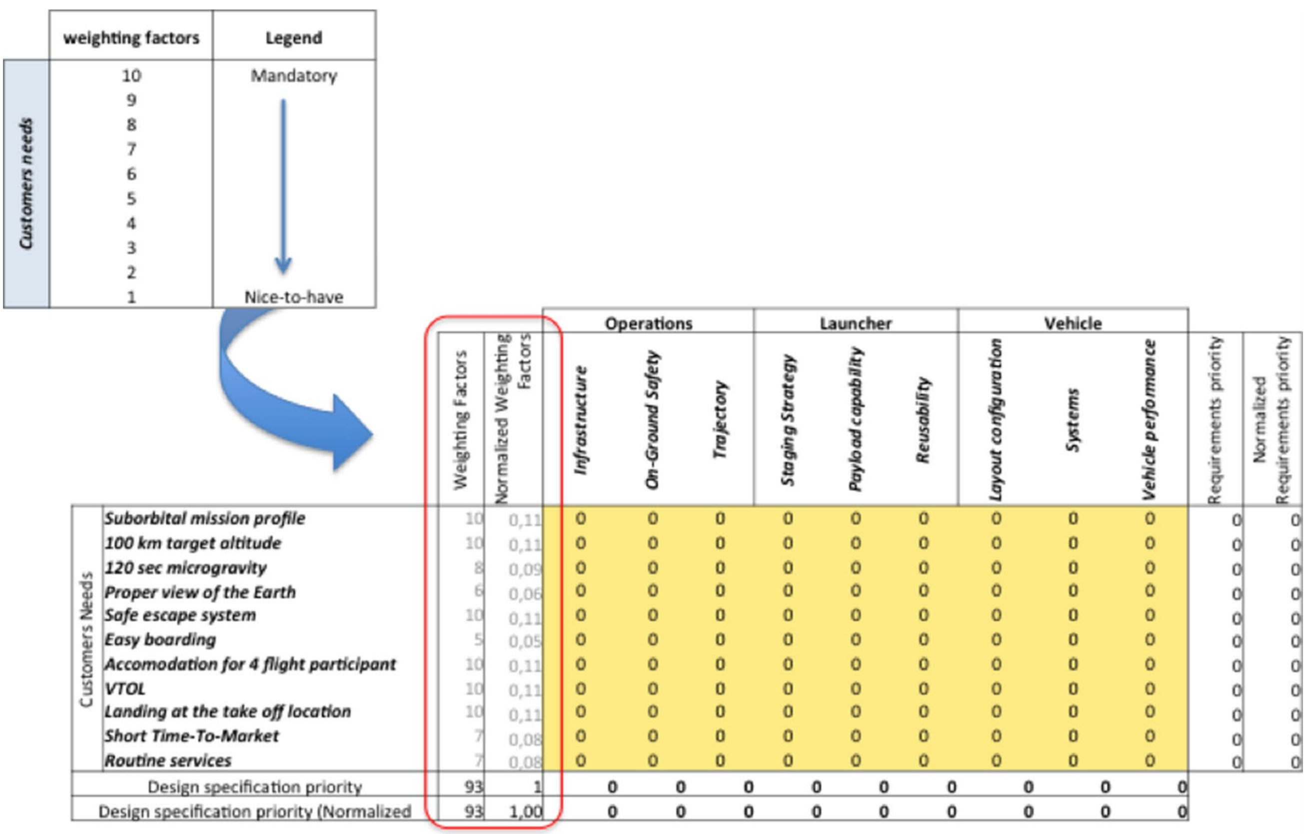


Fig. 10 QFD initialization for the reference case study

	Infrastructure	On-Ground Safety	Trajectory	Staging Strategy	Payload Capability	Reusability	Layout Configuration	Systems	Vehicle Performance
Infrastructure									
On-Ground Safety									
Trajectory									
Staging Strategy									
Payload Capability				+					
Reusability									
Layout Configuration			+						
Systems			+						
Vehicle Performance			+					+	

			Operations			Launcher			Vehicle				
Customers Needs	Weighting Factors	Normalized Weighting Factors	Infrastructure	On-Ground Safety	Trajectory	Staging Strategy	Payload capability	Reusability	Layout configuration	Systems	Vehicle performance	Requirements priority	Normalized Requirements priority
Suborbital mission profile	10	0,11	9	0	9	9	3	0	0	9	9	48	0,14
100 km target altitude	10	0,11	3	0	9	9	9	0	0	9	9	48	0,14
120 sec microgravity	8	0,09	0	0	9	3	9	0	3	9	9	42	0,12
Proper view of the Earth	6	0,06	0	0	3	0	0	0	3	3	0	9	0,03
Safe escape system	10	0,11	0	9	3	9	0	0	9	9	0	39	0,11
Easy boarding	5	0,05	9	3	0	0	0	0	9	3	3	27	0,08
Accomodation for 4 flight participant	10	0,11	0	0	0	0	9	0	9	9	0	27	0,08
VTOL	10	0,11	3	9	9	3	0	0	3	9	9	45	0,13
Landing at the take off location	10	0,11	9	9	9	0	0	0	9	9	9	54	0,15
Short Time-To-Market	7	0,08	-3	-3	0	0	3	-3	-3	-3	0	-12	-0,03
Routine services	7	0,08	9	3	0	-9	0	9	0	3	9	24	0,07
Design specification priority	93	1	327	285	480	261	303	42	366	645	510	351	
Design specification priority (Normalized)	93	1,00	3,516	3,065	5,161	2,806	3,258	0,452	3,935	6,935	5,484		

Fig. 11 Example of QFD for the reference case study: building blocks main features prioritization

	Infrastructure	On-Ground Safety	Trajectory	Staging Strategy	Payload Capability	Reusability	Layout Configuration	Systems	Vehicle Performance
Infrastructure									
On-Ground Safety									
Trajectory									
Staging Strategy									
Payload Capability				+					
Reusability									
Layout Configuration			+						
Systems			+						
Vehicle Performance			+					+	

			Operations			Launcher			Vehicle				
Customers Needs	Weighting Factors	Normalized Weighting Factors	Infrastructure	On-Ground Safety	Trajectory	Staging Strategy	Payload capability	Reusability	Layout configuration	Systems	Vehicle performance	Requirements priority	Normalized Requirements priority
Suborbital mission profile	10	0,11	9	0	9	9	3	0	0	9	9	48	0,14
100 km target altitude	10	0,11	3	0	9	9	9	0	0	9	9	48	0,14
120 sec microgravity	8	0,09	0	0	9	3	9	0	3	9	9	42	0,12
Proper view of the Earth	6	0,06	0	0	3	0	0	0	3	3	0	9	0,03
Safe escape system	10	0,11	0	9	3	9	0	0	9	9	0	39	0,11
Easy boarding	5	0,05	9	3	0	0	0	0	9	3	3	27	0,08
Accomodation for 4 flight participant	10	0,11	0	0	0	0	9	0	9	9	0	27	0,08
VTOL	10	0,11	3	9	9	3	0	0	3	9	9	45	0,13
Landing at the take off location	10	0,11	9	9	9	0	0	0	9	9	9	54	0,15
Short Time-To-Market	7	0,08	-3	-3	0	0	3	-3	-3	-3	0	-12	-0,03
Routine services	7	0,08	9	3	0	-9	0	9	0	3	9	24	0,07
Design specification priority	93	1	327	285	480	261	303	42	366	645	510	351	
Design specification priority (Normalized)	93	1,00	3,516	3,065	5,161	2,806	3,258	0,452	3,935	6,935	5,484		

Fig. 12 Example of QFD for the reference case study: options for operations prioritization

	Infrastructure	On-Ground Safety	Trajectory	Staging Strategy	Payload Capability	Reusability	Layout Configuration	Systems	Vehicle Performance
Infrastructure									
On-Ground Safety									
Trajectory									
Staging Strategy									
Payload Capability				+					
Reusability									
Layout Configuration			+						
Systems			+						
Vehicle Performance			+					+	

