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Application of a System Engineering approach to the preliminary design of cabin compartment alternatives for suborbital space transportation systems.

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Table of Contents

“I get extremely excited thinking about what the scientists and researchers of the world will do with WhiteKnightTwo and SpaceShipTwo. It is so critical that researchers have the opportunity to send payloads to space, or even to fly themselves. I can’t wait to see what great new ideas emerge and which of life’s biggest questions will be solved using data gathered on board our vehicles.”

- Sir Richard Branson
Founder of the Virgin Group

[from official SpaceShipTwo User Guide]

Chapter 1:

Introduction

[SpaceShipTwo during the second rocket-powered test on 29 May 2018. Image source: Virgin Galactic via Twitter]

The author considers this thesis particularly interesting on twofold fronts. On the academic side, topics about space products design in general are discussed, in particular new techniques and strategies are adopted to support the designer to improve the design management, as well as the clear exposition of the design results.
On the industrial side, this thesis has given the opportunity to work on an innovative case-study, dropped into the pioneering context of suborbital flights.

1.1 ABBREVIATIONS AND DEFINITIONS

Before continuing, it is worth to define few keywords that will be used often in the discussion:

- *Payload*: "discrete set of equipment, software, specimens, and/or other items that are designated and treated as a collective whole in support of one or more experiments or commercial objectives" (definition from International Space Station Payload Accommodations Handbook). In the context of this thesis t is a set of hardware, software, experimental samples, and other elements to support one or more experiments. A distinction is made between pressurized and external payloads. The payloads in a pressurized environment are for example those inside the modules of the ISS where the atmosphere is like that of the Earth. External payloads are mounted on external platforms to point towards Earth, to other specific points in space or to be directly exposed to the space environment.
- *Payload structure*: cited from [2.23] "the structural components that are required to keep the payload secured to the rack and properly contained, including all joints, fasteners and other attachment points"
- *PD*: Payloads Developer
- *Microgravity environment*: condition in which the gravitational force, intended as the force that causes the perception of weight, is counterbalanced by another force or sum of forces, that as the gravitational force, are applied on every point of the volumes of bodies that stay in that environment. A typical microgravity environment verifies when a body is free-falling: gravitational force is counterbalanced by inertial one. Actually, it is not perfectly counterbalance, but the resultant is negligible, typically magnitude orders under 10^{-4} g.
  It is important to underline that in a microgravity environment, almost surely the gravitational field intensity is anything but negligible. In fact, into orbit around Earth, it is possible to experience microgravity because the gravitational force is counterbalance by the inertial force of the satellite but the gravitational field is responsible of the centripetal acceleration that maintain it on orbit.
  In this thesis the term weightlessness is used improperly as a microgravity synonym.
- *Suborbital flight*: is a flight in which trajectory lays also into the space domain but do not describe a complete revolution around the Earth. Almost in all cases, an unpropelled parabolic flight path is present and determines a microgravity environment on the vehicle. If it reaches almost 100 km it is intended as a spaceflight.
- *payload accommodation*: it means the integration or installation of payloads into the space vehicle.
- *system*: it is the ensemble of the all components or elements that concurrent together to the accomplishment of one or more objectives and of all relations between them. The system as a whole has functional sense if taken individually, unlike the individual components.
- *the product or aerospace system*: it is the final purpose of the design, the entity that will satisfy the customer. It can be a physical object or a group of physical objects and also includes all the information related to them, for example instructions for construction, use and maintenance, etc.
- *space system*: the ensemble of hardware, software, human resources and relationships among them that compete to the accomplishment of a determined space mission.

- *service*: it is a group of activities requested by the customers which need a solution to a problem. The designer will have to design a set of products that can solve this problem and that can be used to provide such service.
- *project*: in the organization of actions over time for the pursuit of a predefined purpose
- *requirements*: generally speaking, a requirement is a sentence in which a feature of the system is descripted or quantified. They can be distinguished from other key-sentences thanks to their syntax form.
- *mission*: in this work is intended a mission accomplished by aeronautical and/or space systems.
- *design solution*: it is the product that results once the methodology is applied.
- *reliability***:** from [“NASA System Engineering Handbook”, NASA, 2007] “the probability that a device, product, or system will not fail for a given period of time under specified operating conditions”
- *product assurance***:** it is an engineering discipline aimed to ensure the mission will be carried out as planned and according to customers’ desires. ESA defined [https://www.esa.int/ Our_Activities/Space_Engineering_Technology/Product_Assurance/(print)], the purpose of a product assurance activity as designing “failure-proofing missions by ensuring that the materials, mechanical parts, processes and electrical components used to assemble a spacecraft or launcher shall be fit for purpose over the entire life of a mission”. The discipline therefore covers a broad spectrum of topics, from availability and reliability to quality, including often also safety. Quality assurance is a subdiscipline and it is aimed to ensure that the product is free of defects that could negatively affect the experience of the customer.
- *design synthesis*: it is the collection of documents that describes the design solution in detail. It is also the result of the methodology, the final output which will be obtained after the design process.

1.2 SCOPE OF THIS THESIS

Suborbital flights are performed since the beginning of the space history with several purposes. Firstly, as happened for many technological improvements, the development trigger was military, specifically the Nazi V2 and derived intercontinental missiles, as platforms for offence. Suborbital capabilities are then developed for politics purposes into the Cold War and Space Race context, as the Mercury project, and research and technology advancement purposes, as the X-15 case. During the last decades, suborbital flights are conducted via existing sounding rockets, to perform scientific research in microgravity or into the upper atmosphere layers.
The novelty that justify the great interest of the last years that currently persists, is the possibility of using reusable suborbital vehicles to transport people and payloads over the Karman Line regularly and frequently by private companies for commercial purposes, in the context of the New Space Economy.
In fact, after SpaceShipOne exploit in 2004, reusable commercial space vehicles have increased their concrete and credibility as platforms aimed at space transportation. This event underlined the technology development and maturation happened during previous decades, that permitted to enlarge offer and demand of suborbital vehicles. The capability to carry passengers up above 100 km altitude is promising to ensure an experience in microgravity environment and a stunning view of the Earth. A large portion of the demand for sub-orbital flights seems to come from private individuals who want to enjoy this suborbital experience. Furthermore the development of suborbital transport systems is considered a necessary step for the development of reusable Earth-To-Orbit transport systems and hypersonic spaceplanes.

This situation led to numerous initiatives around the world, and also in Italy. In particular, in this context it is worth to underline the agreement between the ALTEC SpA[1] and Virgin Galactic LLC aimed at operating the SpaceShipTwo in the Italian territory. The agreement plans also the construction of a dedicated spaceport in Italy, likely obtained modifying an already existing military airport. Envisaged operations include, aside from space tourism, suborbital microgravity experimentation, pilots and astronauts training and didactic activities.

Among these capabilities of suborbital platforms, into this thesis payload experimentation has been discussed with special focus. Throughout space history, a high number of spacecraft was used to enhance the technological and scientific advancement of mankind. One of more desired capability is surely to perform space-related activities into a microgravity environment. It is sufficient to think to the endeavours towards design and built of numerous space station: the Salyut family, Mir, Skylab, Tiangong 1 and the International Space Station. Moreover, onboard Space Shuttle, in addition to its main capability of payload transportation system and satellite deployer, experiments and test has been carried out.
The possibility to use suborbital vehicles for research, although limited to few minutes each flight, opens new uncertain scenarios. Conducting test on a suborbital platform before repeat the experiment on a space station or use a technology in a mission permits to increase quality and success rate. Moreover, after a space mission an experiment repetition can confirm or invalidate what resulted from space.
According to some sources, the main incomes of the entire suborbital market will be the experimentations from institution and universities. Following this hope, Astronauts4Hire was instituted, to anticipate the large trained astronauts demand for scientific and demonstrating suborbital operations if such a scenario will realize [“Suborbital, Industry at the edge of space”, Erik Seedhouse, 2014]. However, other sources, such as Bryce Technology, former Tauri Group, believe that payload experimentation constitutes only a small portion, while the main use of SRLV will be represented by the market segment of Commercial Human Spaceflight. Other consideration of this topics will be discussed into Chapter 4.

1.3 PURPOSES OF THIS THESIS

The purpose of this thesis is deriving a simple preliminary design methodology from published articles, digesting it with a System Engineering approach and then applying it in a coherent way on a case study of industrial interest, in order to find the most optimized solution.
The case study chosen is the design of a new reusable suborbital vehicle as useful platform for flights related to the execution of experiments or testing of new technologies in microgravity and in the space environment. Aside from this main use, also several different types of missions, such as space tourism or astronaut training, should be discussed.
Further, the obtained option, derived applying the methodology starting from the blank sheet, should be compared with another case study that consists of converting an already existing spacecraft, specifically designed for transport of passengers.

This main purpose is certainly very broad and it can be discussed by several points of view. For simplicity reasons, the problem has been limited to a portion of the vehicle, the core in which these activities will take place on a space vehicle: the cabin. The previous purpose remains so valid in terms of constituting the guideline of the work, considering therefore that only a small part of the entire vehicle will be deeply discussed. The cabin has been chosen because intuitively is the subsystem that is mostly affected by the type mission. Each requires ad-hoc hardware, for example seats for space tourism missions. The

[1] ALTEC (Aerospace Logistics Technology Engineering Company) public-private company owned by Thales Alenia Space and the Italian Space Agency.

methodology represents a tool to generate a small number of viable alternatives, and select the optimal one among them.
Moreover, the thesis explores how the process changes if the input information is modified. At this purpose, along the design of a new cabin for a generic vehicle, another already existing cabin has been adapted to experimental missions. Comparison between these two cases has been carried out.

The System Engineering approach includes the development of a computer model, based on sysML language able to describe all design choices. Finally, particular attention has been paid to the issue of traceability of the requirements and design choices with the use of specific IT tools, which led to the integration of this traceability information into the CAD model of the case study within the SIMULINK simulation environment. The application of the methodology provides so an innovative design synthesis, a CAD drawing into which it is possible to enter the traceability of requirements and other design results.

1.4 CONTENTS OVERVIEW

Chapters 2, 3 and 4 are preparatory for the Chapter 5 in which the case study has been analysed. The author advises to follow with order the succession of chapters during the reading.

Chapter 2: the chapter offers ten paragraphs, useful to the reader to understand the subject of the research and have a broad picture on it. It does not want to be a complete and exhaustive discussion of the suborbital flight and all its aspects, but only a propaedeutic material for a better understanding of Chapters 4 and 5. If the reader is interested to investigate further the topics, it is recommended to read the references, which discuss each subject in a very deep way.

Chapter 3: it is a theoretical chapter, in which the working methodology is presented, as well as the related programs useful to exploit the model-based approach. This methodology has been subsequently applied firstly in Chapter 4 and then to the case study in Chapter 5.
A main purpose pursued in the presentation of the methodology is to underline how this is geared towards innovation and the introduction of new technologies. While representing a risk, innovation is fundamental to gaining a technical advantage over competitors and consequently obtaining an economic return on the carried-out investments. To be sure that the proposed innovation is successful and the proposed technology is sufficiently mature, the designer must however conduct tests and simulations. Moreover, innovation does not occur only with the introduction of new technologies, but also with new business strategies, operations, manufacturing, maintenance and organization. All these aspects are strictly all connected to each other and included into considerations and results that derive from the application of the methodology, leading to integration into the synthesis system design of innovation in all forms, techniques and managerial from the birth of the product to its disposal [3.2].
Innovation must be introduced as soon as possible, when the flexibility of the project is maximum. In the advanced phases, in fact, some constraints may have been introduced that will surely impact and clash in an important way with the desired innovation.

Chapter 4: the case study is presented in a broad manner, and the methodology is applied to this general case. The reason of this approach resides into the top-to-down nature of the methodology. It is always recommended to consider the problem as general as possible, to lower the risk of unappropriated design choices due to a partial overview. In fact, starting from top level permits to increment the confidence level and globally could accelerate the design process of the case study. Moreover, it is indispensable to obtain a complete traceability of the design process.
This chapter focuses especially on the methodology steps, while the following one is more centred on the case study considerations.

Chapter 5: in the first part the chapter 5 includes the development of the cabin compartment for flight aimed at scientific experimentation and technology test and demonstration. The second part presents another case study, the Virgin Galactic's SpaceShipTwo. This spaceplane, as far as can be deduced from the papers and official material, has been developed specifically for the suborbital human space market, to provide a space tourism service. Also mission aimed at payload experimentation resulted to be considered, but related information is extremely limited and without details. Another application of the methodology starts from these data towards the adaptation of this spaceplane, designed for human transportation, to payload transportation mission. Results have been then compared to the first study case, to underline differences of design if the starting point varies, respectively the blank sheet and an existing vehicle.

Chapter 2:

Historical background

[LYNX Spaceplane, Image source: XCOR]

2.1 BRIEF HISTORY OF SUBORBITAL FLIGHTS [2.8]

This paragraph deals with the history of suborbital flight of the western part of the world, to introduce the reader into the background of the argument and give some suggestions to better understand the current status of the suborbital industry. The author believes that the study of the past events is an excellent way to figure out the reasons why suborbital vehicles are nowadays developed and because specific engineering choices have been pursued.

The first vehicle in history that cross the threshold of 100 kilometres that conventionally separates space from the aeronautic domain was the ballistic missile Vergeltungswaffe 2 (called V2), developed by Nazi regime. During the early months of 1944, a test prototype of V2 launched from the military base of Peenemunde, accomplished its flight overcoming the Karman line and kicking off the bombardment program with the first ballistic missile to the damage of England and Belgium.

After the defeat of German during WW2, both American and Russians used this rocket as a starting point to develop their programs in the context of the Cold War and the Space Race.

The URSS come to the R-7, the first intercontinental ballistic missile that permitted, in addition to the possibility of transport of nuclear weapons, the orbit insertion of Sputnik I and Sputnik II in 1957 [2.13].

On the US side, the German project was elaborated into sounding rockets and intercontinental missiles, like the RTV-G-4 Bumper and the PGM-11 Redstone. From the latter, the rocket, a modified Jupiter C, which puts the first American satellite Explorer 1 into orbit (360 km altitude) was developed. Moreover, the program Mercury was established from the just instituted NASA. The program had the goal of putting an American astronaut into LEO and permitting his safe recovery. The first step consisted in trying to complete a manned suborbital flight and for this purpose a large amount of systems had to be developed and tested. At the beginning, chimpanzees were recruited to avoid risks to human astronauts and to be sure to carry a living being to space and return it safely. Moreover, chimps can be trained and among animals, they are the most similar to humans for physical conformation and DNA.

In 1958, a squirrel monkey called Gordo was the first primate to travel in space, following a suborbital flight path. The monkey had no adverse effects from the entry into space or the microgravity condition. Due to the malfunctioning of the parachute, it did not survive the impact at the end of the re-entry.

Further launches with monkeys laid the foundations for launches with astronauts. In fact, in 1961 Alan Shepard was the first American to complete a suborbital space flight, carried to 187 km by a Mercury-Redstone rocket.

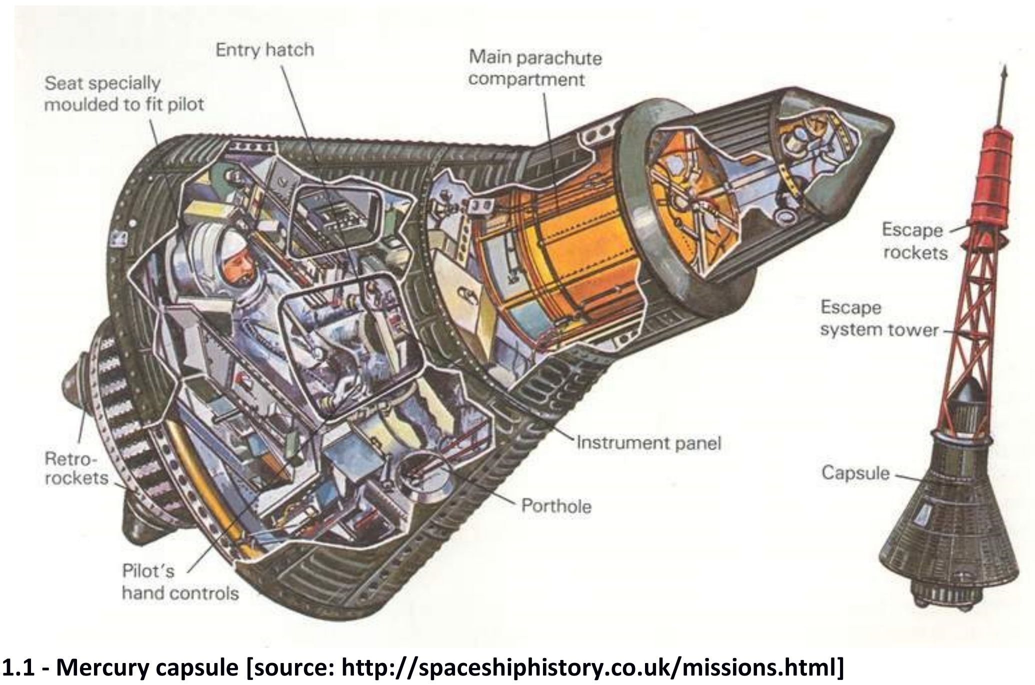

Figure 2.1.1 - Mercury capsule [source: http://spaceshiphistory.co.uk/missions.html]
The capsule cabin could barely accommodate a single astronaut.

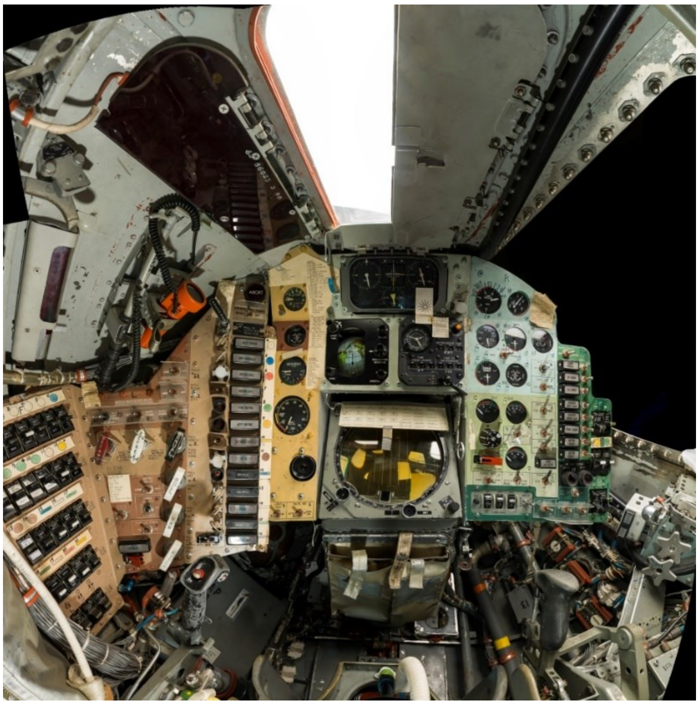

Figure 2.1.2 – Mercury's cabin internal view [http://trooth.info/mercury-spacecraft-cockpit.html]

The following landmark of the suborbital flight history is certainly the North American X-15 program, that made 199 flights between 1959 and 1968. It was the result of a collaboration between NASA, USAF and US Navy and it was the first manned reusable vehicle to reach space following a suborbital flight path. It is also the first winged aircraft to fly into the hypersonic regime until Mach 6 and to perform operations above 30000 meters altitude. Eight pilots reached the Karman line thanks to this spaceplane, gaining the astronauts status. Clearly, to reach these performances, X-15 made use of rocket propulsion, with a liquid engine integrated into the fuselage.

Being part of the X-planes family, the spaceplane is characterized by an innovative, at the time, and experimental design. Many of the sophisticated systems of the vehicle were experimental and a huge amount of data was collected for the developing of future space vehicles, including the Space Shuttle. A first problem that designers encountered was the elevated temperatures that are implied into hypersonic flights. The titanium structure was covered by an experimental nickel alloy called Inconel X that maintains proper mechanical resistance up to 650° C. Moreover, the entire spaceplane was black painted, to dissipate the maximum amount of heat via irradiation. The pilot was assisted by an innovative stability augmentation system and by the first inertial navigation system.

Length [ft]	**Span [ft]**	**Height [ft]**	**Rocket thrust [lbs]**	**GTOW [kg]**
50	22	13,67	57000	15000

Table 2.1 - X-15 Specifications [2.9]

See Appendix B for X-15 representations.

The third milestone of suborbital development came nearly forty years later, in 2004, and opened the door of the suborbital flights to the commercial industry. On the fourth of October the SpaceShipOne (abbreviated SS1), a spaceplane designed and built exclusively with private funds, reached the Karman Line during a public flight and so won definitively the Ansari X prize2 and had a very positive exciting effect on the industry.

The spaceplane is an experimental suborbital reusable vehicle designed by Burt Rutan of Scaled Composites for its program Tier One funded by Paul Allen, co-founder of Microsoft.

The spacecraft was brought at 15 km altitude by a mothership called WhiteKnightOne, designed contextually, with twin turbojets. At release, the unsteerable and unthrottleable hybrid rocket motor is ignited to reach 100 km at the parabola peak. Then it glides transonically and subsonically and finally lands horizontally on a standard runway. It accomplished a total of 17 flights at Mojave Airport from May 2003 to October 2004. The last two flights permitted to win the prize and so partially cover the funding of the

[2] It was a space competition organized by the X-prize Foundation and funded by Ansari entrepreneurs to promote studies and development of commercial suborbital spaceflights It consisted into a 10 million prize to the first private company that had launched a manned vehicle twice in space, with the second flight within two weeks from the first.

project, while the first 15 ones were incremental experimental tests, at the beginning only captive carried and then glided and powered.

Figure 2.1.3 – SpaceShipOne
Now SpaceShipOne is located at Smithsonian's National Air and Space Museum [2.23].

Among spaceplanes, SS1 has unique feature: the rear half of the wing and the tail are hinged to the fuselage so as to change incidence and become airbrakes useful to better dissipate energy during re-entry. Also, a heat shield was required for safety reasons. The thermal liner for the re-entry is made of ablative composite material and is the only part of the craft, other than the fuel and oxidizer themselves, that must be replaced between flights. The main structure design makes a large use of composites, mainly graphite/epoxy. The cabin is pressurized, maintaining a sea level breathable atmosphere. Oxygen is introduced to the cabin from a tank, and absorbers remove carbon dioxide and water vapour. The occupants have not to wear spacesuits or breathing masks, because the cabin has been designed to maintain pressure in case of faults. The pilot sits towards the front, and two passengers can be seated behind.
The barebone cockpit, showed in Appendix B, is particularly representative of the experimental nature spaceplane: only a colour LCD called Flight Director Display (FDD), positioned in front of the pilot, and a few instruments are available to control the vehicle. The FDD displays data from the System Navigation Unit (SNU) on a with different modes for each phases of flight. SNU is a GPS-based inertial navigation system, which processes data from sensors and subsystems. These data are downlinked as telemetry by radio to mission control.

Length [m]	Span [m]	Max Mach [/]	Rocket thrust [N]	GTOW [kg]
8.53	8.05	3.09	74000	3600

Table 2.2 - SpaceShipOne specifications [2.10]

Retired X-15 and SpaceShipOne have many aspects in common (non-exhaustive list):

- Both are released from a mother-ship that carry them to the appropriate altitude. In the SS1 case, the aircraft is the earlier presented White Knight, while on the other hand was the bomber Boeing B-52 Stratofortress;

- Both use an integrated rocket to reach space;
- Both use thrusters to control roll, pitch and yaw at higher atmospheric levels;
- Both during descent are unpowered gliders, with traditional stick-and-rudder approach;

… and some differences:

- The X-15 had an ejection seat for emergencies up to Mach 4 and up to 36500 altitude meters.
- The X-15 was built only for research purposes on the effects of hypersonic velocity on pilots, materials and systems. The SpaceShipOne is of course an experimental vehicle, but its final objective is to be an intermediate step towards the commercial suborbital transportation.
- The X-15 has a liquid rocket engine (LOX and anhydrous ammonia), while SS1 has a hybrid one (nitrous oxide and rubber).

As it is discussed into this brief introduction, history of suborbital vehicles, and of course suborbital vehicles their selves, is characterized by a strong pioneering and experimental nature. SpaceShipOne had its galvanizing effect because it demonstrated that space is no longer an exclusive frontier of governments organizations and space agencies, stimulating further the new space economy.
With this industrial stimulation, in a global context of regulatory uncertainty about suborbital spaceflight, concerns and legal issues about safety of crew and future passengers have been highlighted. So, at the end of 2004, the Commercial Space Launch Amendments Act (CSLAA) was signed, assigning the FAA’s Office of Commercial Space Transportation the task to issue regulations concerning suborbital reusable vehicles. The regulation redacting was limited until 2012, to allow space ventures to mature before the Institution could determine too strict regulations that could restrain the industry. Currently, FAA has released a detailed set of regulations about Commercial Space Transportation, located at Title 14 Code of Federal Regulations, Chapter III, Parts to 400 to 460.

2.2 MANNED SUBORBITAL REUSABLE LAUNCH VEHICLES CAPABILITES AND APPLICATIONS

The purpose of this paragraph is to explain how suborbital vehicles can be applied and so to give the basis for a comparison, discussed in paragraph 2.4, to the different platforms currently used in this fields: drop towers and terrestrial platform, stratospheric balloons, sounding rockets and ISS[3].
A manned suborbital spacecraft can provide five important capabilities [2.8]:

- access to microgravity condition;
- access to the space environment of the low thermosphere (thermal, radiation, vacuum environments). This capability can be performed with external pods, sensors or retractable appendages;
- exposure to the environment of atmospheric layers below 100 km: troposphere, stratosphere and mesosphere;
- exposure to an acceleration and deceleration profiles;
- possibility of carrying humans on board;

Historically, these functions have been covered by space stations, satellites, sounding rockets, drop towers and stratospheric balloons, in order to accomplish a large number of different activities. However, taking into consideration that each of these systems presents own peculiarities, advantages and disadvantages, none of them is capable alone of all the listed functions. On the contrary, manned suborbital reusable vehicles are and for this reason industry has identified the following areas as promising commercial fields for SRLVs application [2.8]:

- science research: to accomplish experiments aimed to increase knowledge in various scientific disciplines;
- aerospace technology test and demonstration: to advance technology maturity and certificate space products;
- space tourism: to provide touristic experience of microgravity with a stunning view of Earth;
- astronaut training: to provide further capabilities to training programs, such as execution of short operations during microgravity reproducing situations that astronauts will find in orbit;
- media relations: to enhance production of promote materials and space-related multimedia contents and to increase brand-awareness;
- education: provide flight opportunities to K-12 school, colleges and universities. Examples of space education activities are “Fly Your Thesis!” and “Fly Your Satellite!” ESA programs.
- remote sensing: to gather multispectral images and data of the Earth’s surface or systems for commercial, civil and military applications;
- satellite deployment: to insert small satellites into orbit;
- point-to-point transportation: to transport cargo or passengers between great distances within two hours, describing an elliptic suborbital trajectory that permits to reach high cruise speed.

A description of each category is provided through the paragraph. In particular the author has focused on science research and technology test and demonstration.

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[3] Generally, all past and present space stations, such Tiangong2, are suitable for science research but only ISS is considered in this work because it is the single currently available to occidental world. There, payloads can also access to external space, to be exposed to vacuum and radiations (for the ISS orbit, conditions of about 400 km altitude).

2.2.1 Science research

Research institutions, universities and companies could benefit from a suborbital platform to fly their scientific payload and experiments. In fact, space research can be both institutional, promoted by governments and institutions, and commercial, for example committed by industries and multinational companies. However, some sources [2.14] forecast that during the next decades only governmental funds will be invested into this activity.
This commercial field embraces all the main capabilities provided by manned SRLVs listed above: experiments range from measuring or react to proprieties of the near-Earth space environment or of upper layers of the atmosphere to studying the immediate compensation of human beings to microgravity (see figure 2.4).
A classification of the three branches of research considered most promising is listed here basing on references [2.14] and [2.8] and will be discussed below:

- <u>microgravity research</u>: includes life sciences, as biology and physiology, and physics science such as material science, metallurgy, fluid and combustion physics;
- <u>earth science</u>: includes atmospheric sciences and earth observations;
- <u>astronomy and astrophysics</u>: takes advantages of the rarefied air of upper atmosphere to gather excellent quality images of the celestial objects and study relate phenomena;
- <u>human research</u>: it focuses on the human body exposed to accelerations and decelerations.

In the figure 2.4, the classification of Tauri Group is reported. Note that both local experiments and remote sensing observations are considered.

Figure 2.2.1 - Example of disciplines, with relative study subjects, suitable for suborbital science research (Source: [2.11])

These categories benefit mainly from all different suborbital capabilities: access to upper atmosphere is useful especially for Earth Science, exposure to space environment for Space Science, exposure to accelerations for Human Research and access to microgravity for Biological and Physical Research.

Regarding life sciences, researchers investigated a high number of topics about biological processes affected by reduced gravity. For instance, the capability to sense pointing of the gravity force vector of individual cells that it is used for example by plants to determine the grow direction on Earth [2.14].
Object of study are so cells, microbes, proteins and macromolecules, organic chemistry, tissues, small animals, mushrooms and plants.
Previous microgravity studies investigated the functioning and the effect of gravity on "increased virulence in microbes, pluripotency of stem cells, and tissue morphogenesis patterns" [2.12], cell division and immune system capabilities. Protein crystallization in this environment permits to obtain high quality macromolecular crystals for further diffraction analyses. On Earth, that quality is unreachable due to convection and sedimentation. Another example deals with mice that are suitable objects for investigation in few minutes microgravity time [2.6].

Life sciences include of course Human Physiology Research. It is aimed to find solutions to a high range of biomedical problems, in favor of both people on Earth and astronauts in space. For example, strong interest topics are the prevention of physical degradation in view of long duration manned space mission, for instance to Mars. Humans exposed to reduced gravity for months experience detrimental consequences on their bodies, such as weakening of bones, muscles and circulatory system and alteration of physiological parameters. The development of pharmaceutical products to reduce effects of space motion sickness (a condition consisting of nausea, visual illusions and disorientation caused by changes of gravitational force's intensity) is also of primary importance.
Another field of life science study is astrobiology, which includes the exposition of organisms directly to space environment, to understand if they can survive and which effect vacuum and radiation has on them. Surprisingly, it was discovered that some organisms, for example bacteria, exhibit extraordinary resistance to space conditions and could be useful to study which elements give them such proprieties. Moreover, this type of investigations hopes to answer some questions about origin and evolution of life.
Reassuming, life sciences studies in microgravity permit [2.12]:

- to deeper understanding a broad range of biological occurrences;
- to investigate response to reduced gravity of biological subjects and humans;
- to developing drugs, vaccines, therapies to cure or alleviate diseases;
- to improving food supply capabilities;
- to improve life support systems for new manned space missions.

Those experiments are currently conducted onboard ISS and sounding rockets. Clearly the latter do not permit a human interaction.
Although it may seem that these experiments require a long time stay into microgravity environment, and actually it is for many cases, but for others the few minutes of a suborbital flight are enough. For example, activation of T-cells of immune system is inhibited immediately by exposition to microgravity [2.14]. A unique application of SRLV to physiology is the generation of data about human response to suborbital flights, especially to ascent and descent acceleration phases, that are currently few and very interesting for scientists [2.8].
Biologic samples require often to be brought back to Earth without damage to be further analyzed. This is a capability that can be offered by suborbital reusable vehicles, that can return to the spaceport at the end of the mission, where supposedly research facilities are collocated. Also sounding rockets have this recovery capability, but the landing spot is determined by the parachute and so payload post-mission access time could be too long.
ISS currently has only one vehicle capable of taking back samples to Earth, the Dragon capsule, but also in this case some researcher could consider payload access time excessive. [2.14]
Many biological experiments require in fact a researcher or specialist that could conduct the experiment, so the available platforms are only space stations and manned suborbital spaceplanes, respectively for long-term and short-term missions. Same requirement also applies for studies on the human body.

On the other hand of research, microgravity opens to many experiments in the field of physics. For the sake of clarity, possible topics are presented as a bullet list [2.14]:

- fluid physics: "fluid physics is the study of the motions of liquids and gases and the associated transport of mass, momentum and energy" [NASA, 2.12]. Experiments of this section are aimed to increase knowledge about behaviour and motion of liquids and gases. Processes such as diffusion and suspension are difficult to study on Earth, due to the presence of gravity-related occurrences, firstly convection and sedimentation. Experiments range includes study of two phase flows, capillary flow, critical point wetting, surface tension, transport phenomena. Results lead for example to improvements of propulsion, thermal and life-support system.

- combustion physics and chemical reactions in general: combustion is surely the most studied reaction in space because of its dangerousness. Actually, it is not a single reaction, but often a chain of even thousands of reactions involving even hundreds of compounds. The process is so very complex and the possibility to study it without the effect of gravity is very useful for deeper understanding of flame behaviour, flammability and pollutant emission. In fact, even simpler combustion reactions are very difficult to simulate by numerical analyses [2.12].
- material science: like fluid, also processes on material are affected by gravity. Interesting topics include directional solidification, crystal growth, diffusion in liquid metals, molten materials behaviour and fracture mechanics. Material science studies permits to develop new materials or to obtain exceptional quality alloys.

Aside microgravity research discussed up to here, the Tauri Group report [2.11] has also identified following three other scientific areas that are promising to take advantage from suborbital research.
Currently, in atmospheric research: there is a lack of knowledge about dynamics and phenomena that regulate the behaviour of the upper layers of the atmosphere. A deeper understanding will lead surely a more accurate climate models. Also sounding rockets could study this portion, but the cost will be higher [2.11]. Technically, these missions require inexpensive and low-profile sensors integrated on board. A well-documented experiment of atmospheric research is the POSSUM project, funded for studying polar noctilucent clouds.
Suborbital astronomy: atmosphere constitutes a shield against substantial portions of the electromagnetic spectrum. At the altitudes reachable by suborbital spacecrafts it is possible to obtain high-quality images, in infrared, visible and ultraviolet. It requires precise pointing and accurate calculation of trajectory and timings.
Finally, with longitudinal human science experiments it is possible to extend the study of the effects of accelerations and microgravity on the human body to a much greater number of people than nowadays. Research on a broad population is important to obtain data for the development of hypersonic travels, a current branch of engineering interest.

2.2.2 Aerospace technology test and demonstration

Suborbital reusable launch vehicles' capabilities can be used to increase the maturity of aerospace technology and products. This is done by executing demonstrations and tests on prototypes, components or systems during a flight. In other words, SRLVs can be seen as suborbital laboratories capable to advance maturity of technological products through tests that can lead to demonstration, qualification[4] or certification [2.11].
To better understand this field of application, that constitutes a central element of the present thesis, it is necessary to introduce the notion of Technology Readiness Levels or TRLs [2.15].
They are a measurement system for quantifying the maturity of a particular technology, originally developed by NASA in the mid '70s [2.16]. It is based on a scale of values from 1 to 9 that covers all the project's phases along the V-model (see Chapter 3).
A description of all level, with official NASA definitions reported also in the figure, follows:

TRL 1 – Basic principles observed and reported.
This level corresponds to the lowest degree of maturity, when only top-level features have been decided or basic properties are known. During developing of innovative technologies, TRL 1 means the transition from scientific research, conducted for the progress of science, to its practical implementation as applied research, conducted for the progress of technology. An example could be the study of general proprieties of a new composite material. To pass to the next level a peer-review or a validation of the available data shall be performed. The concept should be also attached to a mathematical model [2.16].

[4] Actually, because it is unclear what is required by a system to be space-qualified [2.11] it is uncertain if a suborbital vehicle can be used for qualification mission in addition to demonstration mission.

TRL 2 – Technology concept and/or application formulated.
At this level, an application of the results from TRL 1 shall be outlined. In particular, a system or a product that implements those principles is identified and generally descripted. Advantages and disadvantages have to be also documented. Detailed analyses or laboratory tests are not performed and so the feasibility of the application is uncertain. However analytic prediction shall be accomplished to be validated in the next level.

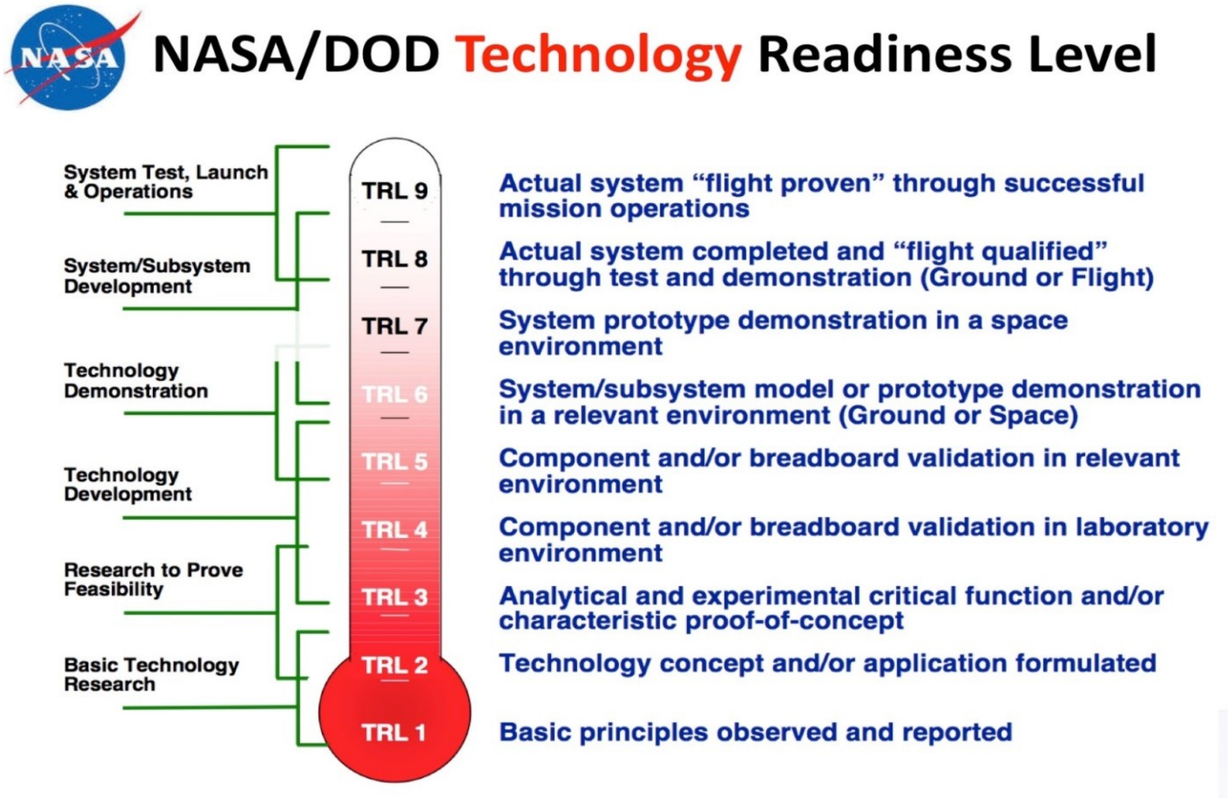

Figure 2.2.2 - TRL scale (source: NASA)
The levels of one to eight refer exclusively to the design phase, while the last involves the operations and in general the entire life cycle. On the right-hand side, the title for each level is shown. On the left part of the figure, the correspondence with the life-cycle’s phases of the product can be observed.

TRL 3 – Analytical and experimental critical function and/or characteristic proof-of-concept.
Detailed analytical and experimental studies validate the concept proposed in TRL 2 and its key parameters.

TRL 4 – Component and/or breadboard validation in laboratory environment.
A basic and low-fidelity prototype of the concept shall to be made and tested in laboratory for testing of basic functions. The work group shall to demonstrate that all components will work together to accomplish the system key functionalities. Some performance expectations should to be outlined.

TRL 5 – Component and/or breadboard validation in relevant environment
The component under development shall show a more elevated degree of detail. It shall be also integrated into realistic framework (at component-level, subsystem level, system level depending or higher, depending on case) and tested in a simulated or real relatively realistic environment.
A realistic environment could be for example a vacuum chamber or a suborbital vehicle.

TRL 6 – System/subsystem model or prototype demonstration in a relevant environment (ground or space)
A representative prototype shall to be successfully demonstrated in the space environment. It can be also a sub-scale but scaleable model of the system or the demonstration can be also similar but not actual to the planned application. It is only important that the actual technology is tested in space, into the foreseen conditions of microgravity, temperature and vacuum.

<u>TRL 7 – System prototype demonstration in a space environment</u>
It is a demonstration in space like the previous, but the prototype shall be at the scale of the planned and the application shall refer to the actual operations. Because of several systems used in space are prototype, many of them are used and remains at TRL 7: this is the case of Mars Pathfinder Rover or the X vehicles.

<u>TRL 8 – Actual system completed and "flight qualified" through test and demonstration (ground or space)</u>
At this level, technologies and the system are tested in space as planned.

<u>TRL 9 – Actual system "flight proven" through successful mission operations</u>
It is the highest maturity level reachable by a technology or a system, when it is successfully used during space mission.

Naturally, all analyses and test executed through levels shall to be accurately descripted and documented.

Suborbital vehicles provide, as already discuss, a relevant environment for many space technologies. Clearly, SRLVs are a further opportunity for engineers who want to increase their hardware's TRL before a space mission. Data gathered from a test not only serve to raise the TRL of a technology but also, in case a technologist is proved to be inadequate, to help understanding which components or subsystems should be developed to reach the system purpose.
Although there is no a lower limit for the TRL of a determined technology being tested on a SRLV, of course customers will propose payloads above level 5, for which the expense for a test in the relevant environment is justified.
NASA, with ISS partners, is the most important customer of this field [2.11] and likely it will be the same for the SRLV segment. Currently, it requires about 4 demonstrations per year on-board sounding rockets and 24 per year on-board ISS. Some companies, that uses systems less complex than NASA's ones, often conduct tests and demonstration with own facilities [2.11]. They should so be removed from the list of possible customers.
Technologies suitable for demonstration onboard an SRLV are, accordingly to [2.11]:

- Mechanical systems (operations within few minutes);
- Fluid systems, in particular propellant handling in reduced gravity;
- Atmospheric sensors;
- Avionics;
- Landing imaging systems;
- Re-entry technology.

Generally, the 25% of historical orbital tests could be conducted on a suborbital reusable platform [2.11]. For a list of possible payloads, the reader can explore the site of NASA's Flight Opportunity program, that aims to advance technologies' maturity (increase TRLs) through distinct types of research platforms: parabolic aircrafts, balloons and even suborbital vehicles. Clearly the latter includes currently only precursors and alternatives of SRLVs, for example the Masten Xaero. The appendix A is a brief collection of payload examples of this interesting program.
The activity of technology testing is strictly related with the science research exposed into the previous paragraph. For instance, a new life support system can be design taking in consideration results of a life science experiment. On the other hand, wanted improvements to a propellant system may require further studies on fluid behavior in microgravity. Generally, technical improvements and new devices can be developed starting from discoveries of previously conducted experiments and, vice versa, new scientific experiments may be needed to investigate some topics that are useful to develop new hardware.
Technological experiments are currently accomplished in ground-based facility and during spaceflights. The first is made up of stands for rockets performances testing, chambers in which the vacuum is practiced or determined thermal, radiation, vibrational and acoustic spectrums are imposed, wind tunnels for

aerodynamic studies and drop towers for microgravity. According with Tauri Group [2.11], some specialized facilities are more required than others, for example advanced wind tunnels. The second category includes experimentation on board the ISS or sounding rockets.
Finally, computer modelling and simulations can be used to advance maturity of a determined system reducing costs and determining in some cases a reduction in duration and frequency of testing services mentioned above.

Environment / Platform	Micro-gravity	Radiation	Thermal	Vacuum	Vibration	Aero-dynamics	Altitude	Launch Loads	Human Factors
SRV	✓	✓	✓	✓		✓	✓		✓
Sounding Rocket	✓			✓	✓	✓	✓	✓	
Balloon								✓	
Aircraft	✓					✓			✓
Drop Tower	✓			✓					
Terrestrial Facilities		✓	✓	✓	✓	✓			✓
Orbital Systems	✓	✓	✓	✓	✓	✓	✓	✓	✓
Sample Tests	pumps, turbines, hydraulics	shielding, electronic commun-ications	heat pipes, ablatives	valves, materials	structures, propellant systems	airframes, control surfaces	sensors	composites	suits, control panels

Figure 2.2.3 - Comparison between existing platforms for technology demonstration (source: [2.11])
Beside vibrations and launch loads simulation, an SRLV flight is closely representative of orbital environment. In most of cases a suborbital vehicle will be less expensive than an orbital system, both ISS and satellites, but terrestrial facilities, could easily be cheaper and even more suitable for testing requirements. SRLVs so have points of strength in the microgravity condition and access to higher levels of atmosphere, united to the possibility of specialist's interaction. They are however lightened by duration of suborbital flight.
It is worth to note the last raw of the table, where some examples of components or systems are given. According to [2.12], on ISS are tested and demonstrated technologies belonging to the following categories: propulsion systems, power systems, robotics, command and data handling equipment, communication equipment, life-support equipment, science equipment, entry, descent and landing equipment, structures manufacturing and thermal management equipment. Satellite system will likely not be demonstrated on SRLVs because the test requirements probably will require longer exposition to microgravity and radiation conditions of the Van Allen belts.

As it will be discussed in the following paragraph, many suborbital vehicles have been proposed. Each of them presents its own peculiarities and can have slightly different testing capabilities. Therefore, given a set of testing requirements, an SRLV could be better than another.

2.2.3 Space tourism

Figura 2.2.4 - Suborbital Virgin Galactic tourists flowing in microgravity (source: Virgin Galactic, artist representation)

Suborbital manned vehicles are designed to carry people to an altitude of above 100 kilometers. Here, over the Karman line which virtually divides atmosphere from outer space, few minutes of weightlessness could be experienced by the passengers and crew, that could also see a unique view of the curvature of the Earth, the blackness of deep space and the thin light blue layer of the atmosphere. Currently, few more than 500 people, between astronauts, cosmonauts and taikonauts have travelled in space [2.11]. This number will so start to dramatically increase when commercial human suborbital spaceflight begins. Virgin Galactic affirms that more that 700 people have already booked a flight on-board SpaceShipTwo.
Now, it is possible to purchase a ticket, about 5,000 dollars, for a weightlessness experience on a parabolic flight. Some years ago, eight wealthy people bought each a two-weeks flight on ISS as tourists, for an expense of few tens of million dollars [2.11]. Suborbital flight price is very expensive than parabolic flights and very cheaper compared to an orbital flight, being between 95,000 and 250,000 dollars. Alternatively, a ticket can be obtained also as reward or incentives promoted by companies and firms, or as a prize of contests or competitions.
Other than have deep enough pockets to buy a suborbital spaceflight ticket, aspirant tourists have also to undergo to medical checks and proper training. According to the source [2.11], the National Aerospace Training and Research Center of Pennsylvania has already trained more than 115 future space tourists and 925 seats have been reserved by flight providers. For Tauri Group, this sector will drive the market, at least during the first ten years.

2.2.4 Professional orbital astronauts training

A commercial suborbital spaceflight mission organized for a space agency has a twofold purpose:

- To train astronauts to execute experiment procedures;
- To verify safety of determined operations in microgravity.

Unfortunately, it seems that the Space Agencies are not significantly interested [2.11]. Further investigations on the topic will be carried out by the author in subsequent studies.

2.2.5 Media and public relations

Another use of suborbital reusable vehicles is to fly commercial products and items, to realize a publicity effect, and so increasing brand awareness. The implicit message that will be given to the consumer is that such a product is good to even be capable to fly in space. Moreover, microgravity environment is suitable for realization of commercial multimedia material, such as video scenes. In fact, simulating weightlessness with computer montage, also with modern special effect, is very difficult and filming directly inside a

vehicle designed for provide microgravity is more viable. We can cite the film "Apollo 13" for the 612 parabolas on a Zero-G Corporation aircraft used to reproduce scenes on a flying cinema set.
In the other submarkets, the interest could increase thanks to successful missions, satisfied customers and well conducted market campaigns. On the other hand, demand could also decrease if accidents happen, as 2014 Virgin Galactic accident, or if customers are disappointed from their suborbital flights experience.
Media and public relations submarket are difficult to analyse as well as the related demand is difficult to forecast. In fact, it is more sensible to factors just listed, due to the media resonance.
Famous persons that will participate to a suborbital mission can help the grow of commercial human spaceflight, generating the effect "me too", focusing the attention of people on the existence of the market and alimenting the market of space tourism.

2.2.6 Education

Suborbital vehicles can provide flight opportunities to several education programs, for all levels from school to university. The more effective educative activity is for some sources the flight of payloads designed and made by students. Currently, universities and schools can afford related costs using rides to orbit for secondary payloads with funds provided by governments and institutions.
Thanks to a lower cost and lower time-to-flight for an educational mission, comparing to sounding rockets, launchers carriers and ISS, SRLV can surely increase the participation of students in space activities. Some commercial suborbital companies have already reserved seats to education purposes, such as Lynx and UP Aerospace [2.8]

2.2.7 Remote sensing

These are all remote sensing applications, excluding scientific studies on Earth (e.g. oceanographic studies) and suborbital astronomy that are classified under "suborbital research". Therefore there are included military applications (spying or monitoring, etc.), civil applications (perhaps making an assessment on environmental status or after an earthquake, disaster management etc.) and commercial applications (for examples monitoring of agricultures).
This is a solid market, and it is quite clear that SRLV will not to subtract market shares from aerial platforms and satellites, that have been offering these capabilities for many years, with great investments in the sector to achieve unparalleled quality and accuracy. The suborbital, however, would offer some advantage over the planes, or from such heights to be able to observe the enemy territory without violating their airspace or being involved in a fight.

2.2.8 Satellite deployment

Satellite deployment into context of suborbital flights means the insertion of small satellite into low Earth Orbit using a SRVL. Since SRLVs do not follow a complete orbital trajectory, an additional propulsive stage is required to accomplish the launch. For example, XCOR Lynx Mark III integrates a dorsal pod aimed to this purpose.
Currently, the launch opportunities for small satellites to LEO are represented by rideshare agreement or cluster launch, or by piggyback where the satellite is stored in the fairing as secondary payload on a scheduled launch. Traditional vertical rocket launchers are so almost exclusively used.

2.2.9 Point-to-point transportation

This mission category deals with extremely fast passenger transportation and package delivery. Clearly, it can be applied to the military context with transportation of troops. Normally, the suborbital flights of the aircraft analyzed in this work, for example those designed primarily to carry out space tourism missions, have a mission profile whose projection on the Earth's surface is no longer than a few tens of kilometers. With the P2P this parameter is extended to many thousands of kilometers, reaching speeds of the order of magnitude required for in-orbit insertion.

The design effort to turn these ideas into real applications is huge and many steps forward have to be made in the fields of gas dynamics, propulsion and propellant management, thermal protection and the study of materials. Technologies and capabilities required by the hypersonic flight make final design synthesis very different from those discussed in this thesis.

2.3 CURRENT PLATFORMS FOR SCIENCE RESEARCH AND TECHNOLOGY TEST AND DEMONSTRATION IN MICROGRAVITY

Through this paragraph, systems that permit to execute scientific research and technology test and demonstration missions under microgravity condition are analyzed. Only space stations and satellites can accommodate payloads that requires more than minutes to be performed. Only parabolic flights and ISS can currently conduct experiments on human in weightlessness.

2.3.1 Drop towers [2.17]

A drop tower is essentially a channel in which the experiment is precipitated. It assumes the status of free-falling body because gravitational force is balanced by inertial force generated by accelerated motion. The first experiments with a drop tower, the Tower of Pisa (although it was not built for this purpose), was conducted by Galileo Galilei in late 1500, to demonstrate that the falling velocity of an object is totally does not depend of its mass.

Drop tubes' typical diameters are comprised between less than 1 m to several meters in diameter. The microgravity duration is descripted by the following formula:

$$t = \sqrt{\frac{2h}{g}}$$

where h is the height of the drop compartment. This formula derives directly from $x = x0 + v0t + \frac{a\,t^2}{2}$ substituting x with h, $x0$ and $v0$ with 0 and a with g. The drop tower can be utilized in both directions. In other words, the platform can be shot upward and then it drops downward. Using this operative mode microgravity time given by the formula is doubled. Clearly, ever modern tower is provided with a deceleration mechanism for the payload arrest at the bottom of the tube.

The microgravity quality of such a conduction, it is not very good, basically due to the atmospheric drag. It is an additional force that increases with the speed of the falling body and depends from its shape. It reduces the microgravity quality and over determined speed the reduction is no more acceptable. Drop towers have been developed in some variants to overcome the problem of air drag:

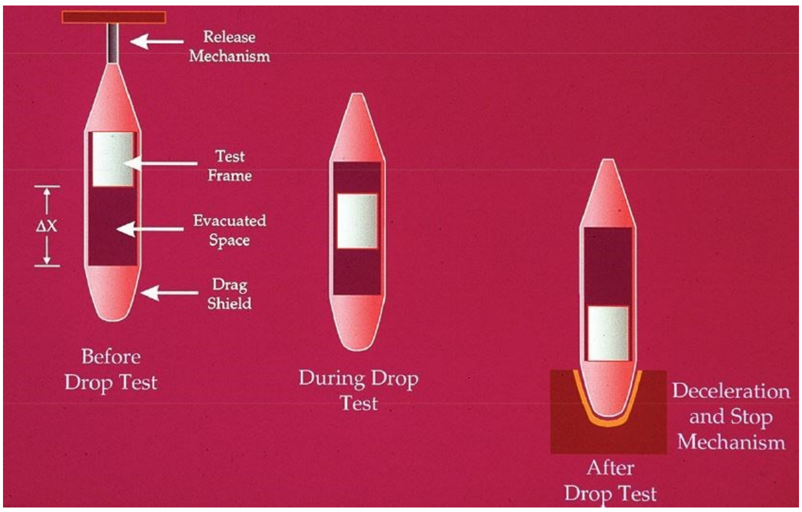

Figure 2.3.1 - Drop tower test with capsule [2.17]
During the entire experiment the payload is comprises between the top and bottom walls of the drag shield.

- Vacuum drop towers: the earliest vacuum towers were built in the late 1700 for military purposes. Within the tube, air is removed entirely granting high microgravity quality along the tower. Duration of the tube evacuation depends clearly by dimensions of the tube itself.
- Towers with capsule platform (also called "drag shield"): the experimental payload is put inside a vacuum capsule as represented in figure. So, it is not required to evacuate the entire tube as in the previous case. The aerodynamic drag

that the capsule experiences does not affect the experiment quality, because of the length of the internal tube of the capsule.

- Guided motion drop towers: the experimental platform is accelerated downward by a guided drop system to balance aerodynamic drag. The guided system can be constituted by rails or electromagnetic accelerators. The time formula is not valid in this case. Microgravity durations varies from 5 to 10 seconds.

To compare different drop towers, following parameters should to be considered: microgravity quality and duration, payload accommodable dimensions, cost of experiments, deceleration profile, assistance and location [2.17].

2.3.2 Aircrafts for parabolic flights

In this case, microgravity is procured inside of a large airplane by the free fall through the acrobatic manoeuvre depicted in figure 2.8. At the beginning of such manoeuvre engine are set to a low thrust value to compensate air drag. By this way, the aircraft describes the parabolic trajectory that every falling body follows under gravitational force. This is also the shape of the coasting phase of the suborbital vehicle, as it will be descripted in Chapter 4.
A single parabola corresponds to a microgravity duration between 20 and 30 seconds. This duration is sufficient to perform short experiments (both “look and see” [2.1] and quantitative). Moreover, during the same flight, the manoeuvre can be repeated multiple times, also around twenty, increasing the total weightlessness time to few minutes.