		Weighting Factors	Normalized Weighting Factors	Operations: Infrastructure	Operations: On-Ground Safety	Operations: Trajectory	Launcher: Staging Strategy	Launcher: Payload capability	Launcher: Reusability	Vehicle: Layout configuration	Vehicle: Systems	Vehicle: Vehicle performance	Requirements priority	Normalized Requirements priority
Customers Needs	Suborbital mission profile	10	0,11	9	0	9	9	3	0	0	9	9	48	0,14
	100 km target altitude	10	0,11	3	0	9	9	9	0	0	9	9	48	0,14
	120 sec microgravity	8	0,09	0	0	9	3	9	0	3	9	9	42	0,12
	Proper view of the Earth	6	0,06	0	0	3	0	0	0	3	3	0	9	0,03
	Safe escape system	10	0,11	0	9	3	9	0	0	9	9	0	39	0,11
	Easy boarding	5	0,05	9	3	0	0	0	0	9	3	3	27	0,08
	Accomodation for 4 flight participant	10	0,11	0	0	0	0	9	0	9	9	0	27	0,08
	VTOL	10	0,11	3	9	9	3	0	0	3	9	9	45	0,13
	Landing at the take off location	10	0,11	9	9	9	0	0	0	9	9	9	54	0,15
	Short Time-To-Market	7	0,08	-3	-3	0	0	3	-3	-3	-3	0	-12	-0,03
	Routine services	7	0,08	9	3	0	-9	0	9	0	3	9	24	0,07
Design specification priority		93	1	327	285	480	261	303	42	366	645	510	351	
Design specification priority (Normalized)		93	1,00	3,516	3,065	5,161	2,806	3,258	0,452	3,935	6,935	5,484		

Fig. 13 Example of QFD for the reference case study: options for launcher prioritization

	Sphere	Blunt Cone	Heat Shield	Biconic	Spacecraft
Sphere					
Blunt Cone	-				
Heat Shield	-	-			
Biconic	-	-	-		
Spacecraft	-	-	-	-	

			Weighting Factors	Normalized Weighting Factors	Vehicle: Sphere	Vehicle: Blunt Cone	Vehicle: Heat Shield	Vehicle: Biconic	Vehicle: Spacecraft	Requirements priority	Normalized Requirements priority
Design Areas needs	Operations	Infrastructure	327	0,11	0	0	0	0	0	0	0,00
		On Ground Safety	285	0,10	0	0	0	0	3	3	0,02
		Trajectory	480	0,16	-3	-3	-3	-3	9	-3	-0,02
	Launcher	Payload Capabillity	303	0,10	-3	3	3	9	9	21	0,15
		Reusability	42	0,01	-3	-3	-3	0	3	-6	-0,04
	Vehicle	Layout Configuration	366	0,12	9	9	3	3	-3	21	0,15
		Systems	645	0,22	-3	-3	3	9	3	9	0,07
		Vehicle performance	510	0,17	-3	-3	3	3	9	9	0,07
	Design specification priority		2958	1	-2646	-828	3906	9720	13455	54	
	Design specification priority (Normalized		2958	1,00	-0,89	-0,28	1,32	3,29	4,55		

Fig. 14 Example of QFD for the reference case study: options for vehicle prioritization

Table 2 QFD weightings rationale (proper view of the earth and routine services)

	Proper view of the earth		Routine services	
	Numerical value	Rationale	Numerical value	Rationale
Infrastructure	0	No specific on-ground infrastructure should be developed to guarantee to the passengers a good view of our planet	9	The need for guaranteeing a routine service has an extreme impact on the infrastructures, as far as maintenance and logistics operations are concerned
On-ground safety	0	On-ground safety is not affected by this stakeholder need	3	Routine services imply a higher frequency of flights and can impact on the level of risk of incidents
Trajectory	3	To guarantee a proper view of the earth, a proper trajectory should be planned, especially as far as the attitude of the spaceplane is concerned	0	The need for routine services does not affect the trajectory definition
Staging strategy	0	Decision about the staging strategy is not affected by this requirement	−9	The need for routine services implies a high reusability of the space segment. This appears to be in contradiction with respect to the presence of multi-stages
Payload capability	0	Payload capability is not affected by this requirement	0	The payload capability is not affected by the need for routine services
Reusability	0	Considerations about reusability of the entire systems or of some of its components are not affected by this requirement	9	On the contrary with respect to the staging strategy, routine services obliges to design the spacecraft guaranteeing reusability
Layout configuration	3	This requirement impacts on the transportation system layout, e.g., in the presence of windows, position, and sizing	0	The external layout configuration is not affected specifically involved in a design aimed at guaranteeing routine services
Systems	3	This requirement can affect the internal layout of the crew compartment. Moreover, considering that windows are not the only way to guarantee this requirement, O-LED screen and other high-tech on-board equipment can be envisaged	3	Spaceplane systems should be properly designed and installed to allow routine services
Vehicle performances	0	Vehicle performances payload capability are not affected by this requirement	9	The major performances of the spaceplane are deeply influenced by this requirement. Please note that among the vehicle performances, key parameters like turn around time

Table 3 QFD weightings rationale (on-ground operations influence on the aircraft design)

	Layout configuration		Systems		Vehicle performances	
	Numerical value	Rationale	Numerical value	Rationale	Numerical value	Rationale
Existing infrastructures exploitation	0	Layout configuration is not affected by operational constraints	0	The trade-off between existing and new infrastructures does not have impact on the design of the systems	3	In case existing on-ground infrastructures should be exploited, several constraints for the vehicle performances can arise. In particular, those related to take-off and landing phases
New infrastructures development	0		0		0	In case, new infrastructures will be developed, no specific performance constraint shall be imposed
Qualified personnel	0		0	The presence of qualified personnel to support on-ground ops does not affect the design of the systems	0	The presence of qualified personnel to support on-ground ops does not affect the vehicle performances definition
Communication architecture	0		9	On-board systems design, selection, and integration on the spaceplane are deeply affected by the selected communication architecture	9	Communication architecture can influence vehicle performances
Sea-based	0		3	The type of location hosting the spaceport can influence the design of certain spaceplane systems	3	The type of location hosting the spaceport can influence the performances of the spaceplane, especially, those regarding take-off, climb, descent, and landing. In addition, the vehicle performances in emergency condition can be affected
Land-based	0		3		3	

Table 4 QFD weightings rationale (launcher option influence on the aircraft design)

	Layout configuration		Systems		Vehicle performances	
	Value	Rationale	Value	Rationale	Value	Rationale
Launcher options						
None	0	Not having a launcher does not imply any constraint for the layout configuration	0	At high level, systems are neither positively nor negatively affected by the option envisaged for the launcher	9	If the vehicle shall be able to perform the take-off without a launching system, systems shall be properly sized, especially the propulsion subsystem
Rocket	0	If a rocket is envisaged as launcher, no special constraints for the layout shall be considered	0		3	The exploitation of a rocket shall moderate impact on some vehicle performances, especially those related to the ascent phase
Helicopter	−3	The exploitation of helicopter, balloons, or a proper airship to lift the spaceplane up to a certain altitude shall influence the layout configuration, imposing a moderate numbers of constraints	0		−3	The exploitation of helicopter, balloons, or a proper airship to lift the spaceplane up to a certain altitude shall influence vehicle performances, especially during the separation phase
Balloons	−3		0		−3	
Airship	−3		0		−3	
Aircraft	−9	The exploitation of mother-ship as launcher imposes the highest number of constraints to the layout configuration	0		9	The spaceplane shall benefit of the presence of a mother-ship, mainly in terms of required thrust and mass of propellant to be stored

notice that many of these initiatives consider the parabolic mission as a demo-mission, having the on-orbit transportation or the sub-orbital hypersonic profiles as final goals. Moreover, considering the very demanding take-off and landing strategies, it is important to take a look at existing or under-development technical solutions to carry them out.

3.3 How to derive mission concept alternatives from stakeholder analysis

From the mission statement and the stakeholder analysis, it is possible to derive one or more top-level functions, expressing what the mission (intended as a group of elements and related relationships) shall do. Starting from these top-level functions, it is possible to start the sub-function elicitation process.

The following pictures give a glance of the way, in which the standardized functional analysis has been implemented for this application. In particular, Fig. 8 shows a functional tree developed for the first analysis level. Within the same level of detail, it is necessary to move from a functional to a physical view of the project, and following the suggestions proposed in [3], a function/product matrix has been built, and it is reported in Fig. 9. This matrix allows connecting each single function to possible elements (hardware) able to perform it. It is convenient to notice that the crosses mean that the considered product could be theoretically able to perform the considered function. For example, depending on the fact that at this level of details, we have not yet decided whether the transportation system will be a single stage or a multi-stage, both the launch segment and the space segment could be in charge of reaching the target altitude. On the other hand, it is clear that tourists will be hosted for sure in the space segment as well as the ground segment will perform all those activities related to mission support.

The exploitation of these two tools typical of the functional analysis serves to build the bases for the application of the QFD tool and the whole QFD tool-chain aimed at obtaining the highest possible number of mission concepts, because from the connection matrix, it is possible to obtain the columns of the first QFD matrix. Indeed, the rows contain the stakeholder requirements (Fig. 5).

Figure 10 shows the initialization of the QFD matrix with the selection of the most important stakeholders' requirements and with the assignation of the weighting factors. Subsequently, the QFD has been exploited with the aim of prioritize the different mission segments.