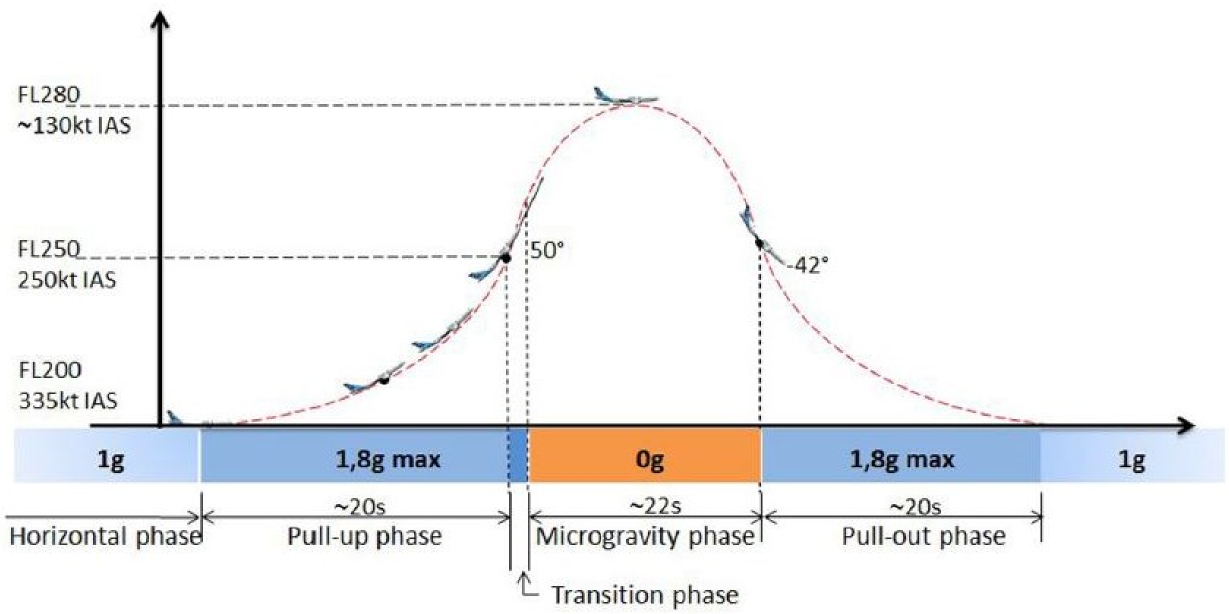

Figure 2.3.2 – Ballistic flight manoeuvre for a typical parabolic flight (source: [2.1], Airbus A310 ZERO-G)

The manoeuvre is composed of three phases:

1) Pull-up: starting from horizontal attitude, pilot gradually increases the pitch angle up to 50° for about twenty seconds, during which the crew experiments a period of hyper-gravity between 1.8 and 2 G. This sub-manoeuvre starts about at 24000 ft. altitude [2.20], which corresponds to about 7.3 km, and it is ultimate at 32000 ft., or 9.7 km.
2) Coasting: it is the actual ballistic free fall, which lasts between twenty and thirty seconds and requires the reduction of engines thrust to a value needed to compensate the atmospheric drag. If engines are shut off like happens in the suborbital case, neglecting difficulty in restarting the air-breathing engine inflight, drag would influence microgravity quality.
3) Pull-out: the aircraft decreases pitch angle to 42° below the horizontal axis and turns then to the horizontal attitude. It is the mirrored first phase.

Pilots shall to be specially trained.

Parabolic flights are used in many countries by space agencies to train astronauts or missions and to accomplish scientific and technological experimentation. Moreover, private companies provide parabolic flights as microgravity experiences, at a fraction of costs of proposed prices of suborbital vehicles (on Zero Gravity Corporation site, $ 4950 + 5% of tax for 15 discrete parabolas, for a total microgravity time of about six minutes).
It is possible to execute also partial-g flight profiles in which gravity levels of Moon and Mars are achieved, respectively 0.16 g and 0.38 g, slightly modifying the injection angle of pull-up phase and thrust in the coasting phase [2.1]. This is particularly interesting to train and experiment looking at future exploration missions.
Microgravity quality during coasting phase is respectively 10^-2 g for experiments fixed to the aircraft's floor and 10 ^-3 g for free floating ones. Currently, main companies that manage parabolic flights are:

- Zero Gravity Corporation: U.S company, uses a modified Boeing 727;
- Novespace: provides research flies in Europe with Airbus A310 ZERO-G, the largest aircraft for parabolic flights in the world, is requested since 2015 for experiments of ESA, CNES and DLR.

Parabolic flights are characterized by short time between the experiment proposal and its performance.
They also permit to study accelerations transient phenomena through the parabolic manoeuvre.

2.3.3 Sounding rockets [2.18]

Sounding rockets or research rockets are small rocket that follows suborbital flight profiles to collect experimental data. The term sounding derives from "to sound", that means "to take measures" in the nautical context. They can carry a payload from 50 to 1500 kilometres altitude. On board larger sounding rockets, microgravity time can reach 9 minutes, but the average value is five minutes. The total flight-time is about twenty minutes.
They have often two or more solid propellant stages to increase the fraction of payload, that it is been recovered by a parachute.
Unlike the two previous platforms, drop towers and parabolic aircraft, in addition to experiments in microgravity it is also possible to carry out experiments on the space environment (Van Allen radiations belts were discovered this way) and observation of suborbital astronomy. Human interaction on board is unfortunately unavailable.
Compared to rockets for orbital insertion, sounding rockets are smaller and lighter: this fact give particularly flexibility to launch logistic. It is possible to set up a temporary launch site, to execute a research mission from remote locations, for example where balloons or satellites cannot be used. Some sounding rockets can be even launched in the middle of the ocean from a specific ship.
Theoretically, sounding rockets are classifiable as SRLV because are recovered and follow typical suborbital flight paths. However for simplicity reason and because this category of vehicles is clear and unmistakable, during this thesis, they are not taken as part of Suborbital Reusable Vehicles. So, when SRLV are discussed, sounding rockets are not taken into consideration.

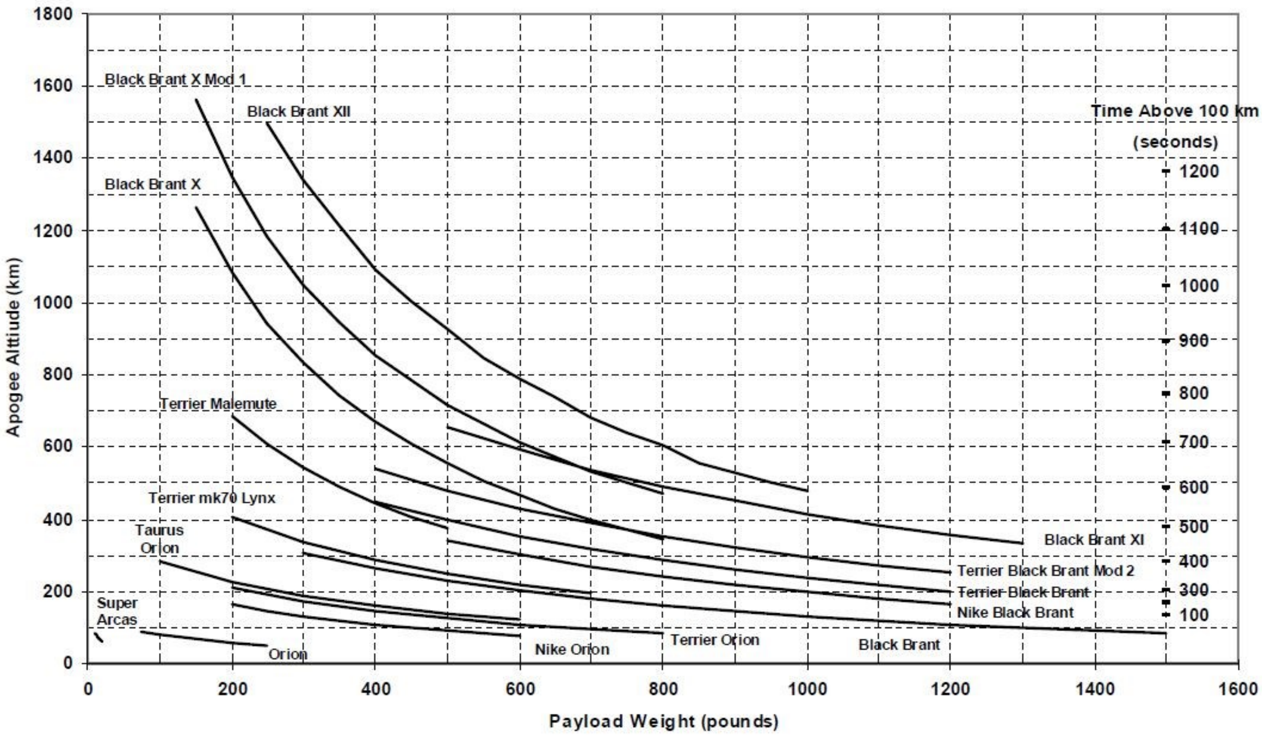

Figure 2.3.3 - Performances of sounding rockets of NASA Sounding Rockets Program (source: NASA)

2.3.4 ISS

The International Space Station is an orbital station, result of the united endeavours of USA, Europe, Russia, Canada and Japan. The station, assembled since 1998 with a modular approach, is an orbital complex of full equipped laboratories aimed to scientific research in microgravity, and Earth and celestial observations, giving more emphasis on long time activities. Until 2014, more than 1762 experiments have been conducted on board (see figure 2.10). ISS permits also to gain experience on maintaining space hardware on orbit and generally to test new equipment and operations for future space mission.
Laboratories of the US segment on ISS are:

- U.S Laboratory Destiny: is the main laboratory for US payloads. It accommodates 13 scientific racks, mechanical enclosures for all research hardware (see the paragraph on payload accommodation on ISS). It is dedicated to general and multipurpose experiments.
- European Laboratory Columbus: it is attached with Node 2 and disposes of External Payload Facilities, for accommodation of payload outside the pressurized module. Columbus provides interfaces for 10 racks.
- Japanese Laboratory Kibo: it is berthed to node 2 and provides 10 rack for experiments. Other than the pressurized module, it is provided also with the Experiment Logistics Module and the Exposed Facility, an external platform for the exposition of experiment to the direct space environment via a robotic arm.

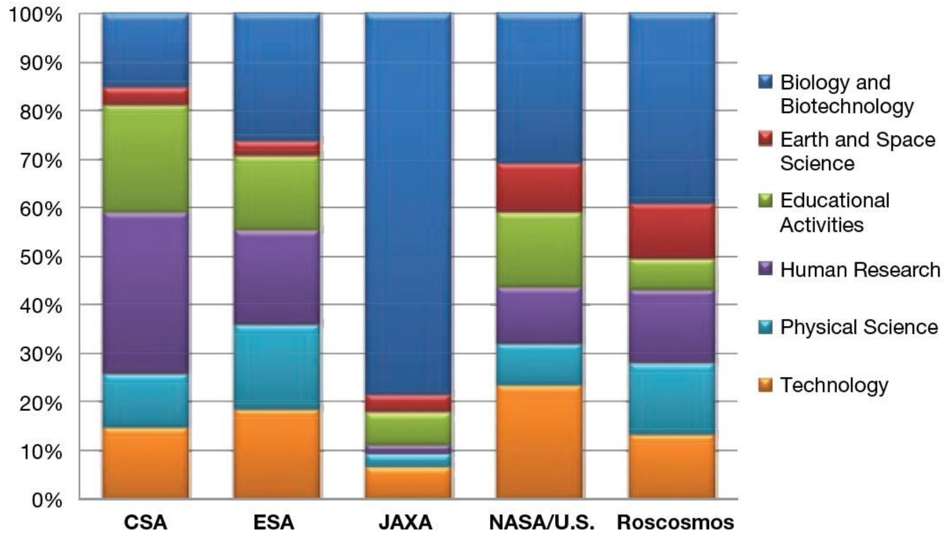

Figure 2.3.4 - Research disciplines investigated by ISS partners between 1998 and 2014 (source: [2.21])

Starting from the left, number of experiments conducted are respectively for each agency: 27, 247, 485, 604, 399.

2.4 WHEN USE SUBORBITAL REUSABLE LAUNCH VEHICLES AND WHEN USE ANOTHER PLATFORM

This paragraph has the purpose to make a comparison between platforms discussed above in Paragraph 2.2 (manned SRLV) and Paragraph 2.3 (drop towers, parabolic aircrafts, sounding rockets, orbital flights and space stations) using an advantages and disadvantages approach. Table 2.4 briefly illustrates differences and limits of each technology. The presence of human on board is believed by the author as of primarily importance for the choice of the platform and so a brief list of additional risk that distinguish manned SRLV from other unmanned platforms is presented.

	Drop towers	Parabolic Aircraft	Sounding Rockets	Orbital flights	SRLV
Microgravity time	2 – 10 s	20 – 30 s	5 – 20 min	Months or more	3 – 4 min
Microgravity quality (g)	10^{-6}	10^{-2}	10^{-5}	10^{-6}	10^{-5}
Fight frequency	daily	about 50/year	about 20/year	always operative	daily
Payload mass (up to) [kg]	Grams to 500	1000	$\mathcal{O}$ 100	$\mathcal{O}$ 1000	$\mathcal{O}$ 100

Table 2.4 - Comparison between different platforms for microgravity research (source: [2.11] and [2.22])

$\mathcal{O}$ is used to indicate "the order of magnitude".

Effective duration of microgravity time on board a suborbital reusable vehicle depends on many factors, such as [2.23] the pilots' flight technique, the effective burn duration of propulsive system, the gross liftoff weight, the presence and use of flight systems and the passengers' activity.

2.4.1. Advantages of SRLVs over other traditional spacecrafts:

- Reduced costs comparing to space stations and sounding rockets: sending a payload to an orbital space station is very expensive using nowadays technologies. A cargo mission with the dragon capsule on ISS is estimated at 133 million dollars and carries about 6,000 kg of material (pages 37 and 74, source [2.19]). At a very first level estimation, it results 22166 $/kg. On the other hand, Virgin Galactic sells space tourism tickets for 250,000 $ per seat. Considering six as total number of available seats on SpaceShipTwo, results a gross income of 1,500,000 $. As available payload mass on SS2 is 600 kg and supposing Virgin Galactic expects the same earnings per flight, results 2500 $/kg (same value also hypothesized by reference [2.5]). To resume, performing the experiment with a suborbital reusable platform can cost an order of magnitude less than the ISS case.
  A research team can so purchase a set of flights and become a long-term repeat customer, while on the ISS the entire budget should be sufficient for only one mission.
  Testing and development costs on ISS can be between 1 and 4 million of dollars per payload. Also compared to the sounding rockets for microgravity or atmospheric science, suborbital mission benefits from a reduction of cost [2.11], in fact booking a sounding rocket for a test launch can cost between 2 and 5 M$ or more.
  According to reference [2.6], a total cost for a middeck locker on Rocketplane XP (for others SRLVs it should not be extremely different) is on the order of 100000 US dollars.
- High response capability and more flexibility compared to ISS and sounding rockets: to embark payload into ISS may require large amount of time, due to long waiting lists, acceptance procedures and scheduling of cargo missions. In this case embarking a scientific payload can require few years, while suborbital private flights can accelerate the process and be more tailored to the customers' timing needs. It will be presumably possible to launch from different locations and trajectories can be adapted to experiments' requirements. Moreover, ground infrastructure should be simplified, allowing the customer in some cases to use the vehicle practically from any airport.

This advantage is particularly suitable for Atmospheric Science, giving the opportunity to study a limited portion of the upper atmosphere with tailored trajectories.
Astronomy capability is surely provided by orbital telescopes, but they are characterized by a slow response due to long waiting lists and so are less suitable for relatively sudden surveys. Furthermore, with suborbital flights it is possible to use relatively cheaper telescopes and optics for risky observations, such as on sun-grazing comets, that could damage billion-dollar orbital telescopes.

- Longer-duration microgravity compared to drop towers and parabolic aircrafts: the suborbital reusable platform is a valid alternative for those researchers that cannot afford an experimentation campaign on ISS but require more than few seconds of continuous microgravity.
- Possibility of a human interaction compared to sounding rockets: all SRLV designed also for space tourism take into consideration the possibility of a payload specialist as flight attendant. It has the main purpose of monitor the correct execution of the experiment but can also execute safe tasks on payload to respond the need of researchers. On sounding rockets payload must to be completely autonomous.
- Gentler g-loading compared to sounding rockets: this advantage is confirmed by [2.23] for SpaceShipTwo vehicle, but the author believes that it is valid also for other spaceplanes. It should be however confirmed from case to case. It is a fundamental advantage for suborbital reusable platforms which so represent suitable vehicles for those experiments that are sensible to high variation of acceleration such as biological samples.

2.4.2. Disadvantages of SRLVs over other traditional spacecrafts:

- Difficulties to fulfill a complete exposition of payload to external environment: on ISS these types of missions are already performed on the Exposed Facility on the Kibo module. These capability is absent to all public projects of SRVLs, except for Lynx of XCOR [2.7], even if currently companies such as Blue Origin and Virgin Galactic are studying solutions.
  Moreover, suborbital astronomy and remote sensing may require little modifications to spacecraft design and structure, for example ports or hatches, that could be not easy to implement. Modifications to windows with high performance glasses are instead a service much more feasible and confirmed by flight providers [2.11] [2.23].
- The vehicle could affect some experiments: thinking to atmospheric research, air sampling could be heated due to ascent motion and so data gathering could be compromised. Moreover, this heat may decompose molecules of interest, providing incorrect measures. Sounding rockets also present this problem. On the other hand, for the high-altitude balloons case, it likely is minimized thanks to lower ascent speed, but only measures in stratosphere are possible.
- Lower duration of the microgravity condition compared to ISS and sounding rockets: clearly, only experiments that do not require extended microgravity duration can benefit from commercial suborbital spaceflight. Typically, a suborbital vehicle, as well as a sounding rocket, can provide only few minutes of microgravity. On ISS, however it is not possible to “simulate” other gravitational field intensities, for example the Martian gravity.
  Some chemical species of interest in atmospheric research are widespread in very low concentrations, even part per billions. The short time of the mission, compared for examples to stratospheric balloon, may prevent a sufficient large sampling. These considerations also apply to winds and temperature profiles measurement.
- Less flexible compared to drop towers and parabolic aircrafts: reduced volume onboard suborbital reusable vehicles underline serious problems in case you have to accommodate voluminous payloads or moving parts. Inside parabolic aircraft, the entire passenger compartment is dedicated to experimentation and payload components shall only pass through large hatches of transportation aircraft, but it always better trying to avoid the “ship-in-the-bottle” approach. Drop towers and parabolic aircraft are available now and research opportunities will likely remain more

numerous. At the Bremen Drop Tower facility, a new generation electromagnetic drive tower, currently designed, will permits up to 100 tests per day. On suborbital case, an experimentation campaign can endure few flights, while for the other twos a campaign can be constituted of lots of repetitions of the lowers microgravity periods. For experiments that required few seconds of weightlessness, these options are more viable.

- More expensive compared to drop towers and parabolic aircrafts: price depends from case to case and in generally making a comparison is quite difficult. In fact, a suborbital flight is certainly much more expensive than a drop or a parabola, but it is not so clear in case of an entire experiment campaign. A typical test program (150 data points = 1000 drops [2.11]) can cost between 200,000 and 300,000 dollars.

2.4.3 Risks for passengers of suborbital missions

In this brief subparagraph, a list of risks of manned suborbital flights is presented. These risks are related to health problems that can occur to all flight participants: passengers, pilots or payload specialists.

- **Rapid decompression**: a leak in the pressurized section of the fuselage has the consequence of decreasing the internal pressure of the cabin. Severity of the health consequences for human beings after a decompression depends on the altitude of the emergency event and they are all related to. The most serious symptom is the loss of consciousness caused by the lack of oxygenated blood available to the brain. This status may come after a variable amount of time, ranging from few seconds if the decompression event happened in the stratosphere to more than 6 minutes if happened under 7600 meters.
  Moreover, the external pressure in the stratosphere is so low that if a human is exposed to, water in the blood may boil, causing damages to tissues.
  A possible solution to limit damages in case of decompression is the pressurized suit, with an oxygen reserve.
- **G-LOCK** (gravity-induced loss of consciousness): the loss of consciousness may be caused not only by a rapid decompression. In fact, both positive and negative high accelerations (indicated as Gz) have the same effect. In this case of high +Gz there is a reduced blood pressure available to brain, that causes disturbs in vision, a dreaming-like status and eventually blackout. If the acceleration rates are high (for example 6 G per second), the induced loss of consciousness comes without any visual warnings.
  This problem is reversible, even though within a certain period of time called total incapacitation time, if accelerations are unloaded.
  Countermeasures to G-Lock are reducing the vertical distance between head and hearts, by using reclined seats, or wearing a G-suit. This is an air-pressurized suit that exerts pressure on legs to reduce the accumulation of blood in the lower part of the body.
  Certainly, the mission profile of the suborbital vehicle should be carefully studied to avoid high acceleration levels, so that most people can endure few G without any noticeable health problem.
  Passengers with heart and cardiovascular problems could be excluded from suborbital experiences.
- **Catastrophic failures**: they range from failures of the rocket motor, to emergency landings, to fire onboard.

However, they are all those problems that can happen also on a commercial flight with aircrafts.
Radiations are not a critical aspect in the suborbital vehicle design, because the dose absorbed during this type of flights is practically negligible [2.8]

2.5 PAYLOAD ACCOMODATION ON THE SPACE SHUTTLE

With this chapter, the second part of the Chapter 2 starts. As already presented at the Introduction, it focuses on the accommodation of payload. This topic will be explored for different space vehicles and, of course for different models of suborbital vehicles.

Neglecting the huge orbiter payload bay, about 18.29 m in length and 4.6 m in diameter, that does not fit with purposes of this work, in this paragraph will be discussed accommodation capability of the Middeck, the pressurized living area for the crew collocated below the Flight deck. Here small payloads are contained into lockers of 2 cubic feet volume or can be directly attached to the standard lockers mounting locations using adapter plates. Larger payloads were accommodated at the galley. See Appendix B for a representation of the middeck.
Electrical feeding is available at 28 V direct current and limits on power for each locker are 115 W for eight hours or 200 W for ten seconds. Also three phases AC power, at 115 V and 400 Hz, can be provided.
A laptop computer called PGSC (Payload and General Support Computer) is available for command and monitoring. However, middeck payloads are almost always autonomous, and has internally all equipment required for these functions. A human interaction is possible thanks to the presence of the astronauts. Regarding heat waste, no types of cooling hardware are available at locations. Therefore, 60 W for each standard location are dissipated via free convection. The payload can however have its own cooling system, with the requirement that the outlet air temperature and surfaces shall not overcome 120 °F. Moreover, a quick disconnect attach for cooling water is available at the galley. The investigator has to supply requested fans and pumps.

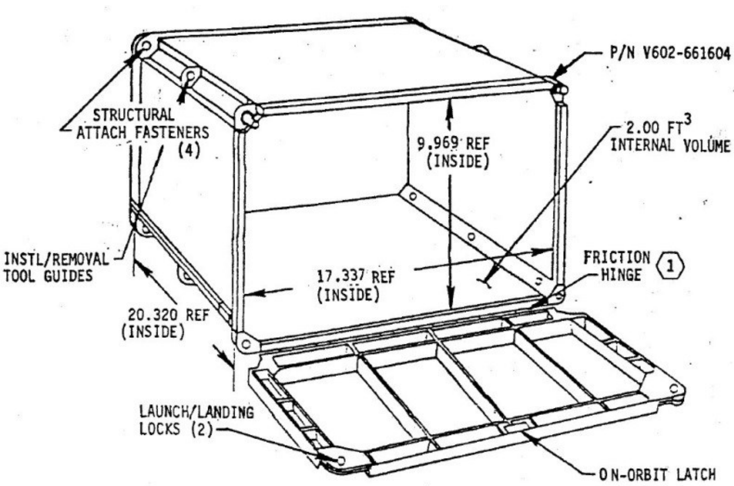

Figure 2.5.1 - Draw of a standard middeck locker (source: [2.25])
Each locker can accommodate up to 54 pound of payload material. It is attached to the avionics wire tray via four rear bolts [2.26]. Correct opening and closing on orbit are granted by a friction hinge and magnetic latch. On the front, removable panels permit to install fans or control devices such as switchers or buttons.

With Space Shuttle dismission, original middeck lockers have been not used any more. They however have established a standard and so, to continue using this standard for payload accommodation on board other vehicles, Middeck Lockers Equivalent (MLE) are established. They are payload containers with same dimensions of original middeck lockers. According to [2.23] dimensions for a single MLE are 18.5 in width, 11.25 in height and 21.5 in deep. Its weight is 14 lbs, or 6.356 kg. This has been taken as reference as a Unit, as happened with 1U CubeSat. Therefore, double and quad MDE exist, with respectively height differences of 23 and 46.5 in.

2.6 PAYLOAD ACCOMODATION ON THE INTERNATIONAL SPACE STATION [2.22] [2.23] [2.24]

"A Principal Investigator developing an ISS research payload will typically spend years of time and millions of dollars in staff cost and hardware development, fabrication, testing and qualification expenses prior to actually getting the payload manifested for flight." Cit. [2.6]
Before descripting how experiments are conducted on ISS, a brief paragraph of experiment acceptance is provided for completeness reason. Same processes with proper modification could be adopted for experiment acceptance on suborbital vehicles.

2.6.1 Accommodation description

This paragraph focus on the experimentation in pressurized environment, so inside the modules-laboratories of the station discussed before. There, for each laboratory are mounted a determined number of locations that represent a standard support structure for payload accommodation: *the International Standard Payload Rack*. Experiments are often already integrated into special drawers or containers called lockers, which are also usually standardized structures and therefore easily interchangeable. Those lockers are physically attached to the support structure of the ISPRs. Basically, an ISPR provide only a standardized mechanical interface with the structure of the module (ISPR showed in the figure 2.12).

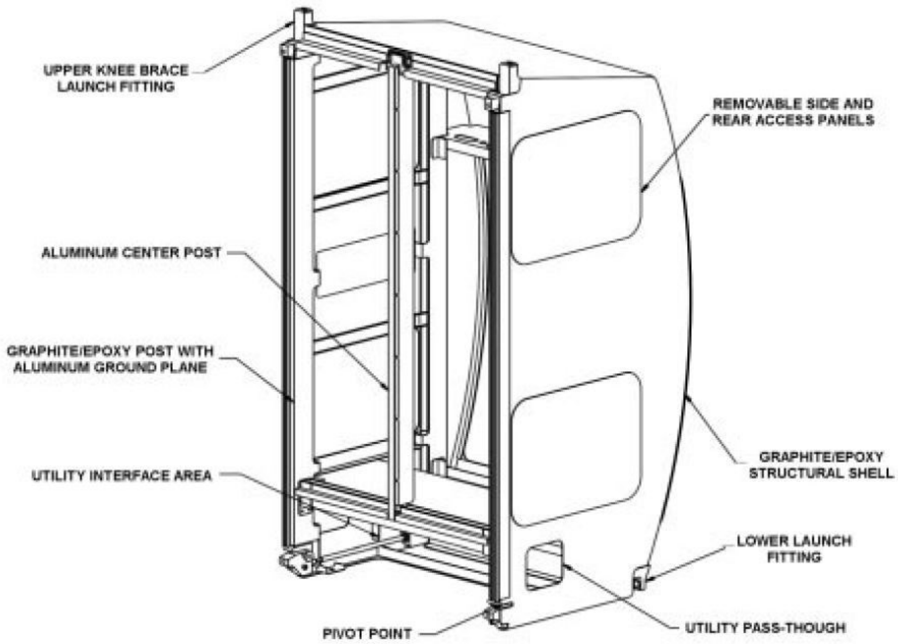

Figure 2.6.1 - Draw of International Standard Payload Rack [2.22]
More detailed drawings of the ISPR are available in appendix B with relative descriptions. The NASA ISPR is made of composite material (graphite/ epoxy) with structural elements in aluminium (it is the case of the figure). The NASDA is made of aluminium alloy at all.

The main structure of the rack is made up of six posts that are provided with mounting holes to attach internal secondary structures, differently from case to case. On the front side of the frontal posts, provisions to mount notebooks, front panels and other utilities are also available. The central posts can be removed, such as in the case of the Express Rack, discussed below. The structure is completed by panels.
Although ISPR is a standard, actually two versions exist: NASA ISPRs and NASDA ISPRs. Differences are on material used, that reflects on the load capability, and on design, that affect the methodology of payload mounting.

The choice to adopt an identical interface permits to swap payload hardware between locations if required and to facilitate the design of experiments that so have to satisfy only a set of interface requirements. Contrarily, the payload should be designed for the specific location and module in which it should have been located. On board the station, 37 ISPR are currently placed.
The table 2.5 reports the racks' main technical specifications.

ISPR technical specifications (source: AIAA, 1997)	Values (from source *) [in] [in^3] [lbs]	S.I. Conversions [m] [m^3] [kg]
Dimensions	41.3 (width) x 33.8 (depth) x 79.3 (height)	1.04 x 0.86 x 2.01
Volume available	73727	1.21
Mass	NASA: 213.7 NASDA:220	96.93 100
Load capability for payloads	NASA: 1561.6 NASDA(six-post): 1772.5 NASDA(four-post): 1037.7	708.33 804 487
Material	Aluminium alloy 7075 for main parts, MP35N alloy for mechanical rack/module interface parts	-

Table 2.5 - Specification for the ISPR
* https://web.archive.org/web/20080909215026/http://pdf.aiaa.org/preview/1998/PV1998_466.pdf [AIAA]

On-orbit, the ISPR is fixed to the so-called standoffs of the module (see figure 2.13 to understand how the rack is mechanically attached to the module). On the bottom side, the rack is opened to allocate the Utility Interface Panel: it is a bended standard plate with holes for pipes and cables to provide services and utilities to payloads accommodated into the rack.
In the six-post configuration, payloads with width lower than 18.2 in [2.22] can be mounted into column 1 or 2. Removing central posts, all the ISPR internal volume is available for payloads less than 37.5 inches in width.

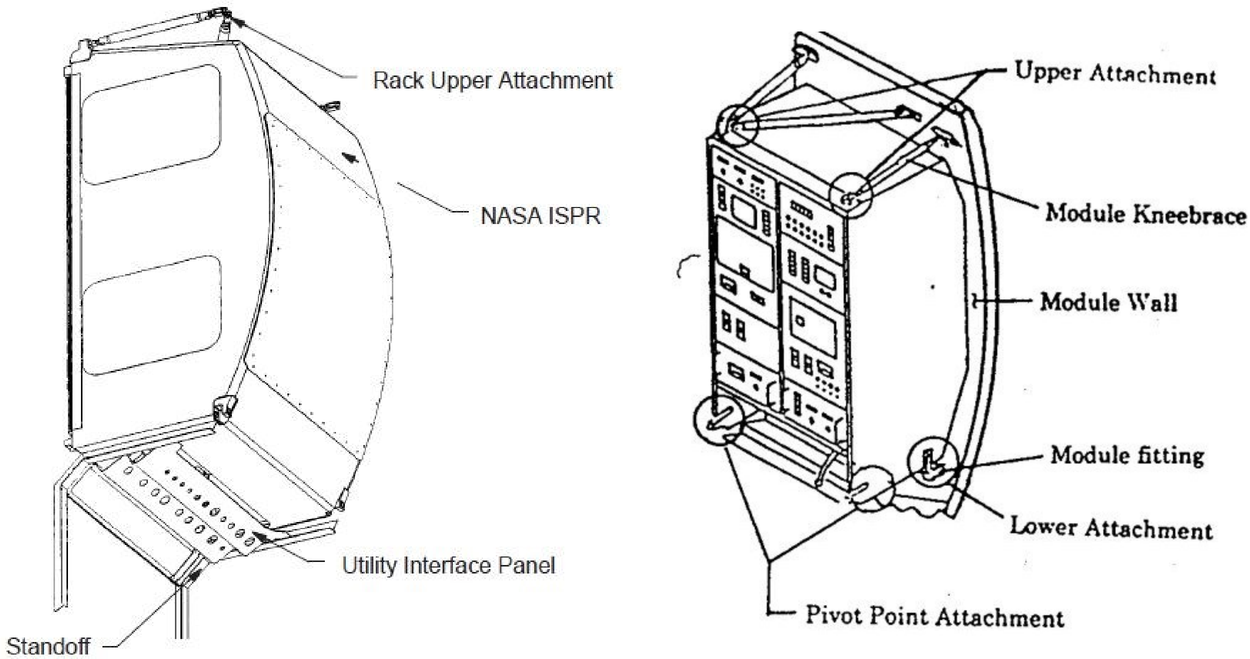

Figure 2.6.2 - ISPR attachment to the module [5.12]
Standoff, Utility Interface Panel (UIP) and Rack Upper Attachment are not part of ISPR. The UIP is required to access ISS provisions, and are customised basing on the ISPR type, as showed in Appendix B.
The left figure shows the ISPR on-orbit. On the right is shown how the ISPR is attached to the module for launch and landing (such into the MPLM). The Pivot Point attachment are required for ISPR on-orbit tilting.

The second table describes which utilities are available to be installed into an ISPR.
Inside the rack, avionics equipment for the air thermal control can be mounted. It is based on a circulating air loop connected by grids with middeck lockers or other payload containers. Thanks to this equipment, up to 1200 Watt can be removed. Moreover, a small amount of heat can be dissipated directly into module air, if the payload investigator/designer equips it with a fan.
A video card can be included into rack to convert the optical video/sync signals to electrical NTSC signal (EIA-RS-170A). Video signals are distributed to three types of users: local onboard monitors, video recorders and a processor for sending to ground via the Ku-band.
The waste gas system vents exhaust gases of each rack to space. It supports up to 275800 Pa into the line and between 15.6 and 45°C gas temperature and it is possible to use it at only one location per module at the same time, to avoid incompatible gas mixtures and unwanted gas exchanges between payloads. On the other hand, the vacuum connection to space, provided by a line with a quick-disconnect, can be used by multiple locations at time. Finally, the investigator shall provide payload with control valves if he wants to use gaseous substances provision.
Selected ISPRs are provided with a device for the suppression of vibrations generated by ISS systems. Called ARIS (Active Rack Isolation System), it isolates the rack internal environment through active electromechanical damping, that acquires vibrational environment data and compensate it with an opposite system of forces before vibrations could affect the experimentation.
The internal volume of an ISPR is customizable on payload requirements. For example, a refrigerator for biological samples is hosted at the location MELFI3 of the Destiny laboratories. In Appendix B there are photos and descriptions of "special" ISPRs of ISS laboratories.

Utility interfaces [2.22] [2.24]	Technical specifications	Comments
Primary electrical power	Power: 3 kW Voltage: 114.5 to 126 V Direct current	Circuit protection at 25 A; Switching and controlling remotely; 8-gauge wiring;

Auxiliary electrical power	Power: 1.2 kW	12-gauge wiring;
High rate data link	100 Mbps	Optical fibers;
Medium rate data link		MIL-STD-1553 Bus Ethernet; Shielded wire pairs;
Time distribution (via MIL-STD-1553 Bus)	1 Hz accuracy: ± 0.5 ms	
Video/Sync Input		Optical fibers
Video Output		Optical fibers
Water Cooling (Moderate)	16 – 24 °C	Max return water temperature: 49 °C; 0.5-inch line;
Water Cooling (Low)	0.6 – 10 °C	Max return water temperature: 21 °C; Only available at selected locations;
Waste Gas	Performance: from 1 atm to 0.13 Pa in less than 2 hours for a volume of 100 liters	1-inch line
Vacuum Resource	Vacuum quality: 0.13 Pa	1-inch line
Maintenance Switch/Smoke Detector		
Gaseous substances	Pressure (N_2): 517 to 827 kPa; Flow (N_2): 0.9 kg/min Pressure (Ar, He, CO_2): 517 to 786 kPa;	0.375-inch line Nitrogen; Argon, Helium and Carbon dioxide in the JEM module;

Table 2.6 – Utilities interfaces available on a generic ISPR rack

Cables and pipes can also run between racks thanks to pass-through ports opened on lateral sides. Primary and auxiliary power have the same voltage. At selected ISPR location also a power support of 6 and 12 kW is available.

It is worth dwelling on ISPR subtype called EXPRESS RACK (Expedite the Processing of Experiments to the Space Station) [2.24]. The EXPRESS is a standardized subtype of ISPR, specially designed by NASA to host experiments in Middeck Lockers and International Sub-rack Interface Standard Drawer (ISIS), providing at the same time power and data interfaces. It is particularly flexible to meet investigator's requirements because integrates utilities into a standard backplate (see the 2.14). Therefore, it gives the advantage of a quick and simple accommodation onboard the ISS requiring less than one year [2.24]). Loading capability allows up to eight middeck lockers equivalent (roughly based on shuttle's middeck lockers), that can access to standard utilities interfaces on the frontal extremities of the backplate, and two ISIS drawers. MLE are bolted to backward of the backplate.

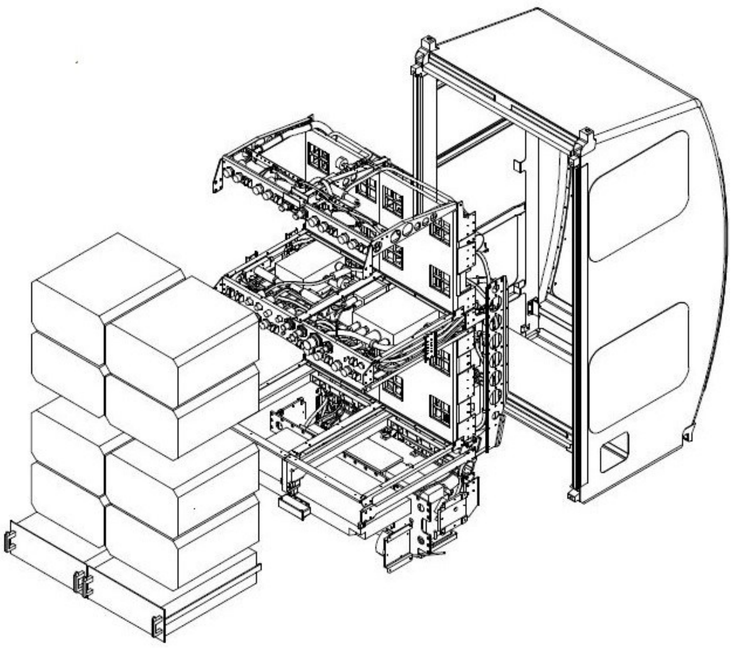

Figure 2.6.3 - Express rack (source: [2.24])

The express is sub-divisible to three main components: middeck lockers and drawers with payloads, the express back-plate and the standard ISPR structure.

Express racks can be also equipped with ARIS hardware.

Source [2.24]	Width	Depth	Height	Volume
Middeck Locker Equivalent for EXPRESS RACK	17 in	20 in	10 in	2 ft^3

For each experiment accommodated into an MLE Express Rack are provided: mechanical support, power feeding, data and video management, water cooling support, air cooling support, nitrogen distribution and vacuum exhaust venting. Payloads into drawers have only power, data and air support.

The rack offers a total of 2kW at 28 volts (as there are overall up to 10 users per rack, 250 W per payload are available, so up to 8,9 A). That power can be dissipated through air and water cooling combined.

2.7 PAYLOAD ACCOMODATION ON PARABOLIC AIRCRAFTS

During parabolic missions, most of the fuselage is normally available to microgravity activities. Information presented into this paragraph is confirmed for Airbuses of Novespace [2.4], but surely they are still valid, even if with possible slight differences, for other parabolic airplanes.
Scientists and engineers in addition to realize the experiment or the testing campaign, have often to realize the primary structure: mechanical interfaces, payload mounting and containers. Therefore, they are customized on the need of the payload and differ in size and provisions. Usually, they are simply parallelepiped frames fixed to the floor in which the experiment and other required components are allocated, as the figure shown.
Electrical feeding is available from power interfaces, for example distribution panels or electrical power block that supplies safety devices (fuses).
Novespace includes also a vent system that connects valves in the test area to the external environment for venting of exhaust gases.

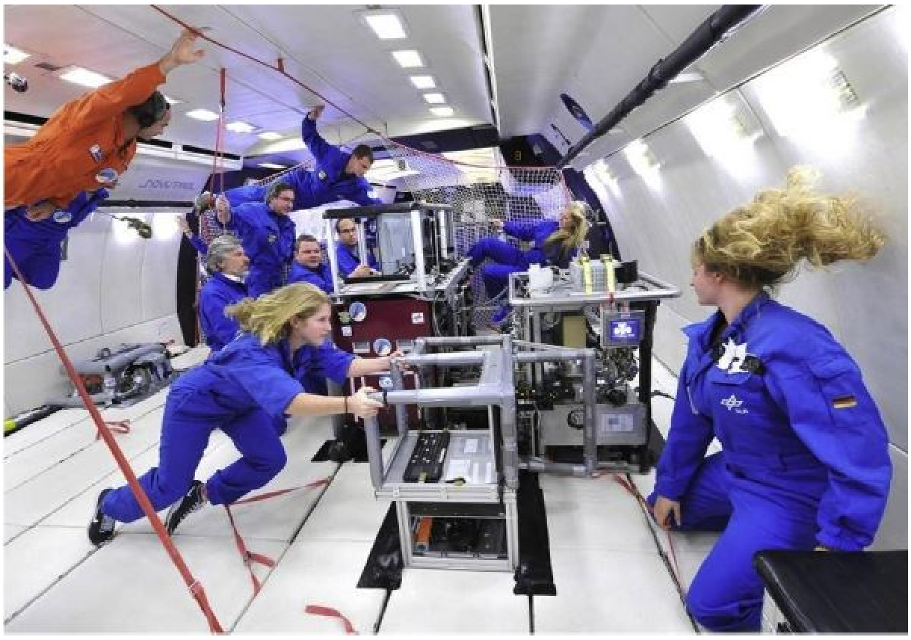

Figure 2.7.1 – Test area during a DLR parabolic flight campaign (source [2.1])
Payload primary structures are fastened into floor tracks (the same tracks used for mounting seats in passenger flights) with attachment fittings. Rings and straps are also available for payload structure fixing especially during take-off, pull-up, pull-out and landing. To permit researchers' movement, cabin side
s are provided with handrail that constitute also an attach point for cameras and other accessories. Clearly, all elements of a selected experiment shall be included into main hatch's dimensions.

The following table provides specification of payload accommodation on Novespace Airbus A310 ZERO-G. The order of magnitude is likely the same for other airplanes.

Cabin length*	**20 m**	*** (experiment area)**
Cabin width*	5 m	
Cabin total volume*	200 m^3	
Total payload mass	4000 kg	
Cabin pressure	825 hPa	
Cabin temperature	17 – 20 °C	On ground, it is not controlled
Handrails diameter	30 mm	
Electrical power	230 V	AC @ 50 Hz up to 14 A, available only inflight (MAX 3.22 kW), Electrical plug required: CEE 7/4 or CEE 7/7
Vent flow rate	200 L/min	Temperature and pressure within 70°C and 100 bars

Table 2.7 – Payload accommodations for Novespace parabolic flights (Source: [2.4])

Looking into bibliography, the author found two brief documents [2.2] [2.3] about an attempt at standardization, the FASTRACK. It is a mounting rack designed by NASA Kennedy Space Center and Space Florida for microgravity experiments and technology development on parabolic and suborbital vehicles. Information about the current status of the project seems to be not in the public domain.
The rack, represented in figure, is composed by an open frame structure that can accommodate two single middeck lockers equivalent or one double middeck locker equivalent. On the bottom side there is support drawer that includes electrical equipment. FASTRACK with middeck lockers weights about as a passenger with the relative seat [2.6] and dimensions are 91.4 cm (height) x 61 cm x 61 cm.
Thanks to presence of a standard rack on the market, the customer can focus on payload design accelerating integration and so potentially take advantage more responsively of flight opportunities.
In addition to provide mechanical interface to middeck lockers, FASTRACK presents:

- Power: batteries (probably 28 VCD)
- Remote cut-off and breakers
- Data acquisition
- Temperature sensor (of the ambient air)
- Humidity sensor (of the ambient air)
- Warning LEDs

It is possible also provide the FASTRACK with gas bottles and other interfaces and resources that are available on the standard ISPR “Express Rack”.

Figure 2.7.2 - FASTRACK payload accommodation (left: single MLE configuration; right: double MLE configuration – source [2.2])

According to source [2.3], the rack flew on September 9th and 10th 2008 on a commercial flight provided by Zero Gravity Corporation in Florida. The rack was designed for their modified Boeing 727 but with the possibility of slight modifications for the adaptations to other vehicles.
During the aforementioned parabolic campaign three experiments were accommodated into the rack. The first deals with the characterization of the internal environment of the FASTRACK with measure instruments provided by Glenn Research Center, the second was a fluid dynamic experiments and the last the demonstration of a biomedical sensor of human hemodynamic.

2.8 PAYLOAD ACCOMODATION ON SUBORBITAL VEHICLES

Many suborbital companies express interface specification and which requirements the payloads shall satisfy in a proper Payload User Guide (it actually happens for all aerospace transportation systems, from parabolic aircrafts to orbital launch rockets). Analyzing these documents, the payload investigator can choose the more appropriate platform for his experimentation.

2.8.1 Payload accommodation on Blue Origin New Shepard

Blue Origin's customers, as declared by the company [Next-Generation Suborbital Researchers Conference (2010), G. Lai, "New Shepard Vehicle for Research and Education Missions"], will have opportunity to mount into the vehicle their own racks, after a safety review. They otherwise can use standard racks and services. Payload can be autonomous, remotely operated, or locally operated manually by a payload specialist.
Up to 2017, the company declares following key features:

- high quality microgravity environment (10^-3 g)
- 3 or more rack positions and high-volume cabin with shirt-sleeve environment
- 120 kg available per position (including rack)
- One window per position with the opportunity of custom transparencies
- Power support: direct current at 28 V
- In-flight communication support: voice communications with crew and ground; low-data rate link
- Video and data recording and storage provided for post flight download
- Actuator control
- Cooling
- Pointing Accuracy +/- 5° per each of 3-axes during coasting phase
- Turning capability
- Quick post-landing access
- Fast approval timelines (order of months)
- Custom hatches or windows may also be possible

Blue Origin offers three types of payload containers, summed up in the table.

	Single Payload Locker	Double Payload Locker	Nano Lab
Width [in]	20.6	20.6	3.9
Deep [in]	16.3	16.3	3.9
Height [in]	9.5	19	7.9
Load capacity [lbm]	25	50	1.1
Power interface	26 ± 4 VDC 200 W peak power	26 ± 4 VDC 200 W peak power	5 VDC 4.5 W peak power
Data interface	Ethernet	Ethernet	USB

Table 2.8 - Standard payload containers for a New Shepard suborbital flight
Lockers, mad of aluminium alloy, have standard fastening patterns on the internal surfaces. Front and rear panels are customizable with fans.

Onboard the spacecraft, at total of 36 single payload locker locations can be mounted. Among these, 24 locations are equipped with power and data interfaces, that are made available between five minutes before launch and five minutes after landing.
Each locker can take advantage of an 85 W-hr amount of energy per mission, or purchase an additional service up to 200 W-hr. An active overcurrent protection device limits current to 2 A.
Supported data protocols for payload communications are Ethernet and RS-232. Ethernet provides spacecraft's data such as elapsed time, altitude, velocity, acceleration via the onboard data computer. Real time telemetry to flight control segment is not currently permitted, but each locker can save data into a

personal 32 GB solid-state memory storage. The locker position includes also a resistance thermometer (RTD sensor) and HD video cameras (standard M12, CS or C-mount) that can save video and photos to a separated microSD card.

External mountings for payload accommodation in the interstage at the top of the first stage, are under development. Experiments are covered up to 65.5 km, the nominal maximum altitude, and here they have access to the external space environment for the entire phases of booster coasting and re-entry.

2.8.2 Payload accommodation on Rocketplane XP

The Rocketplane XP tries to mimic, as far as possible, flight profile of Shuttle, HTV and ATV, in order to have similar peak accelerations (3 G on ascent phase and 4 G on reentry) [2.6]. The pressurized cabin provides a shirtsleeve environment to reproduce conditions that can be found on every ISS module.
The spaceplane uses FASTRACK seen in the paragraph of accommodation on parabolic aircraft as a standard for payload accommodation [2.6]. It is possible to transport up to eight middecks. Also the presence of two or three payload specialists/investigators is taken into consideration during design.
In special cases, for high payload demand scenario, it is possible to mount a large rack that can hold up to twelve middecks. It is a full rack cabin configuration and space for only a payload officer remains.
Services for payloads include high data rate communications (it is possible to command payloads form ground) and multi-channel video downlinks (HD quality). LCD multifunction panel is mounted at the front right seat of the Flight Engineer to monitor and control payload parameters and functions. Standard internet protocol and a solid-state drive complete the list of useful resources available on the Rocketplane XPA.

Figure 2.8.1 - Rocketplane inside cabin [2.6]
The left figure represents the full rack configuration cabin with twelve middeck lockers. The right shows seats for pilot and flight engineer.

Rocketplane designers have included an external rail for mounting payloads into pods centrally on the ventral surface of the spaceplane. So-carried pods can be equipped with multispectral, SAR and LIDAR sensors for remote sensing [2.6]. At the peak of the parabolic free fall phase, a viewshed area of about 1000 km can be detected in any direction. Also, astronomy science is suitable for external pods. All related required equipment for control and data recording are installed inside into available slots for middeck lockers.
Finally, external accommodation capability can be used on XP to launch small satellites to LEO. Launch capacity for this vehicle is of one satellite between 10 and 100 kg. Launching configuration is so of the type “carried on bottom”.

2.8.3. Payload accommodation on SpaceShipTwo [2.23]

Next to the employ for space tourism, SpaceShipTwo is also intended to be used for suborbital experimentation. On the vehicle more than 450 kg of payload material can be stored on board [2.23].

Payloads are stored in standard accommodation systems, such as Middeck Lockers Equivalent, Cargo Transfer Bags and server racks. Actually, other types of custom payload structures are allowable, but safety analyses and test must to be carried out, adding more paperwork that means more costs and time requested for payload acceptance.

These payload containers are fixed to five mounting plates, as represented in figure 2.18. The available volume is equivalent to 20 MLE, while internal volume is 14 m^3.

When SS2 is mated to WhiteKnightTwo, internal conditions, such as pressure, temperature and humidity, are actively controlled by the mothership's subsystem to provide a shirt-sleeve environment. At spaceplane release and for remaining mission duration, any way for temperature controlling or CO2 removing is supplied.

The power bus for payload electrical feeding is currently under development, but it is sure that will provide 50W to each middeck locker location at 28 Volts and will be available from take-off phase.

Accelerations, temperature, pressure sensors and camera are located inside and outside the cabin, and related data can be supplied to payloads via an Ethernet interface. Alternatively, data can be store on SS2's Data Acquisition Units, and then downlinked after landing. Payloads can use also their own data gathering and storage systems.

Virgin Galactic promises a quick logistic management of payload, with a rapid installation and recovery, also to permits multiple flight per day. According to the official guide, "with pre-flight and post-flight access within hours of a launch".

There is also flight opportunity for non-autonomous payloads, thanks to a payload specialist that will flight in the spacecraft with the experiments, having the possibility to a limited interaction (for example the manual system enabling via button). It is possible to have a second payload researcher on board to execute more complex tasks.

Observation experiments are possible thanks to the pointing capability of the spaceplane and mounting payloads to the windows, which can be replaced with high-quality glass with additional costs.

	Measure unit	Value
Payload capacity	[kg]	450 (more than)
Useable payload volume	[m^3]	14
High- quality microgravity duration	[min]	3 - 4
Interior air pressure	[altitude equivalent]	5500 ft
Interior humidity	[%]	75 (less than)
Interior temperature	[°F]	40 – 90
Microgravity quality	g	10^{-3} to 10^{-5}

Table 2.9 – Technical specifications useful to payload accommodation for suborbital research on board SS2

In addition to the SpaceShipTwo itself, also the carrier WhiteKnightTwo is planned to be available for payload campaigns. Clearly, conditions will not include microgravity or space environments, but it is an interesting access to low density atmosphere around 15 km, for more than 35000 lbs of payload carriable mass (equally to 15.89 tons).

In future, an accommodation outside the cabin will be provided to SpaceShipTwo, but no other official information is available on this topic.

No venting systems to the outside are made available on the spaceplane.

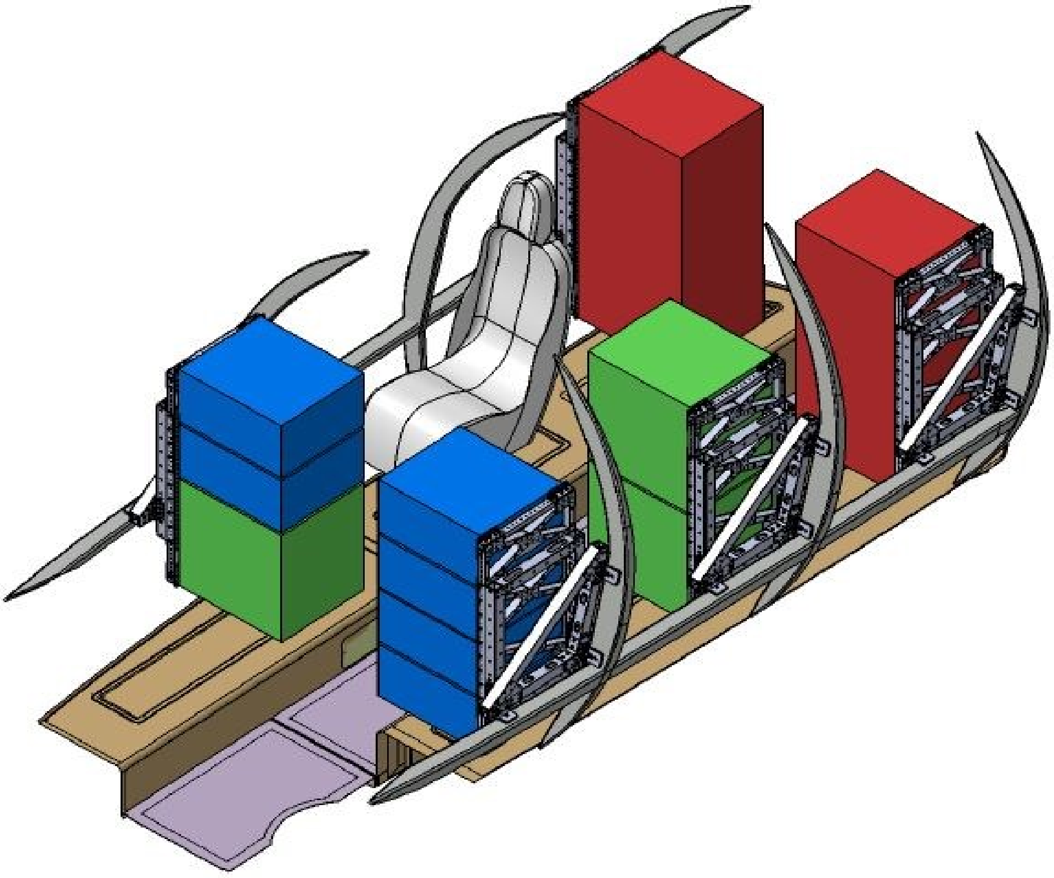

Figure 2.8.2 - Official interior configuration for research payloads (CAD representation, source [2.23])
A total of five payload racks and a payload specialist chair is provided. Red box is representative of a quad middeck locker, green and blue for double and single respectively. They are attached to longerons by a mounting plate represented in Appendix B. Therefore, each mounting plate can support up to 4 MLE and up to 200 lbs in the case of quad MLE. Payloads shall to fit with the main enter elliptical hatch (33 in x 26 in, equally to 84 cm x 66 cm).

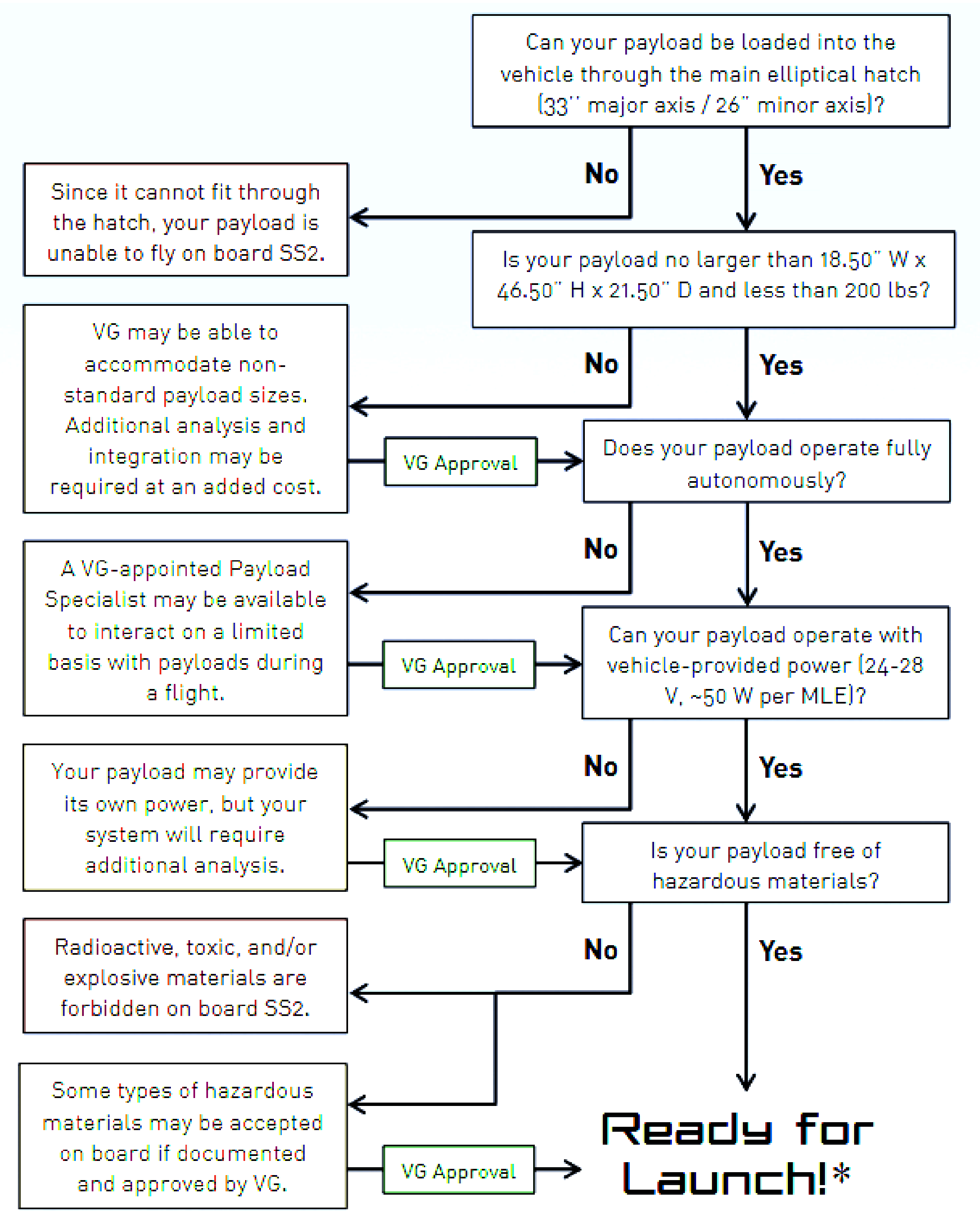

Figure 2.8.3 – Approval process for a SpaceShipTwo flight (Source: [2.23])

2.8.4 Payload accommodation on Lynx [2.7]

Three models of Lynx have been presented, Mark I, Mark II and Mark III. All have the same dimensions, but the third is equipped with an external payload bay on the top of the spaceplane (up to 650 kg of payload mass). It is so capable of all related uses, from suborbital astronomy and remote sensing to even launch of microsatellites to LEO. On the vehicle, payloads must be attached into containers and are subjected to hierarchy:

- Primary payloads: flight trajectory, mission objectives and mission date are decided upon their requirements;
- Secondary payloads: they take advantage on a scheduled mission and cannot determine trajectory and date

The spaceplane offers four locations for payload accommodations and two of them are pressurized (into the cabin), showed in figure:

1. Right-of-Pilot (cabin): it is a chassis attached instead of the passenger's seat. Therefore, only the pilot can be present onboard during flight if this location is used. The mechanical interface to the Lynx structure is a common couple of commercial airline seat track. This location interfaces internally with standard containers: a 19'' 14U electronics rack or two Space Shuttle Middeck Lockers.
   Inside cabin, temperature and pressure in controlled. Acceptable noise derives from the engine burning and it is similar the typical one of commercial airplanes.
2. Behind-Pilot (cabin): it is a small envelope structure with triangular shape for secondary payloads. The experimenter, if he does not want to use standard small boxes provided by XCOR, can design the primary structure of its payload. During flight, the pilot can interact with it by an on/off switcher positioned on the instrument panel. The flight participant can also control the location via a tethered connection.
3. Cowling Port and Starboard (external): on each side of this location, a 2U CubeSat size payload can be accommodated. No pressure, heat or cooling control is provided, so it is exposed to space conditions. An interesting feature is the possible automatically deploy at a determined point by a spring.
   The small hinged hatches, one for each side, can be opened for remote sensing missions.
4. Dorsal Pod (external): only Lynx Mark III has this location, but a smaller version is also available on Lynx I, up to 280 kg of payload. Also, here no controls are available, but it is possible to electrically feed the payload by a 28V connection. A fairing has cover function and can be opened for launching the satellite and load the payload by a slide. Launch can be automatically executed by a spring deployment, by gas pressurization supplied by the spaceplane or with an upper stage.

Dimensions of each location are provided in the figure and in the Appendix B.

	Measure unit	Value
Payload capacity	[kg]	Up to 280 (Mark I), 143 (Mark II) or 650 (Mark III)
Interior air pressure	[KPa]	72.4 ± 2.7
Interior humidity	[%]	20 - 50
Interior temperature	[°C]	≅ 20

Table 2.9 – Some Lynx's accommodation specifications.

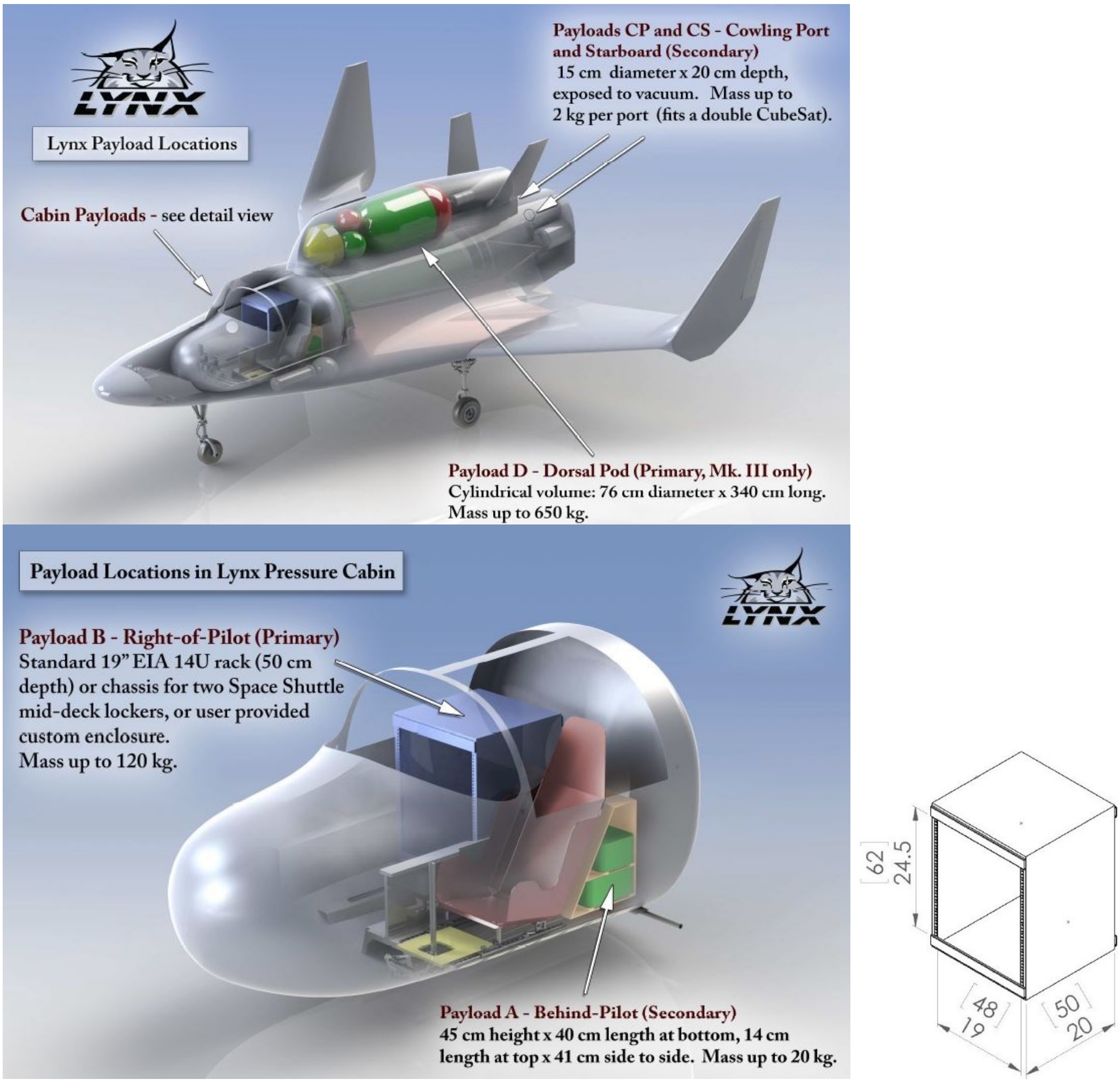

Figure 2.8.4 - Four Lynx's payload accommodation locations
On the right are given measures of the 14U standard 19 inches server rack adopted for location B (Right-of-Pilot).

The electrical standard used is MIL-STD-704. Power source are separated batteries that are not connected to any spaceplane system, but only to payloads, for safety reasons. 5A fuses are installed at locations 1, 2 and 4. At Cowling Port and Starboard there are 1A ones.
For communications, a link for voice, data, telemetry and payload data is available via a single satellite-communication phone.
Lynx provide GPS and INS data to payload, as well as elapsed mission time. A small supply of gaseous nitrogen is available for cryogenic purposes. Two cameras pointed on payload and instrument panel completes cabin’s dotation.
Attitude can be controlled with RCS thrusters up to 15 °/sec for remote sensing missions.

2.9 PAYLOAD TYPICAL REQUIREMENTS [2.7]

Commonly requirements for payload to be accepted for flight onboard previous types of aircraft and spacecraft are written in the following list. During next chapter, the requirement concept is defined and its structure analyzed. This list has the sole purpose of underlining that there are requirements in both direction: the vehicle must satisfy requirements to be safe and to accomplish its mission, which is carrying payloads at the edge of space, while also payloads, that shall to be accommodated on a determined spacecraft, must be compatible with constraints and safety guidelines imposed by such vehicle.
Although the acceleration profile is quite gentler than sounding rockets or drop-towers, payloads must to resist to deformation under flight accelerations (acceleration that are will be possible to meet during a nominal flight) and to ultimate accelerations, which will be presented during catastrophic crashes, without free breaks that could cause extra damages.
Generally, the payload shall demonstrate, with paperwork presented by the Payload Investigator, to not constitute a safety hazard. The endeavour required by the payload team can be relieve adopting standard structure made available by the Flight Provide, because less tests and analyses shall to be carried out. Off-the-shelf components employment is generally encouraged for the same reason. Moreover, it is also convenient to take advantages of on board provisions, such as electrical feeding, cooling and venting systems, because through this way the entire available volume can be used for experimental hardware, reducing at the same time safety analyses that shall to be carried out for payload systems.

- Payload shall have dimensions compatible with enclosures specified on relative payload guide;
- Payload shall not to constitute a hazard for the crew or passengers during an event of depressurization or crash;
- Payload shall not overcome limits on heat release in the cabin;
- Payload shall endure hangar and spaceport environment (temperature, humidity, winds, dust, direct sunlight, sand, etc.);
- Payload shall endure a TBD period of time without any feed for integration into payload (exceptions could be concorded with flight providers)
- Payload shall be attachable to structure provisions;
- Fasteners shall be of aerospace grade;
- Payload shall endure ultimate accelerations of the mission profile;
- Payload shall be connectable to vehicle interfaces if related services are requested;
- Payload shall avoid use of toxic, explosive, corrosive and generally hazardous materials (exceptions could be permitted by flight providers);
- Payload shall to be leak-free (dust, liquids, gases, flames, smoke or debris);
- Payload shall to avoid sharp edges;
- Payload shall be covered with proper insulation material;
- Payload’s structural fasteners shall be of an aerospace grade;
- Payload that uses lasers shall generally be examined and approved by flight provider;
- Payload shall not constitute a source of electromagnetic interference;
- Payload specialists shall have a TBD medical certificate;
- Payload specialists shall receive a TBD train;

Processes on payloads are accomplished commonly by different teams. Three indispensable figures that deals with payloads requirements and related analysis and testing activities are summed up in the table 2.10.

PAYLOAD INTEGRATOR	PAYLOAD DEVELOPER	PAYLOAD SPECIALIST
- Safety assessment and hazard determination **- Interfaces connecting** **- Requirements verification** **- Flight manifest scheduling**	- Payload design - Payload build - Payload testing - Results analysis	- Payloads' systems monitoring - Simple payload interacting - Handling payloads emergencies

Table 2.10 - Payload integrator, developer and specialist duties [2.7] [2.23]

The payload specialist is a role active during mission, while integrator and developer act before the takeoff.

2.10 NASA FUNDING PROGRAMS FOR SUBORBITAL RESEARCH AND TECHNOLOGY

[2.23]

This brief paragraph has the purpose of presenting four funding sources made available by NASA. Although a researcher has competencies to design and realize its payload without external support, build it could be very expensive, without taking into consideration flight expenses. So, funding sources are listed below to illustrate that is the research idea is good, it is possible to obtain funding to fly its own research.

- FLIGHT OPPORTUNITIES PROGRAM: this program offers flights opportunities on board sounding rockets, parabolic aircraft, stratospheric balloon and suborbital spaceplanes to enhance technologies' maturity and increase their TRL. It is part of the Office of the Chief Technologist's Space Technology Program.

- RESEARCH OPPORTUNITIES IN SPACE AND EARTH SCIENCES (ROSES) PROGRAM: it focuses on experiments on the following disciplines: Earth science, planetary science, astrophysics and heliophysics. It is possible to obtain from 100k $ to 1 M $ each year for five years.

- GAME CHANGING DEVELOPMENT PROGRAM: the purpose is to advance space technologies that could be used during future space missions. Funding amounts from 125k $ to 500k $ for payload development. It is offered to both universities and industries.

- HANDS-ON PROJECT EXPERIENCE (HOPE) PROGRAM: it offers funds to new NASA managers and engineers to design, build and fly scientific payload on a suborbital vehicle within a year.

2.11 ITALIAN ENDEAVOURS TOWARDS SUBORBITAL FLIGHTS

Finally, this Chapter is completed by a compendium of valuable initiatives engaged by Italians institutions regarding the suborbital spaceplanes sector. Certainly, among others European States, Italy is at the forefront of these topics and the ongoing initiative for the construction of a spaceport on Italian territory is of particular interest. A viable site could be built in Sardinia, in particular near the Decimonannu military airport.
Another very important topic is linked to the need to establish an adequate regulatory system which, while in the USA is already quite developed, in Italy and in Europe it is in its early stages. Surely, in the Italian and European context will be used U.S. space vehicles such SpaceShipTwo. This highlights further normative constraints, for example issues regarding export control (SpaceShipTwo, according to relative payload guide [2.23], is limited by Arms Export Control Act and Export Administration Act).

- 12 March 2014: A bilateral agreement (Memorandum of Cooperation) was signed at the headquarters of the Italian Embassy in Washington, USA between ENAC (Ente Nazionale per l'Aviazione Civile) and FAA (Federal Aviation Administration) for development of an Italian national legislation on topics related to research, development and operations of commercial suborbital spaceflight, fostering collaborations between Italian and US related companies.
  [source: FAA and ENAC]

- 30 June 2016: A Memorandum of Cooperation on "Commercial Space Transportation" was signed between FAA, ENAC and ASI (Italian Space Agency), hosted by Aeronautica Militare Italiana at "Casa dell'Aviatore" in Rome. The memorandum is the evolution of the previous agreement of March 2014
  for the development in Italy of initiatives of New Space Economy and Commercial Space Transportation.
  [source: https://www.asi.it/it/news/uno-spazioporto-in-italia/]

- 5 December 2016: A Memorandum of Understanding was signed between Altec and Virgin Galactic, aiming to possible suborbital operations from an Italian Spaceport with Virgin Galactic SpaceShipTwo and WhiteKnightTwo. The agreement lays the foundations for the identification of an adequate airport to be converted into the first Italian spaceport. Such spaceport will be used to perform space tourism flight, suborbital research, astronauts and pilots training and education purposes.
  [source: https://www.asi.it/it/news/accordo-altec-virgin-galactic/]

- 18 December 2017: A Letter of Intent was signed between Virgin Galactic and ASI for the conduct of future microgravity research suborbital flights on SpaceShipTwo. The agreement was signed at Next Generation Suborbital Researchers Conference and promises an exclusive suborbital flight for a research mission that will take place in 2019 from the Spaceport America, New Mexico. The mission will be aimed to experimentation with an Italian Payload Specialist. More details about experiments, Investigators and Payload Specialist will be published and confirmed with the contract. ASI will be so the first non-American space agency to flight with Virgin Galactic. Moreover, the latter declared on this occasion that ASI has selected LauncherOne as launcher to insert a SIATEL satellite into orbit, realized in collaboration with ESA.
  The mission could also represent the beginning of astronaut training missions of suborbital vehicles.
  [source: https://www.virgingalactic.com/articles/italian-space-agency/]

- 20 March 2018: at the Aerospace Medicine Department of the military airport of Pratica di Mare, an agreement between the Italian Air Force and the Italian Space Agency was signed for

collaboration in suborbital activities and joint projects, in particular in the field of aerospace medicine.
[source: https://www.asi.it/it/news/asi-e-aeronautica-militare-insieme-per-il-volo-suborbitale]

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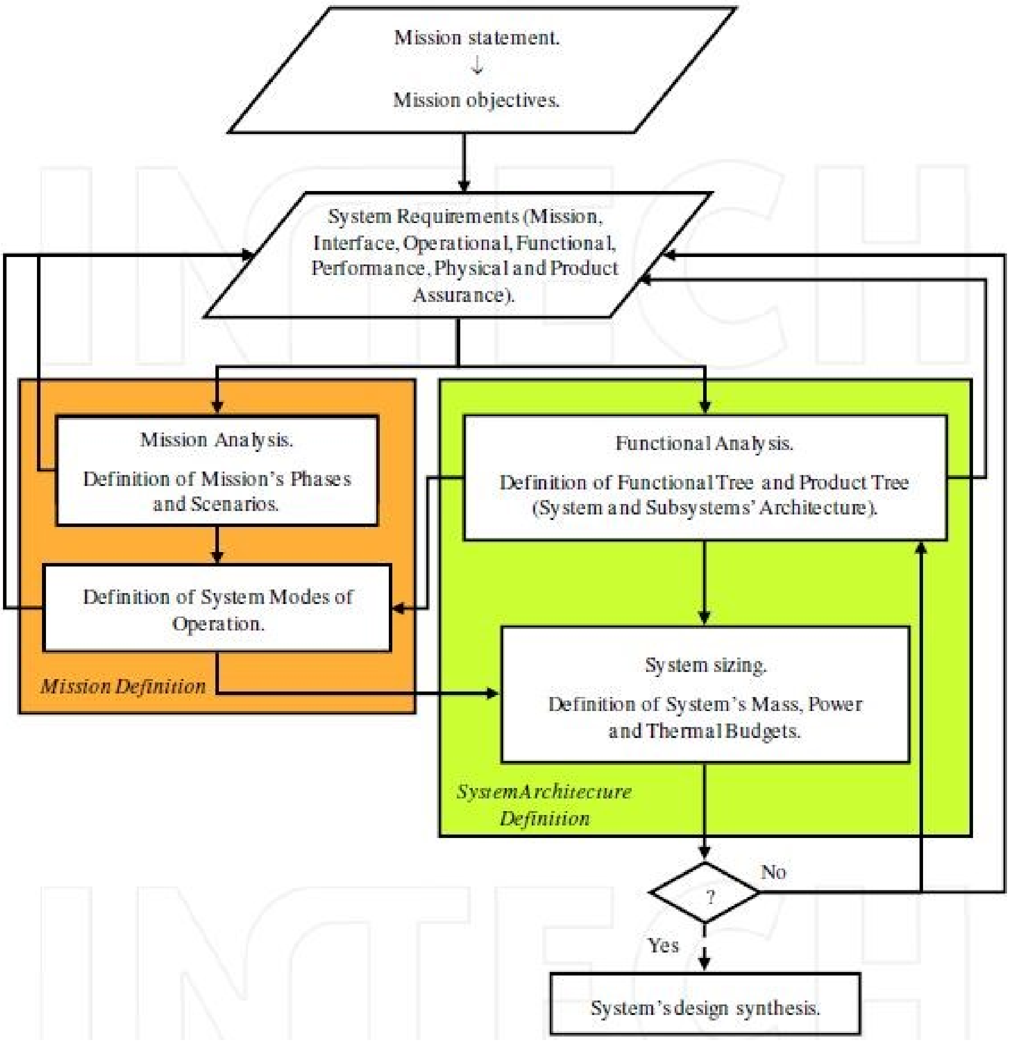
Chapter 3:

METHODOLOGY



[Flow chart of the preliminary design proposed into reference 3.9]

3.1 – INTRODUCTION [3.5] [3.7]

This chapter describes a systematic and general approach to support the design of complex systems that will be called "the methodology". It can be seen as a collection of work procedures and conceptual tools applied as an organized management of the design process. Structured procedures of this type have been discussed from a consistent field of authors and are subjects of study of a multidisciplinary field of engineering called "Systems Engineering" (abbreviated as SE). In this chapter, the author proposes his personal re-elaboration of the methodology, as much as possible coherent with itself and with references.
System Engineering deals with development and organization of large, artificial and complex systems, combining ideas and tools from different fields of engineering and management. Definition provided by the International Council of System Engineering (INCOOSE) affirms: "Systems engineering is an interdisciplinary approach and means to enable the realization of successful systems". It is a holistic discipline that acquires analysis and integration techniques of academic disciplines, specially other several branches of engineering, considering all aspects of a system in a logical approach.
SE covers the entire design process and more generally the entire life cycle of the systems, from the conceptual design through the realization and testing to operations and disposal. In this thesis context, SE is considered for the first part of these phases, relatively to development.
The system engineer shall generally arrange for the product to satisfy needs and imposed requirements, securing that a proper approach has been followed, evolving from the idea to the final version of the product. This is generally eventually aiming to the best **cost-effectiveness** compromise. Another ultimate goal of Systems Engineering is to encourage innovation and development of innovative solutions as much as possible. Tasks required to a system engineer deeply vary from case to case: for instance, generally speaking, the architecture of the system shall to be decided, requirements shall to be derived and allocated. Also a proper set of documents shall be prepared: work packages, specifications, certifications, validations and technical documents constitute examples.

In order to have a clearer understanding of the methodology, it is worth to make a preliminary digression about life cycles. A life cycle of a product is the set of all phases related to its life, intended from the extraction of the raw materials, through production and **operations**, to reuse, recycling or final disposal. Several models have been created to describe life cycles, in particular development and production, constituting useful guidelines and conceptual tools to plan these phases. They are therefore meta-models and those most utilized are the Waterfall model, the Spiral model and the V model. The latter is particularly interesting because underline a close loop connection between requirements, verification and design, and it is descripted into the caption of figure. It subdivided the design process into eight phases, starting from the desires of customers, also called the Voice of the Customer. These phases have put graphically along a consequential path with a V shape. Before examining the figure, it is worth precise the difference between verification and validation: the first means the confirmation that the system complies to constraints and requirements imposed by the design process. The validation, that is very similar in nature, is the check that the system fulfills requirements and desires of the stakeholder, and specially the customers. A validated system is capable to accomplishing its planned operations in the intended environment. As it will be clearer later, the verification therefore confirms fulfillment of system requirements and validation confirms fulfillment of customer's requirements. [3.3] [3.5]

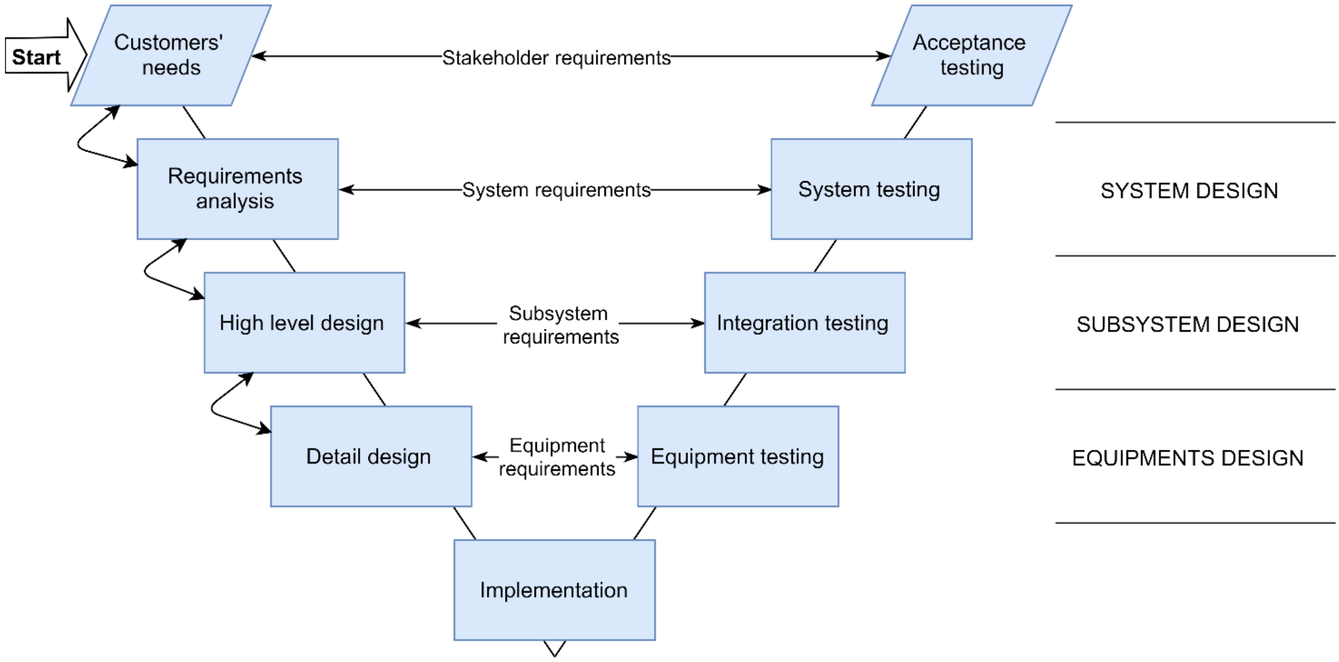


Figure 3.1.1 – The V-model
The starting point is the Customers' need tag, and firstly the left branch of the V is followed, to the system implementation. It deals with analysis and design in the narrow sense, from the system to its components. The right branch is related to tests and verification and the acceptance and testing.

Proceeding into design, the focus of the system engineer will move gradually from the general to the particular, from the system viewed globally to the subsystems and components that constitute it. This approach can be easily modelled as a succession of design levels: system level, subsystem level and component level. Clearly, not all information required to properly design the system are available from the beginning, so they are obtained thanks to this top-down approach. Once derived, it is used at the proper level to improve results. In fact, at first, top level quantities and parameters are obtained within a certain grade of uncertainness, and then such values are refined during design of subsystems and components, achieving exact values when design is completed. The design proceeds only globally from the upper level to the lower level, but actually it is a continuous revisiting design levels.
During design process, requirements play a central role for every row, that reflects the level the design is focused on. A verification process shall be accomplished for the requirements analysis, the high-level design and the detailed design. The validation of the system can be carried out at every point of the design, but it is certainly completed only at the end of the design with the acceptance tests.

With this philosophy, many author decomposes a design process into phases. Here are presented two frequent classification, the following from source [3.2]:

- **Preliminary design** (called also conceptual design, baseline design or feasibility study): designers have to produce a document that presents a description of the new product, together with relevant technical and geometrical information (at the appropriate accuracy level). Through this thesis, this document will be indicated as "system design synthesis". In this phase few people work, but their number exponentially grows during the subsequent ones.
- **Project design**: designers conduct different analysis to increase the technical accuracy of products' quantities and add details to the system design synthesis. Tunnel tests and numerical analysis are typical tools of this phase. Also RAMS, costs and marketing affect the design and their influence is considered. Finally, a ultimate design layout is produced for the manufacturing phase.
- **Detail design**: during this phase CAD documents and manufacturing instructions are generated.

In the case of a totally new project the methodology should be applied at first at the segment level, outlining the main characteristics and parameters of all the systems belonging to the segments and then going deeper and deeper until the smallest screw is defined in its entirety.
In other cases, it is often necessary to design a product taking into account the existence of elements of the same level or of upper ones. It may be required to adapt the product and so introduce constraints.
Theoretically, the methodology can be started and stopped at every design phase and level. As a consequence, the designer can decide which will be the product, i.e. the subject of procedure, and the detail level of the output (the design synthesis): it can be possible carry out a high level preliminary study of the system-of-system to or perform a detailed development of a determined subsystem. This flexibility is one point of strength of the methodology.

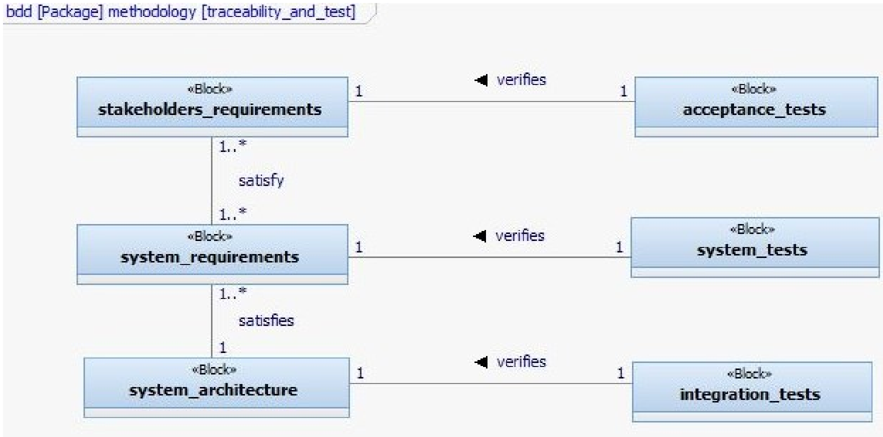


Figure 3.1.2 - Traceability and tests (source: https://www.youtube.com/watch?v=2tN_cVQP214)
System requirements are related to Stakeholder requirements via a satisfy association relationship, and the system architecture is designed to satisfy one or more system requirements. Notice that there is no immediate relationship from the architecture to the stakeholder requirements, but is an implied relationship going through system requirements. In the design model built into Rhapsody software this idea is followed. This diagram is valid for all design levels. It is worth to note that this figure does not represent a true bbd according to the sysML, because the tests being actions cannot be defined as blocks. The sysML style has been adopted only to make the diagram clearer.

3.2 – METODOLOGY OVERVIEW

Now the methodology is presented generally, while the following paragraph describes theoretically every step into details. In the following chapter, the methodology will be applied to the case study starting from the blank sheet of the system-of-systems level, to clarify the steps of the methodology and to underline its potential. A main idea of System Engineering that will be applied into this work is considering the design problem as general as possible. This is especially important in the conceptual design phase, where specifying too much prematurely could lead to unsatisfied customers and potentially to an unsuccessful product [3.2]. Flexibility during design phase is an advantage, not a lack of inputs. The importance of generality will be clear at the Chapter 4.
The proposed methodology has the purpose of helping the designer to satisfy customers in the best and responsive way, organizing and accelerating all the design phases, resulting in a better product designed in less time. In particular, it permits:

- To guide the work group through the design process from the first stakeholders' analysis to the production phase;
- to derive a large amount of different architectures and operational concepts able to accomplish an established group of goals;
- to individuate a small number of feasible options among all possible ones and eventually to the optimized solution [3.4].

Unfortunately, to come to the design synthesis, methodology's steps cannot be performed linearly as showed in Figure 3.2.1 As we will point out further, at a certain point, to continue through the design process, analyses done must to be repeated iteratively to acquire new information that will be inputs for subsequent steps and iterations. In fact, the entire process can be seen as a succession of analyses, that requires inputs and produces outputs, repeated iteratively multiple times to refine results in a "horizontal repetition". Moreover, the methodology shall be repeated also "vertically" in a top-down approach, starting from the highest level, the System of Systems, to each more specific one (segments, systems, subsystems and components).
Given the different nature of each project it is not previously possible to know a priori how many iterations will be required to come to the design synthesis or which steps of the methodology will be excluded in the first iterations.
This figure will be used in the section 3.3 as zoomed versions to illustrate the position of each step within the methodological process.
Functional analysis and ConOps have been highlighted with different colour, because they can be carried out at the same time and because it is likely that here the methodology is interrupted to perform a subsequent iteration. From the next chapter the actual steps' succession will be clear and it will be also clear that some steps at first design levels and first iterations cannot be carried out.
A further step is actually necessary: once the final design solution is identified among different alternatives and it is descripted into a collection of technical documents, its validity has to be verified. This process permits to certificate that the design solution satisfy requirements and constraints.
The design synthesis must include both construction instructions and detailed information for use and maintenance. However, the design work does not end here: any design errors must be promptly corrected and applied to the product in service and to subsequent versions. The modifications that can be applied to the project must also be taken into consideration so that it continues to comply with the law. [3.2]

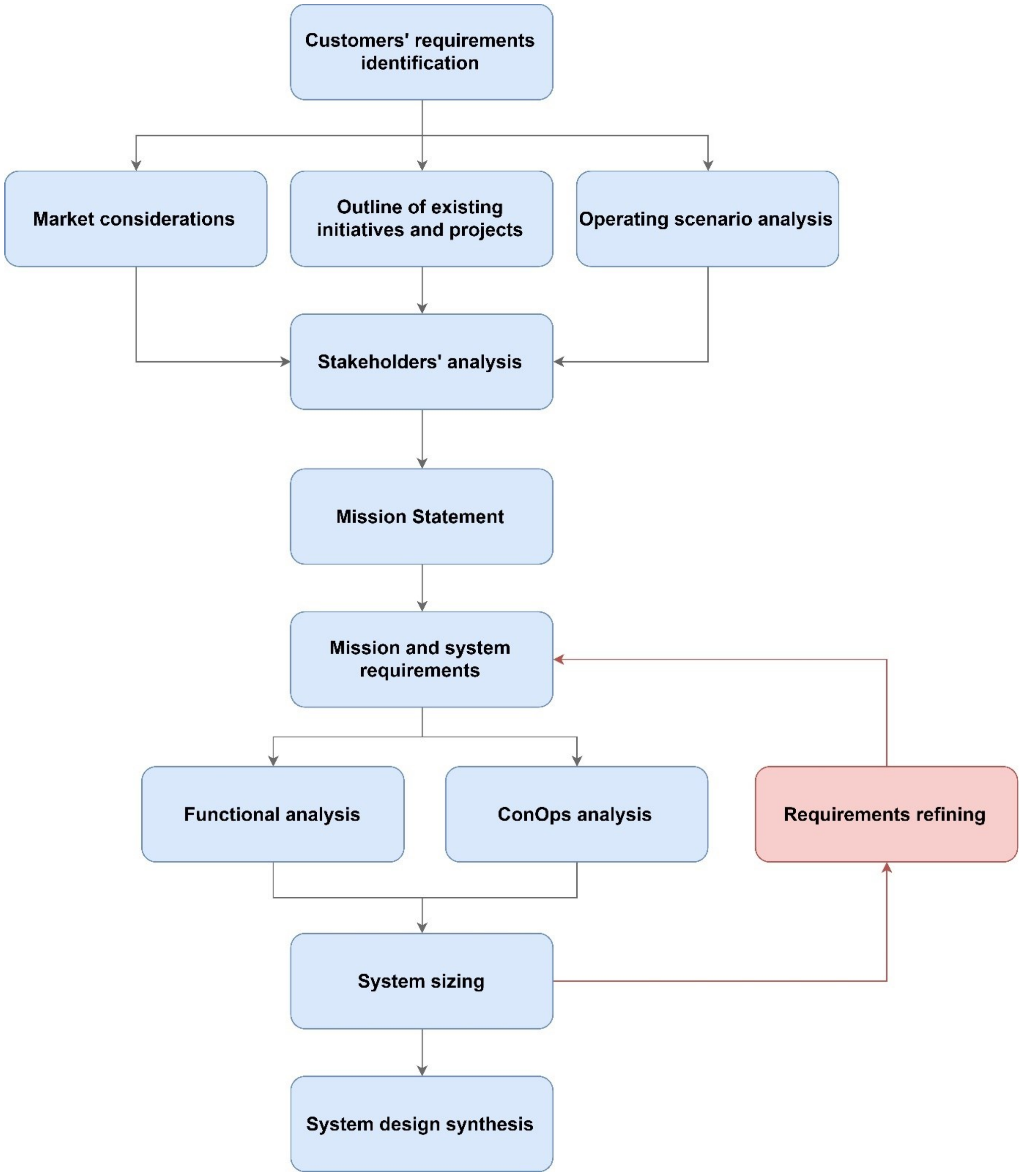


Figure 3.2.1 – Flow chart of the fundamental steps of methodology
This figure represents all the basic steps of the methodology in the order in which they are to be performed. In spite of the diagram shows a linear path though methodology steps, the real work is a process of successive refinements.

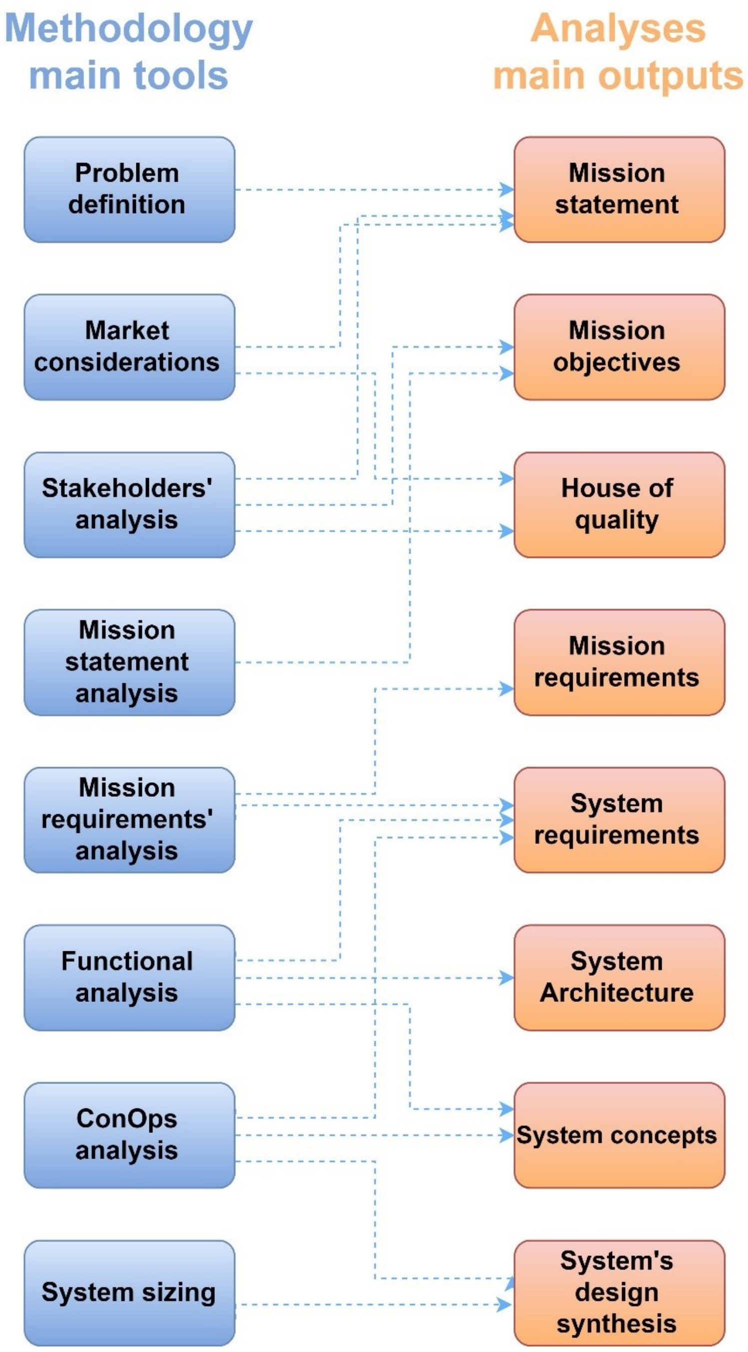


Figure 3.2.2 - Fundamental results of methodology
Main steps cooperate together to produce a high number of outputs that will be grouped into the design synthesis. Every blue-colored step is suitable for iteration, in a process of successive refinement and trade of the results.

3.3 METHODOLOGY STEPS [3.4][3.9][3.8]

In this section the steps of the methodology are theoretically presented, often with examples.
For for a better comprehension, after description, each is matched with a block diagram which is a combination of the two major diagrams exposed in the chapter's introduction. The logical flow chart is zoomed on the current step that is highlighted in blue. It is also linked to main outputs, orange-coloured.

3.3.1 Customers' requirements identification

Normally, a project is started in response to a problem or a need, exposed by an individual, group or an organization into a "project brief" or a "request for proposals" [3.2].
In the aerospace field, editors of such documents can be:

- Customers: they can be privates, industries or investors that want to commission a determined product or service. If customers belong to another industrial or commercial area and do not have the necessary know-how to fully understand the issue, it is important to inform the customers about technological limits and possible inconsistency of some requests.
- Space agencies, institutions or technical societies: they generally exhibit tenders): they generally publish calls for proposals.
- Market analysts: from market research it is possible to understand which product may interest or what are the trends of a determined market. Forecasts can be used to anticipate customers' needs and so offer the right product at the right time.
- Researchers: they can belong to universities' departments or companies research and development office. Innovative technologies may be ready to be utilized and integrated in better products.
- Other collaborators: even collaborators can commission a design case because already existing project needs to be completed or adapted to changed market conditions, to make it more modern or more functional.

From now on, all these categories will be included in the term "customers" and the task of the engineer is designing a system that should satisfy their desires and requests in the best way. They could be gathered as clear, exhaustive and complete as possible, using market analysis or directly interviewing or meeting with the customer.

Then those requests shall be formalized as requirements and drawn up into a list, the customers' requirements list. The subject of these sentences may belong to any design level in the hierarchy of space products. In fact, the client may have general requests about the segment level and system level or may be interested in specific characteristics of the subsystems. It is worth pointing out that it is not necessary to introduce any information about quality, for example information on the quality of the implemented solutions, effectiveness, costs, timing, safety and reliability. In fact it is implied that the characteristic expressed in the requirement must be as satisfactory as possible for the client, compatibly with cost, safety and technical limitations. These issues will be discussed from the stakeholder analysis, where quality analysis will be introduced.

It is worth to immediately analyse which are the constraints, not only technical ("performance and operational requirements, [3.2]), but also" political, social, legal, economic and commercial "[3.2]. At the same time, the introduction of too many constraints, not adequately evaluated could lead to the block of the methodology's iteration, without any compatible product being identified. It is appropriate to postpone the introduction of technical constraints to more advanced phases, such as functional analysis for example, and carefully evaluate non-technical constraints, which are the most difficult to evaluate.
More specific analyses regarding preliminary information gathering are discussed in the next three steps.

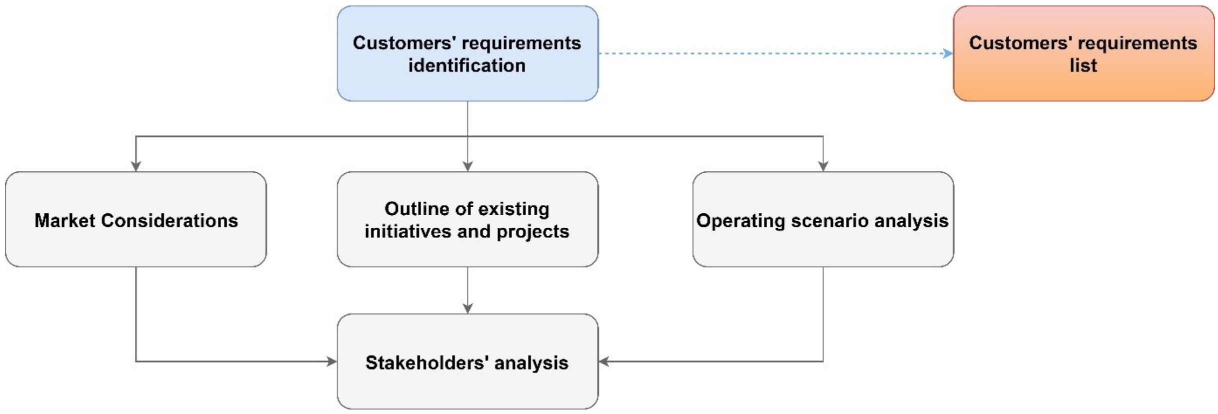


Figure 3.3.1 – Customers' requirements identification

At this step it is important to understand why a new product is needed. With the definition of the problem, it is possible to start gathering more information on the design subject and focus on relevant analyses, such as market analysis, existing projects' outline and the study of the scenario.
The customers' requirements list forms the basis for the analysis not only of the client's needs, but of all the actors who are in some way involved with the new product.

3.3.2 Market considerations

A market analysis is a study that provides information about a determined market field. The analysis shall underline all the relevant elements to direct project choices towards maximum customer satisfaction and maximum profit.
This step could be outlined through two phases, the market information gathering and the data evaluation. The first is accomplished interviewing a sample of potential customers or analysing closed and open source documents such as government budgets, sales data of previous or competing products, internet, academic articles, data from related markets.
Once data are collected, they can be interpreted by the market analyst that produce forecast about future trends and estimations about the evolution of the market. Between the two phases, data could be processed with algorithms to select only the most relevant and generally improve the reliability of forecasts.
A fundamental data to gather as soon as possible is what the market is worth. Revenue projections help the designer to understand:

- Which is the target, i.e. which type of customer the product is intended for.
- How the product has to be cheap or premium to secure a proper profit.

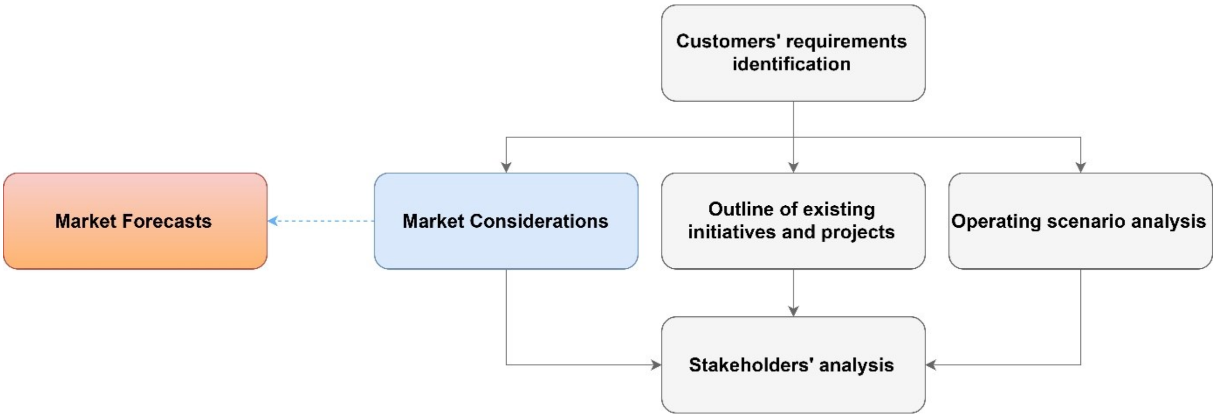


Figure 1.3.2 - Market considerations

A market analysis is really important for further development of the study, especially for the flight hardware development field. Indeed, a highly innovative and effective product may be economically un-competitive and a well-done market analysis rises the possibility of an adequate profit.

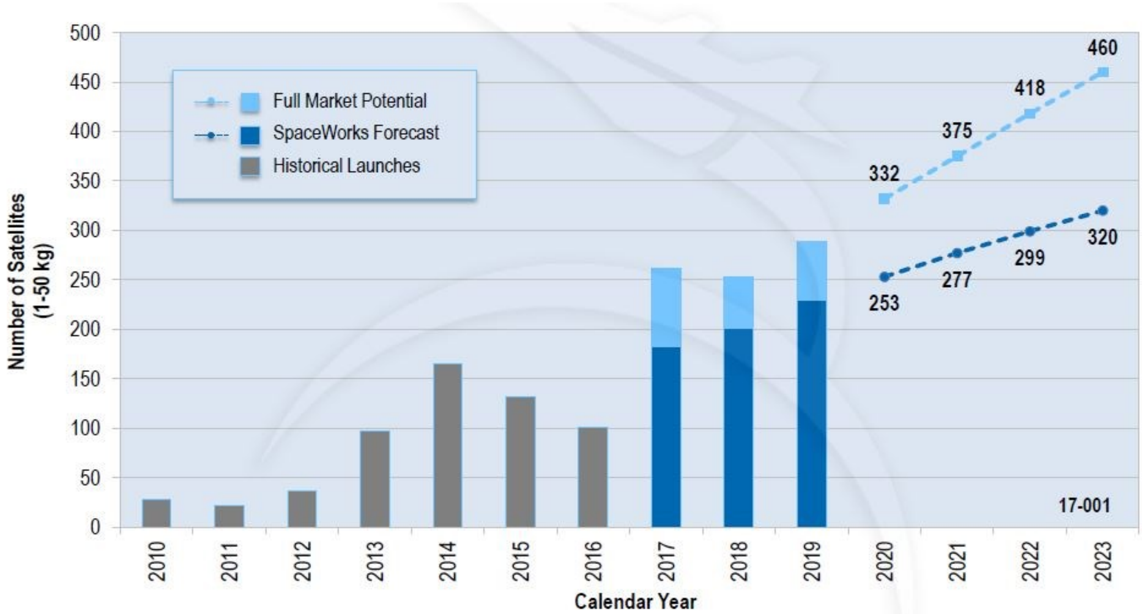


Figure 3.3.3 - Example of a market forecast about the launch of small satellites (Source: SpaceWorks)

The forecast is relative to a 7 years period, from 2017 to 2023. Analysts expect a reversing trend with a 10 % growth year over year. In particular, 2017 was expected to be a record year, with about 80% increase from 2016. The indicator "Full Market Potential" includes also satellites without a specific launch date announced and that could be launched if the delay issues is resolved and the queues carried out. In other words, it represents the number of the satellites launched in an ideal market with responsive launch platforms and without any kind of delay.

3.3.3 Outline of existing initiatives and projects

In context of the preliminary gathering of information, it is important to provide a focus on past, present and future projects to have a source of inspirations for design solutions.

This step consists of analysing existing projects and products that are associated with the operational area. It is important to gather both qualitative and numerical data. In the latter case, it is worth to record numerical values for determined technical specifications (as, in aeronautical and space products, mass, length and thrust).

This way permits to:

- Draw graphs in which some parameters are selected and insert regression lines or interpolations to predict the final quantities of the product (naturally approximate). This is a noticeable help to check methodology results.
- have a source of inspirations for design solutions. Moreover, to associate the characteristics of the products with the sales data helps to understand which features had a positive effect and which have been unsuccessful.

Data could be gathered from various type of publications: books, thesis, articles, databases, presentations, brochures, compendiums and reports. Clearly products that have gone through the entire life cycle are sources rich in useful information, but also initiatives that have not been developed beyond the conceptual design have to be taken into consideration.

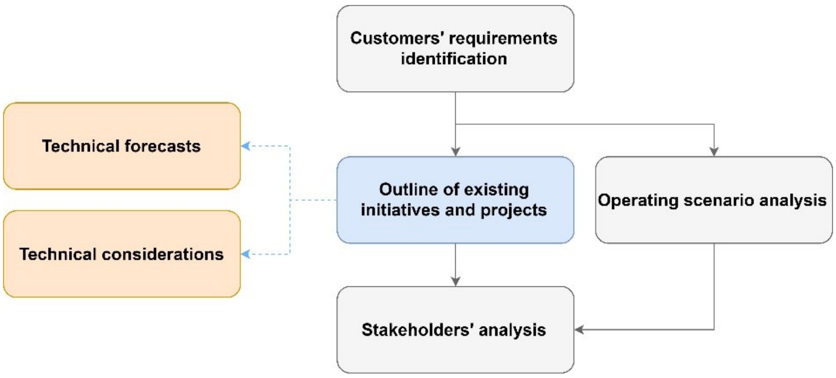


Figure 3.3.4 - Outline of existing initiatives and projects

With "technical forecasting" is intended the generation of approximated values of the product's technical specification of the product starting from the data of the previous products, as is explained in the example below.