In particular, Figs. 10 and 11 show a particular variation of the traditional house-of-quality, because the element contained within the columns are not only the three segments deduced from the functional analysis, but they are presented with some related engineering features or qualities conferring a higher detail level to the elements.

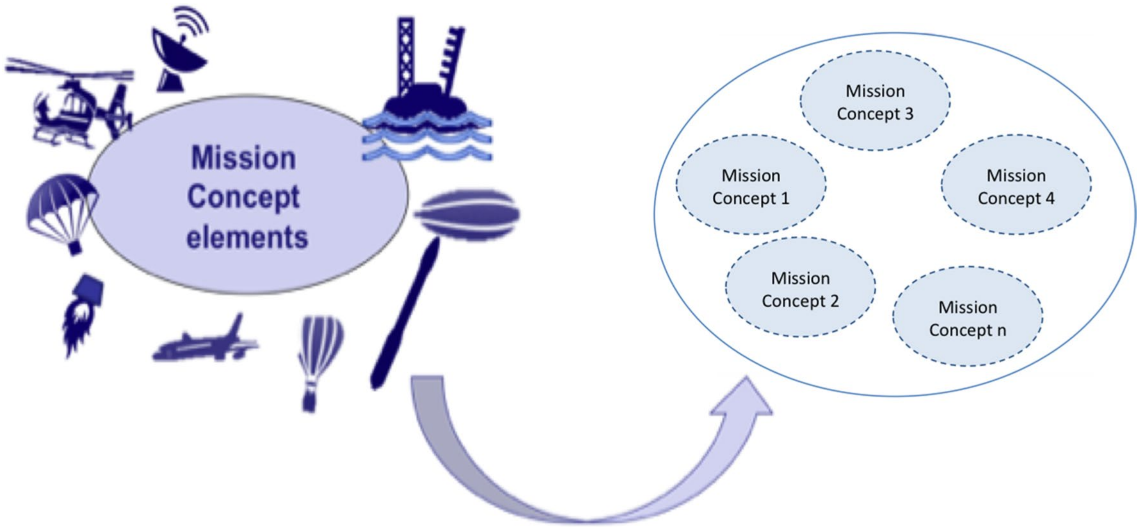
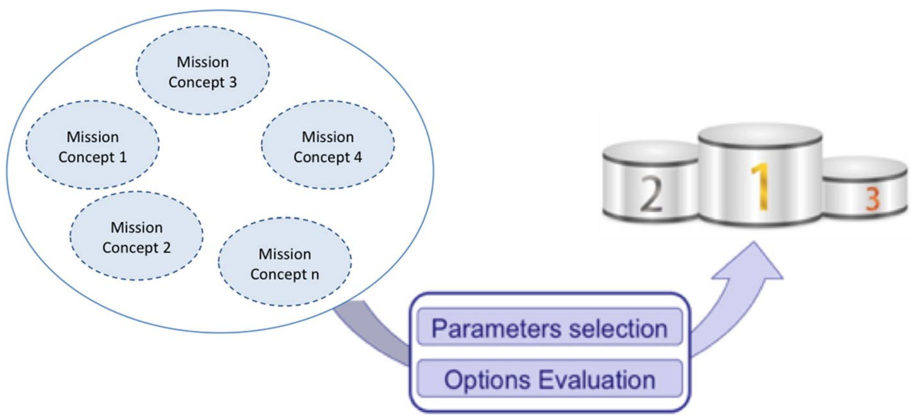


Fig. 15 Sketch of the link between mission concept elements and mission concept proposal

Fig. 16 From mission concepts proposal to the mission concepts selection



Figures 10, 11, 12, 13, and 14 show the QFD obtained for the specific case study following the process sketched in Fig. 5. The exploitation of this QFD chain allows the definition of the main element options for each identified building blocks.

For the sake of clarity, consider that the weighting factors of the relationship matrix have been assigned following the legend in Fig. 4. Considering that the design here reported is at the very beginning of the product development cycle, it is important to notice that it is not possible to associate all the parameters with mathematical evaluations, but some of them remain qualitative assumptions.

Nevertheless, these assumptions are not so fantastic and will have to be confirmed at later stages of development and analysis. For example, considering the need of benefitting of a proper view of the earth has been considered of high importance for the design of the spacecraft, but not of extreme importance (indeed, a weight of 6 has been assigned, instead of 9). The main reason for this choice was that level 9 has been assigned only in those cases, in which the need is so oppressive that the designers can envisage only one way to carry it out, meaning that this need is impacting and strongly affecting the system design. In this case, you can guarantee a proper view of the earth in different ways, for example, you can enlarge your glass surface (with related structural drawbacks) or exploit innovative technologies like O-LED panels and external cameras, able to make passengers feel an immersion in the external environment (with less structural drawbacks but higher power consumption requirement).

Table 2 presents the rationale used to fill in the QFD presented in Fig. 11.

Moving from Fig. 11 to 12, it is important to see that the item “staging strategy” is no more present. This is a clear consequence of stakeholder intervention during this preliminary assessment. They invite designers to erase the

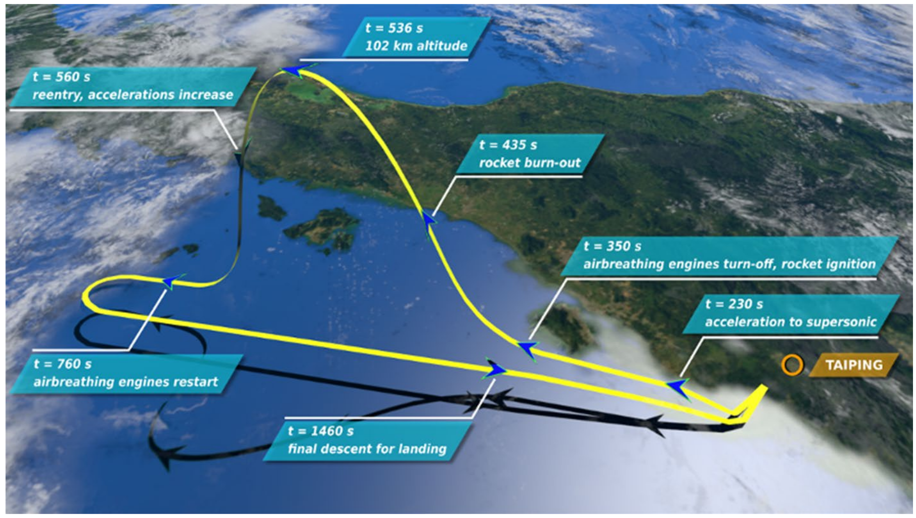


Fig. 17 Mission trajectory for the reference mission [11]

Table 5 Mission phases for the sub-orbital reference mission

Mission phase	Starting altitude (m)	Ending altitude (m)
Take-off	0	20
1st climb segment (transition)	20	300
2nd climb segment	300	18,000
3rd climb segment	18000	60,000
4th climb segment	60,000	100,000
Re-entry (ballistic)	100000	75,000
Powered re-entry	75,000	15,000
Cruise	15,000	15,000
Descent	15,000	20
Landing	20	0

Table 6 Spacecraft operational modes

Mission phase	Un-powered	Powered	Rocketed	Safety	Escape
Take-off		x		x	
1st climb segment		x		x	x
2nd climb segment		x		x	x
3rd climb segment			x	x	x
4th climb segment	x			x	x
Re-entry (ballistic)	x			x	x
Powered re-entry		x		x	x
Cruise		x		x	x
Descent		x		x	x
Landing		x		x	

possibility of having a multi-stage transportation system, while they suggested evaluating different strategies for the launcher.

For the sake of clarity, Table 3 presents the rational process behind the selection of weighting factors in QFD of Fig. 13. In particular, the last three rows of the QFD have been analysed to make the readers aware of the way, in which on-ground operations can affect the spaceplane design.

As far as Fig. 14 is concerned, the authors decided to analyse the first three rows of the QFD, because they reveal the possible effect on vehicle design depending on the type of launcher (Table 4).

The iterations performed using the QFD tools allow defining and ranking a high number of options for each element of the mission. As it has been explained before, at first, the mission concepts are identified as simple unions of elements (Figs. 15, 16). Subsequently, the mission concept options that are selected for further evaluations should be studied in the detail. In particular, a description of the concept of operations, with the identification of the main phases of the mission, a timeline, and a sketch of the main operative modes of the main system (such as the spacecraft, in this case) should be performed (Fig. 17).

Considering Table 2, it is worth to notice that the high-level operational modes here described refer to the system spacecraft. Indeed, it is not possible to define the operational modes without having identified the system to which they refer to.

Moreover, the identified operational modes are:

- Un-powered: this is the operational mode during which the spacecraft does not use neither the air-breathing

Table 7 Characteristics of the helicopter-lifted capsule scenario

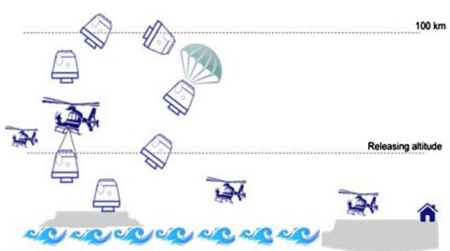
Helicopter-lifted capsule		
Mission scenario	Mission description	Comments
	A helicopter coming from a ground-based infrastructure reaches a sea-based platform and lifts a capsule up to a to be defined (TBD) altitude. Then, after the release, the capsule is appropriately propelled to the target altitude (100 km), allowing flight participants to experience microgravity for few seconds. During the atmospheric re-entry, a series of parachutes should be deployed to slow the capsule down gradually. Additional devices, such as retro-rockets and control surfaces, should be hypothesized to land in the same place from which it takes off	This mission concept is characterized by a high level of complexity and risk mainly due to the presence of the helicopter. On the other hand, the capsule-like architecture of the spacecraft guarantees simplicity of the design but a lower level of comfort with respect to a spaceplane. Please notice that additional on-ground facilities and rescue sub-systems should be envisaged This kind of mission can be suitable for demo missions, such as, for example, those aimed at testing and verifying the vertical take-off and landing capabilities
Mission elements description		
Ground-based platform: the ground-based infrastructures shall support the operations of a heavy-lift helicopter. To minimize the turn around time and for economical reasons, the platform shall be located in a coastal region, in the proximity of a sea-based platform from which the core of the mission is planned to start Sea-based platform: the sea-based platform shall host the infrastructures to accommodate and maintain the capsule and support it during lift-off and landing phases. The location of this platform should be properly evaluated to consider safety constraints mainly related to the storage of the propellant used for feeding the capsule propulsion system and to the ground clearance required during the lifting manoeuvres. Considering these characteristics, an ad-hoc spaceport could be envisaged Helicopter: the helicopter is considered to be the carrier enabling the capsule to start its mission from a certain altitude, reducing the spacecraft mass (thanks to the propellant mass savings), avoiding the exploitation of expendable multi-stage rockets. The idea of exploiting an existing helicopter is strictly related to the size of the capsule. Moreover, the releasing strategy and the flight procedures should be properly addressed Capsule: the capsule can be considered to be the second stage of this complex transportation system. Depending on the releasing altitude, the capsule shall be appropriately propelled to reach the target altitude. To avoid adding additional complexity, the capsule shall be propelled by one or more rockets able to guarantee the required thrust. The rocket ignition shall be envisaged some TBD seconds after the separation avoiding not to endanger the separation phase. After the rocket burn out, the capsule shall reach the target altitude following a parabolic profile. Then, the capsule shall perform an un-powered, but controlled re-entry. This means that the primary propulsion system will not be exploited after the burn out, but a set of parachutes and cold gas thrusters will decelerate the capsule and control its attitude until the approaching phase. Exploiting a properly designed guidance and navigation control (GNC) and attitude determination control system (ADCS) systems, the capsule shall be able to perform a soft vertical landing on the same sea-based platform from which it takes off		

Table 8 Characteristics of the helicopter-lifted spaceplane scenario

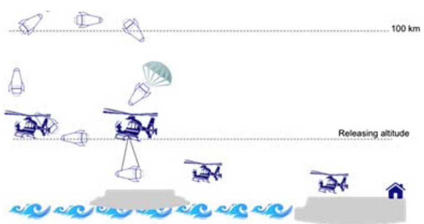
Helicopter-lifted spaceplane		
Mission scenario	Mission description	Comments
	A helicopter coming from a ground-based infrastructure, reaches a sea-based platform and lifts the spaceplane up to a to be defined (TBD) altitude. Then, after the release, the spaceplane is properly propelled to reach the target altitude of 100 km allowing flight participants to experience microgravity for few seconds. During the atmospheric re-entry, a series of parachutes should be deployed to slow down gradually. Additional devices, such as retro-rockets and control surfaces, should be hypothesized to land in the same place from which it takes off	Like the previous mission concept, this is also characterized by a high level of complexity and risk mainly due to the presence of the helicopter. The spaceplane-like architecture of the spacecraft can allow a higher flexibility in the operations and can host passengers with a higher level of comfort. Both these solutions guarantee a proper view of the earth if properly designed and equipped. Please notice that additional on-ground facilities and rescue sub-systems should be envisaged
Mission elements description		
Ground-based platform: the ground-based infrastructures shall support the operations of a heavy-lift helicopter. To minimize the turn around time and for economical reasons, the platform shall be located in a coastal region, in the proximity of a sea-based platform from which the core of the mission is planned to start		
Sea-based platform: the sea-based platform shall host the infrastructures to accommodate and maintain the spaceplane and support it during lift-off and landing phases. The location of this platform should be properly evaluated to consider safety constraints mainly related to the storage of the propellant used for feeding the spaceplane propulsion system and to the ground clearance required during the lifting manoeuvres. Considering these characteristics, an ad-hoc spaceport could be envisaged		
Helicopter: the helicopter is consider to be the carrier enabling the spaceplane to start its mission from a certain altitude, reducing the spacecraft mass (thanks to the propellant mass savings), avoiding the exploitation of expendable multi-stage rockets. The idea of exploiting an existing helicopter is strictly related with the sizing of the capsule. Moreover, the releasing strategy and the flight procedures should be properly addressed		
Spaceplane: the spaceplane can be considered to be a second stage of this complex transportation system. Depending on the releasing altitude, it shall be properly propelled to reach the target altitude. The possibility of ignite the propulsion system at a certain altitude is a non-negligible advantage in terms of mass savings complexity of the spaceplane. Indeed, the possibility of exploiting a lifter-helicopter will avoid implementing a demanding and problematic propulsion sub-system aimed at performing a vertical take-off from the platform. Considering this mission scenario, a single stage with a single propulsion system seems to be the most promising solution. In particular, advanced air-breathing propulsion will guarantee the minimum fuel mass but considering the level of maturity of the technology and the short duration of the mission (please, consider that the advantages of airbreathing with respect to rockets increase with the mission duration), a rocket engine shall be considered. It is clear that this choice impacts not only the vehicle itself but also the sea-based platform facility for the storage of the propellant and also the operational procedures and platform location. Considering the envisaged scenario, the spaceplane should be properly equipped with a landing gear able to support a vertical landing, after the re-entry and descent phases		

Table 9 Characteristics of rocket-launched capsule scenario

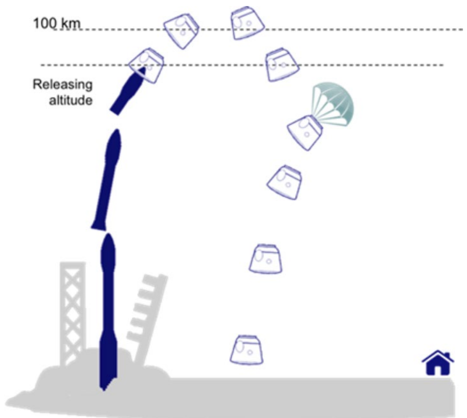
Rocket-launched capsule		
Mission scenario	Mission description	Comments
	A capsule is launched using an existing launcher. Exploiting the thrust provided by each of the different stages, the capsule should be able to reach the 100 km of altitude after the release. During the atmospheric re-entry, a series of parachutes should be deployed to slow down gradually. Additional devices, such as retro-rockets and control surfaces, should be hypothesized to land in the same place from which it takes off	The exploitation of a traditional multi-stage rocket to bring a capsule up to a certain altitude will reduce the problems related to on-ground infrastructure. However, this solution will not fit with the need for guaranteeing a routine service, because of several reasons (e.g., expendable stages, the need of launch windows, very high cost per mission, etc.). Conversely, this solution appears very promising from the spacecraft design point of view. Indeed, a valuable reduction of power and mass budget can be obtained. Passengers requirements on comfort could be not at all satisfied, especially during the descending parabolic phase
Mission elements description		
Ground infrastructure: the ground-based infrastructures shall support the operations of a launcher. This means that existing space centres shall be selected or new ad-hoc facilities shall be built. The facility shall accommodate the required amount of fuel and shall provide workshops for maintenance. The problem of guaranteeing "routine" service shall be addressed		
Launcher: depending on the sizing of the capsule, the launcher could be an existing or under-development one or an enhanced version of an existing one shall be proposed. The use of a multi-stage rocket dramatically simplifies the architecture of the capsule and in particular of its propulsive system		
Capsule: with the possibility of exploiting the different stages of an expendable rocket, the capsule can be un-powered, having only thrusters to guarantee manoeuvrability, especially during re-entry and descent phases. Precise landing is also required and this implies the need for implementing a deceleration sub-system (parachute and thrusters) and GNC and ADCS subsystems. The system could be very simple and existing capsules could be taken as reference. For simplicity, the landing gear could be substituted with inflatable bags, but the bouncing on ground could be non-acceptable for non-trained people		