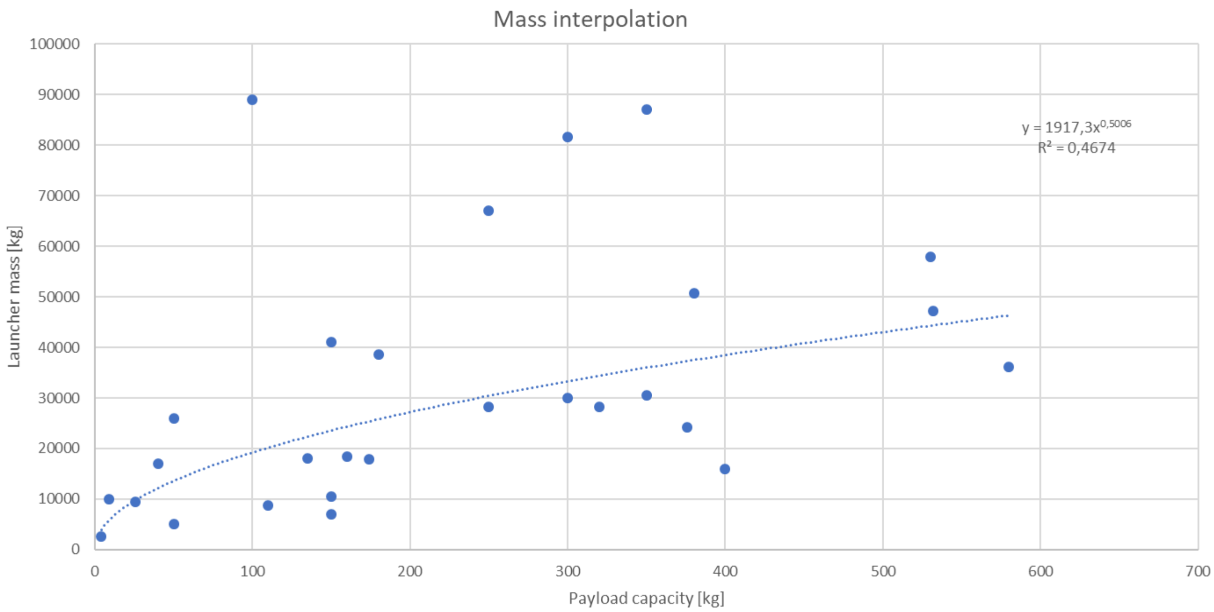


Figure 3.3.5 - Example of a technical forecast about launchers' mass for small satellites

Each point represents a launcher involved in an outline of launchers for small satellites. Their relevant specifications have been recorded into a table shown in the appendix B. An exponential interpolation of data was chosen, providing a trend lines which allows to predict the characteristics of a generic launcher by varying the payload capacity.

3.3.4 Operating scenario analysis

This step deals with the study and description of typical mission that the system will accomplish.
An exhaustive analysis of the operative environment is fundamental. An easy way to analyse is separate it into sub-environments, each focusing on a single aspect, such radiation, electromagnetic fields, thermal loads, vibrational and acceleration profiles or contaminations.
The possibility of using determined technology depends on these environments, as well as the presence of some constraints.
Typical outputs of this methodology step are: a preliminary mission profile, a detailed description of the external physical environments in which the mission will accomplished and environmental requirements.

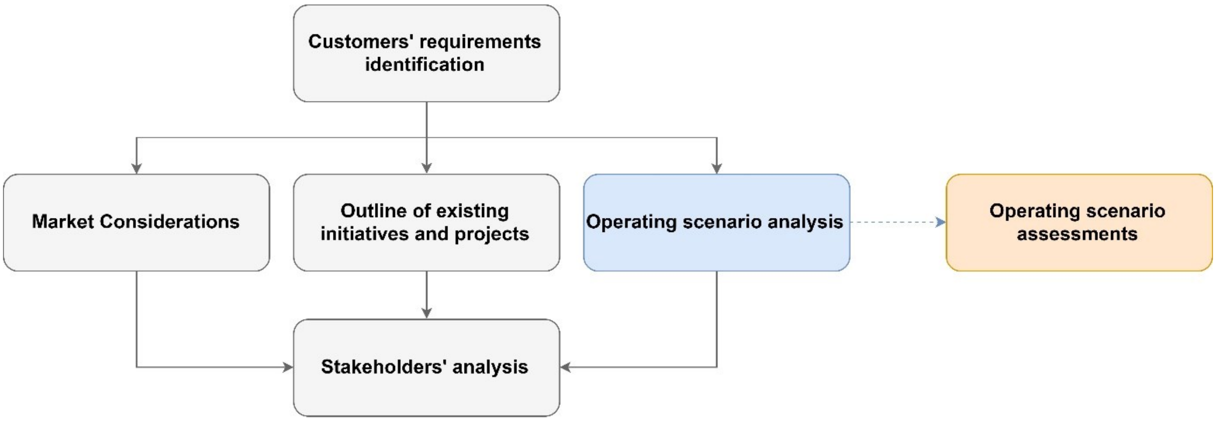


Figure 3.3.6 - Operating scenario analysis

Outputs depends on the specific study case descripted and they are grouped here under "Operating scenario assessments".

3.3.5 Stakeholders' analysis

The present analysis is composed of the following parts: Stakeholders identification, stakeholders' needs analysis e House of quality (HOQ) development. They are a great source of assessments that will be reflected in the whole project and will be fundamental elements to choose between the various alternatives. If, as in this case, the mission's aim is too general or not completely clarified by the customer, the analysis permits to identify those aspects it's better to focus on. In other cases, when the customers desires are clear from the beginning, it is useful to find **hidden objectives**, further desires and needs whose customers are not aware.
Here we will discuss the compromises that must be accepted as well as the characteristics of the products.
Thanks to brainstorming processes, the work team develops the sub-analyses presented below.

Reporting the definition in the reference [3.1], "A Stakeholder is a group or individual who is affected by or is in some way accountable for the outcome of an undertaking". In other words, Stakeholders are all those people or group of people that are involved or interested in the project. Their opinions, behavior or decisions can promote or hinder the satisfaction of mission objectives or design steps.
The first step in the design process is identifying of all those people called Stakeholders and to group them according to their respective roles (Stakeholder Identification).
Generally speaking, a single stakeholder can cover more than one role and affect the project positively or negatively, depending on its nature.
They are so conventionally subdivided into four main categories [3.4]:

- **Sponsors**: stakeholders that provide funds to support economically the design, the realization and the operation of the product. Commonly they are banks and venture capitalist and fix boundaries on schedule.
- **Operators**: stakeholders that operate, controlling, maintaining the product or show some types of industrial interests. Commonly they are engineering companies.
- **End-users**: stakeholders that use, usually free, product's capabilities or results. Usually they are scientists, engineers and common people.
- **Customers**: stakeholders that are directly interested in product's capabilities and are willing to pay for use them or receive some types of services.

Identifying stakeholders is an activity based by the experience of the designer and his work group, which should have a global view and knowledge of the mission and of the field of interest. It is important to understand some key points, as the operative environments, the mission phases, constraint sources and regulatory, public and industrial entities active in the business. At the conceptual analysis of the system, consulting market analysis and future forecast may help. The more the overview is clear, broad and detailed, the more the stakeholder analysis will be accurate. Clearly, this guideline is general and applies to all the following analyses.
An additional stakeholder classification can be made:

- **Promoters**: stakeholders that have high interest and power to help or to derail the activity; they must be fully engaged and keep satisfied.
- **Defenders**: stakeholders that have high interest but low influence; they have to be adequately informed about the activity process.
- **Latent**: stakeholders that have low interest but high power and influence if they become interested; they must be keep satisfied.
- **Apathetic**: low interest and low influence; they should be monitored but with minimum effort.

This classification is also important to understand the importance of each stakeholder and its capability of affect the project. It is possible to graphically dispose each stakeholder in a diagram called "Stakeholder's Map", as is shown in the "First Iteration" paragraph.

The second part of the Stakeholder Analysis consists of elaborating stakeholders' expressed and unexpressed needs.
It is important to distinguish between needs and desirables, due to two different meanings. The first are placed on a higher hierarchical level and satisfying them is essential, while satisfying the second is advisable but not necessary.

The House of Quality, so-called for its shape, is a graphical tool that belongs to the methodology of Quality Function Deployment (QFD) [3.6]. It is an approach to quality assurance that is used from the first phases of conceptual design, to be sure that the product's features will satisfy completely the customers' expectations. The information derived from QFD is organized in a certain number of matrices, the House of Quality, depending on the desired level of complexity. It comes from a series of surveys, assessments, discussions and technical analysis and forms a sort of guide to reach the customers' satisfaction with reference to technical specifications, goals and priorities. QFD is not limited to the House of Quality and other steps exist covering all product life cycle.
A HOQ is therefore built to:

- Have a project guideline to "orient product design toward the real exigencies of the end user" [3.6]. It helps to reach design objectives decreasing developing time and avoid re-design requests during the development process.
- Reduce the probability of neglecting an important aspect for the customer satisfaction.
- List that all the characteristics of the product from customers' needs. In other words, HOQ helps going from the "what" to the "how". Clearly, this is not an automatic process and there is not a

“magic” procedure that permits to realize this. The work group’s brainstorming effort is still required, but a graphical organization of the work certainly simplifies the process.

- Evaluate the qualitative features and requirements assigning quantitative values. It permits to rank these features to find the most important ones and so to concentrate resources in that direction. The highest scores deserve a more in-deep focus to provide additional efforts in those features that mainly affect the more important requirements.
- Explore all faces of quality, finding new unexpressed needs that could improving further the satisfaction of the customer
- Have a graphical output to improve communication through the work group

As we will see later in the case of study, it is possible to write the HOQ for each level of the product design, from the system-of-systems to basic equipment levels.

A structure representation of the house, as a union of matrices called “rooms” follows. Each room is marked by a number (according to the author) that represents the best sequence for completion. Then each room is descripted through a sort of guide [3.7] to build them.

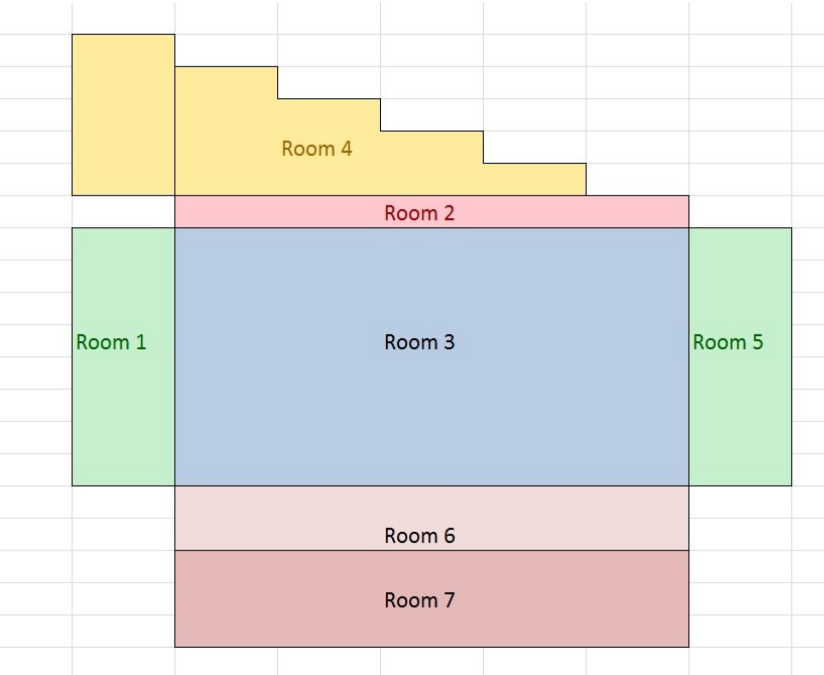


Figure 3.3.7 - General scheme of the House of Quality

- **Room 1 - Customers’ needs list**
  These columns contain the expressed and unexpressed customers’ desires and needs: in other words, the “what”.
  This list derives from the previous two points of the stakeholder analysis, therefore from meetings/interviews or market analysis and forecasts. It is very important recover all the information on every customer’s need. Tools commonly used for this purpose are: questionnaires, marketing analyses, competitor products analysis, interviews to customer samples, data from technical assistance area and from the complaints office.
  To not excessively complicate the matrix, it is better to not include more than 30 voices. If the list of needs is longer, it is suitable to group those requirements that are similar or that belong to the same category.
  Each voice should be weighted with values from 1 to 10 as level of importance, basing on the analyst's experience.

- **Room 2 – Technical specifications list**
  The row lists the features that the product may present to satisfy the customers’ needs of the room 1. Not all the technical specifications should to be included, but only those variables that affect

aspects interesting for the customers. As in the previous case, it is better to avoid a large number of technical specifications to not overly complicate the House of Quality. They can be derived from the market analysis, and in particular from the analysis of concurrent products.
It is worth that each voice, called "building block", is defined as quantitative as possible and related to an appropriate measuring unity. To complete the room, each voice can be matched with a + or – signs indicating the "direction" of improvement as its intensity increases:
+ → the more the intensity of the characteristic is increased, the higher the quality of the product and the more satisfied the need of the customer
- → the more the intensity of the characteristic is increased, the lower the quality of the product and the less satisfied the need of the customer

- **Room 3 – Relationship Matrix**
The two previous rooms are connected, showing how much the requirements affect each product feature. A value, with the related measuring unit, is assigned to each technical specification
A quantitative approach is used, assigning a value to each couple requirement/feature:
0 if the need does not affect the feature: there is not any correlation between the two voices;
3 if the need moderately affects the feature;
9 if the need strongly affects the feature;
-3 if the need represents a moderate constraint against the product design;
-9 if the need represents a strong constraint against the product design;
Clearly, +/- signs of the room 2 and values signs of the room 3 represent the same information and so must be coherent.
Values should be derived from meetings and discussion of the work group and from the experience of the analysts.
It is important that at least the half of the matrix is filled with 0 values. If not, it is probable that weak or negligible correlations were taken into account.
Room 3 comprises also a design specification's ranking raw and a customer's needs ranking column.

- **Room 4 – Relations among technical specifications**
In this room, technical characteristics have been related each other. It is indeed possible that the improvement of a characteristic has positive or negative effects on another one. In other words, the roof highlights possible conflicts between the elements of the specifications list, to detect the need for compromises and meet the customer's global expectations.

- **Room 5 – Customer's Perceptions**
This room provides a survey on customer's reactions to existing products and comprises different columns. A first part of columns compares the new product with the precursor model and concurrent ones: for each requirement is assigned a value which means the degree of satisfaction provided by each product. This value is fixed conventionally between 1 and 5. The second part is represented by following columns:
Improvement ratio: the improvement between the precursor model and the current is highlighted for each requirement dividing values assigned in the first part.
Points of strength: this column establishes points of strength of the new product. An important need that can be satisfied is a sure point of strength and a valued 1,5 is conventionally assigned. Those needs that could become points of strength are evaluated 1,2, while the others are weighted 1.
Absolute weight: this column has the purpose of quantifying the importance of each need during development process.

$$Absolute\ weight\ = weight\ factor(room\ 1) \cdot improvement\ ratio \cdot point\ of\ strength$$

Relative weight: in this column results of the previous one are translated into percentages.

$$Relative\ weight = \frac{Absolute\ weigth \cdot 100}{\sum absolute\ weights}$$

It represents a sort of guide during the assignment of development resources based on the customer's vision: it is possible for example to allocate resources using those percentages. All independent variables can be obtained from market analysis and interviews with customers.

- **Room 6 – Importance of technical specifications**
  Each technical specification is ranked relatively to the customer's perception of quality and so to the weight factors set in room 1. For each column, the priority degree of the technical specification is derived from the linear combination between the column of the relationship matrix and the column of the weight factors. Then Design specification priority can be normalized in percentages.
  Moreover, it is possible to introduce a score from 1 to 5 for the technical difficulty in relating or improving each technical feature.

- **Room 7 – Technical analysis**
  This matrix deals with the classification of the concurrent products and their technical features comparing to the new product. It should be completed by the technical work group basing on the concurrent market analysis. A value conventionally between 1 and 5 is assigned to each product for each technical feature.
  This room has the purpose of checking the goodness of the previous work. If evaluations between room 5 and the present are excessively different, then one of the following situations may be occurred:
  1. Customer's perceptions have not been interpreted correctly or those provided are false.
  2. Relations established in room 3 are wrong or inconsistent and negligible
  3. The technical evaluation accomplished in the present room is incorrect

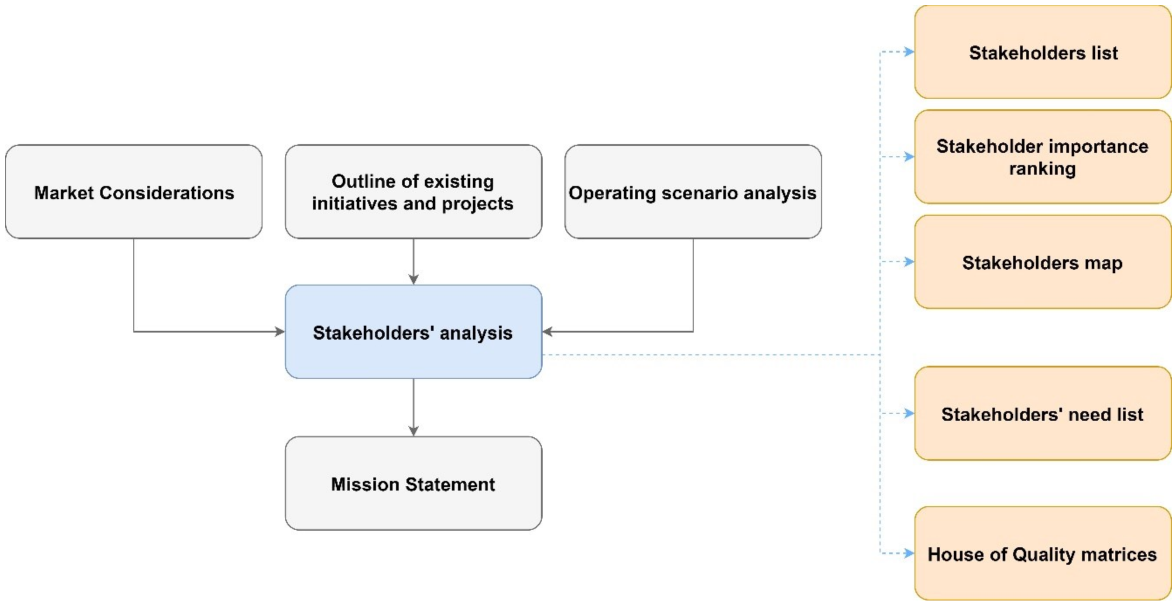


Figure 3.3.8 - Stakeholders' analysis
Stakeholders' analysis represents the first true step of the designer towards the design synthesis.

3.3.6 Mission statement analysis

The list of customers' requirements, the mission scenario and the stakeholder analysis can be elaborated, resumed and stated into so called "mission statement". It is a brief and unequivocal statement that describes for which purposes the mission is required and what the system shall accomplish [3.13].

To properly conduct this analysis, it is worth answering to these questions. Answers are elaborated into the mission statement.

- What is the main problem?
- How the problem can be solved?
- How are the end users?
- Which are the main stakeholders' needs?
- Are there other main goals required by the top-level scenario?
- Are there other significant facts to consider?

It is important to note that at this point it was not still decided what features the system should have and how it shall be composed of. In fact, as the author recommends, it is worth concentrating, at the moment, only on the aim of the mission to not exclude innovative configurations or good ideas due to own preconception. It is also recommended to develop this first phase of system design with a work group, to develop objective considerations and so enhance the methodology potential.
This first phase, that is the basis of the entire design process, shall to be as more clear and unambiguous as possible, to avoid misunderstandings that could potentially affect the entire project [3.1].

After a deep comprehension and formalization of the statement, a top-level list of mission objectives can be generated. A mission objective is a broad goal that should be accomplished by the system to satisfy customers' needs. There are two types of mission objectives:

- primary objectives: they derive from the mission statement and deals with the accomplishment of the mission and its technical and scientific purposes. They are directly connected with the customers' requirements and justify the existence of the mission.
- secondary objectives: they derive from the stakeholder's needs analysis and are related to politics, organizational, industrial and economical topics, the so-called "hidden agenda" of the mission.

Mission objectives shall not be modified during the iterative design process because they are the mission foundation and justify its existence.

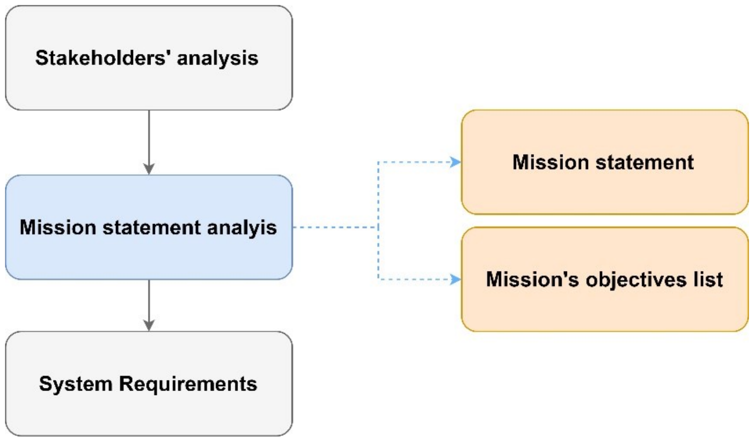


Figure 3.3.9 - Mission Statement Analysis logical flow chart

3.3.7 Mission and system requirements [3.15] [3.1]

This subsection deals with the activity of "requirements elicitation" or "requirements gathering". Requirements are short phrases that specifies in a detailed and quantitative way what characteristics and properties a system shall have to do something or to satisfy a determined need. Requirements may describe a very general property or purpose of the entire system-of-systems or a specific attribute of an equipment. Moreover, each type of constraint can be written as requirements.
At this point, the designer formalizes all considerations resulting from previous step and iterations into those quantitative "shall" statements called requirements.
Many categories of requirements exist and there is not a general rule to derive them. At the first iteration, a concise list of requirements can be gathered. Only mission requirements, that represents among categories a unique list, can be completely defined, deriving from the analysis accomplished in the last step.

- Mission requirements: deriving from mission objectives, they are the highest-level requirements that will be generated by applying the methodology. They do not refer directly on a property of the system but on what and how the system shall accomplish in general. Mission requirements are a special category, logically different from those followers, that could be indicated as system requirements.
- Programmatic requirements: they are commonly given by sponsors and stakeholders and refer to schedules, funding, costs, legal constraints and other topics that do not directly deal with the technical issue of the system's design. Programmatic requirements are generated from project managing activities, from interaction with stakeholders and through the stakeholders' analysis.
- Configurational requirements: they describe which are the definitive configurations and derive from trade-off processes. They refer to global appearance of the system and its subsystems, resulting from structural or morphological characteristics and design choices.
- Environmental requirements: they are related to both internal (into the boundaries of the system) and external environments, especially they establish which feature the product shall present to endure expected conditions. They may include, citing from [3.1]: "acceleration, vibration, shock, static loads, acoustic, thermal, contamination, crew-induced loads, total dose radiation/radiation effects, Single-Event Effects (SEEs), surface and internal charging, orbital debris, atmospheric (atomic oxygen) control and quality, attitude control system disturbance (atmospheric drag, gravity gradient, and solar pressure), magnetic, pressure gradient during launch, microbial growth, and radio frequency exposure on the ground and on orbit." They derive from the operative scenario analysis and from the ConOps analysis, in which the environments are identified and analysed. Also, product life-cycle shall to have been analysed, in order to consider existing environments for instance during test or stowage.
- Functional requirements: they establish what functions shall to be carried out by the product at every design level. They derive directly from the functional tree, that in turn derives from primary mission objectives, as it will be discussed further on.
- Interface requirements: they refer to internal and external interfaces. Internal interfaces link, physically or functionally, subsystems and components of the product. They derive from functional/physical block diagrams that identify what connections exist between product's elements. Possible common interfaces are: mechanical, electrical, thermal, optical, data, functional and humans. External ones, on the other hand, connect the product with outer entities. They derive of course from functional/physical block diagrams, but also from analysis of the entire product life-cycle phases: the product shall not only present external interfaces for users, but also for instance for maintainers, manufacturers, testing and transporting equipment.
- Logistic Support requirements: they are related to all equipment, services and facilities that are required for the development of the system and the conduction of the mission in the best way. Generally speaking, they deal with, not limiting to, the supply chain, testing equipment, transport strategies and facilities management. Logistic support requirements are strictly related to the following category and derive from ConOps analysis.

- Operational requirements: they refer to all operational phases, including tests, integrations and maintenance, and related activities. They include requirements about timelines, operative modes, processes and actions that shall be taken to maximize probabilities of having desired results They derive from iterations of the operating scenario analysis and from the ConOps analysis.
- Product Assurance and Safety requirements: this category comprise those requirements written to lead the success of the product or mission through the study of Product Assurance and Safety (disciplines defined in the Introduction). Requirements are so related to (non-exhaustive list) quality, technologies, certifications, processes, testing, risk, reliability, effectiveness, manufacturing and maintainability. Subtype reliability requirements and safety requirements are particularly important because affects severely product's cost-effectiveness. Event sequence diagrams, FMECA, Hazard analysis, human factor analysis are instances of activities useful to properly generate them.
  A deterministic safety requirement provides a threshold or a range of values for a determined product's characteristic: if the requirement is verified, the product is adequately safe, relatively to the specific characteristic. An example could be: "electrical voltage shall not overcome TBD volts between plates of capacitor". Redundancy is taken into consideration, with requirements that compel the system to operate in a safe status in presence of one or more failures, even with reduced capabilities. A risk-informed safety requirement is related to uncertainness of adverse event and with the estimated probability that such event may occur. For instance, once the probability for a catastrophic failure (such as the vehicle loss) to happen has been calculated with the proper confidence level, a value is matched with this probability and with the severity of the failure. The related risk-informed requirement states that during all life-cycle phases that probability value shall to stay under a safety threshold.
- Performance requirements: they are an evolution of the functional requirements, that are quantified by the system sizing process. Assigning numerical values that assume how a function shall be accomplished establishes "a performance" that the product if required to satisfy. It is possible to set a threshold, for example for such functions that require a minimum value to be carried out, or a range, in which the value shall be comprised into.
  It is important to note that, as it will be repeated along this work, such values shall not to be exaggerated resulting into a too stringent requirements. In fact, if requirement imposes a higher performance than necessary, it is very likely that it is adding improper costs to the product without increasing efficiency and possibly excluding optimal solution from the trade space. To check that each functional requirement has been translated into a performance requirement, answering the following questions can help [3.1]: how often, how well and how long the function shall to be carried out? It is possible to identify some accuracy or tolerance value for quantities involved? What are values that are imposed by environmental conditions or general stresses? Finally, if an output is required, define its quality and quantity. In addition to documenting from which functional requirement a performance requirement derives, it is important also to explain how the threshold/range have been set, for a better and faster modification in case of problems.
- Physical requirements: they are those requirements that express a physical characteristic of the product, such as length or mass. They are generated during the system sizing phase.

A separate category is represented by customers' requirements: they are requirements that are directly provided by the Product/Mission Authority and could be of any exposed type, from mission to physical at any level, from SOS to components. They represent under formalized statement what are customers' need and what customers expect from the design activity.
During the first iteration, only few requirements could probably be derived. The list will be extended, improved and refined iteration by iteration.

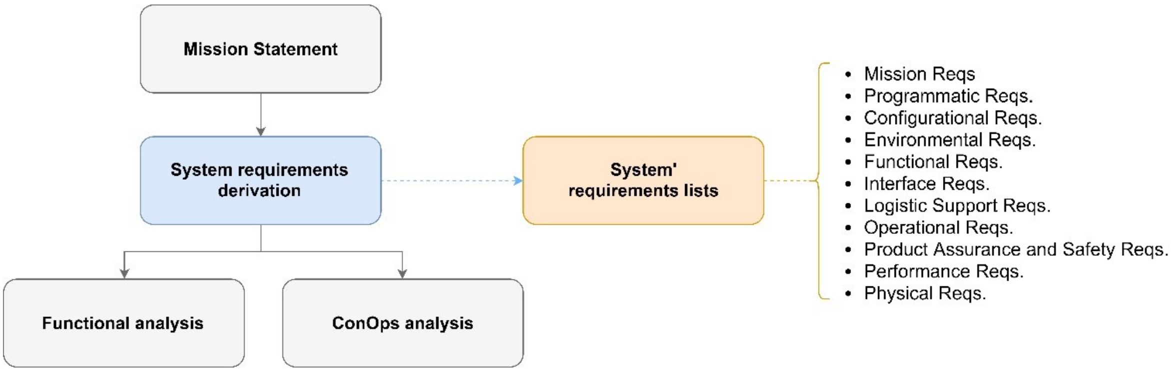


Figure 3.3.10 - Mission Requirements' Analysis logic flow chart

Requirements derivation is a complementary to the other analyses, in particular to functional analysis. As we will see, functional analysis establishes which elements will comprise the systems; on the other hand, requirements specify their characteristics and the technical specifications.

Writing requirements is fundamental during the system sizing step, where they are allocated to subsystems, components, software, people and processes [3.1]. Actually, it is necessary also before, because stakeholders that have to be involved into the design process, can carefully review the list, determining if the product will satisfy their desires or not. This check activity is very important because permits to save time and money: it is sufficient to think about an inconsistence or a misunderstanding that is neglected at early phases. It could force during latest phases or in the worst case when the product is already on the market, to a redesign, a remanufacture or a retirement with a large waste of resources. In the case the requirements' list is consistent with stakeholders' expectations, it is easier to come to a more accurate estimation of costs [3.1] and a more efficient validation and verification phases. Although it is so better making the better choices at top level, setting requirements that have a strong impact on costs and schedules, the list is not carved into stone and it will be modified iteratively during design to have a consistent product. Moreover, it could be cases that require modifies when the product is already commercialized: it is the case for example of enhancement or new versions of the product, particularly evident in software and electronics industries.

It is also important to follow these rules to be sure to writing a good requirement list:

1. **Each requirement must be necessary**: superfluous requirements and redundancy have to be avoided. The writer should ask for each bullet: "There are any consequences if the requirement is canceled?"
   If the answer is no, the requirement is not necessary and should be removed.
2. **Each requirement must be verifiable**: it should be as quantitative as possible or be something that can be quantified, examined or analyzed. Subjective words, such as "useful", "proper", "fast" or "high" should to be avoided. This is a difference between requirements and objectives. The question to answer is "How this requirement is verifiable?"
   If the writer cannot find an answer, probably, the requirement is subjective and should be removed.
3. **Each requirement must be clear**: it should contain one unambiguous topic and be written with a simple and concise style.
4. **Each requirement must be feasible**: it should be achievable under multiple views, for example technology, budget and schedule. To determine feasibility, technological researches and internal reports and studies could be the right tools.
5. **Each requirement must not be confused with its implementation**: the requirement should describe what is necessary, not the solution that is required to satisfy it. For example, the sentence "The spacecraft shall have a cabin" is not a requirement, but it is a possible implementation of "The spacecraft shall be designed for transportation of TBD passengers", that is a requirement. Maybe, an innovative solution can provide another implementation of that requirement and could be accidentally excluded if the author mixes the two types of sentences.

3.3.8 Functional analysis [3.9]

Functional Analysis is a fundamental tool to explore all elements that will constitute the product and to derive the functional architecture of the system. It is a conceptual tool that permits to explore what the system shall accomplish, and which actions or features should to be guaranteed during operations.
More specifically, this sub-procedure permits:

- to obtain the product's functional requirements;
- to relate each function to a physical component;
- to find all the necessary components;
- to guarantee the absence of unnecessary components;
- to obtain some interface and configuration requirements.

The functional analysis can be applied to each product level, from the subsystem level to the system-of-system level but is at the latter that it is especially useful because it permits to explore a wide range of viable solutions.
The first main outputs of the Functional Analysis are the functional tree and the product tree. Then the analysis continues investigating how the components of the product tree are connected each other, developing the functional block diagram and the physical block diagrams.

Functional Tree is a diagram that decomposes a function into simpler ones. This simplification process produces more branches of functions organized into successive levels, depending on the number of decompositions. Eventually the last level contains all those basic functions that cannot be simplified further according to the level of detail of the analysis. At the maximum expansion of the functional tree, each bottom function is directly related to the equipment that performs it.
This procedure is explained with the figure 3 as example.

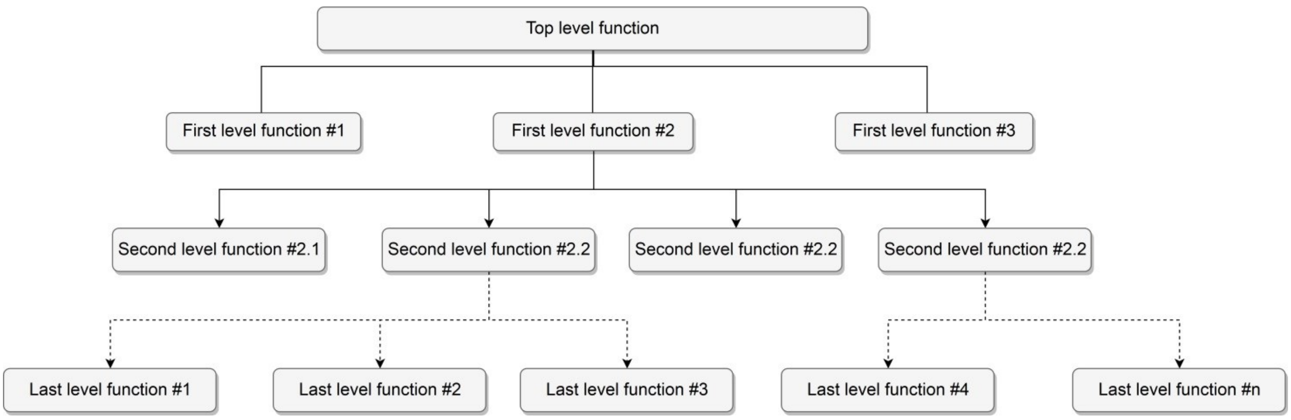


Figure 3.3.11 - Structure of a generic functional tree
Each row represents a level. Bottom functions can belong to different decomposition levels.
Finally, each basic function represents also a functional requirement.

The starting point is the so-called top-level functions that results directly from the mission objectives and are split into bottom functions until each sub-function is no further "divisible". In the next chapter, the analysis will be conducted from the system-of-system level: so, the top-level function will be the function accomplished by the entire SOS itself.
From these bottom level functions, functional requirements are derived and checked. If the tree is well-done and complete, all functional requirements are naturally found. To achieve this result, three operative rules should to be considered:

1. each function should to be composed of a verb and a subject matter;

2. each function should to be as general as possible (naturally, as new levels are produced, functions become more detailed). This rule is fundamental in all the conceptual design process, to help the brainchild of alternative and innovative solutions. It is possible that at a certain level, a function can be split in two or more separate ways, reflecting the existence of two or more alternatives in the system design. Moreover, two different people can produce different trees in according to their vision of the problem. In these cases, all the trees should be conserved and submitted to a later trade-off process.
3. going from higher level functions to lowers, the analyst should to ask himself how that function can be realized. If the splitting is properly done, going the opposite direction from bottom to top, the question that groups lower functions into a higher is "Why?"

The elements, also called "building blocks" [3.4], which perform the bottom functions of the functional tree, can be derived. Formally, for each basic function it is sufficient to answer the question:

"Which component is able to perform this function?"

In the case more than one product fulfills a basic function, a trade-off analysis is fundamental to choose the best between the alternatives. It the ConOps chapter how to perform a trade-off analysis will be discuss. Innovation should be introduced here, thanks to the following questions [3.2]:
1. Which innovative technologies can be introduced at this level (segment, system, subsystem, etc.)? It is very risky to introduce innovations that impact on previous levels, because at each level the flexibility of the project decreases. If an innovation that impacts on the previous levels is introduced, it is better to restart all the methodology to the first level iteration, thus placing correct requisites and constraints.
2. Which benefits, and drawbacks, are involved by the implementation of such innovation? It really determines a usefulness over competitors and existing products? If the answer is "no", it could be not convenient to introduce an innovation that does not involve an effective commercial advantage, unless for the technological demonstrator cases.
3. How ensure that the innovative technology does not constitute a possible element of failure for the entire product?

At least in term of conceptual design, it is worth noting that it is not required to identify commercial products or specific technology, but the generic components. For example, for the basic function "To display information to the crew members" the related product could be "Display System". No reference to the technology or the quantity has been done, such as cathode ray tube or liquid crystal monitors. Moreover, thinking immediately to a monitor could be limiting: a tablet or an electromechanical indicator could accomplish the function, depending on customer's requirements, stakeholder needs, and drivers chosen for the trade-off process. This is a specific task of more advanced phases of the process, such as Concept of Operation and system sizing, and in particular of preliminary and detailed design. The first derived product list has not to be detailed, but it will be refined subsequently by iterations.
The general rule is to try to keep the analysis as general as possible, consistently with the degree of progress of the project. However, the function could be very specific, or a particular equipment could be explicitly requested by the client. For example, for the specific function "to display information without requiring users to look away from their usual viewpoints" the related product will be necessarily "Head-up display", because is the only equipment that can provide augmented reality without forcing the users' gaze to dwell on cabin's instruments.
To build a product list in the correct way, the work group should have a panoramic state of the art of modern technologies and systems, to assign to each function the right component. Each function should be accomplished by an only device, while each device can perform more than one function.

Bottom functions are so fundamentals to derive all the system's components, in addition to functional requirements.
Eventually the two vectors, basic functions and building blocks, are matched by the **Function/Product Matrix**, where it may also result that two or more elements can fulfill a task. Rows show functions of the

selected level of the functional tree, while columns represent which elements are able to accomplish them with cross. It is therefore possible to create a matrix for each level of the functional analysis, obtaining different levels of building blocks. Clearly, at this point of the process, it is impossible to draw a table for all the levels, because a large number of features have not been decided yet (for example the staging strategy). The iterative nature of the conceptual design process is visible: repeating the methodology more than one time, it is possible to complete all the analysis presented here and come to a consistent design. It is also possible to compile variants of this matrix, such as the Costs/functions matrix [3.9], which has building blocks' costs instead simple building blocks. Each function is so related the cost of the element that is required to accomplish it. Summarizing costs along the Product Tree, the total cost of the system results.
Grouping each building block in an analogous way to the Functional Tree, it is possible to derive the **Product Tree**, in which the entire system is decomposed into subsystems and eventually into basic components. Unlike the product tree, the construction of the functional tree follows the inverse process: bottom-up instead of top-down.

Connections between building blocks can be represented complementary in the **Functional Block Diagrams** and in the **Physical Block Diagrams** by point-to-point links. The first deals with relations from the functional point of view (for instance, in the case two components exchange data without necessarily having a physical connection), while the second highlights how building blocks are physically connected each other, usually providing information about the type of connection (for example if mechanical or electrical) and its direction. From the latter diagram, interface requirements can so be derived. Finally, relations represented can be summed up in the **Connection Matrix:** both rows and columns have the same building blocks and in case two elements interacts, the related box is crossed.
The last four outputs of the Functional Analysis constitute the so called Functional Architecture of the system.

With all information generated from previous analysis, we are now able to generate some different descriptions of the system from the operative view, called *Concepts of Operations* or *ConOps.* They are a conceptual level description of how the system will operate, how it provides its functionalities and how it will interface with the other mission elements.

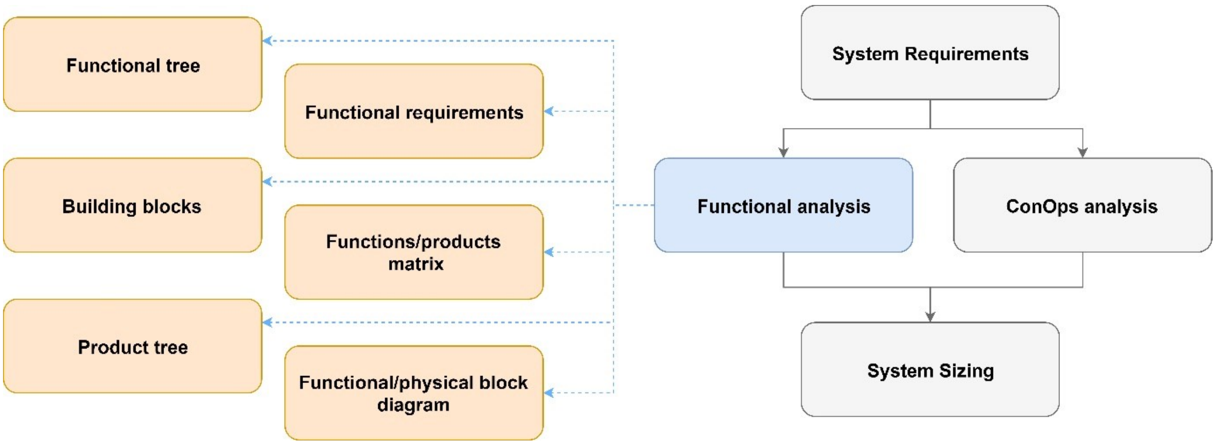


Figure 3.3.12 - Functional analysis logical flow chart
Functional analysis and ConOps analysis (descripted in the following paragraph) have been placed on the same line because the case determines which needs to be performed before.
The derivation of the basic components of the system (Building Blocks' List) is fundamental to make a first attempt to sizing subsystems. In particular, it is possible to come to a preliminary definition of system budgets (such as mass budget or power budget). It is especially useful during the feasibility analysis, because it permits to understand the order of magnitude of the physical quantities involved and so assess whether to continue or resize mission objectives, probably lowering the quality perceived by the customer. However, the sizing of subsystems can be carried out only once the Concept of Operations Analysis is performed and once the baseline is selected.

3.3.9 Concept of Operations analysis

Once all the previous analyses have been performed, designers elaborate different ideas during a brainstorming activity to implement them in a system capable of achieving mission primary objectives. All the following topics, relative to the entire life cycle of the product, should be covered by the ConOps Definition process through iterations, because not all can be developed at the beginning:

- mission architecture: staging strategies, mission phases, phases' timelines, FFBD. Configuration requirements
- operation scenarios
- modes of operation
- communications architecture
- data architecture
- operational facilities
- logistic support
- critical events management

Mission phases are subdivisions of the entire temporal evolution of the mission and each distinguish from others depending on which functions are accomplished, which state of the system is available for operations and which are the environment where operations are executed.
Operating modes (or modes of operations or "states") of the system are sets of functions that the system can accomplish during a determined moment of the mission, determining which subsystem are active or inactive along time. It is an essential result for evaluating budgets during systems sizing, especially thermal and power ones.

After some iterations depending on the study case, the designer develops several alternatives, called ConOps, which descript different versions of the products from the operative point of view. Each ConOps must satisfy both the customers' requirements and the mission and system requirements derived from the Mission Objectives Analysis and the Functional Analysis.
At this point a selection between all different concepts of operation must be performed. This activity is called **trade-off** process and it is based on the definition of mission drivers or **figures of merit**. The resulting architecture will be those that offers the better combination of the figures of merit. The weighting process can be carried out in a large number of ways.
The best ConOps is called **baseline** and it is the one that will be further developed. The selection can be carried out with the help of the House of Quality analysis and its rankings. It is a good rule to involve stakeholders in the choice of the baseline, because new needs can be generated further raising the quality of the product. If needs or weights are modified, the entire methodology must be obviously repeated in a new iteration step.
During ConOps analysis, a high number of considerations are produced, and they will be quantified into requirements.

A fundamental element that represent a point of contact between the functional analysis and the ConOps analysis, usually applied to the conceptual design of phase 0/A, is the Functional Flow Block Diagram (FFBD). Deriving from the functional tree, it permits to define all the different functions and operations that the system should accomplish as blocks and to put them in the correct order of time, from the start point of the mission to the end in a logical sequence, underlining transitions between different modes of operations.
It is possible, according to "what" must be accomplished during the mission, to draw multiple path indicating that more than one function is performed at the same time or that only one are accomplished between more possible choices. Moreover, it is allowed to add loops, to perform a function until a condition occurs. Like all previous block diagrams, it can be developed in series of levels identified by functional decomposition in an analogous way to functional and product tree. FFBDs do not give

information about block's durations, it expresses only "what" must happen not "how" (function-oriented approach).
The diagram leads to the definition of the sequence of operations.

The state diagram represents the operating modes of the product, and which actions or conditions determine the change from the current state to another. In response to one or more events, new functions are unlocked, and others possibly prevented. The state diagram (or state transition diagram) is a graphical tool that is useful for understanding the timing complex relationships between the possible state of the system. In particular, all the system states are represented with ovals balloons that are logically connected by arcs. An arc symbolizes the event that is responsible for the system change, as well as the action or the output taken by the system in response to the event. Evidently, there are events that influence the system but do not produce a state change; this type of arc is a self-loop. A state diagram is often analysed together with timing diagrams to have a more complete picture of the system and a more detailed flow of the system in response to varying inputs. This allows detailed requirements to be developed and verified.
A distinction has been made between "off-nominal" states and "nominal" states:

- off-nominal: state in which the system doesn't concur to the success of the mission
- nominal: state in which the system acts on the external environment and concurs to the success of the mission.

Each ConOps may be properly accompanied by drawn sketches. A sketch is a hand-drawn illustration, usually poorly detailed to save time, which represents the product concept to give an idea of the appearance of an object, or of its functioning.
Its benefits are:

- to illustrate to others the general features of the product
- to visualize the system to derive innovative ideas
- to verify if considerations of previous analysis are correct
- to derive possible new requirements and check those already written
- help the trade-off process

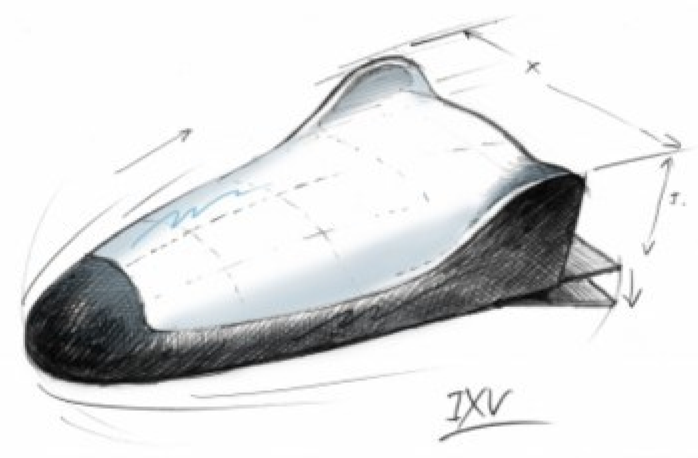


Figure 3.3.13 – A sketch of IXV spacecraft (Source: nasaspaceflight.com)
In addition to illustrating the vehicle, the representation can show some functional aspects (such as the motion range of the body flaps in this case) and operative ones (the lines suggesting the high typical speeds of atmospheric reentry). A sketch could not be the illustration of the final concept, in fact the final shape of IXV is slightly different (it has not the two upper aerodynamics fins).

The methodology descripted above is general, but other analyses could be required depending on the case's nature and on the project phase advancement. Each analysis is a source of new requirements and constraints.

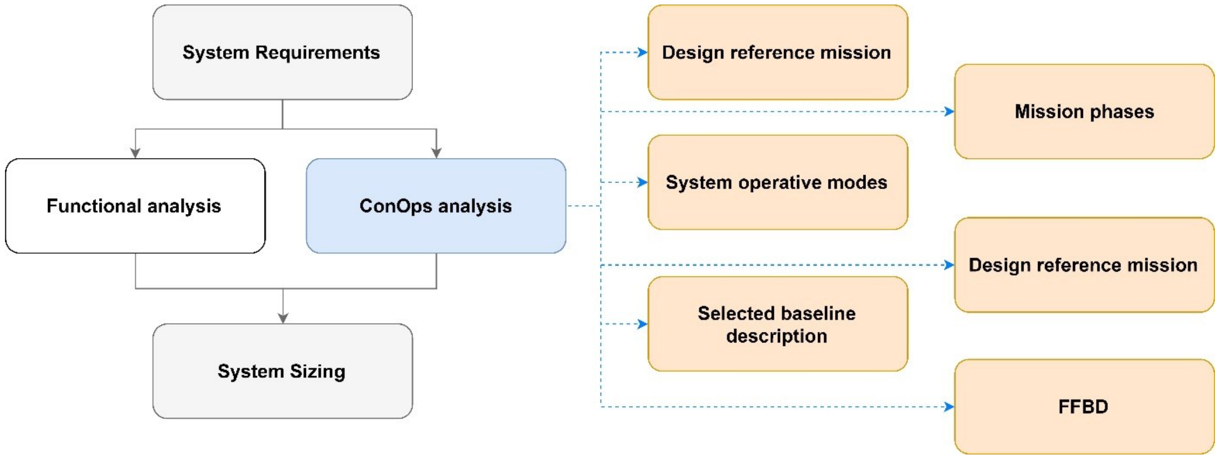


Figure 3.3.14 - ConOps analysis logical flow chart

It is important to notice that ConOps Analysis has a deep impact on system requirements.

3.3.10 System sizing

Together with the previous two steps, the current represents the core of the methodology.

Once the baseline was selected among alternatives, physical and geometrical parameters of the system's elements must be identified or calculated. These quantities must guarantee the full functionality and the performance according to requirements and constraints as well as reliability and safety during the entire operating life.

It is not possible to establish a general way to accomplish this task, because it varies for each element of all the design levels. A high number of documents (a few are suggested as reference) explain how to size a particular system.

Functional requirements can be transformed into performance requirements once they are quantified during sizing.

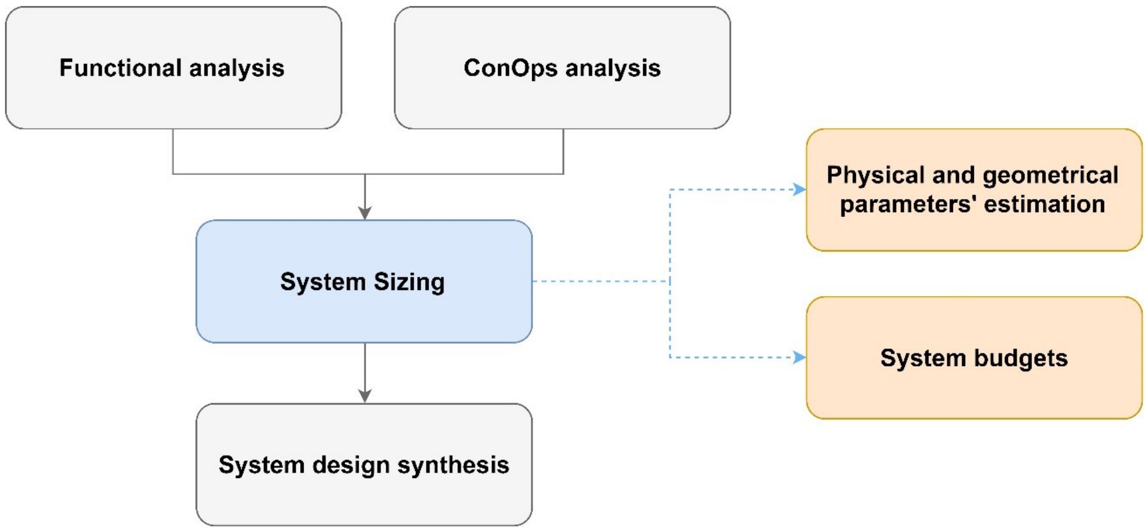


Figure 3.3.15 - Sizing analysis logical flow chart

3.3.11 System's design synthesis [3.8]

The synthesis is the array of documents, mainly technical reports, that describes the product and that are the results of the all previous steps. It is the final output of methodology that is obtained at the last iteration. Practically, to derive a system design synthesis, it will almost always be necessary to perform several iterations of the methodology.

Once final configuration has been selected among the array of sketches and geometrical quantities identified, it is digitized and represented as a 3D model by a **CAD** tool. The acronym means Computer-Aided Design and refers to the use of the computer graphics to support the design process. The first step in the creation of the CAD model is the definition of all physical characteristics of the components to be included such as structural components, preliminarily sketched. This will include a basic draft of the vehicle shape necessary to progress with the early phase of design. As long as the sizing and definition of components was becoming more precise and justified by theoretical calculations, the sketch model was adjusted accordingly and translated into a SolidWorks CAD part, until the final assembly.

This technology permits:

- To easily manage drawing files and share them between multiple designers.
- To quickly create exploded views, cross-sections and technical drawings (with dimensions), useful for the production phase
- To quickly modify some aspect of the model, to correct it or to create an updated version or a derived product.
- To add specific capabilities by integration of portions of source code called "macro". Commonly this functionality is used to automate repetitive drawing activities.
- To use the 3D model for further studies, such as dynamic, thermal or structural analysis. Usually CAD software tools support the integration with own or third parties' extensions to implement these capabilities. It is also possible to export drawing information to use it with other software.
- To collect recurrent components into special archives, called libraries, to re-use them in newer projects. It can significantly reduce development time.

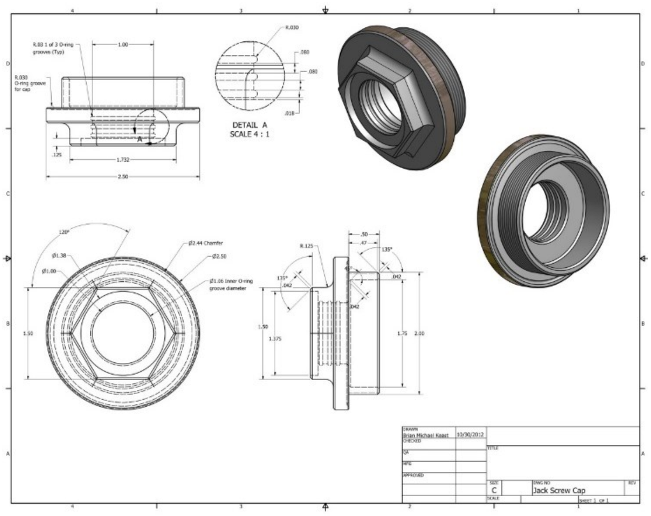


Figure 3.3.16 - Example of CAD drawing: screw cap with technical drawings and dimensions (Courtesy: http://www.idrawdreamsforinventors.com/portfolio-items/technical-drawings/)

In this work, the design synthesis is certainly represented by CAD drawings, but not exclusively. The traceability of analyses and design choices are recorded formally into a Rhapsody file, and requirements have been inserted into a DOORS database. The design synthesis is so not based on documents, but is a computer model, based on software that are presented in the next paragraph. In particular, all information of the model can be group into a unique model by one software, Simulink.

3.4 OBJECT MANAGEMENT GROUP SYSTEMS MODELLING LANGUAGE (OMG SYSML) APPLICATION [3.5][3.10][3.11]

All the methodology steps exposed up to here can be developed on simple computer software such as word and diagram software or even on paper. This has been called "Document Based System Engineering approach" and it is actually the first attempted strategy to performing System Engineering. Considering the high complexity of modern space missions, drawbacks of such an approach are clear:

- Large projects are difficult to manage, especially when a high number of methodology iterations are required;
- Review operations of results are difficult and require a considerable amount of time;
- If the project is based on paper it is difficult to exchange information among all the actors involved into design process

A solution came from advances in digital tools and Information Technology in general. The project can be now based on digital models stored by a data management system and easily shareable among the development members thanks to computer networks.
Information provided by the methodology application can be codified into a model using the SysML language. Doing this, anyone who knows the language can understand the model, which elements it is composed of and which are relations among them, i.e. how the product or the mission works.

Models are easily modifiable, and changes are simply traceable. Traceability is a central topic of this type of modelling, because permits to easily understand from a design choice comes and because it has been pursued, accelerating the verification and validation phases.
According to the NASA System Engineering Handbook [3.1], traceability is "a discernible association between two or more logical entities such as requirements, system elements, verifications, or tasks".
The Institute of Electrical and Electronic Engineers gives this alternative and complementary definition: "The identification and documentation of derivation paths (upward) and allocation or flow down paths (downward) of work products in the work product hierarchy" [IEEE Guide for Information Technology—System Definition—Concept of Operations (ConOps) Document].
With these two definition it is now quite easy to explain what the requirements' traceability is. It is an aspect of the requirements management and focuses on the history of each system requirement, in both forward and backward direction (bidirectional traceability). It permits to understand how high-level requirements are decomposed into low-level requirements and, on the other hand, from where low-level requirements derive. Taken a requirement, distinct kinds of traceability are possible: to/from external sources, to/from other requirements (both higher and lower), to/from design elements, to/from implementations, to/from tests.

Three software has been used to model the design process:

- **DOORS:** it is a database that deals with the managing of requirements lists. The author entered them manually, but it is possible to import from Microsoft Office Tools, ASCII texts, RTF files and FrameMaker. In the software, requirements' lists are called "modules". Each requirement is associated to an ID code that unidirectionally identifies it. It is also usefully to add hierarchical connections between requirements. Moreover, this function can be used to create titles and so to organize them into the categories listed in the paragraph of system requirements. The management strategy adopted by the author consists of creating four modules, one for each design module: mission level, segment level, system level, subsystem level (the equipment level has not been created because the focus of this thesis is only on conceptual design).
  The traceability of the requirements is met thanks to the so-called internal links, indicated by orange triangles pointing to the left. External links that can be used to connect requirements to objects out DOORS's boundaries, such as web sites or documents. Finally, collaboration requirements are useful to link DOORS's objects to external software applications.

- **RHAPSODY:** it is possible to create graphical diagrams and correlate elements each other. Elements could be stakeholders, objectives, functions or products.

- **SIMSCAPE:** this software permits to integrate information coming from DOORS and RHAPSODY into a CAD model drawn with SolidWorks.

3.5 REFERENCES

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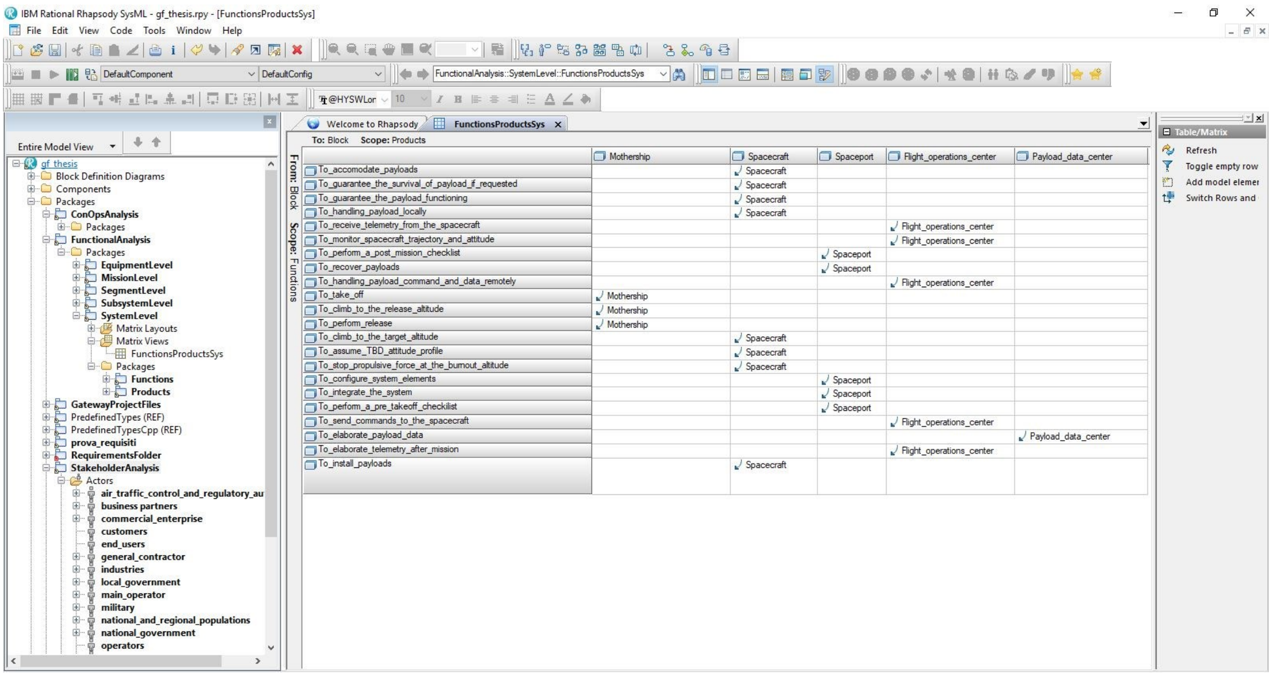
Chapter 4:

Application to Preliminary design of a suborbital mission accomplished by a reusable vehicle (mission, segment and system level analysis)



[Rhapsody interface, with the model of the design process and methodology results represented via SysML]

4.1 INTRODUCTION

In this chapter, a conceptual design process is performed and first iterations of the methodology was applied to the case study.
A fundamental purpose of this work, as explained in the purposes paragraph, is to present a strategy for the traceability of the design process. It must fit with the other fundamental activity, the design process of a subsystem. In these circumstances, to have a complete traceability of the design choices, it is necessary to start from the beginning of the design, from the system of systems. The top-down recursive nature of the methodology leads then to the design of the interested subsystem.
Moreover, generality must be extended as much as possible to follow the methodology and so to enhance its potential of deriving innovative alternatives. For these reasons, the design is not started by immediately imposing a spaceplane aimed at testing and scientific experimentation, but the case study is presented in the broader manner.
Constraints that specify the case study are introduced at the proper level. Each iteration will produce requirements that will affect the subsequent iterations.
This chapter has also the purpose to provide an example of rigorous application of the methodology, before applying it to the core of the case study.

In this Chapter a document-based approach has been followed, in order to simplify the exposition and focus the discussion only on design process. However, some screenshots of SysML Software are provided in appendix B, to underline advantages of the model-based approach.

4.2 MISSION LEVEL ANALYSIS (or System-of-systems analysis)

It is chosen to start from the most general design case, a **suborbital reusable launch vehicle (SRLV)**, while constraints are imposed afterwards. Such SRLV shall be able to accomplish all the typical missions according to the state of the art of suborbital spaceflights.
With “product”, in this paragraph, is intended the system-of-systems (further indicated as SOS).

4.2.1 Customers’ requirements identification

A plausible list of customers’ requirements was written below and it constitutes an input of the design process, the core from which all mission architecture alternatives will derive. Such alternatives shall satisfy these requests differently. As explained above, these customer requests are written as “requirements”, formalized statements that contain product’s characteristics required to accomplish a purpose. The subject of those requirements is indicated as “the system”, taking advantage of the flexibility of the word: depending on the requirement, it will be satisfied by the SOS, by the SRLV or by an element of a lower design level.

- The system shall be able to perform suborbital flights;
- The system shall be capable of reaching space;
- The system shall be reusable;
- The system shall guarantee continuous microgravity condition for at least three minutes (TBC);
- The system shall allow testing of technological payloads;
- The system shall allow conducting of scientific experiments;
- The system shall accommodate a payload specialist;
- The system shall allow testing of enabling technology, such as new engines. This category includes all the components and subsystems that are necessary for the correct accomplishment of the mission;
- The system shall allow training of the astronauts;
- The system shall allow a microgravity experience to space tourist;

Following the sysML approach with IBM tools, those requirements, which are top-level and belong to mission requirements category, was written into DOORS, in a formal module called “mission_level”.
The highest requirement among those presented by importance is "The system shall perform suborbital flights", because contains high-level information that heavily affects all design levels and it is the requisite that mainly defines the type of mission.
It is clear that all these requirements impose a large number of characteristics to the product. For example, it will be a manned spacecraft, because each mission requires the presence of at least a human on board. This excludes pure sounding rockets from the list of possible configurations that could be adopted. The product category will so be a Manned Suborbital Reusable Vehicle. In other words, from customers’ requirements it is possible to understand which type of product is desired and for which type of mission it should be built. The customer wants a reusable spacecraft, which is able to reach the Karman line and to accomplish all listed activities. Thanks to the list, it is possible to identify the context to be analysed for the first three steps of the methodology: the market analysis, the operating scenario analysis and the existing project analysis.

For now, we consider a single SOS that shall have all the listed capabilities. In other words, only one product model will allow astronauts to be trained in one flight and provide an experience for tourists on another flight. Alternatively, the product could be designed to accomplish two or more different mission during the same flight, for instance while space tourists fly for their unique experience, some payloads could generate useful scientific data without interacting or constituting an obstacle to astronauts’ movements. The application of the methodology will tell us which the best strategy is.

Proceeding rigorously in the methodology, we will have to reach an SOS optimized to carry out all these missions. In this case, because some design elements may be important for a mission but useless or harmful for another, it will also be necessary to specify which missions are to be privileged. For example, for space tourism a design element could be the windows. If this is the main mission, it may be sensible or intuitive to try to design them as wide as possible, but this would be incorrect if the main mission was the technological equipment test.
Actually, later we will specify the design process as described in the case study but having done a complete analysis to have a rigorous 100% traceability of methodology steps.
In conclusion, it is clear what has to be designed: a re-usable and manned suborbital vehicle, able to reach, following a suborbital flight profile, the Karman Line in order to carry out some activities. It will obviously have to withstand the environment and be safe.

4.2.2 Market Considerations

During this first step, information about suborbital activities and forecasts is gathered and analysed. It will provide very useful information about how to start the design activity.
The following market analysis was not conducted by the author, that only reported the results provided by references [4.1], developed by Tauri Group. They have forecasted in a period of ten years three different possible scenarios:

- **Baseline scenario**: the market will evolve consistently with the current trends. To consider in the same analysis both flight participant and cargo payloads, they defined the seat/cargo equivalent as 1 seat or as an alternative 3,33 middeck lockers. A total demand of about 4500 seat/cargo equivalents is forecasted for the period.
- **Growth scenario**: it is an optimistic perspective that considers a strong growth thanks to marketing and success of missions. A total demand of about 13100 equivalents is estimated.
- **Constrained scenario**: this pessimistic forecast evaluates only about 2300 equivalents to be sold in the period.

A Tauri report table and a figure follow, illustrating their forecast results.

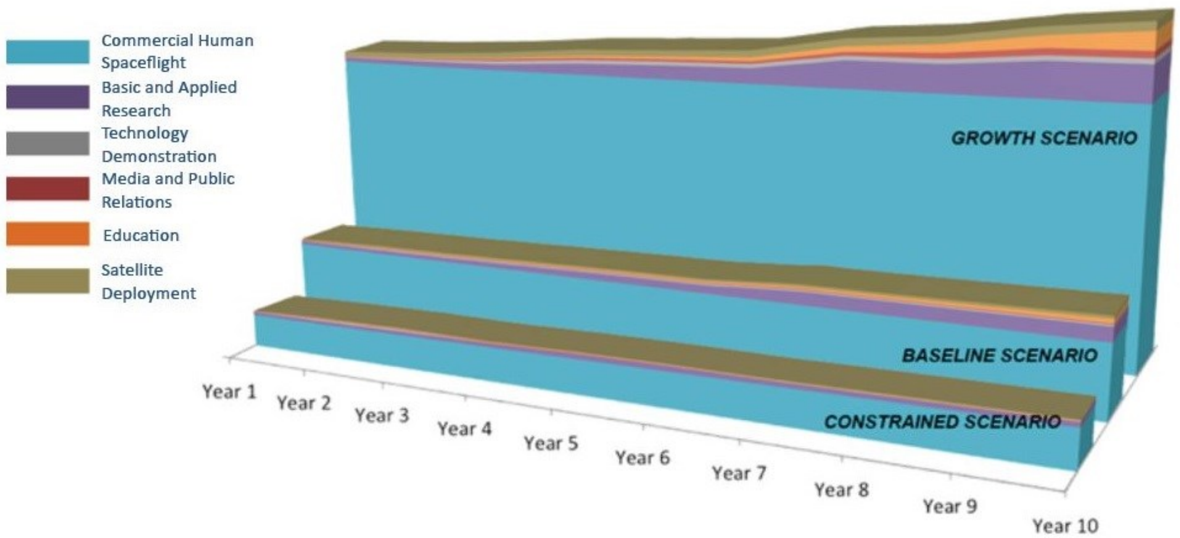


Figure 4.2.1 - Suborbital flights market forecast (Source: [4.1])

According to Tauri Group, the market will be dominated by space tourism and personnel training, highlighted in blue. The second category by incomes is the science research. Technology demonstration is only a small source, almost neglectable, source of revenues. However, this forecast refers to the global market, so it is possible that in the European or Italian context the suborbital human spaceflight will not be the driving category of the market. Clearly, this is only a speculation of the author and it shall to be supported by specially conducted analyses to be discussed.

In the theoretical paragraph, the importance of understand which type of customer the product is addressed to was underlined. In fact, Tauri Group identified customer targets among two macro-categories: individuals and enterprises.

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Total
Baseline Scenario	373	390	405	421	438	451	489	501	517	533	4,518
Growth Scenario	1,096	1,127	1,169	1,223	1,260	1,299	1,394	1,445	1,529	1,592	13,134
Constrained Scenario	213	226	232	229	239	243	241	247	252	255	2,378

Figure 4.2 - Detailed forecast of selled tickets (seat/cargo equivalents) (Source: [4.1])

This analysis permits to know how much big the market is, or in other words, how much revenues it is possible to gain, estimating possible expenses, the number of possible competitors, and their relative market strength. Moreover, it is possible to make some ideas about which product's characteristics will be likely adopted, basing on trends and forecast of likely desires of future customers.
Analysing that information it is possible to understand:

- It is worth to invest resources in the market;
- Which are the type of customer the product will be addressed;
- A very preliminary sizing of the most important characteristic of the product;

Obviously, in our simulation of a design process, it has been hypothesized that it is worth to invest resources in the suborbital market.
For the baseline scenario that is perhaps the most probable, the year of maximum expansion corresponds to about 533 places sold. On average, 452 seats per year will be sold or, since 1 seat-cargo equivalent stands for 3.3 lockers, 1492 middeck lockers per year. This information should firstly provide a rough indication of the payload volume and mass, and so how big the product should be. Assuming two flights in rapid succession once every two weeks (or a single flight a week), since there are about 52 weeks in a year, there should be at least about 9 seats or 30 MLE. In the early years of the baseline scenario or in case of constraint scenario the frequency of flights will decrease, while in the case of growth scenario or in the last years of the baseline, the frequency can be increased.
However, since the existence of at least one competitor is highly probable, for the purposes of this thesis a 50% subdivision of the demand is assumed, therefore, assuming a flight every week with a competitor, it is an accommodation of 4.5 seats-cargo equivalent. Naturally this is a very uncertain fact, deriving from considerations on the highest level and based on a market analysis of years ago. However, for the purposes of this thesis the actual commercial success of the designed vehicle is not important and therefore rounding up the value, it is expected to accommodate 5 seat-cargo equivalents, i.e. 5 passengers or 17 middeck lockers per flight. In this scenario, the vehicle would spend 746 middeck lockers per year on average and as many as the competitor.
During the outline of the existing initiatives and projects a list of which suborbital aircraft that have a similar accommodation, if they exist, should be carried out and taken as a reference.
The number of 5 seats equivalent is purely indicative to continue and can be modified later thanks basing on further considerations. For the sake of clarity, a requirement belonging to the operational class has been generated: "The vehicle shall accommodate 5 (TBC) seat/cargo equivalent locations". If this data should be changed, this requirement must also be modified. Clearly it is not a mission requirement because certainly not all the elements of the mission will deal with accommodating equivalents. For this reason, a temporary module has been created on doors, which also contains a copy of the requirements of the customers, where the requirements of lower levels are written, waiting to be placed at the correct level.
The market analysis has permitted to generate a first example of requirement traceability, illustrated in figure:

Figure 4.3 - Requirements' traceability example

“Payload_load_requirement” is a stereotype that stands for “The vehicle shall accommodate 5 (TBC) seat/cargo equivalent locations”. This requirement is derived from considerations performed by a market analysis. It, in turn, was possible to be performed thanks to the information contained into customers’ requirements.

This situation is common through the design application: a more and more detailed list of requirements is obtained iteratively by performing methodology’s steps.

DOORS software permits to link the payload requirement to its parent requirements, but it is important also include an information about how that requirement has been generated. Therefore market considerations exposed into the previous page shall to be linked by a label in the corresponding raw. So, when the requirements reviewer will examine the database can easily understand, by reading the market analysis, how customers’ requirements cause a choice of a load capacity of 5 seat/cargo equivalents.

4.2.3 – Operating scenario analysis

At the mission level it is important to focus also on the other topics than the spacecraft itself, from the spaceport to the logistic system. The operating scenario analysis helps to focus on these elements, to product considerations and requirements that are fundamental to the correct accomplishment of the mission. This is the right moment to explore the typical operations related to the suborbital product to be carried out, and the characteristics of the environments in which these operations will take place, which may be a help or an obstacle. In order not to overestimate the thesis work, this paragraph has been simplified a lot, and it is only a brief idea of the issues that need to be dealt with.

At first, a general list of mission phases for our suborbital case has been described:

- **pre-flight phase**: mission purposes are defined, as well as mission trajectory. Ground segment and vehicle are prepared for flight, in particular experiments are installed and configured and crew and passengers are boarding. Completing this phase requires the certification for flight readiness, checking the correct behaviour of all the subsystem and equipment of segments and assessing the weather conditions. Finally, the vehicle is fuelled.
- **take-off or lift-off phase**: this phase is different depending on the chosen configuration. The verb take-off is used when the suborbital system takes off horizontally from a runway similar to an airplane or takes-off vertically driven by airbreathing engines like a helicopter. The term lift-off will be used if it will take off vertically by a rocket engine. It is the phase in which the mission operationally starts.
- **climb phase**: the system passes through all the layers of the atmosphere, supported by the Ground Segment. The vehicle performances are continuously tracked and the telemetry is monitored. The ascent into the atmosphere is traditionally allowed by airbreathing or rocket engines. When the air density will be insufficient to ensure thrust of the airbreathing engines, only rocket propulsion will be possible to continue the climb. The phase ends when the rocket is burnt-out.
- **coasting phase**: the vehicle continues to rise obeying the inertia principle. To be classified as a space mission, it must reach the Karman line, conventionally set at 100 km. Since a propulsive force is no longer available and the air density is not sufficient to guarantee significant aerodynamic resistance, the vehicle is subjected to free fall in a microgravity environment. This phase is the core of the mission, where tourists can float and experiments are executed. Telemetry and payload data are obviously captured and transmitted. The vehicle is tracked and attitude operations are accomplished, while trajectory is propagated for a re-entry assessment. The trajectory of the vehicle is an elliptical orbit that intersects the earth and it can be confused with the upper part of a parabola, similar to parabolic flights’ parabolas seen in Chapter 2. At the peak of the trajectory null

vertical speed is reached, and then the vehicle begins to accelerate from gravity, towards the Earth's surface, always therefore in free fall. The phase ends when the air density is sufficient to generate aerodynamic drag on the aircraft to stop the microgravity condition. The altitude at this happens obviously depends case by case, because vehicle speed and its aerodynamic configuration are different.

- **re-entry phase**: the vehicle must dissipate all the potential energy accumulated. Generally this can be done with parachutes, retro-rockets or with aerodynamic surfaces. The vehicle will eventually land at a designated place. The whole phase is characterized by continuous monitoring of the spacecraft trajectory and by voice coordination with the crew on board. It is possible to categorized re-entry methods as wings, parachutes, rockets and rotors.
- **landing phase**: it is the phase in which the mission has operationally ended. It is generally a very delicate.
- **recovery phase**: deals with transportation of the vehicle in the turn-around area. Passengers can exit from the vehicle and payloads are recovered from the cabin and given to owners or researchers. Storage and consolidation of all collected data.
- **turn-around phase**: the spacecraft is physically inspected, systems are checked-out and maintenance activities are executed. Final preparation for the next flight is accomplished.

A visual representation of these phases is showed at figure 4.4.

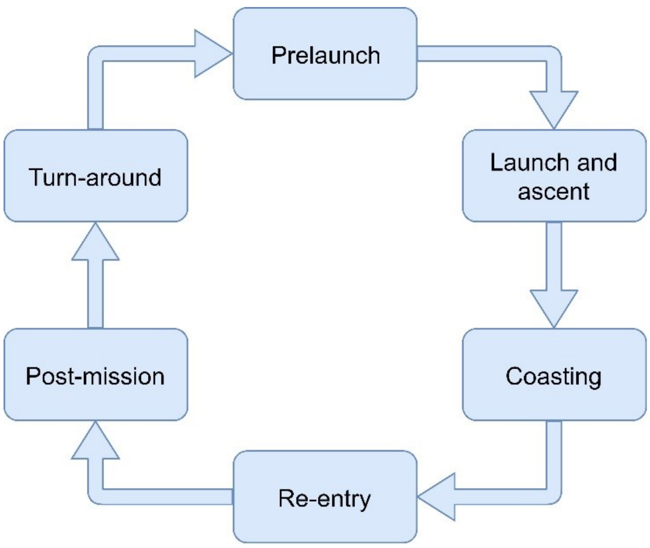


Figure 4.4 - Typical missions operations
This closed loop flow highlights the main operative phases of a typical mission of a reusable suborbital vehicle. As it is discussed further, those phases will be detailed once the mission architecture will be established. For a better comprehension the phase "launch and ascent" is subdivided into two distinct phases in description.

The phases are important for the derivation of the operational requirements. In fact, by identifying and describing them, the environments in which these phases take place are identified at the same time. As regards the preparation of the system until take-off, the operating environment is that of the spaceport, which has characteristics that vary considerably in terms of its location in the world. An example is certainly the temperature, and it is briefly discussed here. At Mojave Air and Space port during a July day, the average high temperature is about 36 °C. The manned reusable vehicle shall so for example provide a comfortable inside environment for passengers or crew that possibly attend the take-off clearance. On the other hand, at Kiruna Spaceport, average temperature in December reaches about -11° C. Therefore, all components of the system that will be exposed to that temperature shall to be certified to resist to it. Sand contamination is a real problem to take into consideration at Mojave Desert, and if not properly handled can cause possible damages to payloads and subsystem or incorrect result from experimentations.

Humidity and temperature in Florida can cause moisture condensation, that is harmful for some payloads and electronics.
These examples want to underline the importance of considering environments parameters that, only at spaceport, heavily affect the design of the system. Neglecting one parameter could cause catastrophic consequences. It is sufficient to remember the dramatic loss of Space Shuttle Challenger in 1986. The vehicle exploded due to a failure of an O-ring seal of the right Solid-fuel Rocket Booster. Low temperature reached under the night before the flight suppressed elastic nature of that polymeric ring, permitting a leakage of glowing gas out of the SRB which caused a structural failure of the external tank, concluding with its explosion and disintegration of the orbiter by aerodynamic forces.

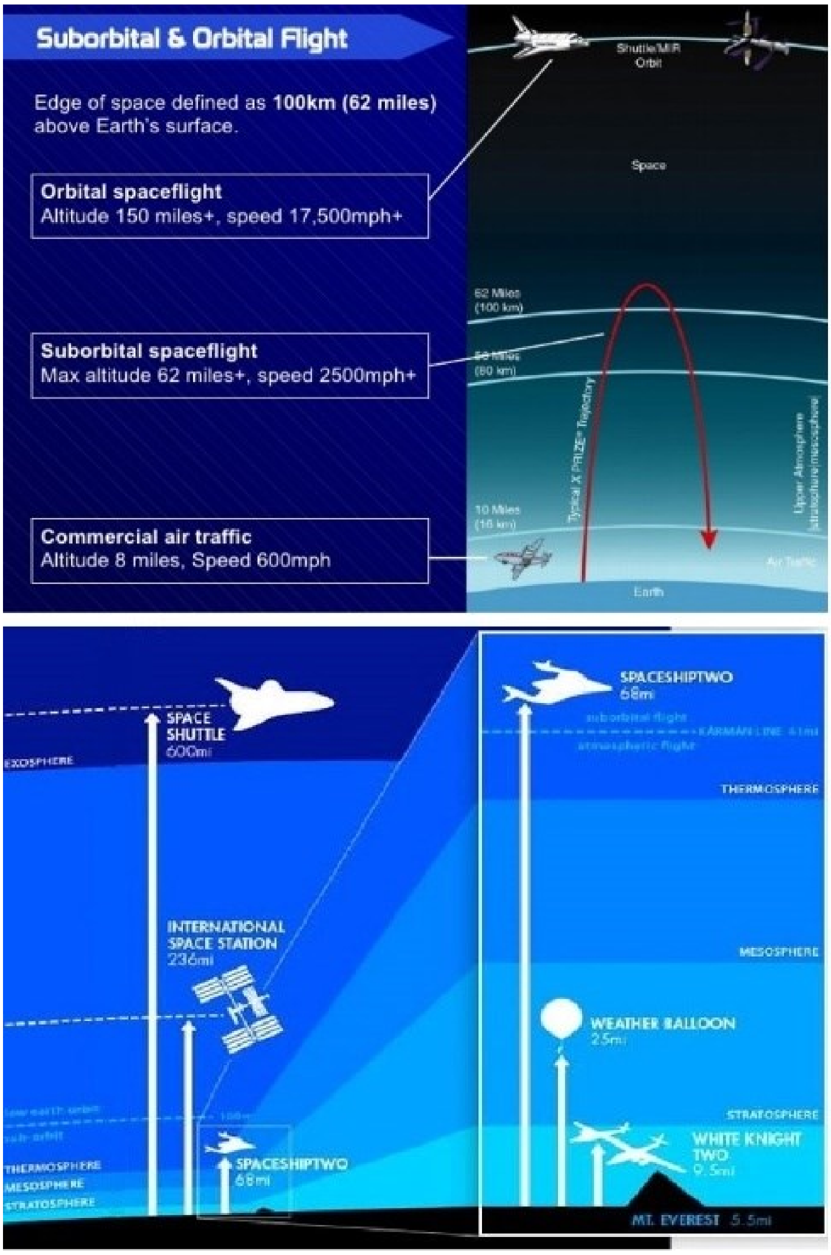


Figure 4.2.6 - Overview about suborbital flight and orbital flight
A suborbital flight is considered a space flight if it overcomes the Karman line. It is not an orbital flights because it does not complete an entire revolution around Earth.
At the bottom figure, typical maximum altitude of several types of spacecrafts and aircrafts (source: www.boingboing.net) are showed.
Space shuttle and ISS are orbital spacecraft, while SpaceShipTwo follows a parabolic suborbital flight path. Measure unit is the mile (1 mile = 1609,344 m).
The typical trajectory shape of a spaceplane, correlated to information as altitudes and timings, is called mission profile, and it is specific for that vehicle.
Source top image: http://trooth.info/sub-orbital-spaceflight.html

The different environments of the spaceports are only the first a suborbital space vehicle shall endure.
After take-off, it passes across almost all layers of the atmosphere reaching eventually the space

environment of 100 km altitude. A suborbital vehicle for all missions proposed shall surely to have a pressurized environment, minimize atmospheric drag or properly exploit it during re-entry, and be designed for withstand outgassing phenomena.
During all phases, aerodynamic, propulsive and other loads must be considered during the operating scenario analysis. The actual intensity of loads and accelerations will be precisely thanks to analysis performed after the sizing of the aircraft, when the shape and the structure of the vehicle is known. But, to find these result, an estimation of loads which will be the loads that the aircraft will have to bear is mandatory: it is another expression of the idea of the recursing and iterative nature of interactions of different steps of the methodology.
In particular, the law distinguishes two types of requirements for the aircraft:

- limit loads: they mean the maximum loads that the vehicle will experiment during operations. The vehicle shall to not present residual deformations. In those cases of overcoming of limit loads, it is mandatory to verify structural integrity through maintenance checks;
- ultimate loads: they determine the structural design because the vehicle shall endure these loads without failures for a limited amount of time. For example, JAR-VLA imposes resistance of at least three seconds under the ultimate loads.

Next to typical acceleration that the vehicle will encounter, same considerations have to be repeated also for thermal loads.
In conclusion, the analysis of the operating environment is extremely complex in the case of aerospace products, as many environments play a key-role with an incredible number of parameters to be taken into consideration and to be allocated as requirements on the system and subsystems.
In the next chapter, it is essential to characterize the environment inside the vehicle, because it must be an environment suitable for the most of payloads. Otherwise many payloads could not be boarded and therefore the vehicle would be out of business.

Now it is briefly described two examples of **mission profiles**. Only publicly available information has been found and discussed, for two spaceplanes, the SpaceShipTwo and the RocketPlaneXP. In the case of commercial study cases it should be worth to collect mission profiles for all the suborbital vehicles available on the market or presented during history.

Virgin Galactic LLC published flight phases durations for a typical SpaceShipTwo flight (source: Virgin Galactic):

- Captive on bottom climb: 60 -90 minutes;
- Rocket climb: about 60 seconds;
- Microgravity coasting: 3 – 4 minutes;
- Re-entry: about 70 seconds;
- Gliding: about 15 minutes;

Rocketplane XP flight profile [4.8]
Rocketplane adopts a horizontal take-off and landing configuration. Thanks to afterburning turbojets, it reaches 40000 feet altitude where the rocket is ignited. Two seconds after, the liquid rocket engine (Polaris AR36) provide maximum thrust of 36000 lbf. The zoom climb at 70° begins.

4.2.4 Outline of existing initiatives and projects [4.3]

In this paragraph a partial survey of the products that have already been presented in the previous years is briefly drawn up.
All suborbital vehicles are rocket powered during the flight phase before the parabolic coasting, because actually there is no other feasible way to have significative thrust at rarefied levels of atmosphere. Despite this common property, high number of different configurations and classifications was presented during the years:

- **SSTO (single-stage-to-orbit)**: the vehicle is composed of a single piece and no parts is jettisoned during the flight. Excluding the propellant consuming, the vehicles lands in the same configuration than the take off. In addition to rocket for the high levels atmosphere climbing, the may use airbreathing jet engines for the lower ones.
- **TSTO (two-stages-to-orbit)**: the vehicle is composed by two stages, each of with provides its own propulsion system.
- **airborne**: in case of or multiple stage to orbit, the suborbital vehicle is carried to an intermediate altitude of trajectory, usually at the boundary of the feasible atmosphere, by a mothership than represents the first stage. Then, vehicle is released to continue the ascending with rocket propulsion, while the mothership returns to ground. The vehicle cannot be airborne if it is a single-stage-to-orbit system, it has to be mandatory autonomous.
- **autonomous**: the vehicle uses its own propulsion system to perform the climb from the ground level to the altitude corresponding to the start of the coasting phase.
- **VTOL (vertical take-off and landing)**: the vehicle can take off and land vertically like helicopters, for example by deflecting downwards the exhaust gases of airbreathing engines. A VTOL approach can easy the implementation of the hovering capability.
- **HTOL (horizontal take-off and landing)**: it is the traditional take-off and landing approach, commonly implemented into planes. It requires a runway.

It is also important to analyse not only suborbital vehicles, but also those projects that are similar under certain views. For example, the Space Shuttle is an orbital vehicle, but could be anyway considered thanks to its aerodynamic configuration and so it could be taken as a reference. In other words, also cases not strictly belonging to the suborbital category can be examples to inspire for some solutions.
Next to sourcing of inspirations, a collection of data about past projects can be a first essential verification database for the results that will be obtained during the sizing phase and a source of forecasting of these quantities.
A cases of manned SRLV found in bibliography are listed and analysed.

Company	**SRV**	**Seats**	**Cargo [lbs]**	**Announced operational year**
UP Aerospace	SpaceLoft XL	-	36	2006
Armadillo Aerospace	Stig A Stig B Hyperion	- - 2	10** 50** 200**	2012 2013 2014
XCOR Aerospace***	Linx Mk I Linx Mk II Linx Mk III	1 1 1	120 120 770	2013 2013 2017
Virgin Galactic	SpaceShipOne SpaceShipTwo	- 6	- 450 (more than)	2013
Masten Space Systems	Xaero Xogdor	- -	25	2012 2013
Blue Origin	New Shepard	3 (more than)	120**	?
Masten Space system				

Table 4.1 - Lists of developed and under developmets suborbital reusable vehicles (Source: [4.1])

The column seat does not consider crew member (one or two) and so is equal to the maximum number of flight participants. The minus sign at the "seat" column means that the corresponding vehicle has no cabin for accomodation of flight participants.
** net of payload infrastructure
*** currently facing bankruptcy [4.9]

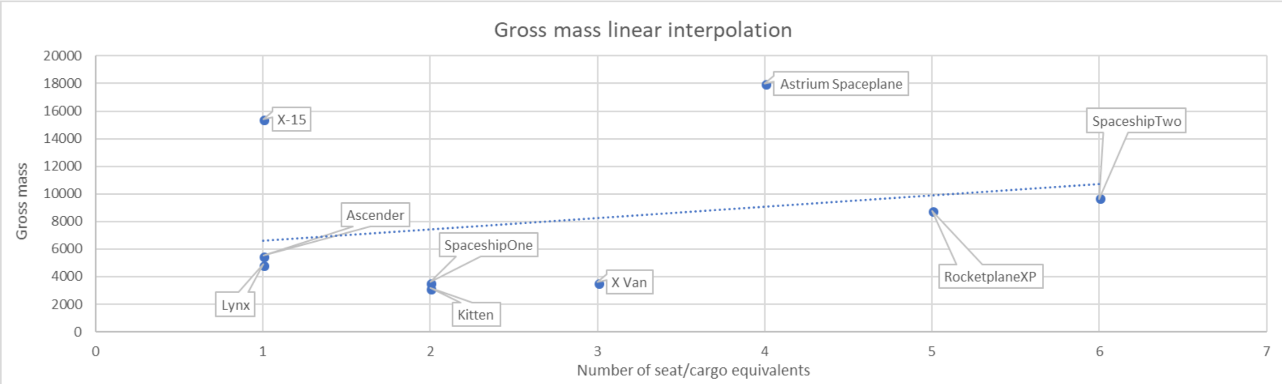


Figure 4.2.7 - Mass values for some suborbital vehicles
This figure represents which type of forecast is possible with a collection of values for a determined parameter, the mass in this case. Data is interpolated with a regression line, to create a continuous function of mass depending on the number of seat/cargo equivalents, i.e. the load capability of the vehicle. Hypothesizing a value on the horizontal axis, for example 5 seat/cargo equivalents, it results a top-level estimation, for the mass of the entire vehicle, of 10000 kg.

4.2.5 Stakeholders' analysis

The three analyses exposed previously are preparatory for the present. Also, the chapter two of this thesis, called "Context Analysis", was written with the same aim to build the preliminary grounding of fundamental notions on which develop all the steps proposed by the methodology, starting from the Stakeholder's analysis.
A list of stakeholders of a generic SRLV program, immersed in the Italian context, is developed below.

I° classification	Stakeholders	Examples for Italian Context
Sponsors	Commercial enterprise	Virgin Group
	General contractor	-
	Other private investment groups, banks and venture capitalists	-
	Space agencies	ASI
	National government	EU
	Local government	Regione Puglia
	Military	Aeronautica Militare
Operators	Main operator	Virgin Galactic or ad-hoc company
	Business partners: for example industrial partners, maintainers and supplier	Altec
	Spaceports authorities	Aeroporto di Grottaglie
	Air Traffic Control and Regulatory authorities	ENAC
	Competitors	Blue Origin
End Users	Scientific community	Politecnico di Torino
	National and regional populations	Italy
	Not-in-my-back-yard movements	-
Customers	Space tourists and privates	-
	Space agencies	ESA
	Scientists and Universities	Politecnico di Torino
	Military	Aeronautica Militare
	Systems engineers and companies	Thales Alenia Space Italia

Now it is useful to convert found stakeholders into the second classification, to assign an importance point to each of them. It is done in table 4.2. The influence column varies from 10 as "has extremely lofty influence on the program" to 1 as "has a negligible influence on the program". The capability of influencing is determined by the stakeholder's size, representativeness, effective and potential resources, knowledge, expertise and strategic collocation in the business.
In the same way, the interest column varies from 10 as "is extremely interested in the program" to 1 as "is poorly interested". The interest level is determined by possible commercial developments, business size, and political pressure. The "Importance" column is the result of the multiplication of the values in the latter two columns, divided by 10.
The respective geographical position of stakeholders is a factor worth considering during points assigning.
Certification authorities are not really stakeholders, but constraints to be taken into account and guides to design process. They have been inserted however for simplicity because in the suborbital context the development of the vehicle goes hand in hand with the normative development.

II° classification	Stakeholders	Influence	Interest	Importance
Promoters	Commercial Enterprise	8	10	8.0
	Other private investment groups, banks and venture capitalists	9	9	8.1

	Space agencies	8	9	7.2
	Local government	3	7	2.1
	Military	6	8	4.8
	Main operator	9	10	9.0
	Business partners	6	9	5.4
	Space tourists and privates	5	9	4.5
	Scientists and Universities	5	8	4.0
	Certification authorities	4	4	1.6
	Systems engineers and companies	3	7	2.1
	Concurrent companies	5	8	4.0
Defenders	Not-in-my-back-yard movements	1	5	0.5
	Enthusiasts	1	6	0.6
	Spaceports	7	8	5.6
Latent	Air traffic control	2	2	0.4
	National populations	2	3	0.6
Apathetic	National government (?)	8	4	3.2

The list of stakeholders with the importance order is: Main operator/Other private investment groups, banks and venture capitalists/Commercial enterprise/Space agencies/Business partners/ Military/ Scientists and Universities/ National government/ Systems engineers and companies/ Local government/ Space tourists and privates/ Certification authorities/ National populations/Enthusiasts/ Not-in-my-back-yard movements/Air traffic control.

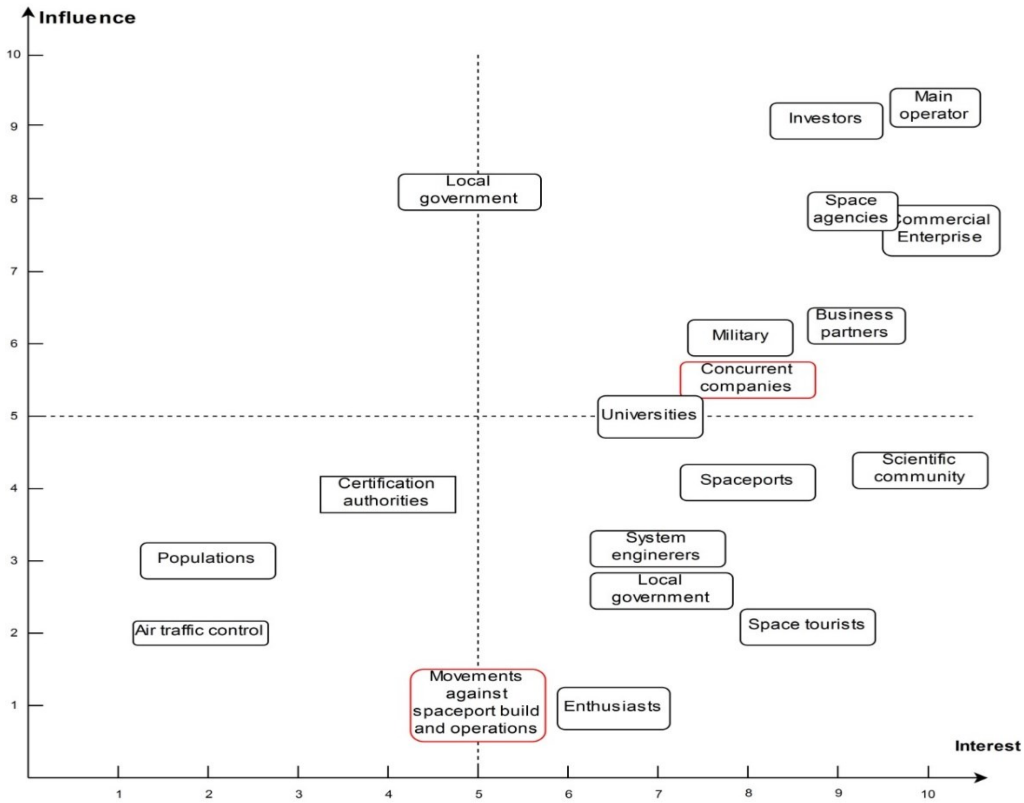


Figure 4.2.8 - Stakeholders' Map

Now a Stakeholders' needs analysis is performed. Practically, this it has the purpose to expand customers' requirements, maybe finding new desirables which may lead to a better product. Generally, needs for SRLVs' missions could be:

Stakeholders	Needs (D means desiderables)
Commercial Enterprise	To get an economic return of the investment.
Main operator	To operate regularly the vehicle, providing few minutes of microgravity condition
Other private investors groups and banks	To get an economic return of the investment. To obtain interest from bank loans. D - To push commercial initiatives in the space transportation field
Business partners	To participate the business in return for funds or services. To support operations
Space agencies	To test new technology in the microgravity environment at a fraction of the cost required for orbital flights. To train future astronauts. To conduct scientific experiments in a microgravity environment. D - To stimulate the development of systems which are useful for their missions, reducing internal costs. D - To cultivate young researchers and engineers. D - To stimulate space education. D - To stimulate space research and new space economy.
General contractor	To build the spacecraft and develop know-how for future versions.
National government	To increase the national economical, tourist and industrial opportunities and create new job placements. D - To increase the technological level of the nation. To obtain financial incomes from the business's related taxes. D - To increase national prestige. To attract investments from foreign Countries.
Local government	To increase the local economical, tourist and industrial opportunities. To attract investments.
Military	To have an additional opportunity to test equipment and new military technologies. To test new military technologies.
Regulatory authorities	To certificate the vehicle and relative infrastructures. To develop new regulations.
Satellite and other national industrial partners, manufactures and supplier companies	To supply spare parts and services. To benefit from new job contracts. D - To acquire other nations' know-how elements. To build the spaceport and infrastructures.
Insurance companies	To provide insurance solution for catastrophic events.
Spaceports	To provide infrastructures for the safe take-off of the system.
Scientific community	To benefit from the results produced by microgravity experimentation.
National and regional populations	To benefit from job creation and new economic, tourist and industrial opportunities.
Air traffic control	To extend the control activities.
Space tourists and privates	To experience microgravity conditions. To see the Earth from space and admire its curvature. To experience an exclusive activity.
Scientists, Universities, systems engineers and companies	To conduct scientific experiments in a microgravity environment. To test industrial payloads in the microgravity environment. To collect data from suborbital space environments.
Concurrent companies	To subtract customers.
Not-in-my-back-yard movements	To hinder the construction of spaceports and its operations.

Table 4.2 - Stakeholders' needs table

Items underlined are whose stakeholders that have reached an importance ranking equal or above 4.0. To simplify the design process, only associated needs, that are the most important, will be used for the house of quality. Actually, in order to follow rigorously the methodology, all needs should be considered.

Needs of the previous table constitutes the starting point to compile rooms of the House of Quality with a brief elaboration: they are grouped into “categories” in room 1 and weighted with values from 1 to 10. Voices of Room 1 are key-words which explain into engineering words what the customer wants. The point assignment should be accomplished basing mostly on the market analysis, but in the present case, values are allocated taking into consideration the scope and purpose of this thesis, so giving more importance to technology testing and scientific experimentation. Categories that are included are:

- suborbital flights, 10: because it is the core need, the product shall be able to perform a suborbital flight and return safely to the spaceport;
- microgravity duration, 9: it is an important topic, because some experiment requires a minimum amount of time to generate valuable data. The duration of the microgravity period is determined by the mission profile, therefore the peak altitude and the length of the two axes of the elliptical orbit, the throw in other words. The first-level affecting factor is the duration of the rocket thrust. Increasing it raises the microgravity period in the first approximation, but at the same time raise the weight of the vehicle. It will be necessary to find a viable compromise between the performance of the rocket and the duration of the microgravity. Once an acceptable duration has been selected, 3 minutes for example, time of the aircrafts already presented, it must be verified that an acceptable part of customer is satisfied with this value and can load their experiments;
- technology testing, 10: in spite of the Tauri’s market report forecasts the most of incomes from the commercial human spaceflight, the maximum value was assigned to this need because of motivation exposed above. Moreover, Tauri refers to the global market and not to the Italian and European market that could so be different;
- regular flights, 7: stakeholders are satisfied if they can make flights in rapid succession, because it is possible to maximize the number of annual flights and therefore the gains, both for example because the researchers could propose experiments that require more flights at different times of the day, or to confirm the results of a just carried out experiment.
- astronaut training, 5: the commercial human spaceflight is surely an interesting and challenging type of mission, but because in the Italian context there are initiatives that encourages experimentation, as seen in Chapter 2, and there is necessity of simplify the case study, this type of mission has been neglected.
- suborbital space tourism, 5: as the previous point.
- scientific experimentation, 10: the spaceplane used for testing new technologies is identical to that for scientific experiments and the methodology can confirm it. Since it is a topic of high interest for this thesis, he was awarded full marks.
- peak altitude, 7: it is true that the maximum altitude reached is of great interest to space tourism, in fact it is necessary to reach 100 km in height to be classified as astronauts. However, the maximum height is also important for land observation missions, to have a wider view radius, or to make atmospheric measurements at high altitudes.
- accommodation for payload specialist, 8: although the presence of a payload specialist is not essential for the success of the mission, it provides an important monitoring function and therefore useful for the safety and can perform small operations on non-autonomous payloads.
- enabling technology experimentation, 6: although this type of mission may be similar to the technology test, for simplicity it is not taken into account for the development of the thesis.

To get an economic return of the investment is not inserted into the list because is a common need to each sponsor. The SRLV will not be a technology demonstrator, but an industrial product and so it is implied that it shall be as most profitable as possible, with a proper balance between revenues and customers’ satisfaction. To participate the business is a need for companies, but it is not affecting design choices.

From the needs weighting, it is already clear that the SRLV shall be basically optimized for technology testing and scientific experimentation. Actually, due to simplicity reasons of this thesis, from now it is focused on these two categories to mission, neglecting the human spaceflight. Operatively, it is equivalent

to put artificially weight values of astronauts training and space tourism to zero in the room 1 of the House of quality. The resulting spacecraft will be a product dedicated and optimized to payload missions, with any capability for commercial human spaceflight.
Now, the most relevant features of the system-of-system are listed and analyzed in room 2:

- ground-segment services: they are services accomplished by ground-segment as for example payloads integration or mission supporting;
- mission profile: it includes the staging strategy, the flight trajectory shape and the number and duration of mission phases;
- RAMS: decisions and implementation of reliability, availability, maintainability and safety disciplines;
- payload capability: how much weight and volume of payload the spacecraft can carry;
- space-segment effectiveness: how well the spacecraft accomplish its mission;
- SRLV configuration: it indicates the “type” of the vehicle, if it is a capsule mounted on a rocket, a fuselage spacecraft plus a wing like the shuttle or a supporting body.
- launch-segment performances: how well the launch-segment performs;

With this list for the room 2, three SOS’s segments have been identified. They will be however confirmed with functional analysis.
To complete room 3, how need affect product’s features has to be evaluated.

Ground Segment Services						
Mission profile						
RAMS	x	x				
Payload capability						
Space segment effectiveness				x		
SRLV configuration	x	x	x	x	x	
Launch segment performace		x	x			

		Weight factors	weight factors norm	Ground Segment Services	Mission profile	RAMS	Payload capability	Space segment effectiveness	SRLV configuration	Launch segment performace	Needd priority	Needs priority (normalized %)
Stakeholders' needs	suborbital flights	10	12,65822785	0	9	9	0	0	3	3	303,8	22,099
	180 sec microgravity environment (TBC)	9	11,39240506	0	9	0	0	0	0	3	136,71	9,9448
	technology testing	10	12,65822785	3	0	0	9	9	0	0	265,82	19,337
	regular flights	8	10,12658228	9	0	9	0	0	0	0	182,28	13,26
	astronauts training	5	6,329113924	0	0	0	0	0	0	0	0	0
	suborbital space tourism	6	7,594936709	0	0	0	0	0	0	0	0	0
	scientific experimentation	8	10,12658228	3	3	0	9	9	0	0	243,04	17,68
	100 km altitude	8	10,12658228	0	9	0	0	0	0	3	121,52	8,8398
	accomodation for payload specialist	8	10,12658228	0	0	0	0	0	9	3	121,52	8,8398
	enabling technology experimentation	7	8,860759494	0	0	0	0	0	0	0	0	0
	Design specification priority	79	100	126	267	162	162	162	102	105	1374,7	100
	Design specification priority (normalized)	1086	100	11,602	24,586	14,917	14,917127	14,9171	9,39227	9,6685		

Figure 4.2.9 – Simplified House of Quality for the system-of-systems design level

The diagram completed provides important indications for the planning of the project design: the percentages highlighted in orange indicate the quantity of resources that should be invested in each item to achieve optimal product development, for satisfying the customers in the best possible way.

4.2.7 Mission statement analysis

Considering all the considerations performed during previous analyses, the following mission statement is draw up:

"The mission shall allow regular and safe suborbital space flights, to provide both space tourism service and unmanned/man-tended microgravity activities. In particular, the latter consists of testing of technological payload, conduction of scientific experiments and training of pilots/astronauts."

Therefore, from the analysis of the mission statement and stakeholders, the following list of mission objectives was developed:

	Mission Objectives	Comments
Primary Objectives	To perform multipurpose routine suborbital space flight	The system, already designed and ready to start commercial regular services in the next few year, shall be able to reach space and safely land. The system also shall be able to follow a parabolic flight path, allowing microgravity experience and operations.
	To allow flexible payload accommodation and execution of experiments	The system shall have all the hardware and software required to perform operations on technological payloads with purposes of testing and demonstration, to increase their TRL and to rapidly advance technology development in general. The system shall also have all the hardware and software required to perform scientific experiments to increase knowledge of a determined scientific topic.
	To allow training of the astronauts.	The system shall have all the hardware and software required to making astronauts familiar with microgravity condition and related operations.
	To allow a microgravity experience to space tourists.	The system shall provide enough cabin volume and comforts to enjoy the microgravity experience.
	To allow enabling technology integration and demonstration	The system shall have all the hardware and software required to test enabling technologies for the increasing of the technological maturity for next suborbital missions with that and other vehicles, such as testing of new propulsive systems.
Secondary Objectives	To demonstrate the feasibility and safety of commercial suborbital flights	The vehicle shall prove to be reliable and safe, concluding a considerable number of mission with the satisfaction of customers and without accidents.
	To be economically profitable	The mission shall generate profit for the main operator and revenues for investors
	To validate innovative mission concepts for flexible access to space	The mission shall constitute an intermediate step towards future developments of suborbital technology, by validating existing concept

Table 4.3 - Mission objectives

At first sight, mission objectives might seem like a simple re-edition of the customers' requirements. But actually information provided by the customers has been enriched through the previous analysts, in particular that of the stakeholders.

The first primary objective is more general than others and it can be seen as the top-level objective. The functional analysis should adopt such objective as top level function. However, it has been established during the analysis of the House of Quality, for simplicity purposes, that the spacecraft is only aimed to scientific experimentation and technology testing. So, from now, only the first two primary objectives will be considered. As a consequence, a lower-level statement could be derived:

“The mission shall allow regular suborbital space flights to provide a flexible platform for technological payload testing and scientific experiments execution in microgravity environment, also with support of a payload specialist.”

4.2.8 System requirements’ analysis

At the first iteration, a few of top-level requirements will be clear. In particular, customers’ requirements have been written in the first paragraph, while mission requirements will be derived now from mission objectives. “The system shall to perform multipurpose routine suborbital space flight”, the requirements that would be generated from the first objective is too vague and generic and so it is not included in the list of top-level requirements showed below into the table. See the caption of the table to understand how to read it. Appling the Model-based approach, they are entered to DOORS software into the folder “Mission_level”. For the sake of completion, also requirements from excluded mission objectives have been written.
Each requirement must have a verification method, which must be agreed with the customer.

The left column shows the category of requirements (for simplicity reasons logistic support requirements, interface requirements, product assurance and safety requirements are not taken into consideration in this thesis). The center column provides a unique code to each requirement, so that they can be unambiguously identified during all phases of life-cycle: the first couple means the level, ML= mission level, SEL=segment level, SYL=system level, SUL= subsystem level; the second couple is an abbreviation of the category and the number the unique identifier in the section. The right column presents the requirements their self; the code at the end is a simple way to provide traceability: the first couple means at what methodology step the requirement has been generated:

ML	SEL	SYL	SUL
Mission level	Segment level	System level	Subsystem level

MR	Mission requirements	MC	Market considerations and analysis;
PR	Programmatic requirements	OU	Outline of existing initiatives and projects;
CN	Configurational requirements	OS	Operating scenario analysis;
EN	Environmental requirements	ST	Stakeholders analysis;
FU	Functional requirements	MS	Mission statement analysis;
IN	Interface requirements	SR	Mission and system requirements analysis;
LS	Logistic support requirements	FU	Functional analysis;
OP	Operational requirements	CO	ConOps analysis;
PR	Product assurance requirements	SS	System sizing;
PE	Performance requirements		
PH	Physical requirements		

The number is the iteration of that methodology’s step at that level and the last couple of letters the identifier of the level. So, for example MS-1-ML means that the requirement is generated at the first-conducted mission statement analysis at mission level.
Requirements with the symbol [/] will not be furtherly decomposed for simplicity reason explained before.

Mission Requirements	ML-MR1	The mission shall allow execution of scientific and technologic experiments. (MS-1-ML)
	ML-MR2	The mission shall allow training of the astronauts. (MS-1-ML) [/]
	ML-MR3	The mission shall allow a microgravity experience to space tourists. (MS-1-ML) [/]
	ML-MR4	The mission shall allow enabling technology integration and demonstration. (MS-1-ML) [/]
	ML-MR5	The mission shall demonstrate the feasibility and safety of commercial suborbital flights. (MS-1-ML)
	ML-MR6	The mission shall to be economically profitable. (MS-1-ML)
	ML-MR7	The mission shall to validate innovative mission concepts for flexible access to space. (MS-1-ML)
	ML-MR8	The mission shall follow a suborbital profile. (MS-1-ML)
Performance requirements	ML-PR1	The mission shall be designed for carrying 5 (TBC) seat/cargo equivalent locations along the suborbital flight path. (MC-1-ML)
Environmental requirements	ML-EN1	The system shall endure flight loads without residual deformations. (OS-1-ML) [/]
	ML-EN2	The system shall endure ultimate loads without ruptures or causing the loss of control of the system for at least TBD seconds; (0S-1-ML) [/]
	ML-EN3	The system shall endure mission environments; (0S-1-ML) [/]
Operational requirements	ML-OP1	The mission shall guarantee that duration of pre-flight operations for preparation are compatible with flight frequency required by the market demand; (OS-1-ML)
Configurational requirements	ML-CN1	The mission shall to be designed for a safe human accommodation.
	ML-CN2	The mission shall to be accomplished with partially or totally reusable elements.

Table 4.4 - Requirements at mission level on first iteration

The complete list of requirements will be available only after many iterations. Since a real project is not taken into consideration, the programmatic requirements have not been taken into account. The functional requirements will be obtained following the methodological order in the next paragraph, as well as the physical ones.

4.2.9 Functional analysis

The macro-function that the SOS shall to accomplish could be "To test and experimenting payloads during suborbital spaceflight". It is immediate to assess that the associated product is a manned reusable suborbital vehicle, that comprises all elements that concur to the accomplishment of the mission, according to the System-of-systems definition.

At this point of process, little information about the product itself is available. Functional Analysis represents a considerable step in the direction of design advancement, outlining what the System-of-Systems shall perform. Starting from customers and mission requirements, the functional tree can be developed for the case study as:

Top-level function	Segment-level functions
To experiment payloads during suborbital spaceflight	To reach the target altitude
	To follow a suborbital mission profile
	To carry payloads
	To operate the payloads
	To support the mission
	To prepare the SOS for the mission
	To restore the SOS

Table 5 - Functional tree until segment-level

The top-level function is general and explain what the system-of-systems shall do. It does not contain information about its implementation. Derived functions belong to the segment level because they match a product of the segment level.

Six functional segment-level requirements have just been generated. They will become operational during sizing.