Table 10 Characteristics of rocket-launched spaceplane scenario

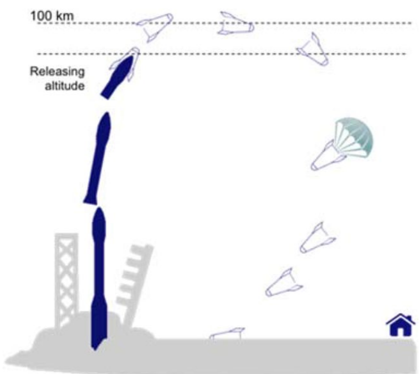
Rocket-launched spaceplane		
Mission scenario	Mission description	Comments
	A spacecraft is launched using an existing launcher. Exploiting the thrust provided by each of the different stages, the capsule should be able to reach the 100 km of altitude after the release. During the atmospheric re-entry, a series of parachutes should be deployed to slow down gradually. Additional devices, such as retro-rockets and control surfaces, should be hypothesized to land in the same place from which it takes off	The exploitation of a traditional multi-stage rocket to bring a capsule up to a certain altitude will reduce the problems related to on-ground infrastructure. However, this solution will not fit with the need for guaranteeing a routine service, because of several reasons (e.g., expendable stages, the need of launch windows, very high cost per mission, etc.). Conversely, this solution appears very promising from the spacecraft design point of view. Indeed, a valuable reduction of power and mass budget can be obtained. After the release, the spaceplane can safely accommodate passengers also during the re-entry phase
Mission elements description		
Ground infrastructure: the ground-based infrastructures shall support the operations of launcher. This means that existing space centres shall be selected or new ad-hoc facilities shall be built Launcher: depending on the sizing of the capsule, the launcher could be an existing or under-development one or an enhanced version of an existing one shall be proposed. The use of a multi-stage rocket dramatically simplifies the architecture of the capsule and in particular of its propulsive system Spaceplane: the spaceplane shall be designed to fit into the launcher upper stage. With the possibility of exploiting the different stages of an expendable rocket, the spaceplane design can be simplified. It can be un-powered, having only thrusters to guarantee manoeuvrability, especially during re-entry and descent phases. Precise landing is also required and this implies the need for implementing a deceleration sub-system (parachute and thrusters) and GNC and ADCS sub-systems		

Table 11 Characteristics of powered capsule scenario

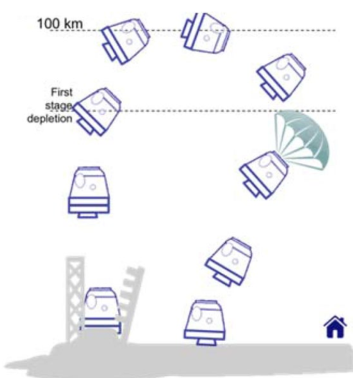
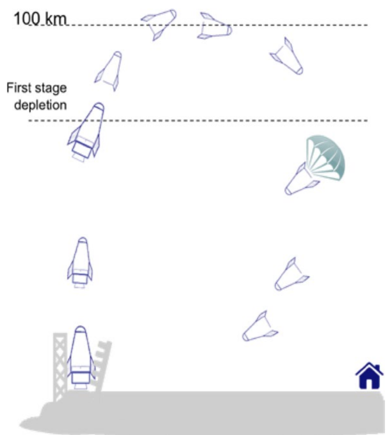
Powered capsule		
Mission scenario	Mission description	Comments
 	A capsule (single or multi-stages) is able to vertically take-off exploiting the thrust produced by its embedded propulsion system. To accomplish the mission requirements, the capsule should be able to reach the 100 km of altitude after the release. During the atmospheric re-entry, a series of parachutes should be deployed to slow down gradually. Additional devices, such as retro-rockets and control surfaces, should be hypothesized to land in the same place from which it takes off	This mission concept deletes all the problems related to physical and operational interfaces with the launcher but a very high level of complexity of the spacecraft sub-systems characterizes it. Furthermore, this mission concept option has a moderate impact on the infrastructures and can enhance the frequency of the service provided. The level of comfort for the passengers is not very high
Mission elements description		
Ground infrastructure: the ground-based infrastructures shall support the operations of a single-stage or two-stage capsule-like system. Depending on the capsule architecture, the ground Infrastructure could vary from a complex centre, similar to a space one but with ad-hoc launch facility, to a simple prepared pad from which the capsule can autonomously lift-off, exploiting its own landing gear legs. The facility shall accommodate the required amount of fuel and shall provide workshops for maintenance. The problem of guaranteeing "routine" service shall be addressed		
Capsule: this scenario allows different architectures for the capsule system architecture. Indeed, depending on the staging strategy and on the degree of reusability of the overall transportation system, different alternatives for the propulsion system could be envisaged. After trade-off analyses, the alternative envisaging a single-stage capsule, completely reusable, and rocket propelled have been preferred. The use of a rocket-based propulsion system, since the beginning of the mission, implies the construction of ad-hoc on-ground facilities and a widening of the clearance area required for the operations		

Table 12 Characteristics of powered spaceplane scenario

Powered Spaceplane		
Mission scenario	Mission description	Comments
	A spaceplane (single- or multi-stage) is able to vertically take-off exploiting the thrust produced by its embedded propulsion system. To accomplish the mission requirements, the vehicle should be able to reach the 100 km of altitude after the release. During the atmospheric re-entry, a series of parachutes should be deployed to slow down gradually. Additional devices, such as retro-rockets and control surfaces, should be hypothesized to land in the same place from which it takes off	Similarly to the previous mission concept, also in this case, interface criticalities with the launcher do not exist. Furthermore, this mission concept option has a moderate impact on the infrastructures and can enhance the frequency of the service provided. The spaceplane system configuration can be very complex, and the related mass and power budget can be very demanding. Please consider that this solution is the best option from the point of view of the passengers, because very similar to a typical aircraft aimed at transportation purposes
Mission elements description		
Ground infrastructure: the ground-based infrastructures shall support the operations of a single-stage system able to automatically performed take-off and landing manoeuvres. The spaceport could be a simple prepared pad from which the system can autonomously lift-off, exploiting its own landing gear legs. The main problems could be related to the storage of propellant into the facility and the logistic and maintenance support		
Spaceplane: the envisaged spaceplane shall be a single stage, which shall be able to perform a vertical take-off in tail-sitting or (more preferable) in Harrier-like position. To overcome exiting environmental regulations forbidding the use of rocket propulsion under a certain altitude, an air-breathing propulsion system will be exploited during the take-off and landing manoeuvres. The air-breathing propulsion system will be exploited up to its ceiling altitude, when rocket will be ignited. Then, the spaceplane will be powered by rocket motors to reach the target altitude. After the parabolic phase and a first part of un-powered re-entry, the air-breathing propulsion system could be re-started to enhance the accuracy of the descent and landing phases. Controlled and precise landing manoeuvres could be carried out		

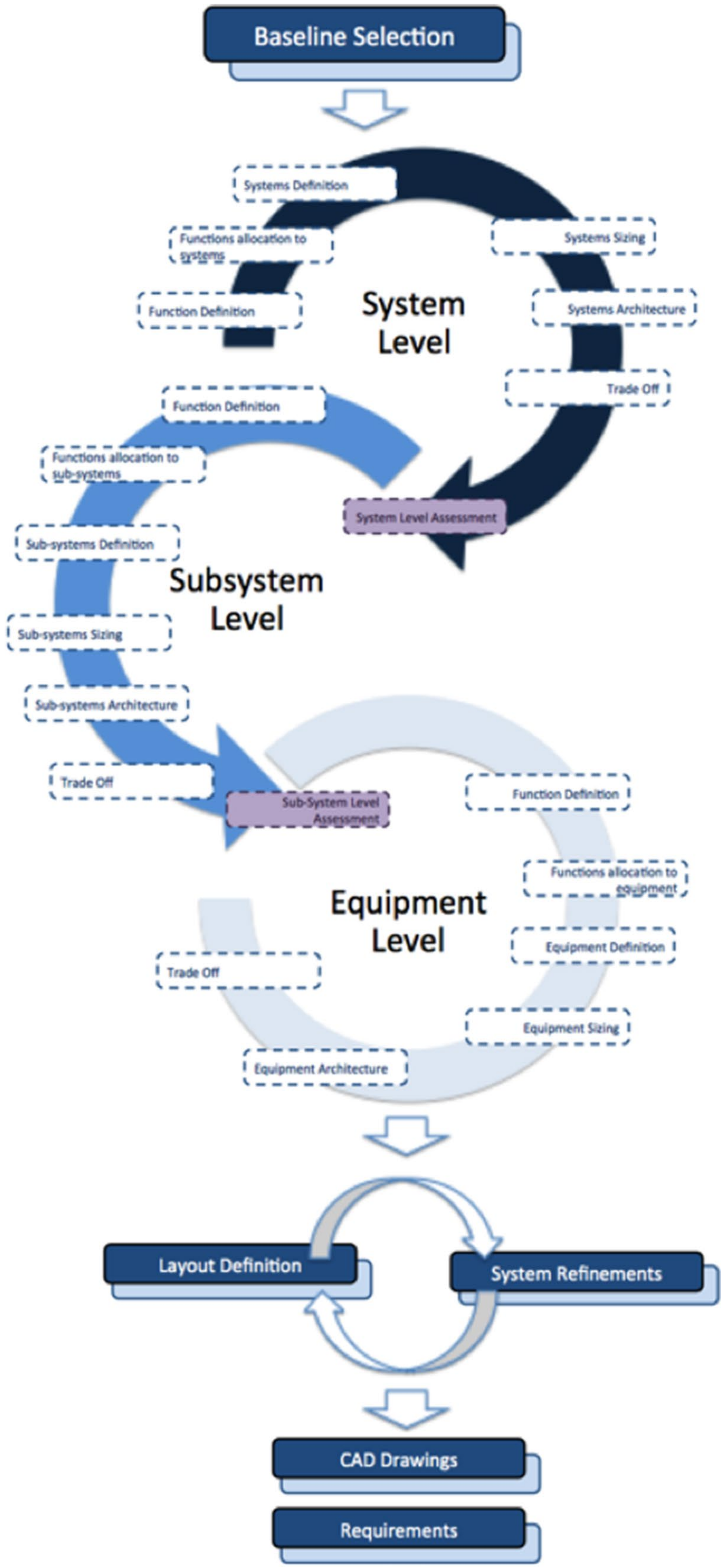


Fig. 18 System and sub-systems design methodology

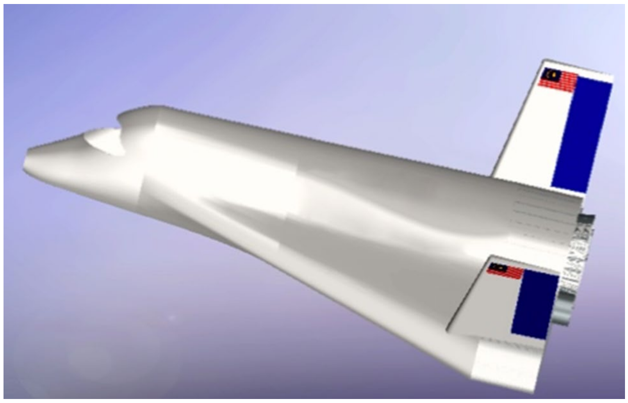


Fig. 19 CAD drawing depicting a typical spacecraft external layout

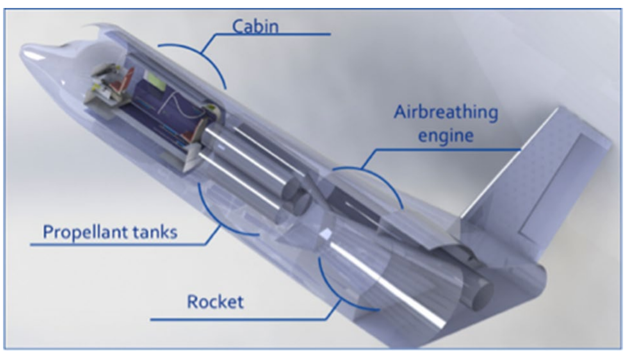


Fig. 20 CAD drawing depicting typical spacecraft sub-systems

engines nor the rocket one and its motion is governed by the inertial forces,

- Powered: this is the operative mode, in which the spacecraft exploits its air-breathing engines,
- Rocketed: this is the operative mode, in which the rocket engine is ignited,
- Safety: it is the typical operational mode that is encountered each time a minor failure or malfunctioning is identified. Depending on the phase, in which it happens and the associated level of risk, the trajectory could be modified and the spacecraft sub-systems could change their operative modes to overcome the problem,
- Escape: it is the operative mode related to the highest level of risk. In this case, the spacecraft is considered no more able to carry out the nominal mission. The spacecraft is separated into two pieces. The small one, corresponding to the front fuselage, contains the crew and related vital systems and should be designed to allow the crew and passengers' survival, landing, after a ballistic, un-powered phase.

3.4 Design reference missions

In this sub-section, the authors aim at showing the great variety of mission concept options obtained from this kind of process. As example, six different mission concepts able to comply with the initial stakeholder requirements are described. Each mission concept option is correlated with a brief textual description of the mission and some comments. Please note that these lists are a direct consequence of the scores obtained by the mission concept options in the QFD tool applications (Tables 5, 6, 7, 8, 9, 10, 11, 12).

3.5 Baseline selection

Among the hundreds of alternatives of mission concepts arisen from the application of the conceptual design methodology, following the results of the analyses, the last option proposed in the previous sub-section has been selected as baseline. The selection has been carried out evaluating the final ranking (based on the previous QFD matrices), and it is interesting to notice that the numerical suggestions are in accordance with the qualitative comments presented in the previous table. The stakeholders and the developers usually jointly perform this fundamental selection, and it is in this special moment that new top-level needs or requirements can arise implying a new iteration of the methodology.

3.6 System and sub-system design

This sub-section aimed at giving some additional details about those systems and sub-systems that deeply affect the vehicle architecture. Indeed, aiming at defining the general architecture of the mission and the layout of the transportation system, the authors mainly focused on those systems having a greater impact on the vehicle and spaceport layout. In particular, crew compartment, propulsion system, and escape system have been in-depth studied. Conversely, the other sub-systems as well as additional details about these elements will be surely evaluated and published as soon as the proper detail level of the design will be reached.

Once the baseline scenario has been selected and fixed, the main attention has been devoted at developing those elements of the mission that have been defined critical during the previous analyses. In particular, in this case, the design of a vehicle with such challenging characteristics has been selected as special system to be developed [11–15].

In particular, at the beginning, considering the very high design level, the major attention has been devoted to the development of those sub-systems with the major impact on the general layout of the spacecraft. This goal has been reached following a typical system engineering approach, in which the methodology presented and applied at high level all along the paper, has been recursively exploited to define the systems and sub-systems levels (see Fig. 18).

From the architectural perspective, the spacecraft Fig. 19 can be regarded as a hybrid configuration, standing between a pure wing-body and a pure lifting body. Indeed, the vehicle shape has been derived after several considerations, considering different design peculiarities, such as sub-systems allocation, weight and balance boundaries, crew safety, and trajectory. Indeed, the vehicle should be able to perform a quite long atmospheric flight, produce sufficient amount of lift at altitudes, where the atmosphere does not allow the assumption of continuous flow, but is very rarefied and resists at the high g and heat loads. As it is possible to see in Fig. 20, the spacecraft hosts the crew compartment in its forward part of the fuselage. This location guarantees the crew compartment the maximum distance with respect to the propulsion sub-systems and allows the creation of a detachable escape system. Indeed, as it is detailed in a following sub-section, this part of the fuselage can be separated from the main body of the spacecraft in case of very dangerous critical events.

3.6.1 Propulsion sub-system

Considering the mission statement, mission objectives, and the first list of requirements, some of them could deeply impact the design and the sizing of the propulsion system:

- to reach the target altitude of 100 km,
- to vertically take-off and landing from/to the same location, and
- to safely carry four passengers.