Now segment-level functions are associated to "building blocks" which perform them (thanks to the question "Which component is able to perform this function?"). Results are summed-up in the functions/product table:

	Launch segment	Space segment	Ground segment
To reach the target altitude	x		
To execute a parabolic flight path	x		
To carry the payloads		x	
To allow payloads operations		x	
To support the mission			x
To prepare the SOS for the mission			x
To restore the SOS			x

Table 3.5 – Functions/products matrix for the mission of the commercial suborbital vehicle for the segment level.

Grouping each building block in an analogous way to the Functional Tree, it is possible to derive the first level of the Product tree:

MANNED REUSABLE SUBORBITAL VEHICLE (SYSTEM OF SYSTEMS)		
Launch segment	Space segment	Ground segment

In this simple initial product tree the elements composing the SOS are seen as black boxes that interact with each other through rules modelled by the designer.

4.2.10 ConOps analysis

It is fundamental to study the existing and under-development solutions, underlining advantages and drawbacks of each. A state of the art analysis permits to understand which features are able to fulfil customers' requirements and stakeholders' needs and so to carry out possible reference configurations. A reference configuration is a possible configuration of the system that could satisfy customers' requirements.
The ConOps analysis, at this starting phase of the conceptual design, deals with the following activities:

- to detail mission phases, basing on considerations done during previous analyses;
- to choose mission drivers that will guide all the design process;
- to initiate to explore possible mission concepts, configurations and a proper flight profile.

Mission phases are those exposed during the operating scenario analysis, but it is possible to add some details. During climb phase samples of atmospheres or other types of measurements and observations may be taken. But it will be during the coasting phase that the microgravity experiments will be performed. Also the astronomical observations will be made here. For this purpose, the vehicle's attitude can be changed to allow better results.
We have seen that the system of systems consists of three components, the segments, connected to each other in a functional way. There will certainly be some physical connections. Now we allocate the segments to the phases of the mission.

Phases	**Products**
Pre-flight	Ground segment
Take-off/lift-off	Launch segment
Climb	
Coasting	Space segment
Re-entry	
Landing	
Recovery	Ground segment
Turn-around	

Table 4.6 - Allocations of products over mission phases

Clearly it is possible that more than one product is active during each phase, for example it is clear that the ground segment will be active throughout the mission. Here it is highlighted the protagonist of the phase.

Mission drivers, also called figures of merit [4.2] [4.3], allows a rationale trade-off analysis. For the case-study safety, design simplicity, innovation, cost and effectiveness were chosen and then weighted as showed in table.

Figures of merit	Value	Normalized values (%)
Safety	4	23,5
Design simplicity	3	17,7
Innovation	1	5,9
Cost	4	23,5
Effectiveness	5	**29,4**
Sum	17	100

Table 4.7 - Trade-off drivers

Values of 1 to 5 are assigned arbitrarily. The author thought that this is a product that should repeatedly perform similar missions (the mission profile is always the same without payload differences that may require lower peak altitude), insert innovative solutions should not be the main purpose of the design. Instead, it was decided to insert versatile and effective solutions that could embrace the needs of as many payload as possible, keeping costs as low as possible. Therefore, the last two drivers could be grouped into “cost-effectiveness” that refers to their balanced combination: the system must provide the better results for the resource expended.

4.2.11 – Other iterations of the methodology at mission level

Before performing a new iteration, the list of requirements must be updated:

Functional reqs.	ML-FU1	The mission shall allow to experiment payloads during suborbital spaceflight. (FU-1-ML)

Until now, starting from the blank sheet, the application of the methodology has introduced some elements, that made the system that has to be designed and its context clearer. Because it has considered only missions aimed to technology demonstration and scientific experimentation, it is worth to repeat methodology steps in order to take the consequences of this choice.
At first, the market analysis will be detailed with a focus on this type of mission. The source is the same of the previous [4.1].
Tauri group believes that NASA will be the first customer for test and demonstration. In fact, it is already planning to fly some payloads on suborbital flights, as it is shown on the flight opportunity program list. They have forecasted that during years the agency will move a certain percentage of payloads from current used platforms to cheaper SRLVs. Obviously, this shift will not involve all technologic payloads, but only those that are SRLV-suitable and nowadays more expensively accommodated, such as onboard sounding rockets. Basing on historical data, about the half of payloads launched on Space Shuttle Middeck Lockers that fit suborbital vehicles’ capabilities will be involved into the transition, along with about the one-sixth of payloads currently tested on ISS that do not require an extended exposition to microgravity.
These amounts of payloads will be so likely available in the next years, but they could be increase if ISS international partners will consider suborbital test mission as a preliminary step of payload development to propose them later more efficiently to ISS. In fact, this would allow to understand if there are any problems before sending it to the station, as well as having already partial data on the experiment. Three minutes of microgravity could therefore be sufficient to identify the criticalities of the payloads or to highlight areas of possible improvement.
NASA however is not totally satisfied by this advantage, due to the limited ISS budget: give this preliminary opportunity means increase the total cost of the ISS program. Similarly, other customers could judge a double expense as excessive.
Government agencies, in particular of United States, are seen also the main founders of scientific experimentation on suborbital reusable spacecraft, joined by Universities and no-profits.
According to the Tauri Group, demonstrating and scientific activities will be not the main driver of the SRLV market. Below two tables with their forecast are reported [4.1].

Basic and Applied Research	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Baseline Scenario	19	21	25	32	40	44	71	73	75	78
Growth Scenario	21	25	31	56	68	76	132	135	168	171
Constrained Scenario	18	19	22	23	30	32	28	28	28	29

Figure 4.2.10 - Forecast of estimated demand for scientific experimentation suborbital missions
Numbers are expressed in seat/cargo equivalents and year 1 is identified with the year of beginning of commercial missions. Remembering that a seat/cargo equivalent is equal in volume just over 3 Space Shuttle Middeck Lockers, the baseline scenario presents the average of 48 seat per year so slightly less than 158 middecks per year. The growth refers 247 middecks per year while the constraint 85 middecks (always average of values in the table).

Furthermore, these seat/cargo equivalents dedicated to scientific experimentation are subdivided with this percentages: 48% suborbital astronomy, 25% microgravity research, 19% atmospheric research and 9% human research [4.1].

Aerospace Technology Test and Demonstration	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Baseline Scenario	2	9	9	9	9	9	9	9	9	9
Growth Scenario	4	9	15	17	19	20	21	22	24	25
Constrained Scenario	2	9	9	1	1	1	1	1	1	1

Figure 4.2.11 - Forecast of estimated demand for test and demonstration suborbital missions [4.1]

The baseline scenario considers about 30 middeck lockers per years. The constrained forecasts only 3 middeck per year, while the best scenario expresses an average of 18 seats per year, equivalent to 60 middeck per year.

Analysing forecast results and considering always the baseline scenario, it seems clear that average values at stake are very different from those hypothesized generally in the first market analysis at the beginning of the chapter. There, a requirement was generated: **"The vehicle shall accommodate 5 (TBC) seat/cargo equivalent locations"**. Because the SRLV discussed in this thesis shall accomplish only test and scientific missions, the requirement suggests that 18 middeck lockers should to be accommodated onboard and so it is a direct affection on the vehicle size. Moreover, this number has been taken considering a flight once every week, so for a total of about 746 middeck per year.

Summing 158 middecks per year of the science research with 30 middecks of technology and dividing by two to consider the concurrent, it results a value of 94 that is one orders of magnitude lower than the requirement case, based upon all suborbital commercial activities. In fact, in the figure 1 of this chapter, scientific research and technology demonstration represents a small strip of the diagram, indicating small percentages of the total amount of seat/cargo equivalents.

First thinking, it may seem appropriate to reduce vehicles dimensions or the flight frequency, to do not exaggerate the payload capacity. In fact, during design, overcoming a design parameter may be as detrimental as not satisfying a requirement, because in both cases it may lead to a system that is unable to accomplish the mission, impractical or too expensive.

If vehicle dimensions are not decreased, annual flight demand would be satisfied within five missions, due to the small size of the market. In this case, the unique advantage of multiple flights in rapid succession to acquire data in different conditions seems to be impractical, unless the customer interested in a iterative experiment do not buy all the flight. If mission frequency is not reduced, the annual demand would be covered with a payload capacity of about 2 middeck lockers per flight.

Under these circumstances, one solution that can be actually pursued seems to perform a test and demonstration mission at the same time of a commercial human spaceflight on the same vehicle. The SRLV should so perform more than one category of mission and be designed to do this on a single flight. Or, on the other hand, a reduction of both frequency and dimensions could be introduced, for example the combination of about 10 middeck lockers and a flight about once per month. However, doing some analysis, it may likely occur that revenues from a so small number of payloads are not sufficient to cover design and operation costs.

Anyway, it is equally true that positive developments and news, like those reported in the Chapter Two, can stimulate the market, energizing scientific community, and increase participation attracting new organizations. For this reason, it is not to be excluded that perhaps in the coming years, a better scenario than the "Growth" hypothesized by Tauri Group may occur.

The first solution however is in contrast with the hypothesis of simplification done at the previous iteration of the methodology, that imposed only technology tests as the aim of the mission. Furthermore, the second does not goodly match with one purpose of this thesis that is precisely to understanding how an SRLV totally dedicated to these missions would be and what changes it would require to subsystems compared to a "traditional" mission with passengers.

For these reasons, within the present work, it is considered anyway an accommodation of 5 seat/cargo equivalent locations like the vehicle would have to satisfy a demand of 18 middeck lockers once every week. In other word, passengers demand has been simply transformed in demonstration demand, to effectively make the comparison exposed in the previous sentence, despite the real market situation.
All this discussion has highlighted again the importance of iteration to introduce considerations, hypotheses and data resulted from previous steps into the design stream: the present market analysis underlined that a SRLV aimed exclusively to technology testing and scientific research is likely not commercially feasible. The market analysis is a very useful tool to provide new stakeholders, to identify instances of them and to recognize which entities it is better to consider as customers.

4.3 SEGMENT LEVEL ANALYSIS

At this point, it is necessary to specify and detail the elements of the systems-of-systems at a very high level and how they are logically or physically connected. In other words, the architecture of the mission should be descripted specifying what segments are made up of.
This sub-chapter should be concentrated on the analysis of the three segments. However, for reasons of simplicity the analysis will simplified level and the Ground Segment will be neglected.
As in the previous iteration, the requirements must be updated.

Functional reqs.	SEL-FU1	The launch segment shall allow to reach the target altitude experiment. (FU-1-ML)
	SEL-FU2	The launch segment shall allow to execute a parabolic flight path. (FU-1-ML)
	SEL-FU3	The ground segment shall prepare the SOS for the mission. (FU-1-ML)
	SEL-FU4	The space segment shall carry the payloads. (FU-1-ML)
	SEL-FU5	The space segment shall operate the payloads. (FU-1-ML)
	SEL-FU6	The ground segment shall support the mission. (FU-1-ML)
	SEL-FU7	The ground segment shall restore the SOS after the mission. (FU-1-ML)

Preliminary analyses (market considerations, outlines of existing initiatives and projects, operating scenario analysis and stakeholder analysis) will not be repeated in this chapter nor the mission statement will be changed.
At the segment level we do not start with the functional analysis but at first we do the ConOps to detail well what each segment will have to do and to choose some preliminary configurations.

4.3.1 ConOps analysis

The drivers chosen during the mission analysis are used to start high-level design. Firstly, it is fundamental to choose which configurations to adopt. There are various types of configurations, the most important are [3.5]:

- **staging strategy**: it indicates the number of stages. A stage should not be thought only in the context of rockets, but in a broad manner: different types of other vehicle can constitute a stage. The airborne case is particularly exemplary, because the carrier is an aircraft that performs a first stage function. As we have seen before, the staging strategy can be a single-stage, two-stage or multi-stage configuration;
- **propulsive strategy**: various techniques can be used to ascend during the climb phase. The traditionally used systems are airbreathing engines for layers of the atmosphere where the density is high enough and rockets for space and for rarefied ones. Also the type of rocket can be chosen here, taking into account qualitatively the advantages and disadvantages of each type. However, the general guideline of the methodology of postponing a decision as far as possible is always valid;
- **take-off and landing strategy**: it indicates how the vehicle performs take-off and landing. Two strategies exist, vertically or horizontally. This configuration has a deep impact on operations, and on the choice of proper sites for launch.
- **aerothermodynamics strategy**: this strategy refers roughly to the “shape” of the space vehicle, the external geometry, that affects the distribution of aerodynamic and thermal loads on the surface.

The table summarizes the choice for the first strategy conducted by the author. Possibilities have been scored for each driver and then summed all the weighted values. The configuration with a higher score is considered the best and chosen. In our case it is a Two Stage configuration.
This require a further choice for the first stage: shall it to be airborne or autonomous (in other words integrated with the second stage into a single spacecraft)? With the same weighted process it results

airborne. The other three analysis are suspended for now. In the course of this thesis, however, they will no longer be carried out.

	Safety	Design simplicity	Innovation	Cost	Effectiveness	Design prioritization
	4	3	1	4	5	17
	0,235294	0,176471	0,058824	0,235294	0,294118	1
Single-stage	9	9	9	3	3	5,823529
Two-stage	3	3	9	9	9	6,529412
Multiple-stage	0	0	9	9	9	5,294118
Airborne	3	3	3	9	9	6,176471
Autonomous	9	9	9	3	3	5,823529
VTOL	3	0	9	3	3	2,823529
STOL	3	3	3	3	3	3
HOTOL	9	9	0	9	9	8,470588

Figure 4.3.1 - Mission level trade-off: mission strategy

It could be easier choosing at first the staging strategy and then the space, launch and ground segments configurations, as showed in the Excel table below. To perform the choice, a value is assigned to alternatives for each figure of merit. Then, values are linear combined with relative weights of drivers and a final mark results. This trade-off includes also the choice of the take-off and landing strategy, that will be not discussed. This types of trade-offs can generate configurational requirements for mission level, segment level and also for system level.

An airborne first stage is very effective for the satisfaction of stakeholders, because it allows to launch almost by any site on Earth.

Now the designer can continue with ConOps analysis, deriving further information, or postponing the choices later and proceed with other steps. This second option is advisable, because it allows to trade-off when the number of information available is maximum. As for simplicity we will not conduct ConOps analysis at this level later, this paragraph ends with some considerations on what should be done, for illustrative purposes.

Once the staging strategy has been decided, a further iteration of ConOps analysis can be done to proceed. Normally, the design activity will be in order:

1. Identify which architectures for each segment are available to satisfy the segment-level functions;
2. Combine such configurations to produce different mission architectures to accomplish the top-level function. Actually, the different type of segments identified at the previous point shall be combined also with the found staging strategy. Advantages and disadvantages of each are evaluated and reported. Combining segments' configurations, the designer can find a large number of mission architecture. Describing some examples: reusable rocket + spherical capsule or expendable rocket + blunt cone capsule;
3. Perform a trade-off analysis on the architectures thanks to drivers chosen;
4. Estimate nature and duration of the mission phases.

Generating configuration is done by brainstorming activity. For this purpose, paragraphs "Outline of existing initiatives and projects" and "Operational scenario" are extremely useful. The output is outlined in the table below. More than one configuration can be chosen for a determined segment: for example, a land-based launch facility can be chosen for the ground segment, but also a mission control center shall be added to accomplish the mission.

So, for the first point, architectures could be:

Launch segment	Space segment	Ground segment
Balloon	Spherical capsule	Sea based launch facility
Helicopter	Blunt cone capsule	Land based launch facility
Expendable rocket	Heatshield with afterbody capsule	Mission control center
Reusable rocket	Lifting body	
Aircraft	Winged body	
Propulsion system integrated into the space segment		

A possible output of the ConOps analysis is:

- Staging strategy -> Two-stage, a mothership and a spaceplane
- Launch segment -> Mothership and a rocket integrated in the spaceplane
- Space segment -> Winged body
- Ground segment -> Land based launch facility and a mission control center

4.3.2 Functional Analysis

It is possible to expand the functional analysis with lower level functions.

SEGMENT-LEVEL FUNCTIONS	SYSTEM-LEVEL FUNCTIONS
To reach the target altitude	To take off
	To climb to the release altitude
	To perform release
	To climb to the target altitude
To execute a parabolic flight path	To assume a TBD attitude profile
	To stop propulsive force at the burnout altitude
To prepare the SOS for the mission	To process the system elements
	To integrate the system
	To perform a pre-take off checklist
	To install payloads
To carry the payloads	**To accommodate payloads**
	To guarantee the survival of the payload if requested
To operate the payloads	**To guarantee the payload functioning**
	To handling payload command and data remotely
	To handling payload locally
To support the mission	To receive telemetry from the S/C
	To send commands to the S/C
	To monitor the S/C's trajectory and attitude
To restore the SOS	To perform a post-mission checklist
	To elaborate mission data and telemetry
	To recover payloads
	To elaborate payloads' data

So now it is possible to identify products that constitutes segment levels. It has been considered as black boxes:

	Spaceplane	Mothership	Launch facility	Mission control center	Payload data center
To take off		x			
To climb to the release altitude		x			
To perform release		x			
To climb to the target altitude	x				
To assume a TBD attitude profile	x				
To stop propulsive force at the burnout altitude	x				
To process the system elements			x		
To integrate the system			x		
To perform a pre-take off checklist			x		
To install payloads			x		
To accommodate payloads	x				
To guarantee the survival of the payload if requested	x				
To guarantee the payload functioning	x				
To handling payload command and data remotely			x		
To handling payload locally	x				
To receive telemetry from the S/C				x	

To send commands to the S/C				x	
To monitor the S/C's trajectory and attitude				x	
To perform a post-mission checklist			x		
To elaborate mission data and telemetry				x	
To recover payloads			x		
To elaborate payloads' data					x

Table 4 – Functions-products matrix

It is assumed that the Launch facility is the same spaceport on which the spacecraft will land at the end of the mission.

4.3.3 Further considerations: different functional decomposition approach for segment level

For the general case study, with all the primary objectives, the functional tree would be:

Top-level function	Segment-level function
To perform multipurpose routine suborbital spaceflight	To reach the target altitude
	To follow a parabolic flight path
	To host pilots
	To carry payload
	To carry passengers
	To allow testing of technological payload
	To allow training of astronauts
	To allow conducting of scientific experiments
	To support the mission

Table 4.7 - Example of a functional tree for the generic mission of the commercial suborbital reusable launch vehicle

Another common way to outline a functional tree is to focus on mission phases:

Top-level function	Segment-level function
To perform multipurpose routine suborbital spaceflight	To perform pre-flight operations
	To perform take-off preparation
	To perform launch operations
	To perform in-flight operations
	To perform post-landing operations

Table 4.8 - Example of a functional tree with operations approach

4.4 SYSTEM LEVEL ANALYSIS: SPACEPLANE

In this subchapter, the methodology is iterated focusing on a single element of the space segment: the spaceplane. Customers' requirements have been defined at SOS levels and there are not new requirements at system level for the space segment. Also, considerations about market and operating scenario rest valid and are not repeated.

4.4.1 Outline of existing initiatives and projects

Follows a description of all available spacecraft aimed to suborbital flights with an air-launch strategy. An example follows. Technical specifications should to be collected in order to made technical forecasts.

Vehra-SH Manned Suborbital Vehicle by Dassault Aviation [4.4]

This spaceplane was presented in 2006 by the Astronaute Club Européen, a French association with the aim of promoting suborbital flights in Europe. Now, no recent news is available about this project that should have been developed within the scope of The Student Aerospace Challenge[5] and also by Dassault Aviation, Safran and Thales. It is based on existing studies, such as Hermes spaceplane and X-38. The carrier mothership is a commercial jet and the launch strategy is "captive on top". The spacecraft is powered along a suborbital flight by a LOX/kerosene rocket engine.

4.4.2 Sizing

Final configuration of the system cannot be considered complete until some subsystems that impact on the external shape of the spacecraft are analysed. They are:

- Propulsion sub-system;
- Flight control sub-system;
- Crew and payload compartment: it should be placed in the forward part of the fuselage, to be far away from internal heating sources. The configuration of this part of the vehicle is strictly affected by the type of the mission that the spaceplane is called to accomplish. Also for this reason it has been choose as subject for the development at system level.

Although the cabin has to be designed at the next level, the shape of the spacecraft depends on this subsystem, so first you need to decide the length and width of the cabin.
At this point it is also worth to underline the importance of the simulation of the trajectory, which allows to get to finish more and more the mass budget.

[5] www.studentaerospacechallenge.eu

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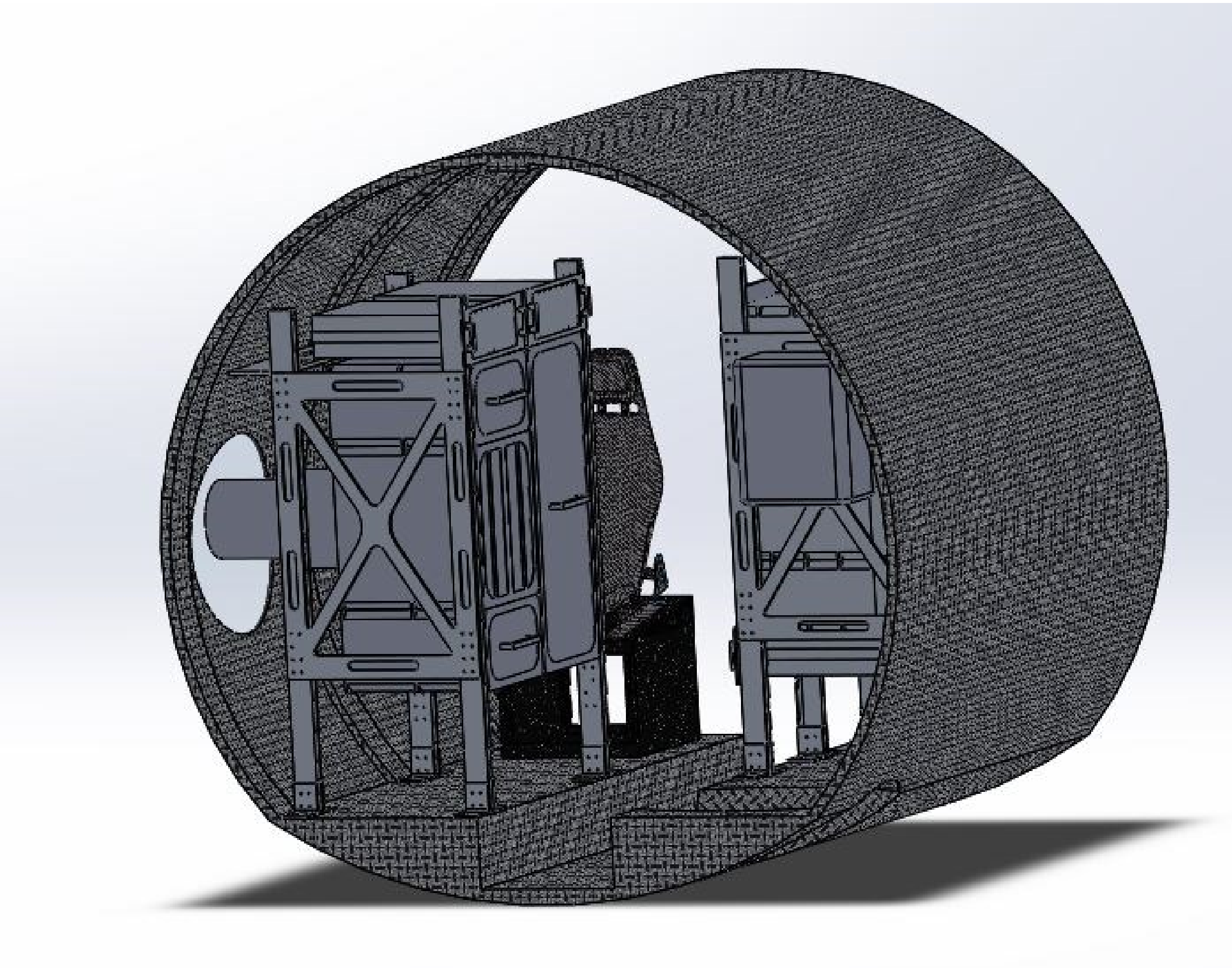
[4.8]	"The XP Spaceplane: A Multi-role Suborbital Reusable Launch Vehicle for Space Testing and Microgravity Science Applications", Charles J.Lauer, D. Faulkner, M. Onuki, 2008
[4.9]	http://www.blueorigin.com

Chapter 5:

Preliminary design of a suborbital vehicle's cabin aimed to technological testing and scientific experimentation (Subsystem and equipment level analysis)



[CAD representation of the cabin resulted as optimized for experimental missions]

5.1 INTRODUCTION

This introduction summarizes the considerations made in the previous chapter and continue with the methodology application at the lower level. To obtain an estimate of the length of the spaceplane to be designed, it is essential to perform some iteration at subsystem level to develop the cabin, the core of operation of a suborbital experimentation mission. Once a cabin design synthesis is obtained, it is possible to return to a higher level and continue with iterations developing the entire vehicle. The design process is therefore a continuous bidirectional shift between design levels.
For the purposes of this work information about suborbital market considerations, outline of existing initiatives and products and operating scenario discussed into previous chapters are sufficient to continue.

5.1.1 Stakeholder Analysis

The analysis outlined in the previous chapter is simplified in the current paragraph for the experimentation case study with some developments and additions, focusing on the cabin and neglecting funding-related needs.

Stakeholders	**Needs**
Main contractor	To operate regularly the vehicle, providing few minutes of microgravity condition.
Business partners	To support operations. To provide cabin equipment.
Space agencies	To test new technology and conduct scientific experiment in the microgravity environment at a fraction of the cost required for orbital flights. To acquire measurement and data via remote sensing missions.
Military	To test new military technologies. To observe area of military interest
Satellite and other national industrial partners manufactures and suppliers companies	To supply spare parts, equipment and services.
Spaceports	To provide infrastructures for the safe take-off of the system. To integrate technology payload into the cabin. To perform checkout tests and verifications.
Scientists, Universities, systems engineers and companies	To test industrial payloads in the microgravity environment and carry out scientific experiments. To benefit from the results produced by microgravity experimentation.

These needs are taken as basis to carry out those customers' needs that, in order to apply the QFD approach, have to be included into Room 1 of the House of Quality. The second part of Chapter 2 is fundamental to this purpose, because it provides an overview of previous implementations of these needs on a flight system, permitting to identify those hidden desires that can improve the system quality. Therefore, elements of Room 1 are listed and commented below:

- <u>High number of flight opportunities</u>: the cabin should provide a large number of flight per month or even several times per day, in order to maximize available loading opportunities during each mission. You can achieve this with a greater frequency of flights and increasing the number of payloads inside the cabin. Perhaps increasing flight frequency is more economically viable than increase payload accommodation locations onboard the cabin. In fact, before a large number of customers are willing to purchase the opportunity, the vehicle must have demonstrated high reliability, performance and cost-effectiveness. So, at the beginning of the suborbital activity, number of customers will be likely under the potential one, to then grow up with time. For this reason the spaceplane could be maybe more optimized if frequency is chosen as variable parameter to increasing flight opportunities: it can be raised with time while customers demand

increases, while a high number of accommodation could impose negatively on the activity since the beginning if customers' enthusiasm should be lower than expected. The connection with RAMS is bidirectional: to increase demand among customers it is required a very reliable and safe system, but the more the aircraft becomes reliable that the more missions are carried out.
Ground segment operations for payloads installation are not affected, but their frequency is.

- Flight opportunities for high volume payload: a significant part of revenues could come from those who have voluminous payloads to experiment, and could be a right choice include them into flight opportunities, even with an assembly service inside the cabin. However, the hardware must be able to enter the main hatch. However this service could be provided for one or two payloads, the others have to be assembled outside to not overcomplicate ground integration procedures. These operations protocols must be modified and there must be someone who integrates inside the payload aircraft that cannot be entered integers from the hatch in a payload container. Naturally, these systems have not a standard mechanical interface with the Payload Developer integrates its hardware, such as the Middle Locker, but must be ad hoc made, reducing the safety and increasing cost. A large load definitely changes the number of other payloads that can be carried, because the volume available for them is certainly smaller. However, it could become very time-consuming to manage a big payload. Another problem of bigger payloads, but it can vary among cases, is that they could also likely require high powers or fluid flows, over capability of vehicle-supplied resources. Moreover, too heavy and large payloads could move the center of mass of the out of the design safety range.
- On-flight human attendance on payload: All cases analysed present during flight a Payload Specialist: for Lynx, its work is provided by the pilot itself. The introduction of a Payload Specialist seems so essential, in order to both monitor the cabin and to provide support to non-completely autonomous payloads. A location for a PS decreases the available space for payloads, but it could be designed to be easily removed if required. If the design methodology leads to operate the vehicle autonomously, under the control of remote pilot or onboard computers, the Payload Specialist will determine the vehicle as "manned" and therefore complicate design and operations with necessary higher safety standards.
- External exposure opportunity: the payload could be exposed directly to the space environment, or "indirectly", for example behind the glass of a window. This capability requires additional integration procedures. Exposure to the external environment involves small or large modifications of the aircraft, and of its external configuration, with impacts in aerodynamics or structural that should be studied. It certainly requires a tailored attitude vs time profile and specific resources lines could be necessary. Perhaps with an external pod configuration, payload installations could be easier. Any external payload could then represent a performance constraint, in terms for example of maximum reachable Mach.
- Payload support services: they represent all those payload dependencies or resources necessary to the payload to functioning. They will be explored later in the functional analysis. Adding new services extend surely capability and effectiveness of the spaceplane, but could increase mass, costs and complicate procedures and maintenance. The vehicle design could result more complicated due to add or modify subsystems. In conclusion only services that will be surely used extensively by payloads should be likely implemented, while occasional ones could be integrated decreasing volume available for payloads.
- Responsive capability: it means the ability to change experiment, to replace it, to modify some parts and to modify the trajectory or the flight arrangement within a short time. Compatibly with other experiments' necessities.
- Competitive cost: it should cost less than an orbital flight, that likely offer more operational and performance advantages. Costs can be decreased with the flight frequency and the complexity of operations, maintenance, and ground integration services. In other words, adopting more standard as possible could increase prospects of success. Under the design point of view, decreasing slightly performance, such as a smaller apogee altitude, could permit to lower prices. Clearly this considerations remain hypotheses until they are verified or calculated by analyses or simulations.

So, parameters that it is possible to explore during design are:

- Ground Segment Services: onboard payload integration services, mission control, mission planning, customer relationship. It represents the operations that must be completed on the ground to prepare the flight and monitor it during operations;
- Flight frequency: how many times in a month or day the vehicle is launched. It represents how many times ground segment services have to be performed;
- RAMS: reliability, availability, maintenance, safety;
- Mission profile: parameters of the trajectory, such as attitude, apogee altitude or each flight duration;
- Internal available volume for payloads: how much volume is available for each payload;
- External available volume for payloads: how much volume is available for external experimentation;
- Payload replacement rate: which is the speed the payload inside the spaceplane can be replaced;
- Number of payloads on board for each flight: the number of payloads launched on each flight;
- Systems: on-board systems that need to be added or modified due to the introduction of payload-related capabilities;
- Performances: such propulsive, aerodynamics performances or acceleration profile of the aircraft. It is connected to the target share and the duration of the microgravity.

Before presenting the House of Quality, it is worth to discuss how these features interact each other. Higher safety and greater reliability certainly reflect on the procedures that must be carried out on the ground, from assembly, to maintenance, to non-destructive tests. Clearly, all these procedures take some time, which is affecting negatively the flight frequency. This perhaps could be partially restored by increasing the speed at which the payloads inside the cabin can be replaced.
Some mechanism of external exposure and further systems certainly lowers safety and reliability, and redundancy in this case could be insufficient. The more payload there are, the payload replacement rate is lowered, but in any case it depends on the type of payload, if it is big and very customized.

	Ground Segment Services	Flight frequency	RAMS	Mission profile	Internal available volume	External available volume	Number of payload on board	Payload replacement rate	Systems	Performances
Ground Segment Services										
Flight frequency										
RAMS	x	x								
Mission profile										
Internal available volume										
External available volume			x							
Number of payload on board										
Payload replacement rate		x					x			
Systems			x							
Performances										

			Operations				Vehicle							
							Cabin layout							
	Weight factors	Normalized	Ground Segment Services	Flight frequency	RAMS	Mission profile (trajectory and attitude)	Internal available volume for payloads	Available volume for external exposure	Number of payload on board for each flight	Payload replacement rate	Systems	Performances	Requirements priority	Requirements priority (normalized)
Maximize flight opportunities	9	0,195652174	0	9	3	0	0	0	9	9	0	0	30	0,47619
Flight opportunities for high volume payloads	6	0,130434783	9	-3	3	0	-9	0	9	-9	3	0	3	0,047619
In-flight human attendence on payload	5	0,108695652	3	0	0	0	-9	0	3	0	0	0	-3	-0,047619
Opportunity for external paylaod accommodation	6	0,130434783	3	0	-9	9	0	9	0	-3	3	-3	9	0,142857
Provision of resources to payloads	8	0,173913043	0	0	3	0	0	0	0	0	9	0	12	0,190476
Payload accommodation flexibility	7	0,152173913	9	0	0	3	0	0	-9	0	0	0	3	0,047619
Cost optimization	5	0,108695652	-3	9	0	-3	9	-9	9	0	0	-3	9	0,142857
Design specification priority	46	1	135	108	15	60	-54	9	132	9	108	-33	63	
Design specification priority (normalized)			2,934783	2,347826	0,326087	1,30434783	-1,173913043	0,1956522	2,8695652	0,195652	2,347826	-0,717391		

5.1.2 Subsystem Objectives

Objectives	Comments
To allow execution of experiments.	-
To maximize the number flight opportunities.	-
To extend flight opportunities to as many payload categories as possible.	Payloads of all dimensions and for different types of mission
To permit payload handling by a Payload Specialist.	-
To decrease flight access costs and time as much as possible.	-
To maximize the payload carrying capacity in terms of mass.	The cabin design should adopt ways and techniques to lighten systems and structural elements as much as possible, to increase carriable payload mass per flight
To adopt the as much standardized interfaces and elements as possible.	-
To include, as far as possible, interfaces that are present onboard the ISS for payload experimentation.	-
To maximize reliability and safety.	-

Analysis and updating of the requirements is skipped and presented at the end of the paragraph.

5.1.3 Functional analysis

Firstly, the functional tree is expanded by another level, with functions performed by spaceplane's subsystems. It is worth to note that only functions related to the specific activity of experimentation with the spaceplane has been developed. The analysis applied to the case study follows; first is showed the functional tree produced and then functional requirements derived.

SYSTEM-LEVEL FUNCTIONS	SUBSYSTEM-LEVEL FUNCTIONS
To accomodate payloads	To expose payloads to external environment [/]
	To cointain payloads in a controlled environment
To guarantee the survival of the payload if requested	To control moisture level
	To control temperature
	To control internal pressure
	To guarantee a proper acceleration profiles*
To guarantee the payload functioning	To isolate the payload from vibrations
	To feed the payload with electrical power
	To feed the payload with fluidical power
	To feed the payload with pneumatic power
	To remove waste gases or substances
	To feed payload with substances (he, co2,ecc)
	To allow payloads to aquire external remote sensing data
To handling payload command and data remotely	To send receive commands from GS
	To send payloads data and telemetry to GS
To handling payload locally	To control attitude pointing
	To physically manipulate the payload
	To restart payload and solve first-level problems
	To manage payload data and telemetry locally

Table 5.2 - Functional decomposition at subsystem level

The "To expose payloads to external environment [/]" function is difficult to implement and will not be pursued in this design simulation. However, it will be discussed in a dedicated paragraph.
* in reality this is a function that will be accomplished by the vehicle and the propulsive system.

As explained in previous chapters, from bottom functions it is possible to derive those basic products that accomplish them. To expose graphically this process, a **function/product matrix** is used, with functions and products respectively listed in the rows and columns.
Only the rows are known at the beginning and the columns have to be derived from the analyst's experience. The process ends when all functions are associated with a basic product.

	Cabin's mechanical structures	External exposure system[/]	ECLSS	Anti-vibrations system	Electric system	Hydraulic system	Pneumatic system	Avionic system	Payload specialist
To expose payloads to external environment [/]		x							
To cointain payloads in a controlled environment	x								
To control internal moisture level			x						
To control internal temperature			x						
To control internal pressure			x						
To isolate the payload from vibrations				x					
To feed the payload with electrical power					x				
To feed the payload with fluidical power						x			
To feed the payload with pneumatic power							x		
To remove waste gases or substances			x						
To feed payload with substances (he, co2,ecc)			x						
To allow payloads to aquire external remote sensing data	x								
To send receive commands from GS								x	
To send payloads data and telemetry to GS								x	
To control attitude pointing								x	
To physically manipulate the payload									x
To restart payload and solve first-level problems								x	
To manage payload data and telemetry locally								x	

Table 5.3 - Functions/products matrix for subsystem involved into suborbital experimentation activity (subsystem level)

It is important to remember that in this work all these systems will not be completely analysed also with regard to their mission functions, but only limited to the mission object. In other words, the cabin and those parts of the other subsystems that are involved with it or reside therein will be analysed in order to effectively perform the experimentation activity. Moreover, only the cabin's structure and the electric system will be deeply analysed.

4.2.2 System Requirements

SUL-CN1	The cabin shall be properly equipped for payload testing and experimentation
SUL-CN2	The cabin shall have a properly equipped external pod for payload testing [/]
SUL-CN2	The cabin shall accommodate a least a Payload Specialist
SUL-FU1	The External Exposure System shall to expose payloads to external environment [/]
SUL-FU2	The cabin shall cointain payloads in a controlled environment
SUL-FU3	The ECLSS shall control internal moisture level
SUL-FU4	The ECLSS shall control internal temperature
SUL-FU5	The ECLSS shall control internal pressure
SUL-FU6	The Anti-Vibrations System shall isolate the payload from vibrations
SUL-FU7	The Electric System shall feed the payload with electrical power
SUL-FU8	The Hydraulic System shall feed the payload with fluidical power
SUL-FU9	The Pneumatic System shall feed the payload with pneumatic power
SUL-FU10	The ECLSS shall remove waste gases or substances
SUL-FU11	The ECLSS shall feed payload with substances (he, co2,ecc)
SUL-FU12	The cabin shall allow payload to gather external remote sensing data
SUL-FU13	The Avionic System shall send receive commands from GS
SUL-FU14	The Avionic System shall send payloads data and telemetry to GS
SUL-FU15	The Avionic System shall control attitude pointing
SUL-FU16	The Payload Specialist shall physically manipulate the payload
SUL-FU17	The Avionic System shall restart payload and solve first-level problems
SUL-FU18	The Avionic System shall manage payload data and telemetry locally
SUL-OP1	The cabin shall allow payload installation and recover
SUL-PE1	The cabin shall allow payload replacement within hours
SUL-PE2	The cabin shall support a payload capacity of at least TBD kg
SUL-PE3	The spacecraft shall guarantee at least of TBD m^3 of pressurized volume

Table 5.4 - Requirements at subsystem level

5.2 CABIN PRELIMINARY DEVELOPMENT

5.2.1 Mechanical interfaces

In this paragraph the subsystem “cabin” will be developed. Firstly, a functional decomposition for the first function is performed.

To contain payloads in a controlled environment	To separate payloads from external environment
	To enclose single payloads
	To fix payloads to the structure preventing collisions
	To prevent unwanted payload movements

Ora identifichiamo i prodotti

	Cabin’s pressurized airframe	Payload containers	Mechanical interfaces
To separate payloads from external environment	x		
To enclose single payloads		x	
To fix payloads to the structure			x
To prevent unwanted payload movements			x

The cabin’s pressurized airframe is the main structural element of the cabin. It is the first part of the fuselage that will be designed and so it is a source of deriving constraints, such as width and cross-sectional shape, that shall be considered for fuselage designing.
The cross-sectional shape is certainly one of the first choices that should be carried out. For this parameter, a trade-off process is not explicitly performed in this work, but the shape is simply derived basing on many existing sources on the topic, such as the Airplane Design Part III [5.10]. From this reference, the category of executive jets has been taken into consideration because they have about the same number of seat of spaceplanes presented in Chapter Two. Finally, the shape of the Embraer EMB-121 has been chosen as reference, as showed in the next figure.

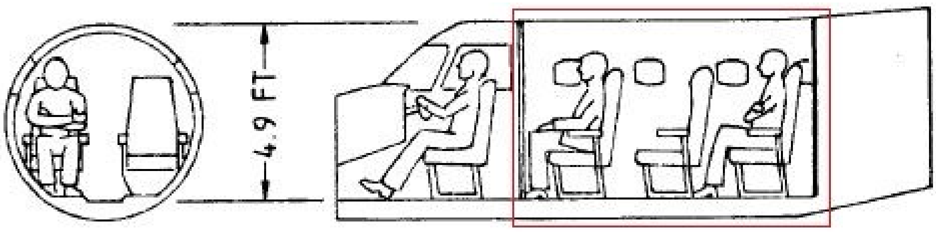


Figure 5.2.1 - Embraer EMB-121 Xingu [source: 5.10]
Only the fuselage enclosed into the red rectangular will be analysed in this chapter.

Excluding for now other discussions on the argument, it is worth to focus on the other two products.
Brief descriptions of some types of payload containers have been provided during the second part of the Chapter 2. The following list recap which cases could be adopted by Payload Developers to include the payload hardware. For each one, technical specifications are provided in table.
To maximize the effectiveness of the cabin, the mechanical interfaces that performs as support structure have to be as more lightened as possible.

- Middeck locker equivalents (MLE): they are described in Chapter Two;
- ISS lockers: they are very similar to those of the previous point, but differ in slightly lower measurements and in the presence of three front panels on the front access door;
- Cargo Transfer Bags (CTB): they are stowage bags made of Nomex, containing and packaging cargo during launch, on-orbit, disposal or return operations;
- CubeSat containers for CubeLabs: they are small payload containers based on the CubeSat standard, developed by NanoRacks. The mechanical interface is represented in figure;

- <u>ISIS drawers</u>: they are small standardized lockers designed for ISS applications;
- <u>19’’ server</u>: they are standard case for computers and other electronic equipment;

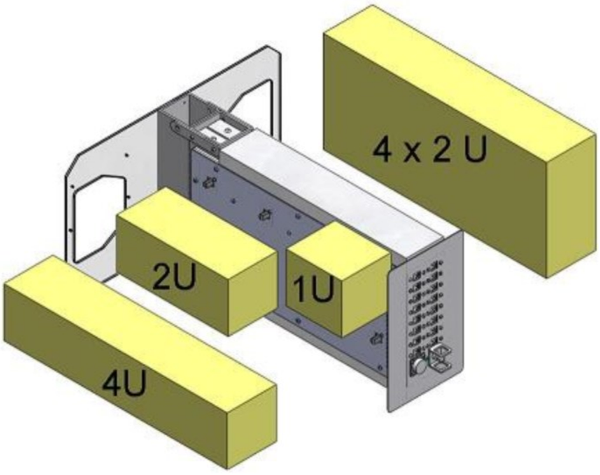


Figure 5.2.2 – CubeSat containers and CubeLab interface [5.13]
CubeSat containers are represented in yellow, and they can be attached to a specifically designed plate. Up to 16 1U CubeSats can be installed. The front panel of the plate permits to exchange data with payloads though 16 USB connectors. The same plate includes the connector with LED to power them and a circuit breaker.

Figure 5.2.3 - ISS locker (source: ESA and NASA)
One the left the figure represents a closed ISS locker. On the right, it shows an opened one and a CubeLab system. The CubeLab is designed to be placed with its CubeSats inside the locker removing the central panel on the locker’s doors.

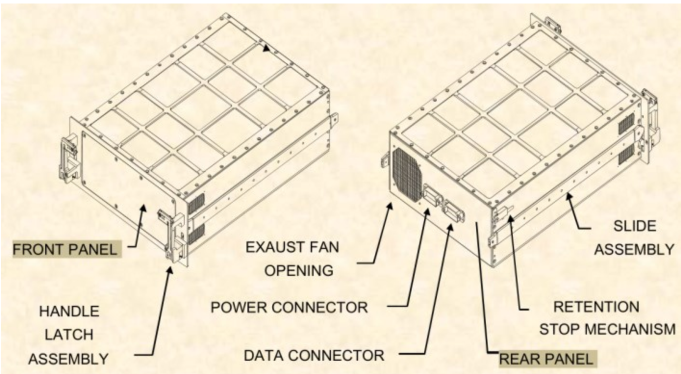


Figure 5.2.4 - ISIS Drawer representation (source: [5.3])
Power and data connectors are blind-mate, so connections are granted by simply inserted the drawer into the proper ISPR. As we see later, ISIS Drawer can be inserted into EXPRESS Racks and European Drawer Racks (EDRs).

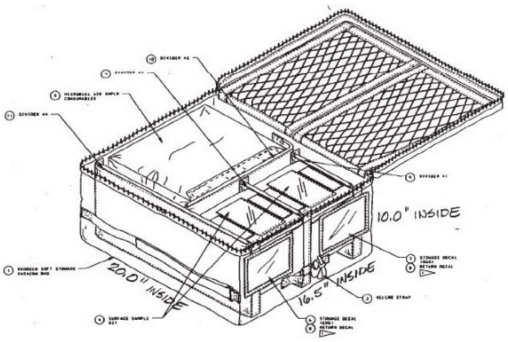


Figure 5.2.5 - Cargo Transfer Bag [5.6]
In this figure is represented the single CTB and in the table measures are given referring to this size. Other sizes exist: half, single, double and triple. Internally, removable and reconfigurable dividers and restrain systems are available. CTB have been used as stowage solution into MPLM, ATV and HTV and ISS.

Type	Width [in]	Height [in]	Deep [in]	Maximum load [lbs]	Weight [lbs]	Volume [litres]
Single MLE	18.5	11.25	21.5	50	14	73.32
Double MLE	18.5	23.00	21.5	100	< 28	146,64
Quad MLE	18.5	46.50	21.5	200	< 56	293,28
ISS Locker	17.34	9.97	20.32	59.5	13	56,63
ISIS Drawer	15.94*	5.88*	23.23*	?	26	35,68
CTB	19.75	9.75	16.75	60 (strapped)	4	?
CubeLab 1U **(only containers)**	3,94	3,94	3,94	Circa 2,2	Probably from 100 to 200 grams	1
19'' server 1U	19	1.719	?	?	?	?

Table 5.6 – Technical specifications of common payloads containers (Virgin values) [5.3] [5.4]
The three types of MLE differ only in height. The width value is incompatible with the ISPR racks, unless the central posts are removed. An average cargo for the single CTB is found at 22.6 lbs, and is about 38% of the maximum allowable load.
*internal measures

Alternatively, payload hardware could be attached directly to the cabin through a mechanical interface with a custom container, designed by the Payload developer or by the Principal Investigator. This solution surely increases costs and time access, due to the unstandardized approach that require more work for safety evaluations.
As for the mechanical interfaces:

- simple ISPR: they are support structures described in Chapter Two. To save weight, they will not be introduced in their entirety but only main structure elements, shown in figures, will be adopted for cabin design. See the detailed photos below with the measurements and the cad;
- EXPRESS Racks: it is a ISPR subtype, described in Chapter Two;
- European Drawer Rack: it is a subtype of ISPR, located at Columbus laboratory and aimed to provide a flexible access to the module services. It is compatible with up to four ISS lockers and three ISIS drawers, for a rapid and cheaper turnaround of payloads.
- FASTRack: also this interface has been described in Chapter Two, but information about it is very few and dated.
- 19'' Server rack: it is a standard frame to enclose electronic equipment. They are commonly used in server farm or scientific labs to attach computers into racks.
- Custom interfaces: in this case, existing mounting hardware are not used, but solutions are developed on the case study basis. It is likely the most expensive choice in terms of spent time and resources. Mounting plates proposed by Virgin Galactic for the SpaceShipTwo adaptation to experimentation mission are an example.

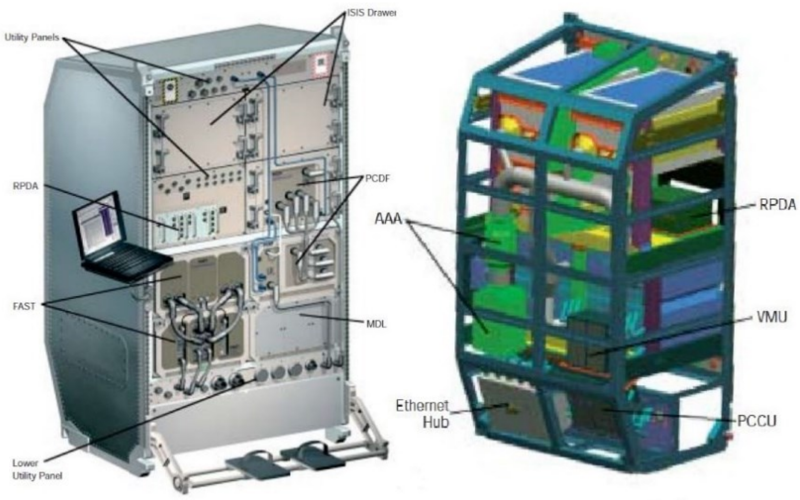


Figure 5.2.6 – European Drawer Rack (Front and rear views) [5.5]

EDR has five subsystems to distribute resources to payloads. They are:

- Power Distribution Unit (PDU): it distributes Columbus main power at 120 V DC to ISIS drawers and converts it to 28 V DC for ISS lockers. In both cases current is available up to 10 A.
- Process Control and Command Unit (PCCU): this subsystem is a communication interface between Columbus and EDR payloads. It performs functions related to Command and data handling: distributes external commands, time and other data to payloads, manages the laptop interface, monitors and controls other EDR subsystems and downlinks payload data. PCCU can be reconfigured on orbit.
- Ethernet Hub
- Video Management Unit (VMU): it gathers high-data-rate analogue or digital video from payloads through NTSC interfaces and IEEE 1355 serial lines. A 72 GB data storage is available for high definition videos that cannot be directly transmitted by downlink.
- Avionics Air Assembly (AAA)

Cooling water, nitrogen and vacuum are simply connected to the front of payload containers. For the nitrogen provision there is a manual shut-off valve.

Now that a brief overview on possible implementation of products has been presented, the cabin design can be effectively started. Two main parameters to be determined are cabin length and width.
These two quantities depend on various factors, that are listed:

1. Number of payload that the cabin shall to accommodate per flight. It is an average value that it has been found with market analysis performed in the previous chapter. 5 seat/cargo equivalents resulted and so, considering that an equivalent stands for 3.33 Middeck Lockers, it gives 17 Middeck Lockers Equivalent to be accommodated for each flight.
2. Payload containers dimensions. They are provided in table 5.x;
3. Number, type of Mechanical Interfaces and their dimensions. The number derives from the previous two points;
4. How elements are disposed internally;
5. Manoeuvring spaces necessary for the installation of payloads. Operations heavily affect a system sizing process and each phase should to be analysed to derive possible constraints or design opportunities.
6. Any spaces for subsystems or other functions. For example, the Payload Specialist location, or the space required for cable lying.

Following the points order, it is worth to discuss about the first, strictly related to the loading capability.
The Tauri Group analysis had equated a position to about 3.33 middeck lockers. In reality this is an average value, that was made estimating accommodation capabilities of ten suborbital vehicles [5.2, p. 1]. The value must therefore be taken with a grain of salt and is absolutely indicative, because in the average we take vehicles with very different purposes and requirements. It is sufficient to think about the Lynx, a spaceplane with a strong orientation to experiments: with only one seat and its small size it can accommodate as many as 28 middeck lockers. Another case that it is worth pointing out is the SpaceShipTwo, with similar characteristics to the study case of this thesis. Its payload capacity is estimated from reference [5.2] as 36 middeck lockers, so the seat/cargo ratio would be 1: 6 and not 1: 3.3.
Furthermore, it does not state whether equivalence is valid in terms of weight, volume or both. To figure out the meaning of this equivalence, the Middeck Locker Quad, a container which is slightly more capable than 3.33U, can help. Its structure weights less than 56 lbs and it can carry up to 200 lb, so it results is a total weight of 256 lbs (116.22 kg), a value that may be approximated to the weight of a person plus a seat and relative structure. The weight equivalence can be considered as satisfied. The equivalence in volume instead is not satisfied as can be seen from the comparison made with a CAD software: as for the volume of the passenger seat the distance between one seat and another must also be considered, as well as the necessary space above the passenger's head.

This unclear equivalence has been presented to underline that carrying a market analysis has a very strong influence on design. The cabin will be sized basing on the requirement "The cabin shall accommodate at least 17 Middeck Lockers Equivalent" that derives from the Tauri Group analysis. If it is unclear or outdated, a system will be likely uncapable to satisfying customers' requirements. Because of the current design has only didactical purpose, the equivalence value of 3.33 is taken, so the requirements rest valid even because the mass equivalence has been satisfied.

Figure 5.2.7 - Comparison between seat for passenger and middeck locker quad
The man figure, 1.80m tall, help to give the idea of the dimensions. The middeck locker quad only occupies the seat, while for equivalence in terms of volume a cargo/seat should take into account the total occupation of the entire location.
The seat has been obtain from GrabCad.

Before focusing on the second point, it is crucial to report an idea from a reference consulted during a research conducted by the author on the suborbital commercial market:

"It is expected that most microgravity science and research payloads will elect to use the standard payload interfaces and modules found on the Shuttle and ISS, specifically the mid-deck locker (MDL) payloads found in an ISS Express Rack.[…] Principal Investigator developing an ISS research payloads will typically spend years of time and millions of dollars in staff cost and hardware development, fabrication, testing and qualification expenses prior to actually getting the payload manifested for flight." cit. [5.1].

As the suborbital flight could be seen as a preliminary step for experimentation campaigns on board the International Space Station, it would be convenient provide the same interfaces findable on ISS. So, in the related trade-off, 9 value would be assigned to efficiency for these elements. Such trade-off, indispensable to understand which type of container and mechanical interfaces to insert in the cabin, follows.

	Safety	Simplicity	Innovation	Cost	Effectiveness		Prioritization
	0.26	0.18	0.06	0.24	0.29		
MLE	9	9	3	9	3		7.17
ISS lockers	9	9	3	9	9		8.91
ISIS drawers	9	9	3	9	9		8.91
19'' server	3	9	3	9	3		5.61
CubeSat	9	9	9	9	3		7.53
ISPR	9	9	3	9	9		8.91
EXPRESS Rack	9	9	3	9	9		8.91
EDR	9	9	3	9	9		8.91
FASTRack	3	9	9	9	3		5.97
19'' Rack	3	9	3	9	3		5.61
Custom Interfaces	0	3	9	3	3		2.67

Table 5.8 - Trade-off for payload containers and mechanical interfaces

All elements listed are safe and relatively simple. Custom interfaces are not intrinsically unsafe but safety analysis shall to be performed. Moreover, they as likely 19'' rack and FASTRack have not flew on a space mission and related data are unavailable. ISS lockers are more functional because they are compatible with

ISPRs. Instead, the servers can only test electronics and are therefore less flexible. FASTRacks are flexible but are designed to support only 2 MLE, so all the above space would not be used. The custom interfaces are effective but there is the risk of having to change them often basing on evolution of the market. They also require time and resources to be developed, while other elements are immediately available. CubeSat container for CubeLabs can only test CubeSat or very small payloads.

The trade-off analysis's result indicates a preference for ISS lockers, ISIS drawers and ISPR Racks. Since a rack can accommodate 8 ISS lockers and 2 drawers, the demand can be satisfied by two racks. Any remaining spaces into the cabin can be exploited through smaller and more flexible containers in terms of volumetric employment, such as CubeLabs and CTBs.
Before continuing it would be worth realizing the payload containers and racks into CAD, they will be needed later.
All CAD models of this thesis have been designed with SolidWorks 2017, a drawing software for parametric CAD which has been developed specifically for mechanical engineers. In other words, measures are defined with keywords, to whom numerical values (for this thesis in inches) are assigned in a specific table, that is also shareable between models. In this way, modifying a parameter, for example the width of the MLE, length associated will change in the document and in related ones. To define the sketch it is also necessary to introduce the so-called constraints between lines and points, for example parallel, coincident and fixed point. With SolidWorks, it is possible to perform a structural analysis of the drawing, hypothesizing a force load configuration. These type of analysis will not be performed into this thesis, but it is fundamental in the sizing analysis, because can enlighten possible structural weaknesses or spot when some material can be removed saving mass.

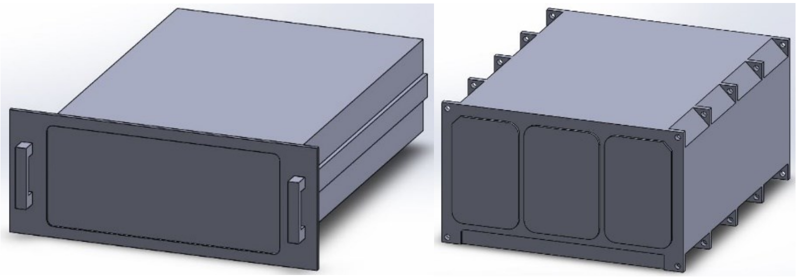


Figure 5.2.8 – CAD representations: ISIS Drawer and ISS Locker.
These drawings, as followings, are poor-detailed in order to simplify the execution of the preliminary design of the cabin.

Drawing the racks, measurements were taken from references [5.11] [5.12]. Some original drawings have been included in the appendix. Only two drawings with measures follow.

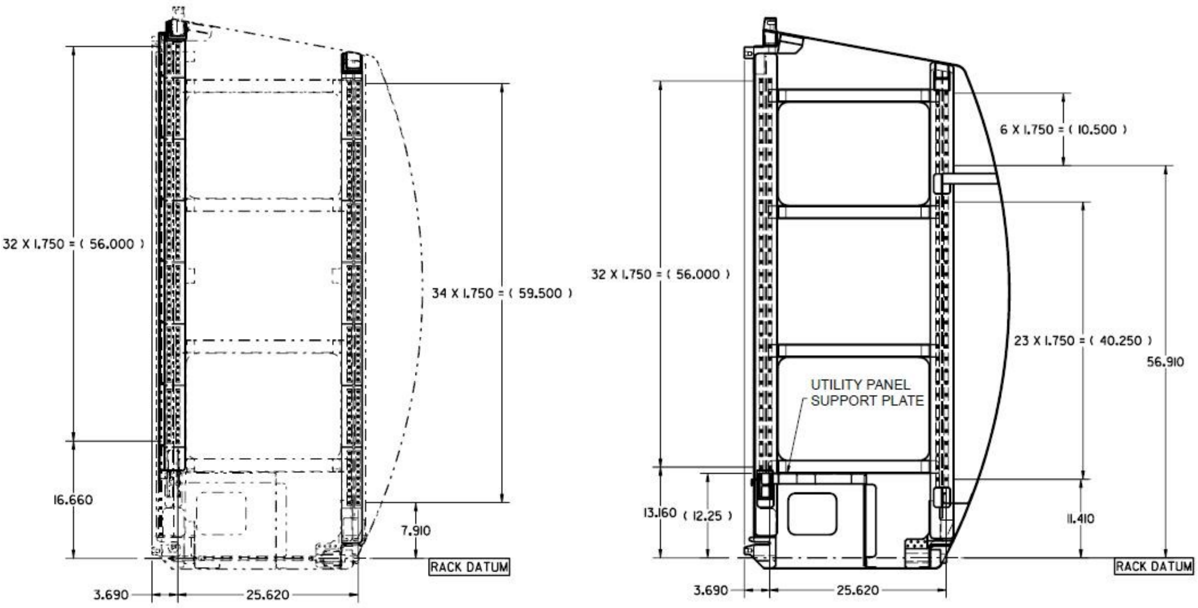


Figure 5.2.9 - ISPR central and lateral posts measures [5.7]

From the drawing it is assumed a distance between lockers (not MLE) equal to 1,894 inches. The distance of the central post which cannot be used at the top for middeck lockers measures 56 + 16.66-7.91-59.5 = 5.25 in. So the useful distance is 56- (56 + 16.66-7.91-59.5) = 16.66 + 7.91 + 59.5 = 50.75 in. The quad MLE can be comfortably measuring 46.50 inches in height. The rack width, including the posts, is: 25.62 + (3.375 -2.31) + 2.31 = 28.995 inch.

As seen before, a configuration that wants to emulate ISS interface has been chosen.
However, it is inconvenient to insert a complete rack inside the spacecraft, due to its weight exceeding 100 kg. For the CAD representation it was decided not to represent an ISPR in its entirety, but only the main structural elements, the posts, trying to save as much material as possible. In other words, only the mechanical interface elements with payloads are reproduced.
The key element of this design are the holes on the posts, which reflect in all those of the real case, including their height from the floor. It will then be possible to mount this lightened ISPR in a real version of the current case study instead of the original. However, it is clearly not certified and structural analyses must be carried out, with which it will also be possible to further reduce the mass. If you put a original rack in the cabin, with the same arm interfaces connecting the rack to the module wall, no structural analysis should be performed, because structural analysis on ISPR has already been completed by NASA and the product has been certified for launch.
The following figure shows how secondary structure elements permit to fix payload containers to posts.

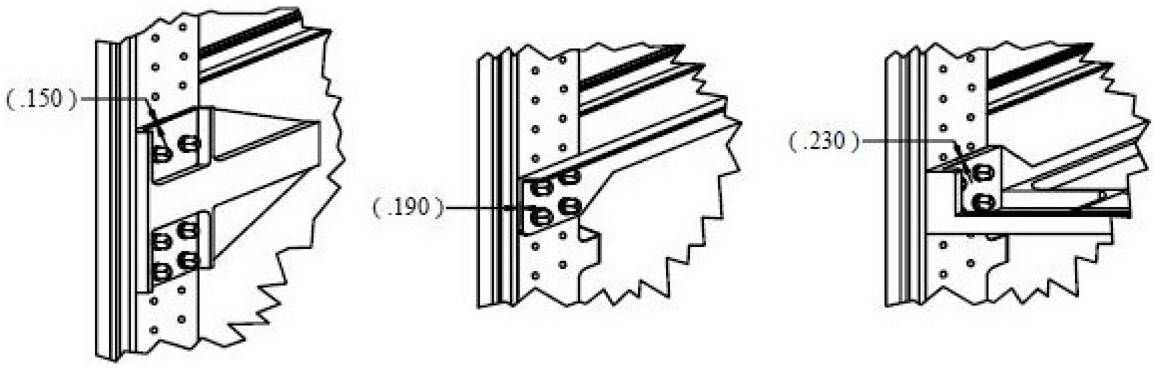


Figure 5.2.10 - Examples of three possible payload attachments to post [5.7]

Figure 5.2.11 - ISPR representation in CAD

Since the side panels that give rigidity to the rack are not present, they have been replaced with reinforcement plates, in order to keep the weight low and give adequate transversal stiffness. Furthermore, the upper cross member [5.11, page 3-22] is inserted. The lower part of the rack has been modified, fixing the posts to the floor with flanges.
The original NASA ISPR weights about 100 kg. This simplified version weights 75 kg, with a savings of 25%. This data was obtained through a specific function of mass calculation of SolidWorks, starting from the density of the material that has been fixed at 2810kg / m ^ 3, density of aluminium alloy 7075, that is the material of the structural elements of the NASA ISPR.
Into the cabin, it will be sufficient to assemble the parts progressively upwards and towards the front. If more space is required, the central post can be removed. If it occurs to introduce some custom containers, they shall be designed to be compatible with the existing holes on the post. Detailed photos of the CAD are present in the Appendix C.

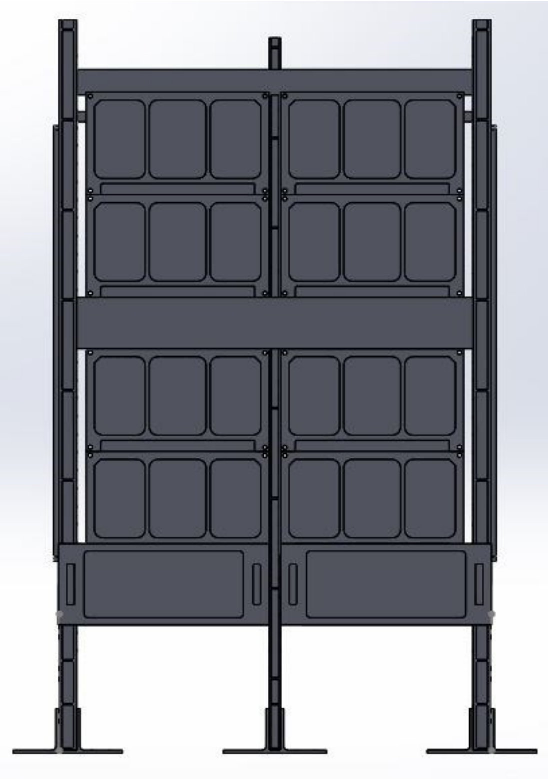


Figure 5.2.12 – CAD representation of EXPRESS Rack
All measurements are taken from the sources and checked accurately. The only ones that have been hypothesized are the heights of the control panels, but with a good estimation.
Disegnare i fori nelle control panel e l'utility interface panel sotto.

The minimum Payload Specialist's location shall to be composed by a seat, representing by CAD in the figure.
The work of the Payload Specialist during the mission is:

- To monitor payloads and its parameters and functions to determine if they are nominal;
- To take action as far as possible in case of malfunctions
- To execute simple activities, such as enable determined equipment manually;

Spaces required for payload installation and recover are further discussed during the sketching. Clearly it shall be sufficient to allow passage of an operator with an ISS locker or ISIS drawer. Basing on shape chosen in the Embraer figure, the aisle can surely be designed for this purpose. Another essential element is the hatch: it is supposed the same of that adopted by Virgin Galactic.
Now we have all information to estimate the length and width of the cabin. Only a sketch, a cross-sectional view, is produced to estimate the fuselage diameter, thinking how the two ISPRs has to be located internally. Then, the CAD can be used to determine length of the cabin.
Unlike what is written in the methodological part, the sketch in this specific case can be avoided for determine that parameter, because the two ISPRs that have to be accommodated have already been CAD-represented with the actual measurements. More specifically, the design was carried out by first drawing a temporary cabin assuming a generic length and a radius indicated in the figure. Then the hatch, the two ISPRs and the PS location were allocated. The cabin has therefore been shortened of the necessary. Only the results of this procedure are presented here.

Figure 5.2.13 - PS's CAD representation [source:GrabCAD]
Author: Tom Van Ryn

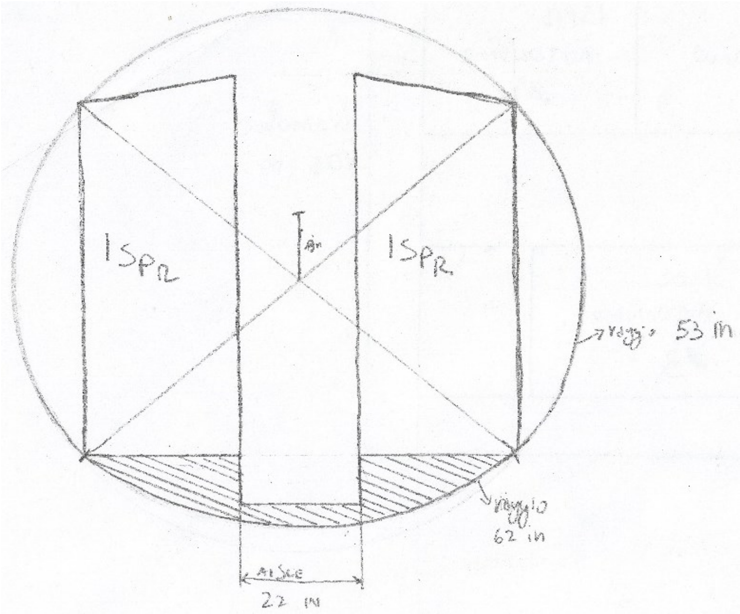


Figure 5.2.14 - Cross section of the cabin, two ISPR opposed (cabin)

The cross section is not precisely a circle, but it is the result of the intersection of two circles. A reason that conducted to the choice of a circular section is that this shape is the best for endure pressurization.

Figure 5.2.15 - Cabin, front view

This configuration provides an intermediate aisle (22 inches wide, chosen from page 116, part II, Roskam [5.9]), which allows the pilot to reach the cabin without an additional hatch, and it would be width enough to install payloads inside the ISPRs. The diameter that envelopes the cross section is 2.68 m. For a comparison, diameter on SpaceShipTwo is 2.3 m

The cabin result 2.31 m long. Within the CAD SolidWorks environment, carbon fibre has been set up as a material. Therefore, given the geometry and density of the material, the software calculated a weight of only 1035 kg. In the photo below you can see the elliptical hatch and a circular window. In order to lighten the structure the floor is hollow and reinforced with some ribs, as shown in the third figure.

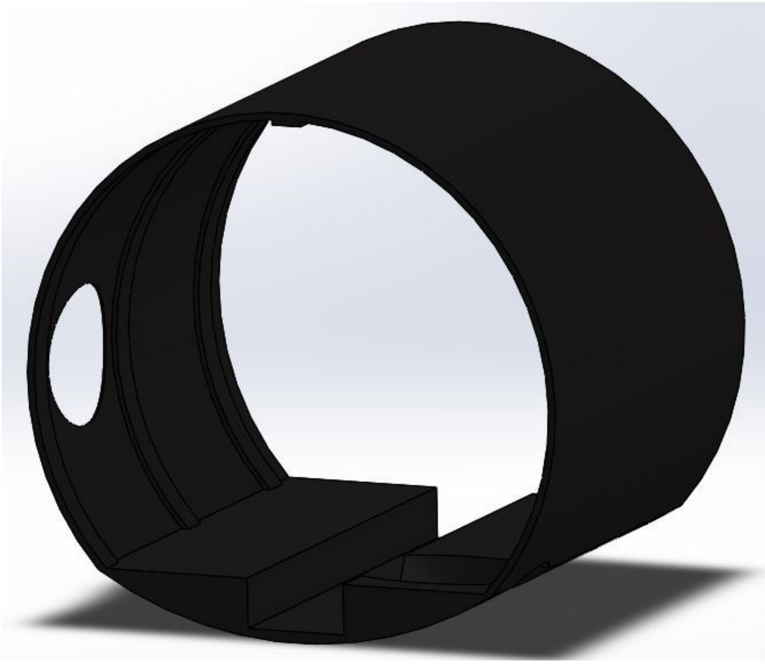


Figura 5.2.16 - 3D view of the Cabin

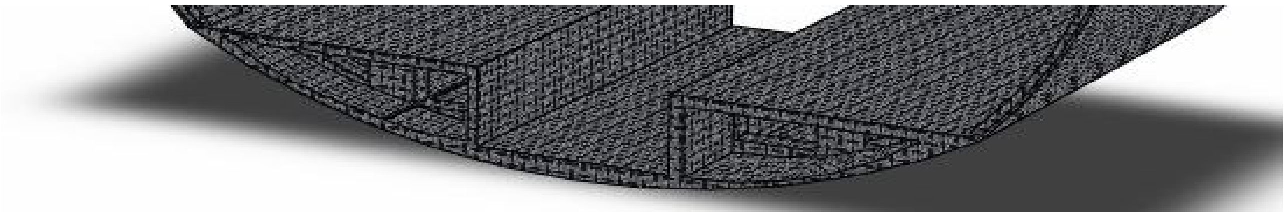


Figure 5.2.17 - Focus on the internal ribs

Following figures focus on the mechanical interfaces for payloads. ISPR have been chosen thanks to their standardization onboard the ISS, giving the opportunity to integrate together suborbital and orbital research. The purpose of the next trade-off is to find out which subtype configuration is better for a suborbital application. For "simple ISPR" is mean only the six-posts complex shown in figure [ispr cad].

	Safety	Simplicity	Innovation	Cost	Effectiveness		Prior
	0.26	0.18	0.06	0.24	0.29		
2 simple ISPRs	9	9	3	9	0		6.3
2 EXPRESS RACKs	9	3	9	3	3		6.75
1 EXPRESS RACK and 1 simple ISPR	9	3	9	9	9		8.19

Table 5.9 - Trade-off

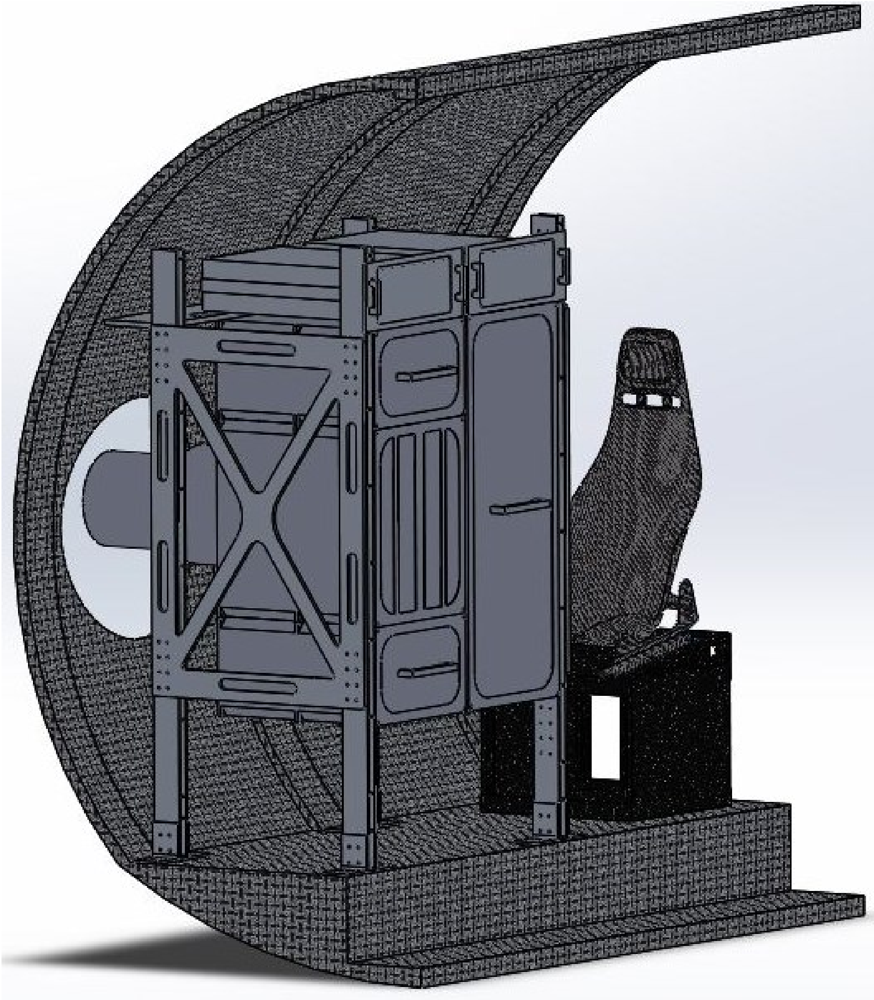
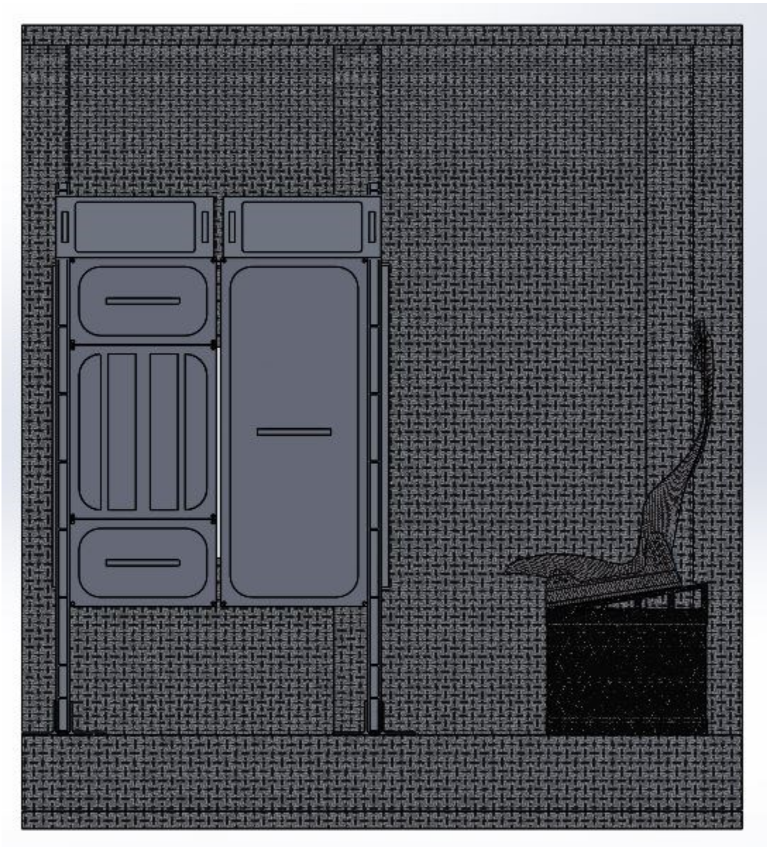


Figure 5.2.18 – Starboard 3D view and 2d view

Locating two simple ISPR is extremely straightforward and it does not require any connection to vehicle subsystems. All payloads must nevertheless be equipped with all required hardware, such power system or data storage devices. Two EXPRESS Rack permits to payloads to take advantage of commonly useful resources, more similarly to what happens on the ISS. A significant amount of payload however could be services-independent, with the risk of oversizing subsystem required to EXPRESS Racks. Moreover, this ISPR subtype has a unremovable backplate that prevents the allocation of large payloads. The result could me more mass and less effectiveness.

Finally, one EXPRESS Rack and one simple ISPR appears as the best compromise between two mechanical interfaces, providing on one hand simplicity and the possibility of accommodating oversize payloads and on the other hand the flexibility of integrated services.



In conclusion, this is therefore a cabin optimized for the testing mission, following the methodology process form data of the Tauri's market analysis. Now it is possible to return to the system level and choose an aerodynamic configuration. In fact, cabin's diameter and length, respectively 2.68 m and 2.3 m, gives this fuselage portion a squat shape. For this reason, it might be worth evaluating a lifting body configuration, after performing proper considerations.

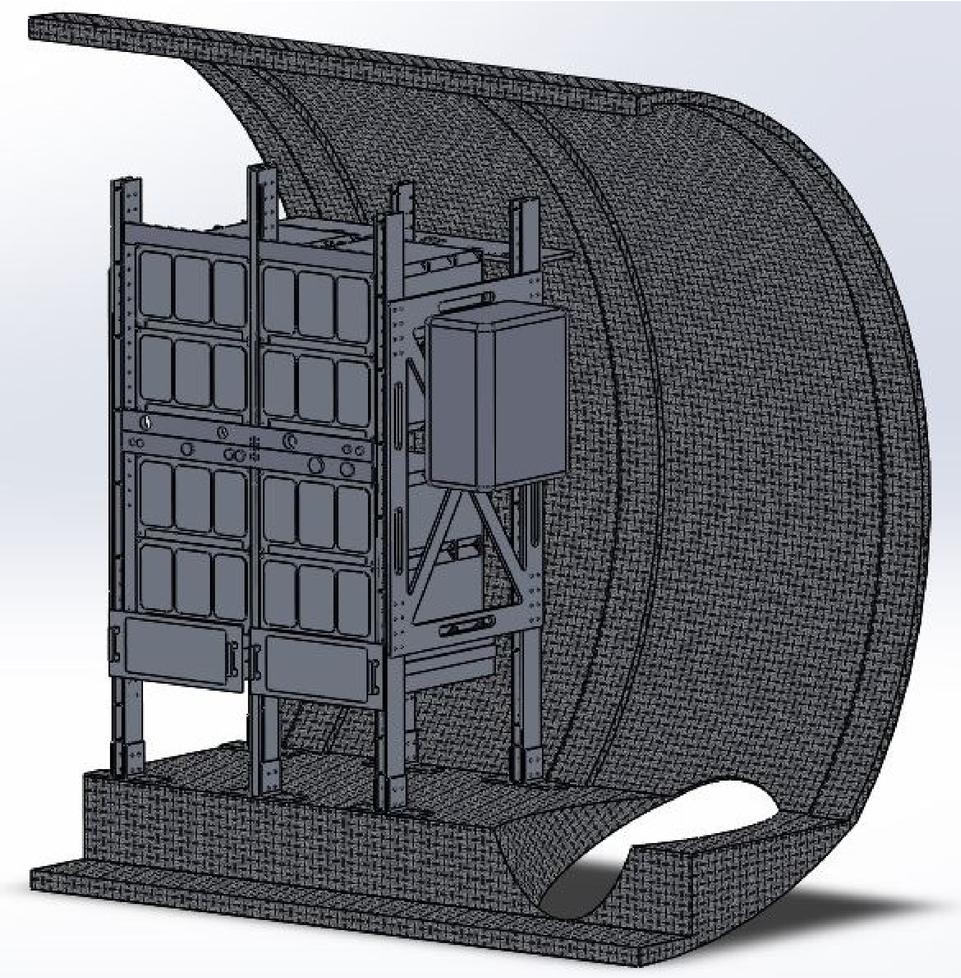


Figure 5.2.19 – Port 3D View
On this side a simple ISPR is located. It is possible, removing the central post, to accommodate containers not specifically designed for ISPRs, such as Space Shuttle Middeck Lockers. In this case of example, a quad MLE, two ISIS drawers and two single MLE are located. In addition, a generic simple telescope model is putted corresponding to the window, that can be equipped with high performance glass for remote sensing.

Towards the stern is the Payload Specialist location. He can monitor payloads parameter and interact both with the ISPR in front or with the EXPRESS Rack on his left side.

As mentioned before, the seat as been taken from Internet, but the basis has been designed by the author. In fact, to increase effectiveness of the spaceplane, it seemed worth taking advantage of that space to accommodate additional payloads. So the basis, made of carbon fibre, has been designed basing on standard of the 19'' racks, so it is possible to insert servers and other electronic equipment, equipped with their own power system (unless future changes). This solution has been inspired form the Lynx Spaceplane discussed in Chapter Two. Moreover, as in the Lynx case, it is possible to accommodate in a 19'' rack also other types of payloads, such lockers, with an appropriate mechanical interface. Also this location is within PS's reach.

For more detailed CAD see Appendix C.

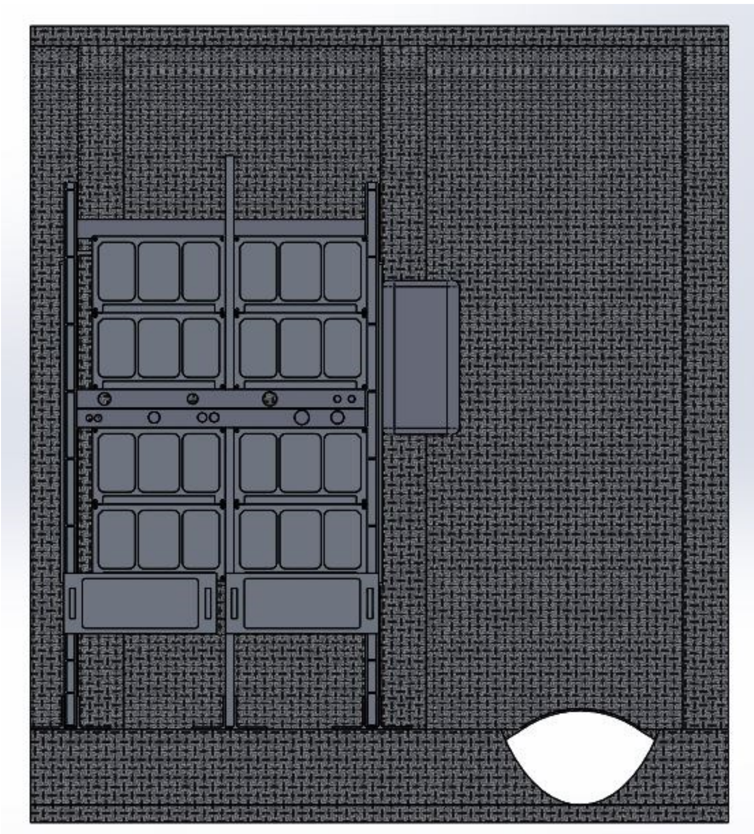


Figure 5.2.20 – Starboard 2D view
Towards bow the elliptical hatch has been located, and the EXPRESS Rack is next to it. Above the hatch is it possible to attach a Nomex CTB, to increase cargo capabilities. The payload into the CTB, if active, has to be completely autonomous.

5.2.2 Electric System development

To feed the payload with electrical power	To generate electric current
	To connect payload with current source
	To provide protection against overcurrent
	To provide proper voltage and amperage values

Functions	**Products**
To generate electric current	Electrical power source
To connect payload with current source	Cables
To provide protection against overcurrent	Circuit breakers
To provide proper voltage and amperage values	Power controller

For safety reason, the electrical system serving the payloads has been separated from that of the spaceplane.
At first, it is required to estimate the amount of power to feed payloads, in other words to define the power budget associated with the payload.
This is provided directly by the document [5.8] which states that the EXPRESS Rack support electrical power up to 2000 W.
Now it occurs to size the products and choose their type. For the study case, batteries can be used. A trade-off among all the available energy sources should be performed: radioactive sources, condensers, fuel cells, generators. Then it is required to make a second trade-off for the battery type: the lithium ion has chosen, thanks to the rapid discharge capability.
The 2000 W, full electrical load of the rack, must be supplied continuously from detachment until the end of the coasting phase, so for a time that is estimable at 6 min.

Capacity of the battery assembly is given by the following formula:

$$C_r\ [Wh] = \frac{P\ [W] \cdot t[h]}{DOD \cdot \eta}$$

- P is the maximum power required, 2000 W;
- t is the time of discharge, 6 min= 1/10 h;
- DOD represent the Depth of Discharge, that is the percentage of total capacity that will be discharged at the end of the performance. For lithium-ions batteries 80% is considered a deep discharge (in this case DOD=0.8). For this case study a DOD=0.75 is chosen;
- is the transmission efficiency between the battery and the load, supposed 0.9;

With these values it results $C_r = 277.8\ Wh$.
Often the amount of energy stored in the batteries is expressed in mAh, id est the amount of electrical charge needed to deliver one milliampere of current for one hour. We carry out the conversion, keeping in mind that the supply voltage will be probably v = 28 V, supply value of the majority of space made batteries.

$C_r\ [mAh] = 1000 \cdot C_r \cdot v$ = $9922\ mAh$.

With this value it is possible to apply the methodology for designing a battery or look for a ready-made one on the market, possibly among the components called COTS. This second strategy has been pursued and specifications of a battery model identified on the market follows. It was chosen because it is specifically designed for space applications with several levels of safety.

28V Space Grade Battery System (28VSG)		
Manufacturer	SAFT	
Mass	11.5 lbs	
Nominal voltage	28 V	
Capacity	3000 mAh	
Maximum charge voltage	32.8 V	
Max continuous discharge rate	30 A	
Pulse discharge capability	250 A @ 200ms	
Width	5.5 in	
Length	8.68 in	
Height	6 in	
Features	Designed for high levels of shock and random vibrations, respectively 1300G and 40 Grms, particularly suitable for rockets and launchers.	
	Separate charge path and electronics for charge monitoring	
	Built-in electronics for overcharge detection and prevention, voltage and temperature monitoring, cell balancing	
	Internal heater for low temperature application	

Table 5.10 - Technical specifications for the battery chosen [source: battery datasheet from Saft website: https://www.saftbatteries.com/]

The Pulse discharge capability refers to the current the battery is capable to supply for very short amount of time (200ms for the current case).

Four batteries of this type are sufficient for the application, since through a parallel connection it would reach a capacity of 12000 mAh.

However, it is necessary to make a note on the maximum discharge current, which for the chosen battery is equal to 30 A. Supposing to supply 2000 W at 28 V, there would be a discharge current of 71.43 A, higher than the reference value. Dividing by 4, however, since the batteries are in parallel configuration, the discharge current stands at 17.86 A. The achievement of high currents for a substantial time interval can be source of thermal problems and potential failures, so it is necessary to verify with the manufacturer the thermal requirements of the batteries if high discharge currents are assumed. Mass of the battery pack will be 46 lbs (about 20.9 kg).

For the cable an insulated 2 AWG (American Wire Gauge) copper cable has been chosen. It has a cross-section of 33.6 mm^3, based on the table at http://amasci.com/tesla/wire1.html#awg, and on the fact that in the cable should pass in the worst case about 71.42 A. In the case of the ISS, the cables that connect the ISPR to (see what they are connected to) are smaller, 8 gauge, because voltage is higher, ranging from 114.5 to 126 V DC [5.9].

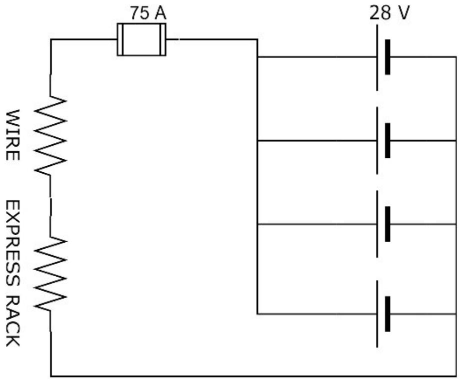


Figure 5.2.21 - Circuit diagram of the cabin's electric subsystem

In order to improve safety, it is independent from the electric subsystem of the vehicle, so in case of its failure, the mission can be safely aborted or concluded with reduced performances.

The greatest risky components are certainly the batteries. They will be placed outside the cabin (after choosing if this area must be pressurized) where temperature and fire sensors can also be arranged.

AWG	Cross-section [mm^2]	Resistance [Ohms/Kft]	Resistance [mOhms/m]	Weight [Lbs/Kft]	Conservative current [A]	Maximum current [A]
2	33.6	0.1563	0.5127	200.90	88.492	132.74

Table 5 - Cable specifications [source: http://amasci.com/tesla/wire1.html#awg]

A fuse has been added to the circuit for protection during any system faults.

The loss of voltage in the cable between the battery and the ISPR is considered negligible: in fact, assuming a 3 m long cable (indeed it will be supposedly much shorter) and applying the law of Ohm:
ΔV = RI = 0.5127 * 1000 * 3 * 71.42 = 0.109 V, equal to 0.4% of the provided voltage.

The power supply for the express rack designed here is so very different from the analogous one on the ISS. Therefore it is necessary to modify the electrical sub-system of the EXPRESS Rack, removing also all the components working at 120 V. A diagram representing that modified subsystem follows.

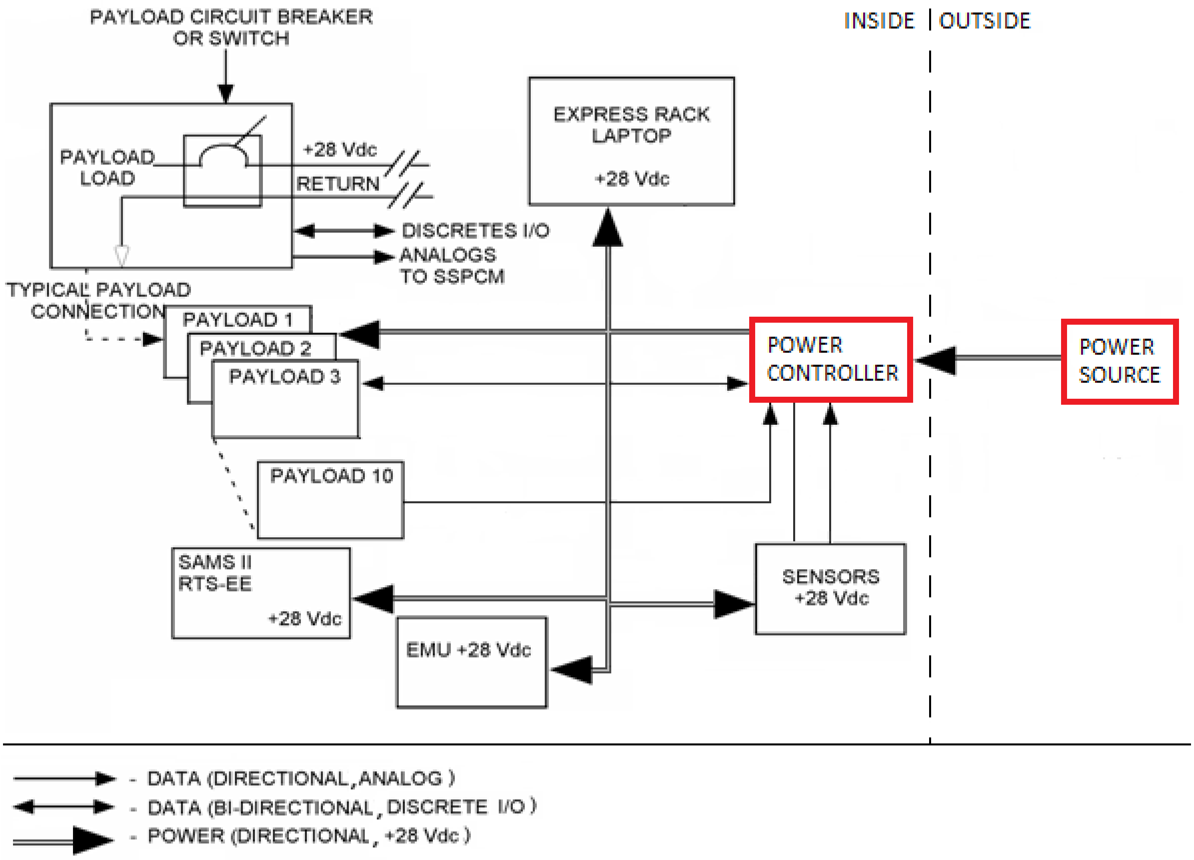


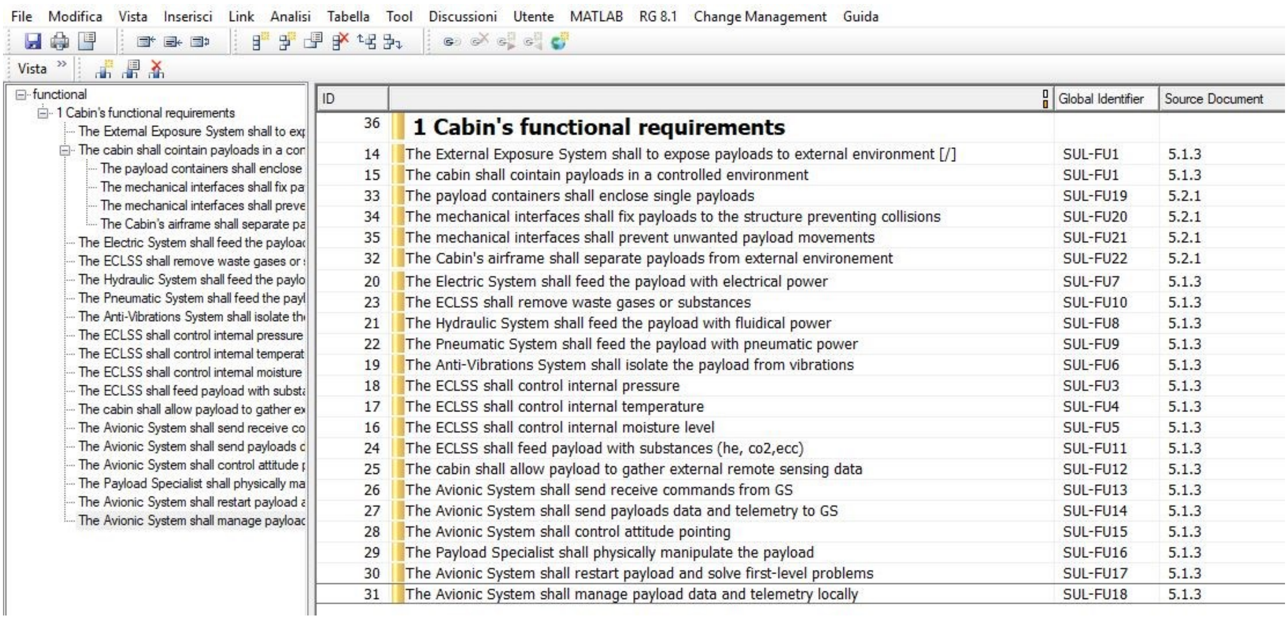
Figure 5.2.22 - Simplification of the EXPRESS Rack electric power distribution diagram [obtained modifying the diagram at source 5.7, reported into Appendix]

5.3 REQUIREMENTS TRACEABILITY VIA DOORS AND SIMULINK

Taking advantage from these two software, it is possible to show visually which requirements, previously implemented into DOORS, are related to the CAD imported into Simulink. In other words, it is possible to associate to an assemble or even its parts some requirements. This is particularly useful during verification process: from the CAD it is possible to flow upstream to requirements that have generated that CAD object or equally to requirements that have to be satisfied by that object itself. To do this, it is possible to follow the subsequent procedure:

- export the CAD assembly clicking on ***Tools>Simscape Multibody Link>Export***, after installed the tool into SOLIDWORKS. An xml file will be created and this could require several minutes;
- open MATLAB with administrator privileges;
- execute the command ***rmi setup*** and then ***[1]***;
- after confirmation "Installation succeeded", open DOORS with administrator privileges;
- execute the command on MATLAB ***smimport('filename.xml')***, checking that the file is in the current directory. This operation could require several minutes;
- save Simulink model (slx file);
- open the DOORS formal module that corresponds to the CAD draw that is desired to enrich;
- on Simulink open the desired element subsection and, with right mouse button menu, click on ***Requirements traceability>Link to selection in DOORS***;
- clicking on ***Requirements traceability>Open link editor*** it is possible to check requirements inserted.

Before performing this procedure, requirements have been imported into DOORS's formal modules, for each requirement class. The import procedure is simple: it is sufficient save requirements into a txt file, checking than all requirements are separated by a black raw. Then click on ***File>Importa>Testo normale*** select such file. Each requirement is automatically matched with a number called ID, that identify each requirement within the formal module. However, considering all formal modules, more than one requirements likely have the same ID. It is possible to overcome this problem adding information to the requirement list, through new columns, called "attributes", for example a Global Identifier, that assigns a univocal code to each requirement, valid for the entire requirements repository. To add this type of data under the form of column it is sufficient to click on ***Modifica>Attributi>Nuovo***. The following image explain this more clearly.



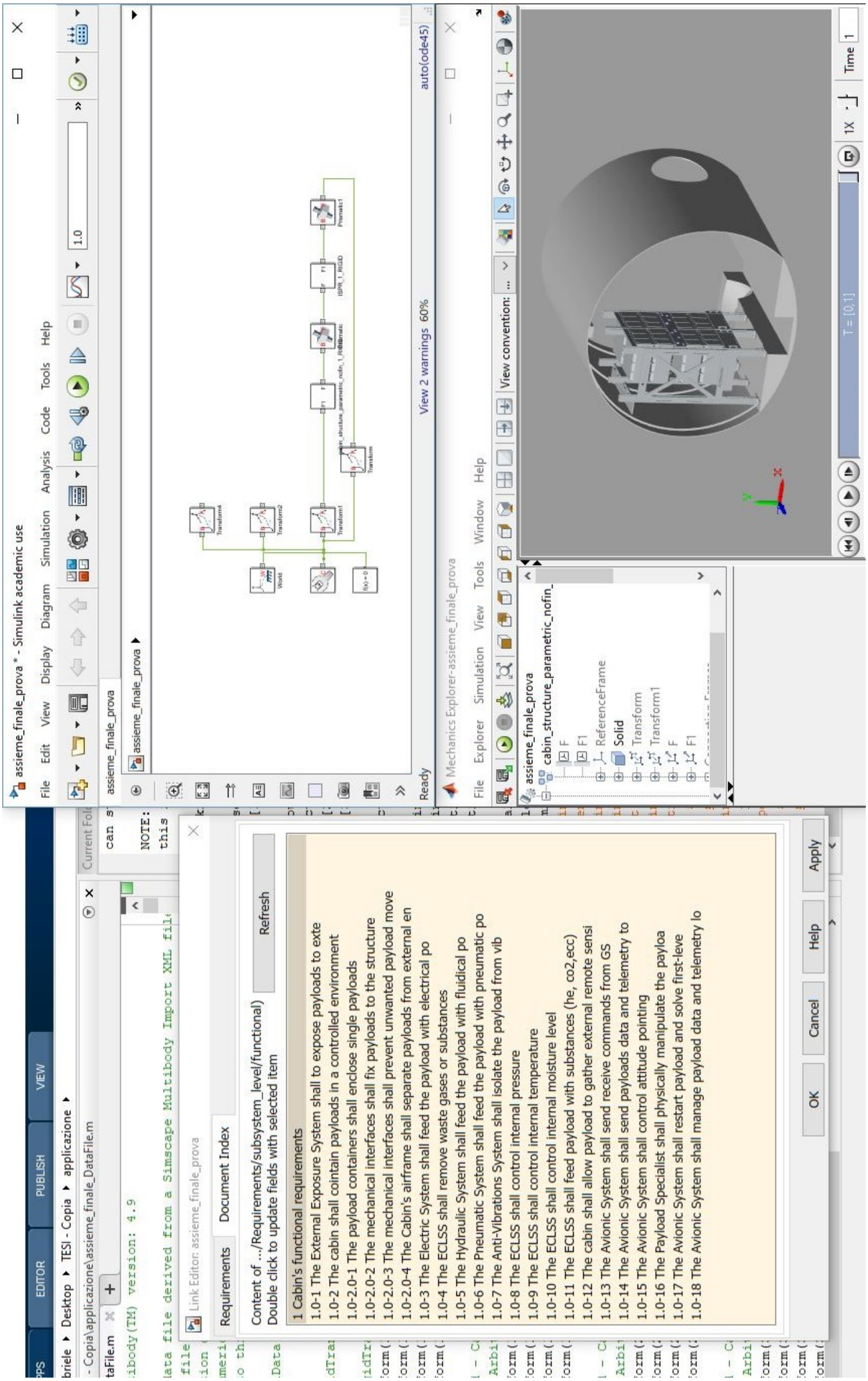
ID		Global Identifier	Source Document
36	**1 Cabin's functional requirements**		
14	The External Exposure System shall to expose payloads to external environment [/]	SUL-FU1	5.1.3
15	The cabin shall cointain payloads in a controlled environment	SUL-FU1	5.1.3
33	The payload containers shall enclose single payloads	SUL-FU19	5.2.1
34	The mechanical interfaces shall fix payloads to the structure preventing collisions	SUL-FU20	5.2.1
35	The mechanical interfaces shall prevent unwanted payload movements	SUL-FU21	5.2.1
32	The Cabin's airframe shall separate payloads from external environement	SUL-FU22	5.2.1
20	The Electric System shall feed the payload with electrical power	SUL-FU7	5.1.3
23	The ECLSS shall remove waste gases or substances	SUL-FU10	5.1.3
21	The Hydraulic System shall feed the payload with fluidical power	SUL-FU8	5.1.3
22	The Pneumatic System shall feed the payload with pneumatic power	SUL-FU9	5.1.3
19	The Anti-Vibrations System shall isolate the payload from vibrations	SUL-FU6	5.1.3
18	The ECLSS shall control internal pressure	SUL-FU3	5.1.3
17	The ECLSS shall control internal temperature	SUL-FU4	5.1.3
16	The ECLSS shall control internal moisture level	SUL-FU5	5.1.3
24	The ECLSS shall feed payload with substances (he, co2,ecc)	SUL-FU11	5.1.3
25	The cabin shall allow payload to gather external remote sensing data	SUL-FU12	5.1.3
26	The Avionic System shall send receive commands from GS	SUL-FU13	5.1.3
27	The Avionic System shall send payloads data and telemetry to GS	SUL-FU14	5.1.3
28	The Avionic System shall control attitude pointing	SUL-FU15	5.1.3
29	The Payload Specialist shall physically manipulate the payload	SUL-FU16	5.1.3
30	The Avionic System shall restart payload and solve first-level problems	SUL-FU17	5.1.3
31	The Avionic System shall manage payload data and telemetry locally	SUL-FU18	5.1.3

Figure 5.3.1 - View of a DOORS formal module (specifically the module of functional requirements)

Adding new attributes has been possible include the column of global identifiers, for the univocal identification of requirements, and the column “Source document”, that in this case match each requirement with the corresponding paragraph of this thesis that explains it and its origin. On the left part of the figure it is possible to see the hierarchic relationship that link each requirement.
The heading, the row with ID=36, although it could seem redundant, is important for the import procedure into Simulink, as it is shown below.

If attributes are not displayed when the module is opened, it is sufficient to click on ***Inserisci>Colonna*** and choose the desired attribute.

Now it is possible to apply the procedure shown at the beginning. Working with administrator privileges is important to avoid software crashes, that occurred with the author’s computer configuration in user mode. Likely, with other IT systems it is possible to perform the requirements traceability without these privileges, that decrease security. At Appendix B, the Simulink diagram translation of the CAD is shown.
In the following figure it is shown as an example of that software integration: a simplified CAD file, that describes the cabin’s structure and an ISPR represented in the right lower part of the figure, is obtaining via simulating the Simulink model. The complete CAD model of the cabin is too computationally heavy for a dynamic simulation, but can be used without simulating it for matching requirements with relative CAD parts. Above the CAD is presented the Simulink model, where blank blocks represent the two CAD elements, while other block describes mechanical constraints. In the left part of the figure, under the tab ***Document Index***, the functional requirements that the system “Cabin” and its subsystem shall to satisfy are highlighted. Selecting the tab ***Requirements***, it is possible to change requirement type, such as configurational or performances.
Into tab Document Index only first 66 characters of each requirement will be shown.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File Edit View Display Diagram Simulation Analysis Code Tools Help
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Mechanics Explorer-assieme_finale_prova
File Explorer Simulation View Tools Window Help
View convention:
assieme_finale_prova
cabin_structure_parametric_nofin_
ReferenceFrame
Solid
Transform
Transform1
Time 1
T = [0,1]
Link Editor: assieme_finale_prova
Requirements
Document Index
Content of .../Requirements/system_level/subsystem_level/functional)
Double click to update fields with selected item
Refresh
1 Cabin's functional requirements
1.0-1 The External Exposure System shall to expose payloads to exte
1.0-2 The cabin shall cointain payloads in a controlled environment
1.0-2.0-1 The payload containers shall enclose single payloads
1.0-2.0-2 The mechanical interfaces shall fix payloads to the structure
1.0-2.0-3 The mechanical interfaces shall prevent unwanted payload move
1.0-2.0-4 The Cabin's airframe shall separate payloads from external en
1.0-3 The Electric System shall feed the payload with electrical po
1.0-4 The ECLSS shall remove waste gases or substances
1.0-5 The Hydraulic System shall feed the payload with fluidical po
1.0-6 The Pneumatic System shall feed the payload with pneumatic po
1.0-7 The Anti-Vibrations System shall isolate the payload from vib
1.0-8 The ECLSS shall control internal pressure
1.0-9 The ECLSS shall control internal temperature
1.0-10 The ECLSS shall control internal moisture level
1.0-11 The ECLSS shall feed payload with substances (he, co2,ecc)
1.0-12 The cabin shall allow payload to gather external remote sensi
1.0-13 The Avionic System shall send receive commands from GS
1.0-14 The Avionic System shall send payloads data and telemetry to
1.0-15 The Avionic System shall control attitude pointing
1.0-16 The Payload Specialist shall physically manipulate the payloa
1.0-17 The Avionic System shall restart payload and solve first-leve
1.0-18 The Avionic System shall manage payload data and telemetry lo
OK
Cancel
Help
Apply

5.4 COMPARISON BETWEEN THE PRESENTED CABIN AND SPACESHIPTWO CASE [5.14]

An objective of this work is to assess if it is possible and convenient to convert an existing spaceplane designed for space tourist transport to experimentation missions.
In this chapter an already existing suborbital spacecraft is considered for its adaptation to experimentation missions, and then compared with the case presented into previous paragraphs. Among spaceplanes presented into Chapter One and Two, surely the most similar to the case study is the SpaceShipTwo.
The design process is clearly different from the adaptation process.
Firstly constraints and other those requirements that cannot be changed shall be considered. The dimensions of the cabin and of the hatches, the diameter of the windows and the width of the central aisle are certainly of this category. Lengths have been gathered by images 2.18, 5.4.1 and 5.4.2. All measurements of the interior of the cab have been obtained from the drawing assuming the drawing is to scale. In case of pre-existence of a cabin, so if a cabin has to be re-designed, it is the moment to introduce existing constraints as requirements. For example, if dimensions have been already fixed, two physical requirements should be added:

- The cabin shall have a cylindrical shape;
- The Cabin's length shall be 3.7 m;
- The cabin's diameter shall be 2.3 m;

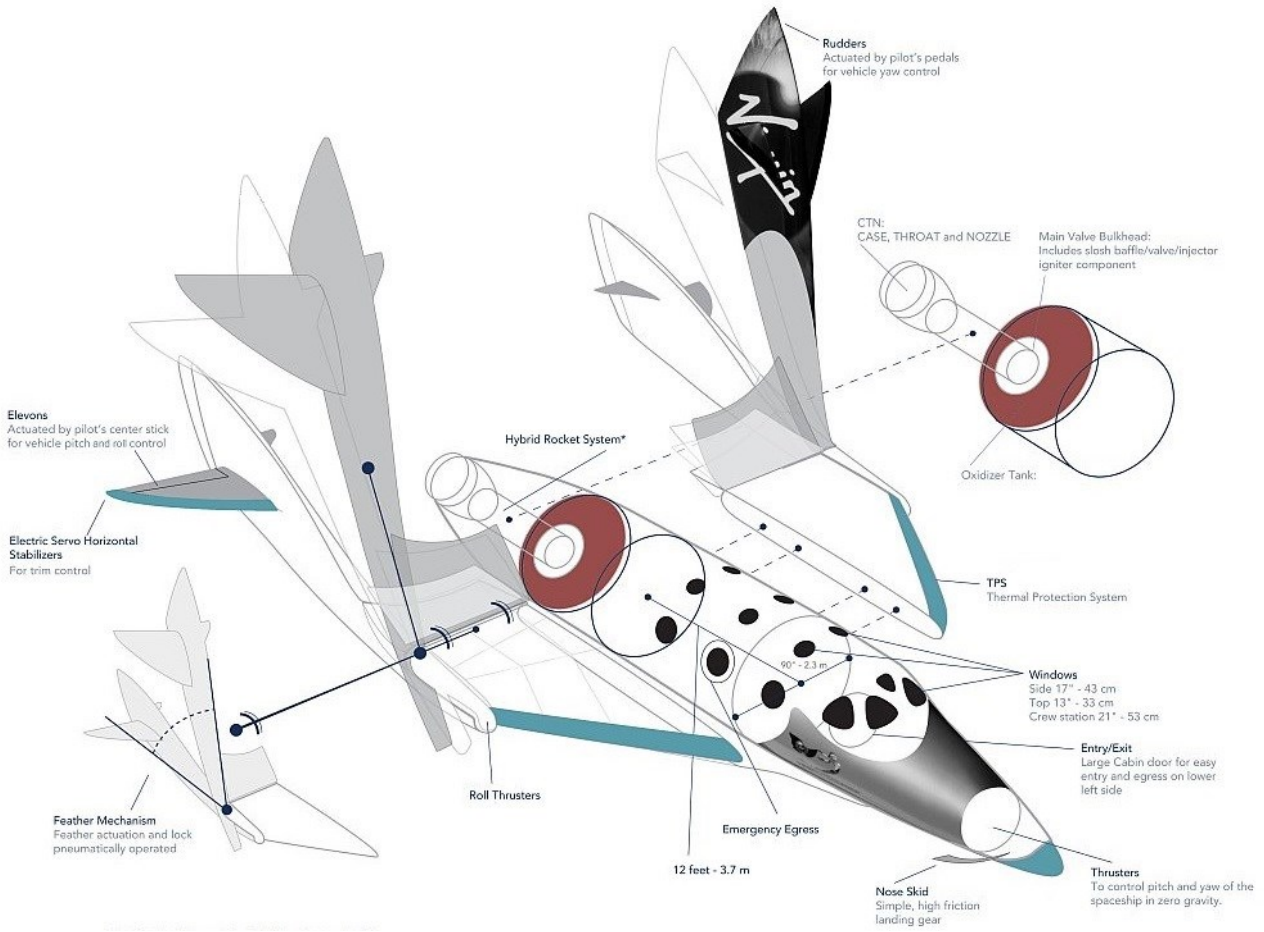


Figure 5.4.1 – SpaceShipTwo's design elements (source: Virgin Galactic)

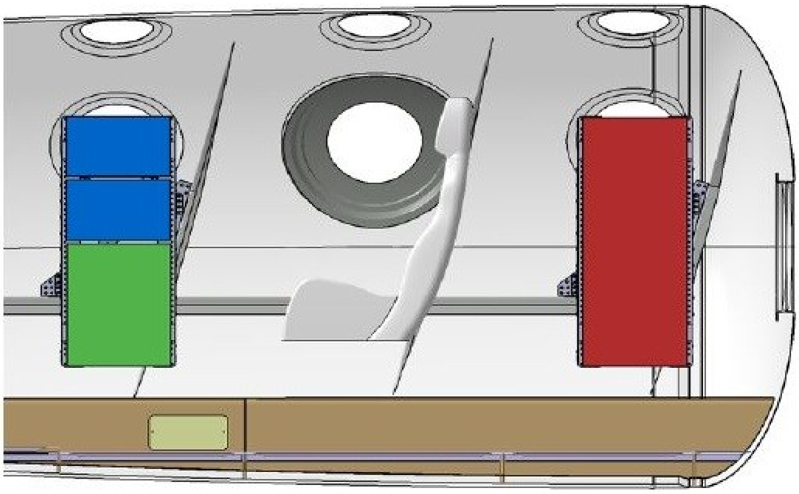


Figure 5.4.2 - SS2's cabin starboard section (source: Virgin Galactic)
Data for representation of the cabin's parametric CAD has been extracted from this drawing.