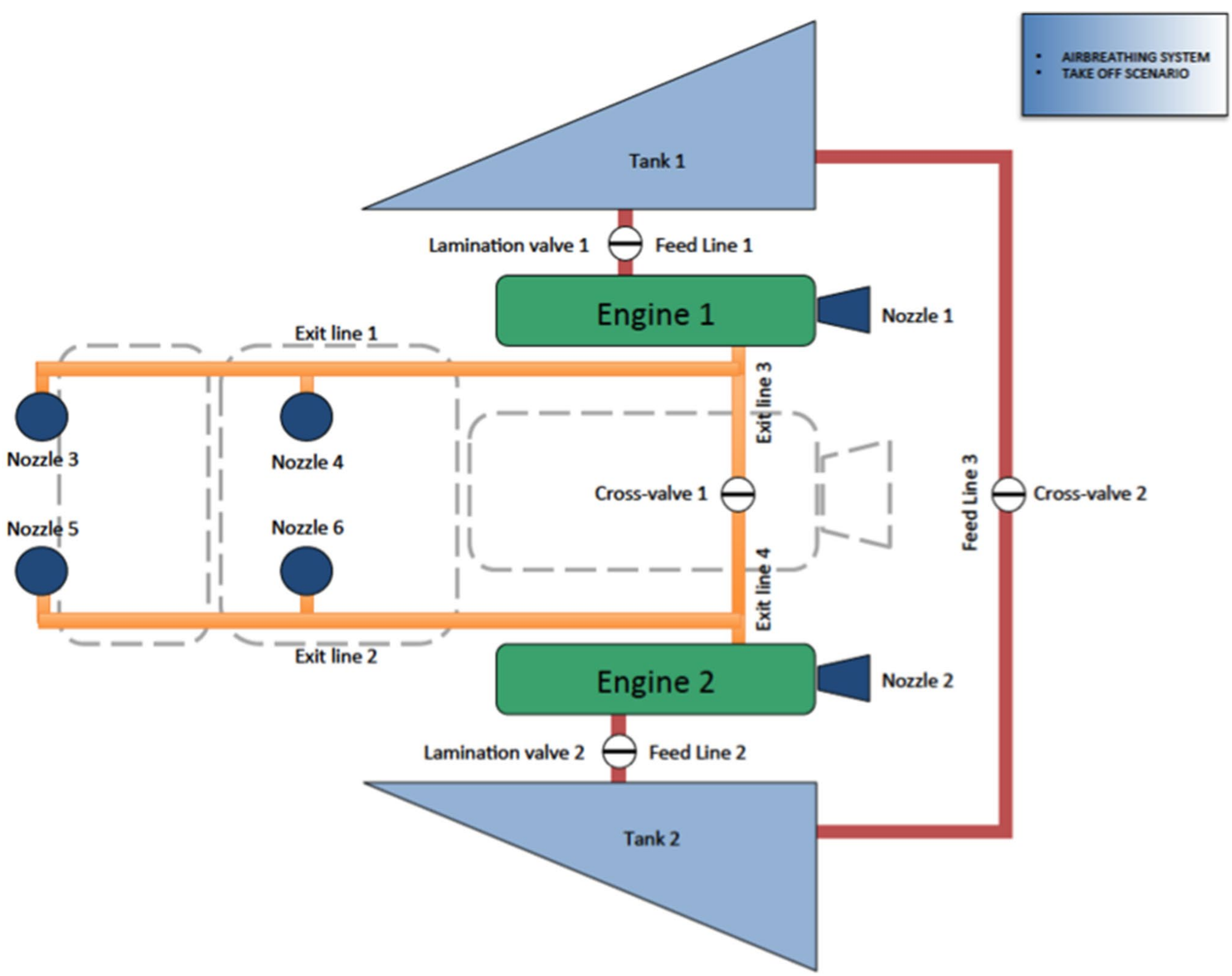


Fig. 21 Potential air-breathing propulsion sub-system scheme

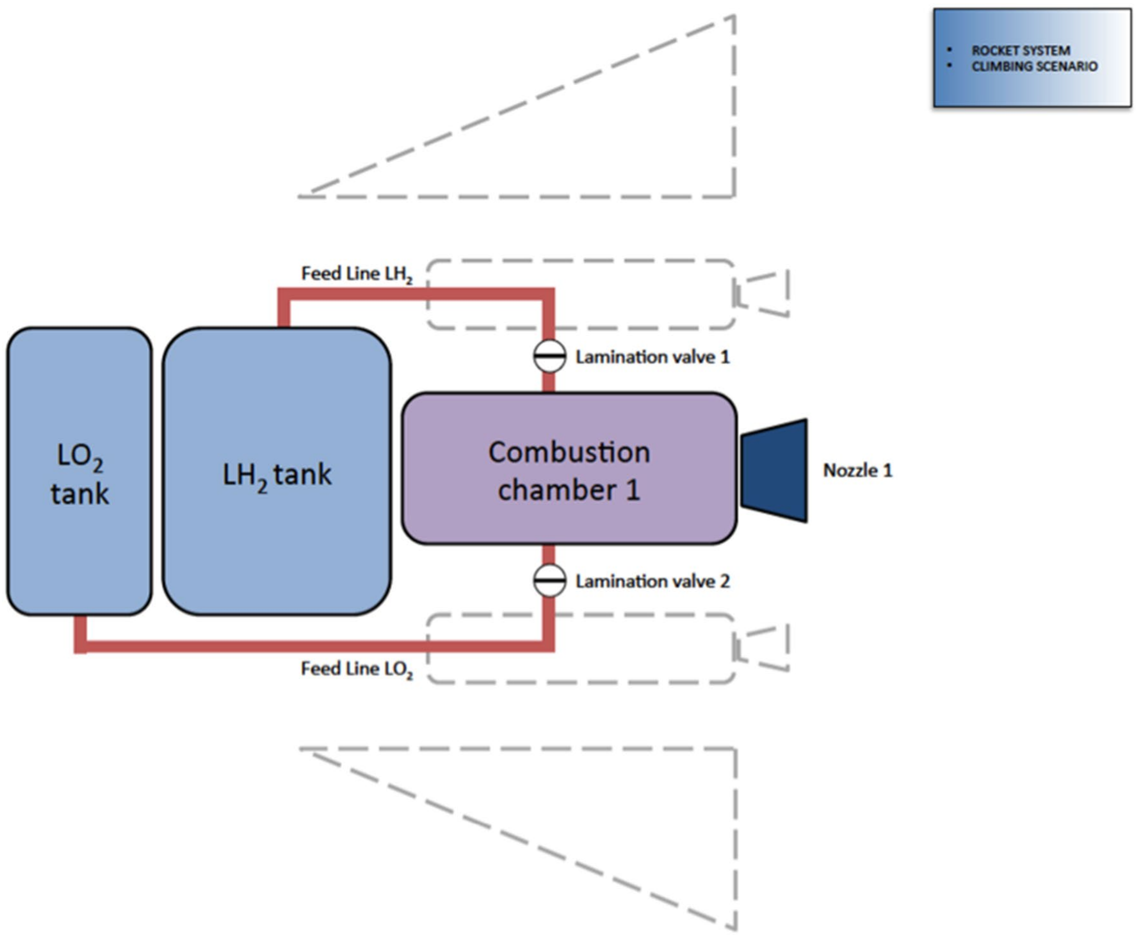


Fig. 22 Potential rocket propulsion sub-system scheme

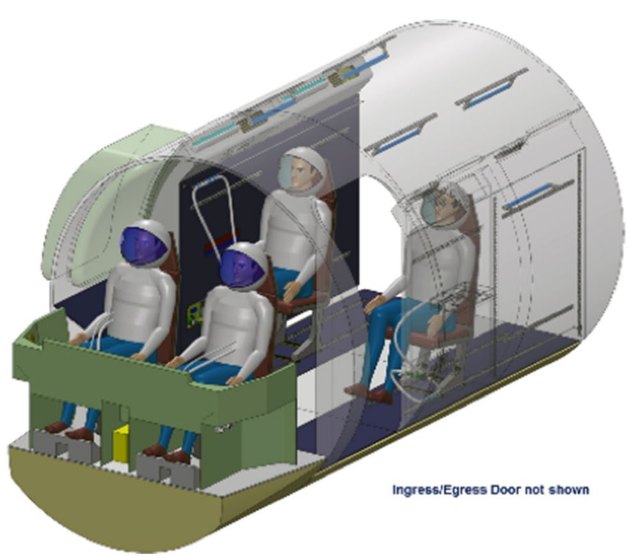


Fig. 23 CAD drawing depicting the internal view of a possible crew compartment layout

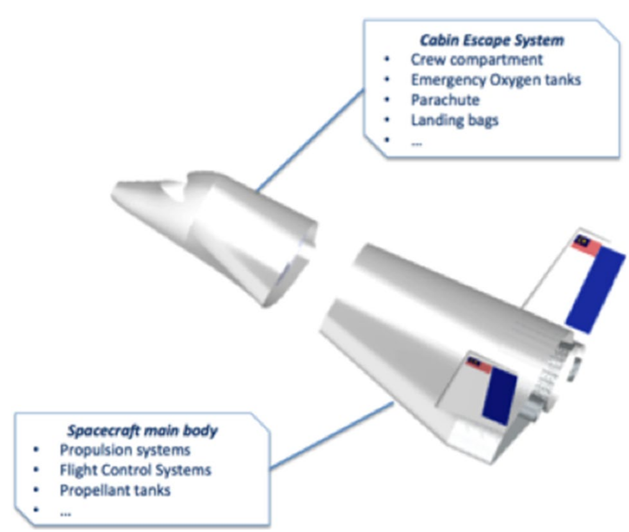


Fig. 24 Detachable crew compartment

To accomplish all these goals, two different propulsion sub-systems have been developed: an air-breathing-based sub-system and a rocket-based sub-system.

The first sub-system consists of two air-breathing engines and related feed sub-system (with tanks, pipelines and valves) able to guarantee the vertical take-off and the first climb segment, up to 18 km of altitude. Several solutions have been evaluated to implement feasible system architecture for overcoming the problem of the vertical take-off of this configuration. A potential solution is sketched in Fig. 21. During the take-off manoeuvre, the two main engines provide hot exhaust gases to steerable nozzles placed on the bottom part of the main body (Nozzles 3–6 in Fig. 21), while the two primary rear-mounted nozzles are closed (Nozzles 1, 2, in Fig. 21). In this condition, if properly sized, the engines shall be able to produce the total amount of thrust required to lift the spaceplane up to a certain altitude, where the transition to the climb segment shall take place. During the transition, the nozzles placed on the bottom part of the vehicle shall be steered to introduce a horizontal component to the resulting thrust vector. Simulations performed to understand this complex phase revealed that it would be necessary to act not only to modify the direction of the thrust vector but also to change its module. After some seconds, when a TBD angle of attack is reached, the nozzles placed on the bottom surface of the spacecraft shall be closed and the hot exhaust gases shall be directly diverted backward in the main rear-mounted nozzles. This propulsive configuration will be exploited up to reaching the ceiling altitude (or a lower and more convenient altitude). At this point, the air-breathing engines shall be shut down and, at the same time, the rocket engine shall be ignited. The rocket engine (Fig. 22) shall power the spaceplane up to a certain altitude defined as the burn out altitude (in this example 80 km). Starting from this moment, the spaceplane continues its mission performing a parabolic flight, reaching the target altitude (100 km) and starting the un-powered re-entry phase. When the spaceplane reaches its ceiling altitude, the air-breathing engines can be re-started, guaranteeing a higher accuracy in approach and landing phases. In particular, from the point of view of the system operative modes, approach and landing are specular with respect to climb and take-off.

The propulsion sub-systems can be hosted within the main body of the aircraft and consist of two air-breathing engines and a rocket motor placed between the two (Figs. 21, 22). Considering the air-breathing engines, they are fed by the fuel coming from the two major tanks located within the wing volume. Proper feed system has been designed to allow cross-feed, guaranteeing both the engines to be able to work also in the case, one of the fuel pumps is not properly working a part from the classical engine outlets; additional steerable nozzles are placed on the lower surface of the spacecraft to allow vertical take-off and landing. As far as the rocket engine is concerned, as sketched in dotted lines in Fig. 22, the motor is installed between the two air-breathing engines, while its related propellant is stored in proper tanks placed closer to the centre of gravity.

3.6.2 Cabin crew and escape sub-system

The crew compartment (Fig. 23) has been designed to accomplish some of the primary objectives of the mission:

- to carry two passengers and two crew members up to 100 km,
- to make passengers experience microgravity, and
- to guarantee an amazing view of the earth.

To perform the sizing of the crew compartment, aeronautical regulations [16] have been considered to sketch the minimum structural envelope and to size the room required for the crew. Then, looking at existing manned space projects, the sizing has been further detailed.

Considering the peculiarity of the mission and the advanced technologies that will be implied, a cabin escape system has been envisaged. In case of emergency, the front part of the fuselage can be detached exploiting some cartridges located in the intersection of the two bodies. Then, following a ballistic trajectory, the capsule should be able to decelerate using a set of parachutes and then, to safely land on water or terrain exploiting inflatable bags to reduce the effect of the impact.

The escape system has been conceived to overcome serious failures with the impossibility of safely landing with residual propellant on-board (Fig. 24). Solutions consisting in seat ejections have been considered, but the development of a solution for four seats appears to be too complex (also from the equipment and redundancy point of view) to be further developed.

Other sub-systems, such as landing gear, ECLSS, and power sub-systems, in this specific case, will not affect the external layout of the spacecraft, and for this reason, only general evaluations have been performed, while detailed analysis will be performed in the following development stages.

4 Conclusions

This paper deals with an innovative conceptual design methodology for complex aerospace designs proposing a practical approach for the development and the management of a high number of mission concept options. In particular, the methodology is applied to the definition of a transportation system able to perform parabolic sub-orbital flights.

The methodology revealed to be very useful and interesting, because it allows to manage a very high number of possible alternatives, at different design levels, suggesting the best solution among the several options, on the bases of the stakeholders needs expressed at the beginning of the project. Then, the suggested solution shall be in-depth analysed to verify the feasibility of the concept and to go on with following design and development phases.

After a theoretical overview of the methodology, a peculiar application to a sub-orbital transportation system was reported. Special attention has been paid at the accomplishment of the most demanding and challenging requirements and constrained fixed by the stakeholders, such as the vertical take-off and landing capability. The suggested transportation system is a single-stage spaceplane able to automatically take-off and landing, with a double propulsion system (air-breathing and rocket) and a detachable crew cabin to enhance the level of safety of the transportation system.

Future studies will deal with enhancing the degree of automation of this kind of methodology, finding out different algorithms to be implemented for the weights assignment process during the trade-offs. Moreover, in-depth studies will be carried out to continue the design of the envisaged single-stage spaceplane.

References

1. Andrés Gálvez and G. Naja-Corbin. Space Tourism. ESA's View on Private Suborbital Spaceflights. Published on ESA bulletin 135, 2008
2. Viola, N., Corpino, S., Fioriti, M., Stesina F.: Functional analysis in systems engineering: methodology and applications. In: Systems Engineering—Practice and Theory/Prof. Dr. Boris Cogan. InTech, p. 26, pp. 71–96, ISBN: 9789535103226 (2012)
3. Viscio, M.A., Viola, N., Fusaro, R., Basso, V.: Methodology for requirements definition of complex space missions and systems. Acta Astronaut (2015). doi:10.1016/j.actaastro
4. NASA Systems Engineering Handbook, NASA/SP-2007-6105 Rev1, National Aeronautics and Space Adminstration, NASA Headquarters Washington, D.C. 20546 (2007)
5. Akao, Y., Mazur, G.H.: The leading edge in QFD: past, present and future. Int J Qual Reliab Manag **20**(1), 20–35 (2003)
6. Chan, L.-K., Wu, M.-L.: Quality function deployment: a literature review. Eur J Op Res **143**(3), 463–497 (2002)
7. Aleina, S.C., Levrino, L., Viola, N., Fusaro, R., Saccoccia, G.: The importance of technology roadmaps for a successful future in space exploration. 9th IAA symposium on the future of space exploration. Torino (2015)
8. Viscio, M.A., Gargioli, E., Hoffman, J.A., Maggiore, P., Messidoro, A., Viola, N.: A methodology to support strategic decisions in future human space exploration: from scenario definition to building blocks assessment. Acta Astronaut **91**, 198–217 (2013). **(ISSN 0094-5765)**
9. Aleina, S.C., Levrino, L., Viola, N., Saccoccia, G., Fusaro, R.: Effective methodologies to derive strategic decisions from ESA technology roadmaps. International astronautical congress (IAC 2015), Jerusalem, Israel (2015)
10. Micouin, P.: Model Based System Engineering: Fundamentals and Methods. Wiley, Oxford (2014)
11. De Vita, F., Viola, N., Fusaro R., Santoro, F.: Assessment of hypersonic flights operation scenarios: analysis of launch and reentry trajectories, and derived top level vehicle system and support infrastructure concepts and requirements. In 20th AIAA international space planes and hypersonic systems and technologies conference (p. 3540). doi:10.2514/6.2015-3540
12. Raymer, D.P.: Aircraft design: a conceptual approach. In: AIAA Education Series, American Institute of Aeronautics and Astronautics, Inc., ISBN: 978-1-60086-911-2 (2012)
13. Chiesa, S., Di Meo, G.A., Fioriti, M., Medici, G., Viola, N: ASTRID-aircraft on board systems sizing and trade-off analysis in initial design, Research Bulletin, Warsaw University of Technology, Institute of Aeronautics and Applied Mechanics (2012). **(ISSN 1425-2104)**
14. Viscio, M.A., et al. Conceptual design of a habitation module for a deep space exploration mission. Proc. Inst. Mech. Eng. Part G J. Aerosp. Eng. 227(9), 1389–1411 (2013). doi:10.1177/0954410012457292
15. Viscio, M.A., et al. Habitable module for a deep space exploration mission. International astronautical congress: IAC proceedings (2011)
16. European Aviation Safety Agency: Certification specifications for large aeroplanes CS-25, Amendment 3 (2007)