5.4.1 Cabin's adaptation

A good starting point is the official Virgin Galactic image shown in figure 2.18. Here 5 mounting plates that support middeck lockers are shown. Finally, a location is dedicated to the Payload Supporter. Each rack can hold up to 4 middeck lockers, so a total of 20. Each middeck weighs 14 lbs and can carry up to 50 lbs, for each flight, this configuration can carry up to (14 + 50) * 20 = 1280 lbs = 581 kg.
However, the author believes it is unlikely that this maximum volumetric efficiency is achieved, in other words that all middecks carry the maximum load allowed for each flight. Also with only 20 middeck lockers, the interior space is underutilized. 25 lbs (11.35 = kg) for each MLE, about 33 MLEs would be required to reach the total amount of 581 kg of transportable payload per flight. Guessing an average of payload mass of 25 lbs (11,35 = kg) for each MLE, about 33 MLEs would be required to reach the total amount of 581 kg of transportable payload per flight.
First of all, a CAD model of the cab was built, shown in the figure.

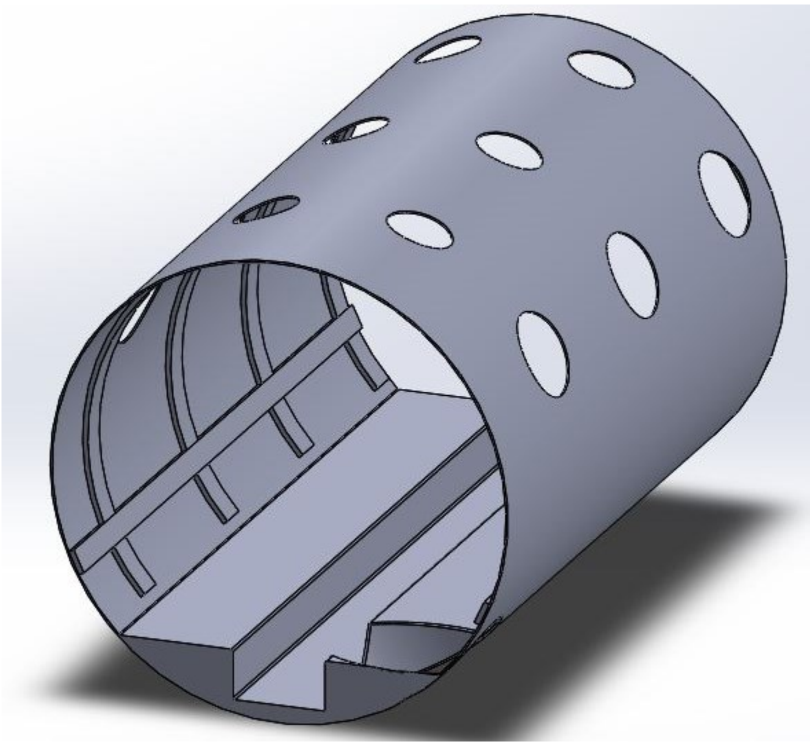
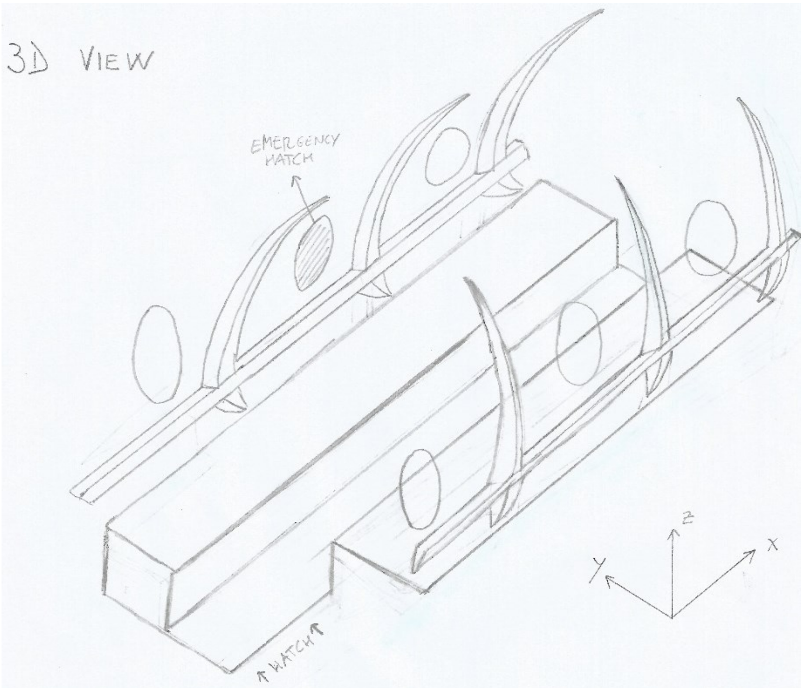
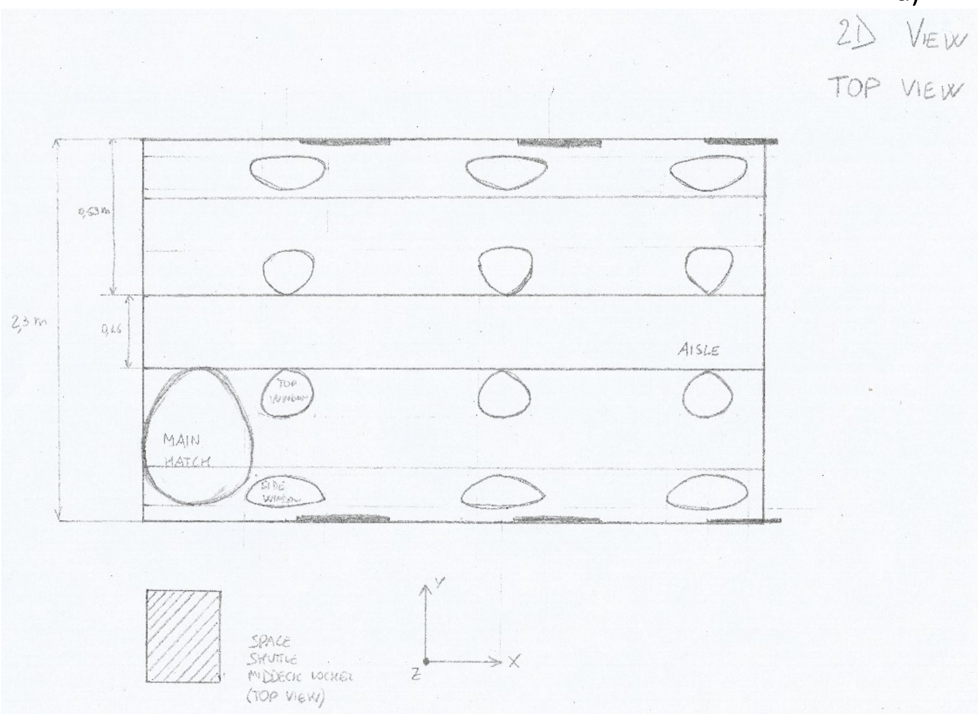


Figure 5.4.3 – Author's CAD representation of the SpaceShipTwo's cabin
Formers' shape has been simplified.

Then, starting from the case study definitions and its technical data, the author sketches the structural framework of the cabin, including structural constraints, into one 3D and two 2D views, respectively called "2D Front view" and "2D Top view".
The same reference system of the "SpaceShipTwo Payload Guide" has been adopted and basic dimensions have been appended.
These structural basic illustrations, showed in the following figure, are been photocopied and taken as basis to draw on. This approach permits the rapid handmade production of a large number of different internal configurations, having in common the structural constraints of the reference spacecraft's fuselage.



a)



b)

Figure 5.4.4 - Sketch of SpaceShipTwo's cabin, a) 3D view and b) top view

These sketches have been photocopied and used as basis for further sketching: so it is possible to try different configurations with pencil and then delete if the result is not satisfactory. The eraser will erase the last changes in pencil leaving this image, because it is imprinted on the sheet with the toner. With this method, it is possible to produce many different configurations in a short time.

In this configuration also a top viewed MLE appears, at scale. The positions of the formers have been hypothesized. It was also done with the width of the corridor, hypothesized 18 inches, basing on draws from the Roskam's Airplane Design Part III, Chapter 3, from page 86 to page 90.

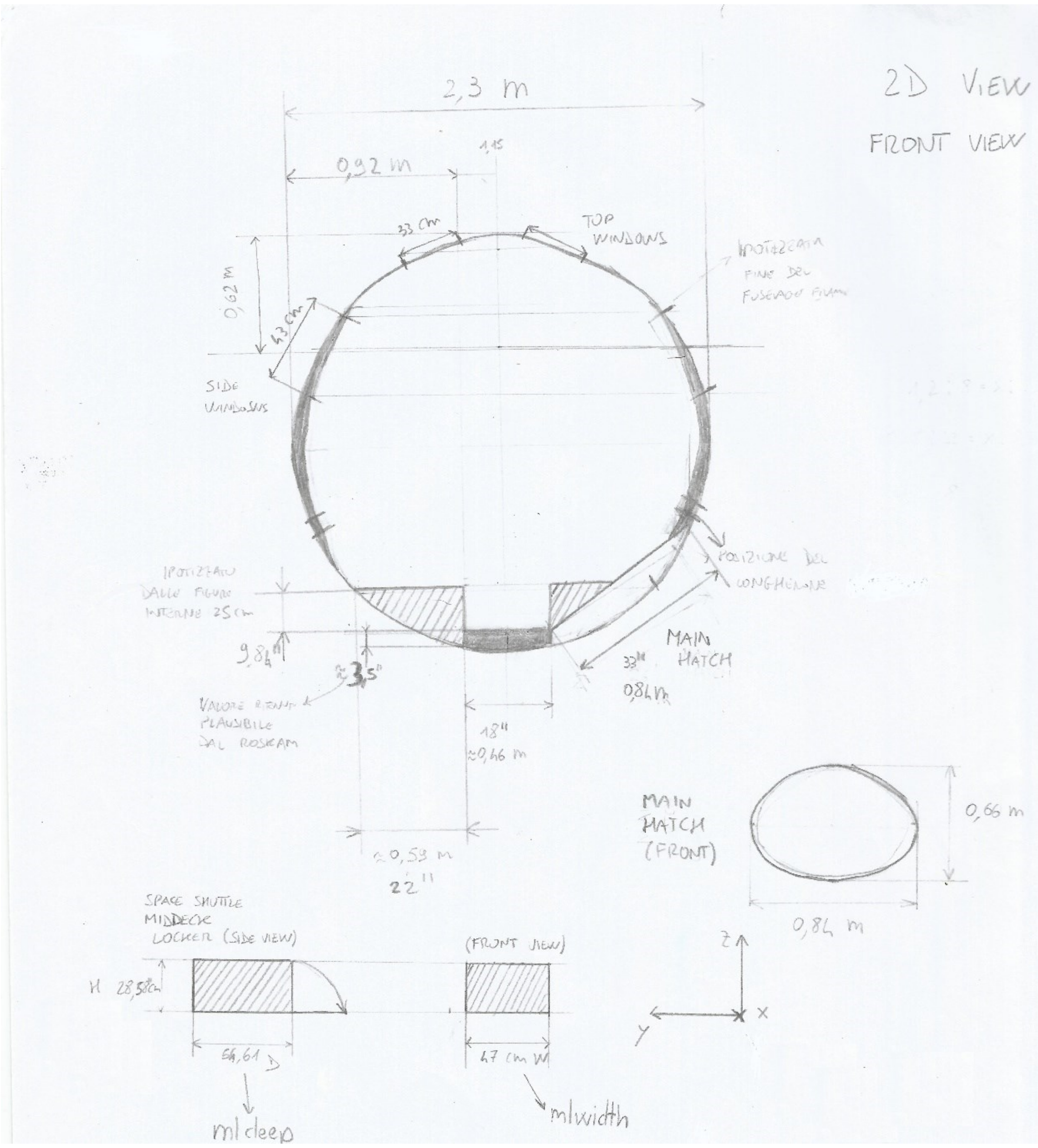


Figure 5.4.5 - Sketch of SpaceShipTwo's cabin, front view
This image represents the cross section of the fuselage. There is also front view and lateral view of MLE and of the main hatch. The spar position has been hypothesised, while the height of the step and the lower part to the aisle have been supposed as in the previous figures basing on Roskam's book.

To increase the effectiveness of the solution proposed by Virgin Galactic, it was decided to increase the volumetric efficiency through three alternatives:

1. Introduction of a truss to mount payloads centrally using all the possible space;
2. Accommodation of as many MLEs as possible by adding more mounting plates;
3. Adopting mounting plates welded to the main structure, allowing payloads attachment with a modular approach;

Some sketches describing these configurations follow.

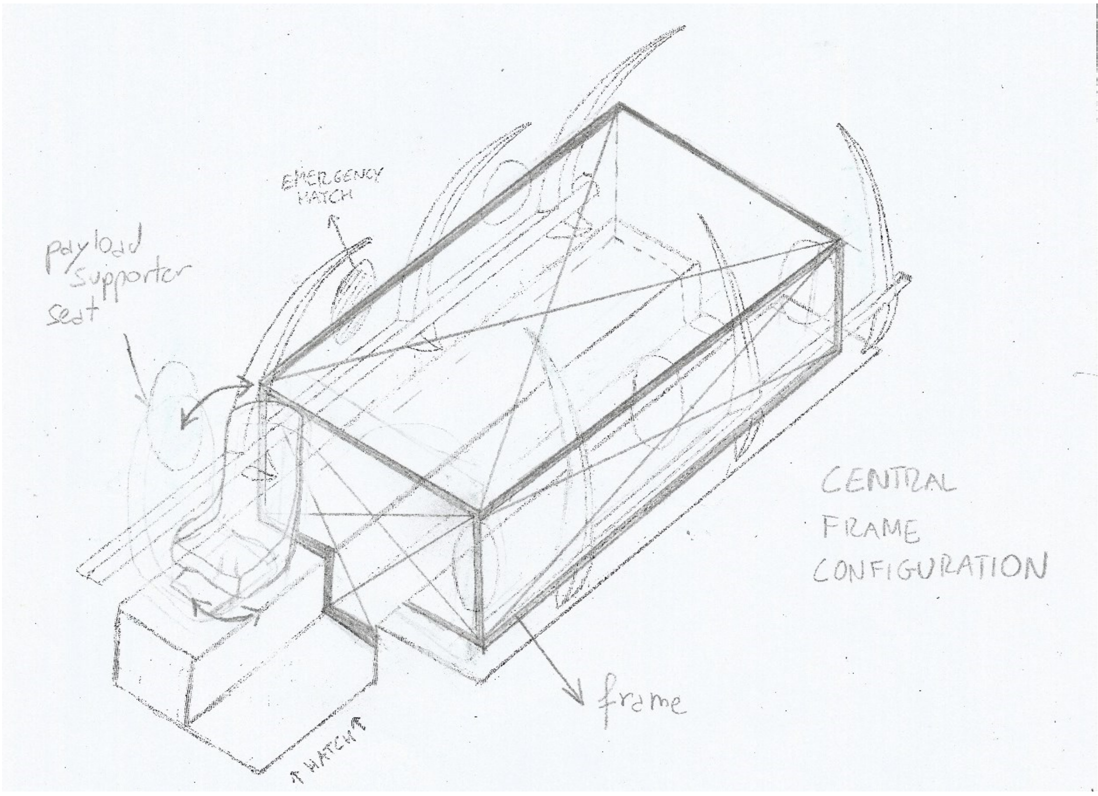


Figure 5.4.6- 3D view for the first configuration.

A central frame, composed of removable truss segments, occupies the most of internal space. The payload supporter has a seat at the front of the cabin and in case of emergencies the main hatch could be used. A major disadvantage of this configuration is that the emergency hatch is unavailable due to this peculiar payload container. Its seat is set facing forwards during the rocket burning to have the best loading on the supporter's body. During coasting phase the seat has rotating capability (90°) along the vertical axis, to have access to the frame. A control panel would be installed at the front of the frame. Utilities interfaces, for example data or power, will be present at the bottom surface.

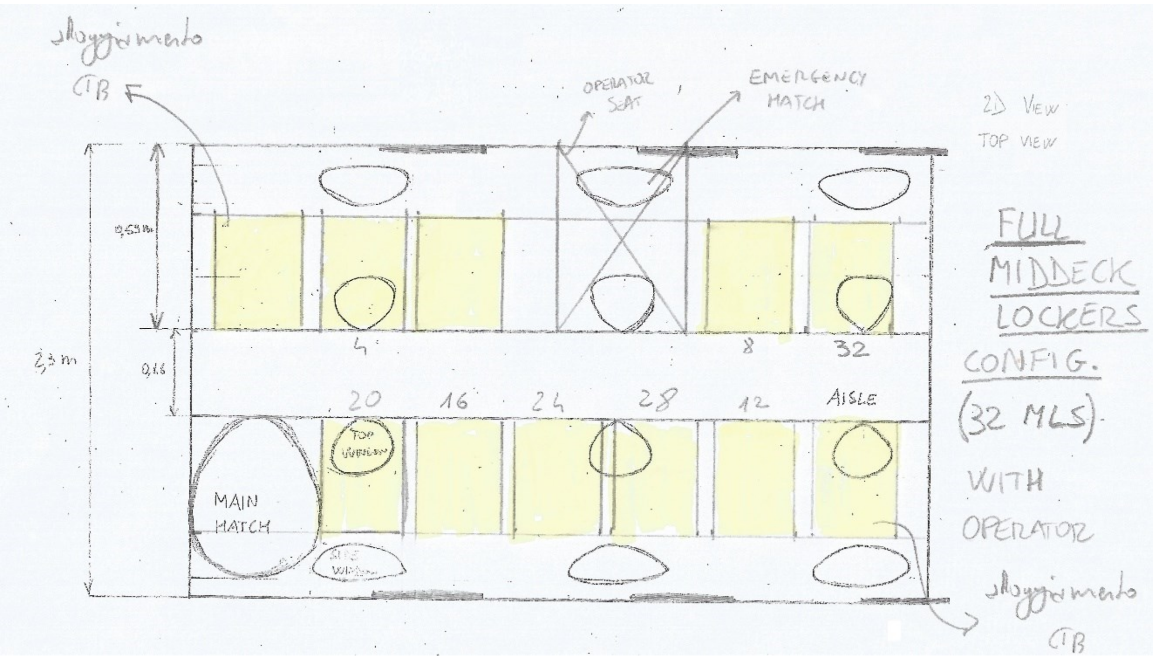
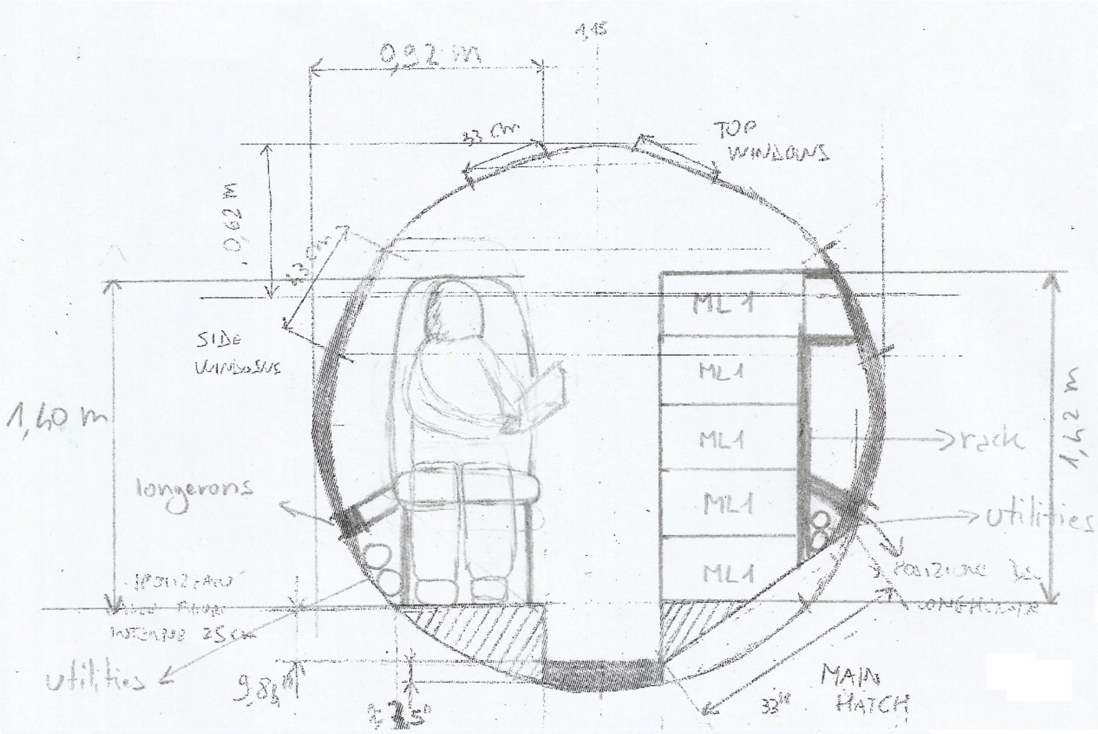


Figure 5.4.7 - Top view for second configuration.

Taking SpaceShipTwo's cabin dimensions, it is possible to accommodate up to 11 MLE columns (in yellow), in addition to the Payload Supporter, that is located next to the emergency exit. More details are available into descriptions of next image.



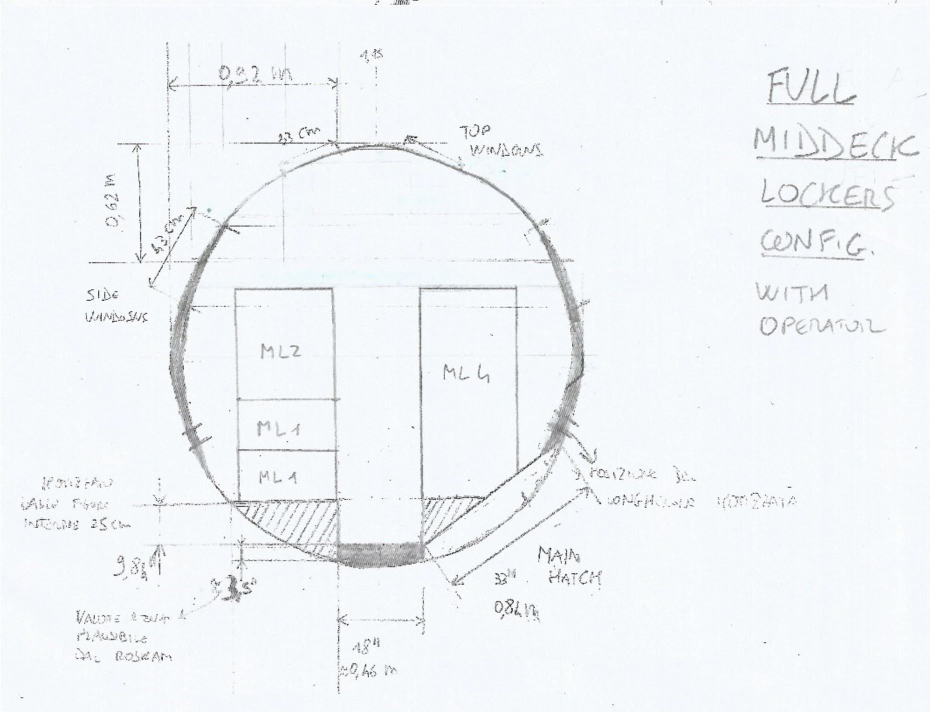


Figure 5.4.8 – Cross sections for second configuration.
The top figure shows a column with five middeck lockers and the payload supporter with a laptop. Utilities are located between MLEs and the cabin main structure. The mounting plate is the filled shape fixed on right longeron. The bottom figure shows the same section with two four MLE columns (ML1 means the 1U MLE). The central aisle is fundamental for positioning payloads during integration at the spaceport.

With the five-MLE per column (11 columns) there would be 55 MLE, with a total empty weight of about 349 kg (14 lbs each MLE). Guessing a payload capacity of the spaceplane of 581 kg, as showed, the lasting amount for the carried payload would be 232 kg, or about 4.2 kg per MLE.

With the four-MLE per column there would be 44 MLE, with a total empty weight of about 280 kg. In this case, it would be about 300 kg, that is equal to about 6.8 kg per payload. This value is however 30% of allowed payload mass per MLE. To reach the plausible 50%, the 11.35 kg discussed in the introduction of the present paragraph, it would be necessary about 32 middeck lockers. In figure 15, position of these MLE are identified with numbers. They are distributed as represented to avoid an excessive displacement of the center of mass and guarantee a proper balance with the weight of the payload supporter. Each pile or column would allocate four MLE, the pile in front of the Payload Supporter can be replaced with a small desk with monitor for basic operations and the twos remaining could be occupied by Cargo Transfer Bags. Handholds for the payload supporter would complete the configuration.

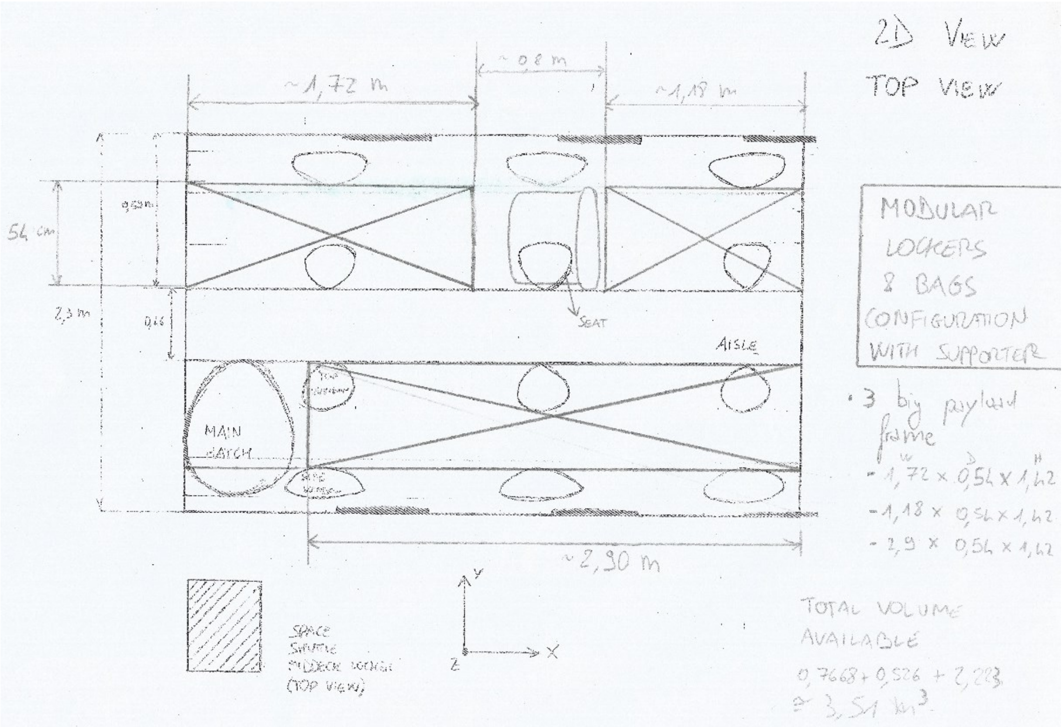


Figure 5.4.9 - 2D top view for the third configuration.

This configuration is a sort of combination of the previous. There are the central aisle and three large mounting plates, tow located at starboard and one larger at port. On these plates can be attached some types of payload containers, such as MLE, CTB or frames with the same deep of standard lockers. The seat length and pitch of 0.8 m was supposed basing on Roskam's Airplane Design [5.9].

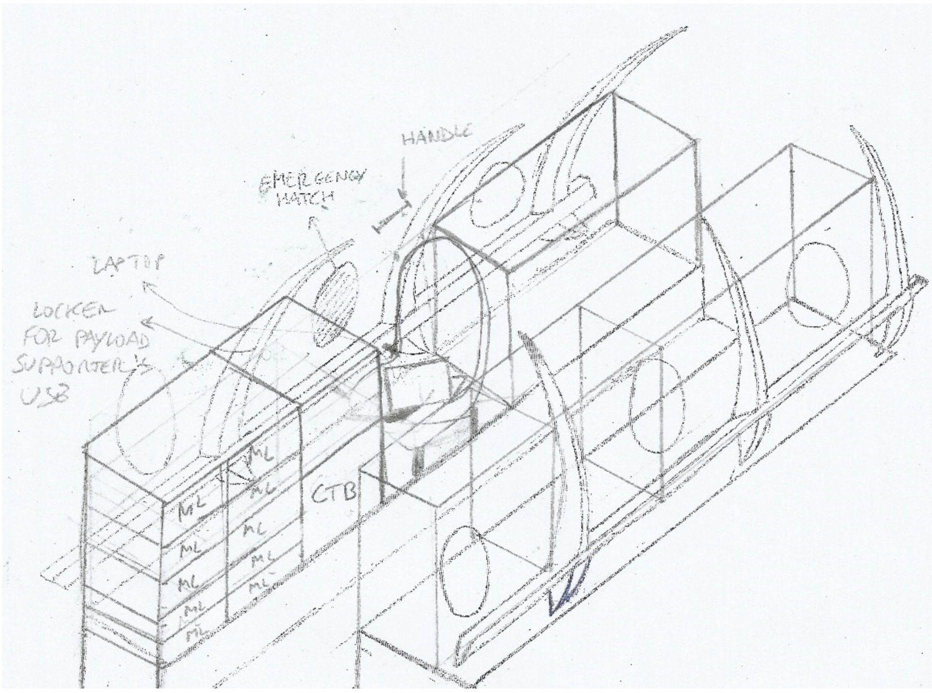


Figure 5.4.10 - 3D view for the third configuration.

It is showed a possible use of the mounting plates, with two piles of five MLE each.

Now a comparison between the three configurations is performed, to choose one with a trade-off process.

	Advantages	Disadvantages
First config.	It is possible to exploit a large amount of the space available in the cabin, about 7660 litres. It permits to carry large payloads, as long as its components get through the main hatch.	The non-standard mechanical interfaces would probably require a lot of paperwork for each flight and time for a correct integration. Payload and truss integration shall start from the bottom and continue forward: payload developer have to take it into consideration. Virgin Galactic does not recommend the "ship-in-the-bottle" approach.
Second config.	Middeck Locker standard permits to save time and money during the payload acceptance and integration phases. It would not likely require heavy modifies to the current configuration of the SpaceShipTwo, because only adding mounting plates is strictly required.	It permits to add 953 litres to the only 1466 litres available on the original configuration, so for a total of 2419 litres. It can excess the vehicle payload capacity if average payload mass per MLE overcomes 11.25 kg.
Third config.	It is possible to use both standard interface as MLE and use custom payload containers to maximize accommodation flexibility. The aisle permits a quick installation of payloads.	3510 litres are available (calculated in the figure).

Table 6 – Comparison between configurations

The available volume for the first configuration has been calculated supposing top dimensions of 2.90 m for the long side and 1.78 for the short one (0.59 *2, floor width, + 0.46, aisle width) and a height of 1.42m. So, considering also the aisle volume, it results 2.9*1.78*1.42 + 2.9*0.46*0.25=7.33+0.33=7.66 m^3 (0.25 is the aisle height). For comparison each MLE can contain 73.32 litres.

For the CAD representation, the third configuration was chosen, applying the trad-off table. CAD drawings follows.

	Safety	Simplicity	Innovation	Cost	Effectiveness		Prioritization
	0.26	0.18	0.06	0.24	0.29		
Config. 1	3	0	9	0	3		2,19
Config. 2	9	9	3	9	3		7,17
Config. 3	9	3	3	9	9		7,83

Table 7 - Configurations trade-off

All configurations are safe after structural analyses have been performed. However, the configuration 1 inhibit usage of emergency door and therefore, the main door should perhaps be redesigned in order to be opened in emergency conditions. This solution, certainly a particular one that would allow hosting large payloads, however, is not simple with regard to construction, assembly and testing, which will increase costs for the customer. For the evaluation of the efficiency, table 15 has been taken as basis and the third configuration has been considered the best compromise.

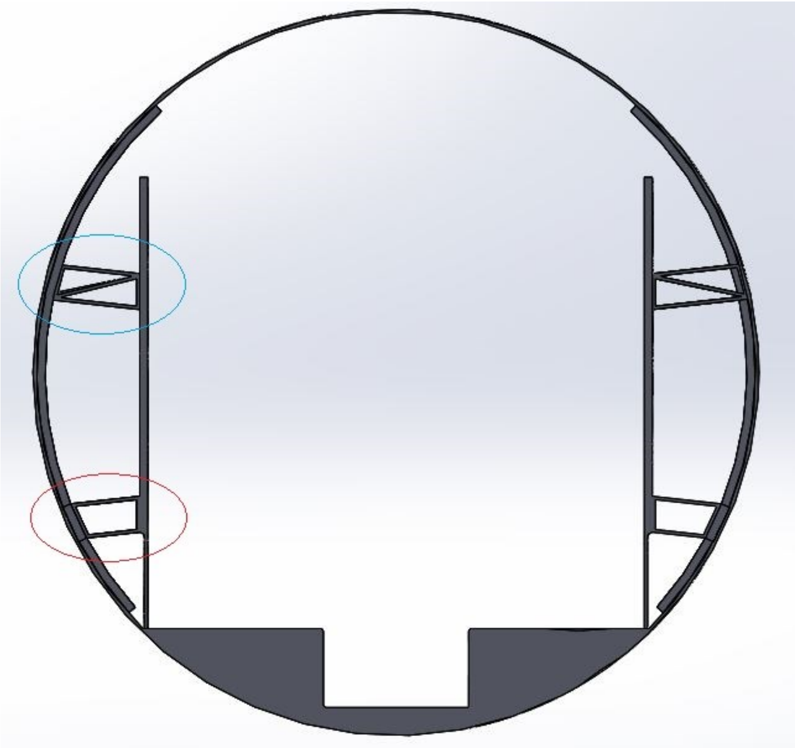


Table 5.4.11 – Third configuration with modified mounting plates (front view)
Mounting plates are fixed to fuselage via support attachments highlighted by coloured ovals. Mounting plates' structure is symmetric. The blue-highlighted element has only a structural purpose. On the other hand, the lower element constitutes a channel for the passage of electric cables, data and possible pipes. In the following figures it will be shown how to make the connection between cables and payloads. Through this channel, it is also possible to install any connections between the payloads behind the mounting plates.

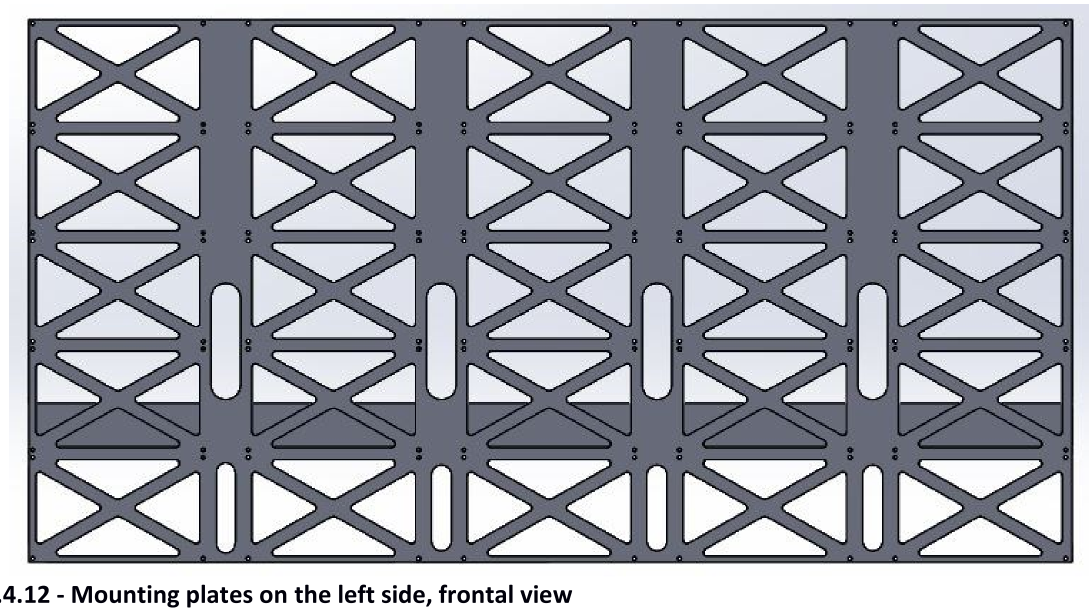


Figure 5.4.12 - Mounting plates on the left side, frontal view
The plate has been designed to attach 5 piles of 5 MLE each, but other categories payloads can be mounted. It is only necessary to add new standard holes in order to increase this capability. The lightening holes respect the shape of the middeck lockers so the Payload Designer can insert fans inside the middeck lockers and push the heat behind the mounting plates through these holes. The eight slots straddling the support channel, four above and four below, allow the passage of the cables for the connection on the front surface of the middeck, just as happens in the ISPR case. The cables can exit the support cannel through openings shown in the next figure.

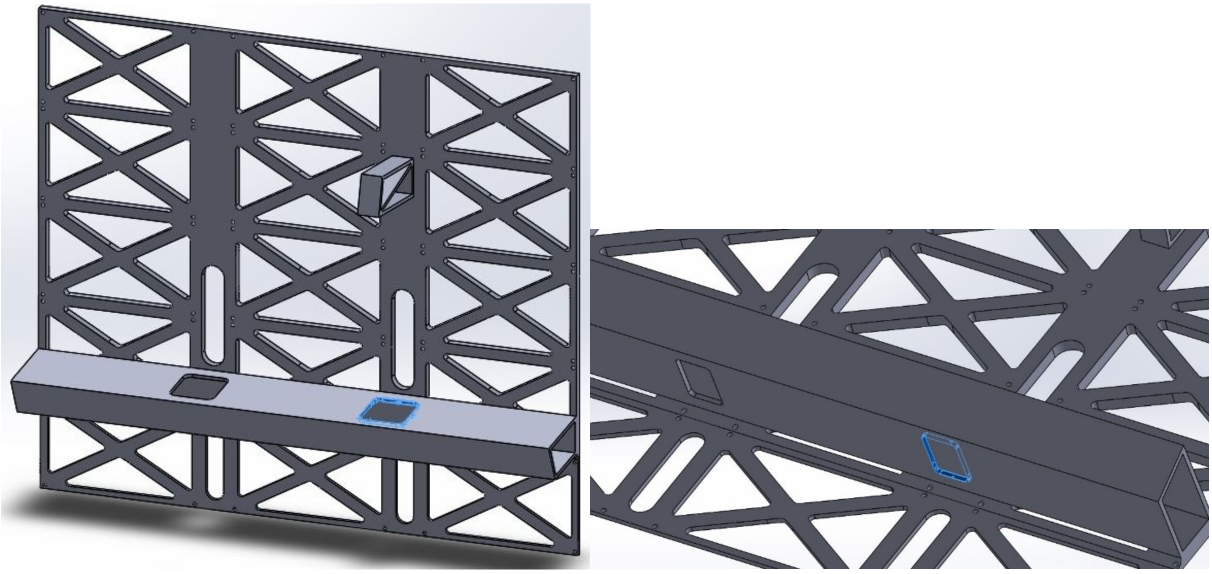


Figure 5.4.13 – Opening for cables along the support channel
Two openings, one on the top and one on the bottom, are blue-highlighted.

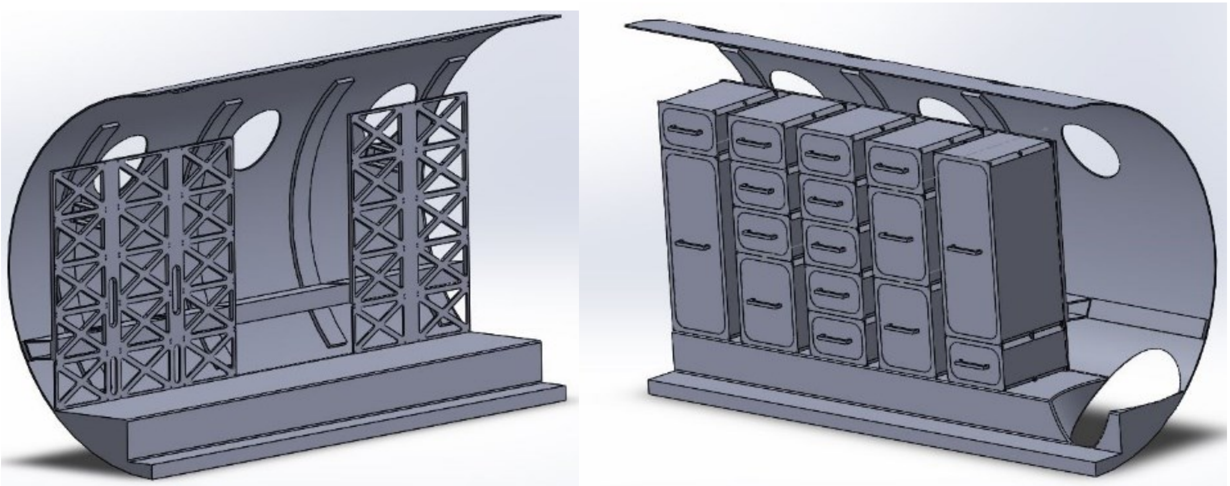


Figure 5.4.14 - Starbord and port sections
The mounting plate has been separated to allow the payload specialist to be placed next to the safety exit. The afterwards plate is designed for those payloads that need only a mechanical interface.

In the case study, two opposed ISPRs has been integrated. However, in the Virgin Galactic spaceplane, such a solution would not be feasible, because the dimensions of the cabin do not allow it, as shown in figure.

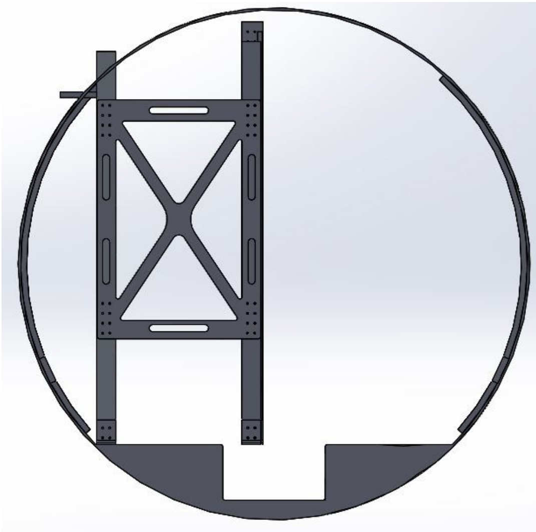
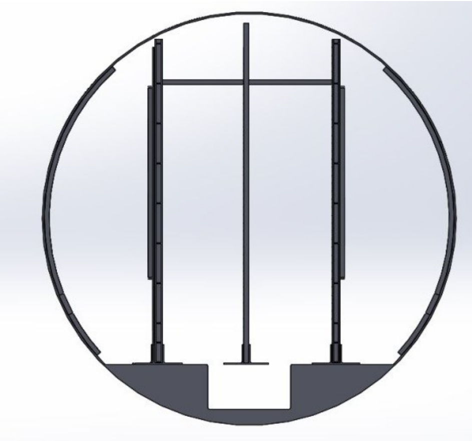


Figure 5.4.15 - ISPR and SpaceShipTwo incompatibility
To solve the problem, the ISPR could be adapted removing those parts of posts that are not used due to holes lack. However, the standard would be modified and customers cannot take advantage of using such standard interface. Pursuing this compromise, the vehicle could hold up to 3 ISPRs, hence 24 ISS Lockers, slightly more than the official configuration.



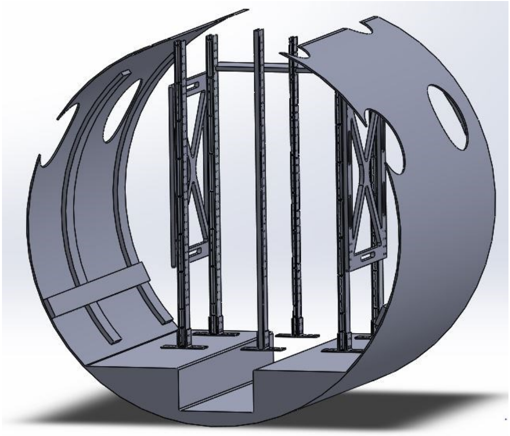


Figure 5.4.16 - Configuration with one ISPR on the back part of the cabin

A single ISPR could be placed, saving the standard, on the bottom side of the cabin, letting space for the Payload Specialist and some plates for MLEs at the front. The best subtype of ISPR could be the EXPRESS Rack, to provide resources to payloads. This configuration has not been analysed, because the payload specialist seat would be necessarily faced forwards and so unable to see the rack.

5.4.2 Comparison

Adopting length and diameter of the SS2's cabin has been introduced a "product constraint": the system shall be a re-engineered version of the Virgin Galactic spaceplane. As the commercial sense of such an operation is to convert an already existing SpaceShipTwo to carry out experimental missions, seems clear that it is impossible to modify the external shape of the spaceplane, because it would have a huge impact on costs and timeline. It would be required to redesign, recertificate and test a new spaceplane. Modifying only interiors and avionics, the adaptation would be feasible. But this imposition has fundamental repercussions on the design, because it imposes the choice of a specific product without rigorous trade-off procedure that would lead to other solutions, perhaps more optimized. However, this is completely normal during a re-design process, since the levels above the system to be redesigned already exist and must be used or at least slightly modified within the limits of reasonableness.
In the Virgin case a cabin with a large volume is functional to the fluctuation of people, while in the case-study the cabin is shorter and larger to accommodate standard interfaces, and so optimized for experimental missions. In this latter case only a window, located behind one ISPR, is larger enough to allow remote sensing capabilities, while in the other case twelve windows are provided: they permit to passengers to enjoy a wonderful view of the Earth, but their disposition and size hider installation of remote sensing hardware

5.5 PROBLEMS RELATED TO THE EXPOSURE OF PAYLOADS TO THE EXTERNAL ENVIRONMENT

An external exposure system significantly extends the operational capability of the spaceplane. In addition to gather samples, data or take measurements, such extension could permit launch of small satellites using an ad-hoc-designed small launcher.
Adding these capabilities to the vehicle is definitely challenging, especially during a reconfiguration of an existing one. In this case, in addition to the redesign of the system, it would be necessary to repeat the structural, aerodynamical and thermal analyses, that would probably force to recertify the vehicle.
During the design process of our case study, considerations about an external exposure system should be discussed before of diameter and length sizing. Actually, four system architectures and a trade-off have been carried out and they are reported here.

- External cargo bay: this architecture has been inspired by the Space Shuttle. A cargo bay, with double clamshell door, is located along the ventral or dorsal fuselage of the vehicle. In the Appendix B has been presented a sketch of the dorsal case.
  Both impose significant design constraints on the carrying vehicle and on the air-launch strategy, because the cargo bay occupies additional space above or below the cabin. During microgravity phase a mechanism, such as those of the space shuttle shown into Appendix B, shall to open doors and maintain them opened. Before the end of the phase, such mechanism shall safely close the bay. Actuators shall conduct these operations within seconds, to allow operations for few minutes.
  If a failure prevents door closing, the altered aerodynamic configuration could even cause the loss of the vehicle during re-entry or descent. So, safely operations require doors closed and latched at the end of the microgravity phase. In-depth studies should be conducted on this problem and on minimizing the risk under an acceptable level. When Space Shuttle was on orbit, if a malfunction of the cargo bay's actuators happens, the door could be closed manually by astronauts.
  On the other hand, for a suborbital spaceplane, tight time constraint of the microgravity phase could prevent the use of a manual closing procedure.
- External pod: this architecture has been inspired by XCOR LYNX Mark III and it is similar to the previous case. Here there is not a door, but a simple opening on the front. It presents same advantages and disadvantages, while to design an emergency close system could be likely simpler. Among these alternatives it is the only one to have been chosen for a suborbital vehicle, although it is no longer under development.
- Internal exposure mechanism through the window or a hatch: an electromechanical system opens the window and extract the payload on a sled out of the vehicle. Considering the already designed cabin, the payload and the sled system with linear actuators can be placed into the simple ISPR in front of the windows. It is required to design bulkheads to isolate that ISPR from the pressurized environment, allowing at the same time the installation of the payload and relative hardware.
- Internal exposure mechanism with doors: it is similar to the previous case, but the exposition will be accomplished through a door on the fuselage, and not through the window. This solution is inspired by the Stratospheric Observatory for Infrared Astronomy, that is a Boeing 747 modified with an aperture in the after fuselage to allows the telescope to perform astronomical studies. A pressurization bulkhead shall be placed around the exposition system.

All these presented solutions seem to have safety hazards that could conduct to a catastrophic accident, because are based on mechanism inevitably subject to probability of fault. If one would be adopted, it should be guarantee, through proper risk matrices, that such faults have infinitesimal chance of happening or that a single fault cannot undermine the vehicle and the mission.
Clearly it is always possible to install temperature, pression and other low-profile sensors on the surface of the vehicle.

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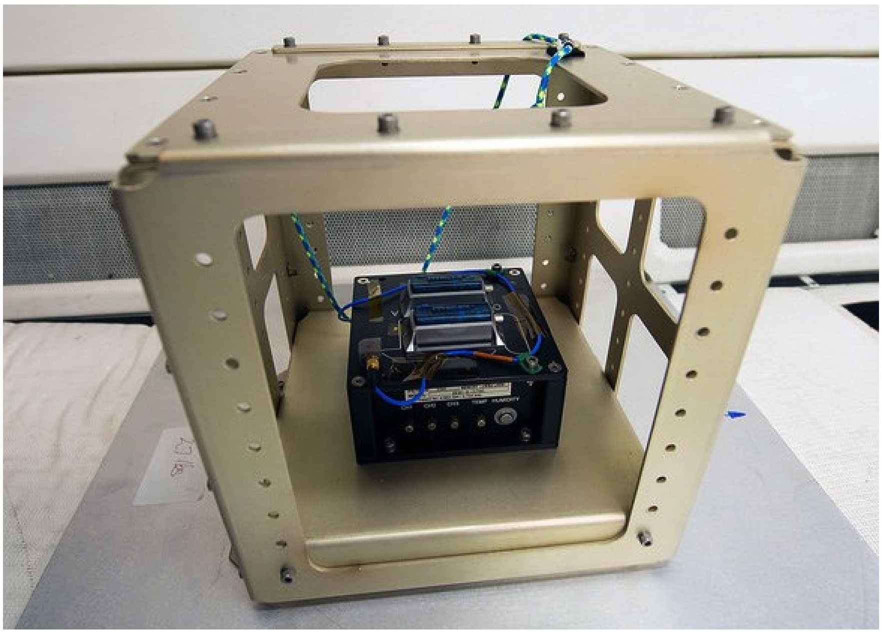
[5.14]	“SpaceShipTwo, An Introductory Guide for Payload Users”, Virgin Galactic, 2016

CHAPTER 6: CONCLUSIONS

The formalized and applied methodology permitted to focus the development on a particular case study, the generation of cabin alternatives for a general spacecraft aimed to suborbital flights. Moreover, the study has been limited to a cabin dedicated to technological research and experiment execution.
The methodology can be thought as a function that produce a final result, the design synthesis, starting from an input. In other words, the process can be conceptually approximated to a sort of transfer function. The input is the desires and needs of the customers and stakeholders, that, once formalized into customers' requirements, constitute the only independent variable that affect the design synthesis. Slightly modifying those requirements, the design synthesis could be radically different. The comparison between the two cases of Chapter 5 has been made to underline that. The first case described the generation of a cabin from the blank sheet, so the methodology has the potential to conduct to an optimized solution. A high number of cabin that can satisfy customers' requirements can be outlined, but only one do that in the best way. In fact, the cabin size is strictly based on the purpose of the mission and so designed taking into consideration the market analysis.
In the second case, one requirement has been added to the customers' requirements list: the cabin shall be a re-adaptation of the cabin of the SpaceShipTwo to experimental purposes. This involved, differently from the previous case, that the cabin size are fixed parameters, independent from the market analysis and other customers' requirement. The derived cabin, that is still the optimal solution considering all requirements and imposed constraints, is completely different from the first case. There, structures are designed around the mission objectives, here the mission objectives were reached adapting a product that had been designed for other mission, the commercial human spaceflight. To produce such a difference the introduction of a single requirement was sufficient.

An activity of significant interest that should be pursued during future studies concerns the development of the methodology and its refinement, through the integration with additional techniques and topics of system engineering and project management.
In addition, this approach should be validated through its iterative application to further case studies of industrial interest that constitute frontier topics in the design of aerospace systems and indispensable for the development of the new space economy. In addition to suborbital vehicles, hypersonic transport, the study of ground operations and infrastructures and small satellites are topics of considerable interest. The identification of other possible fields for the application of the methodology must surely take into consideration spatial exploration issues, such as the development of enabling technologies for future missions and technological aspects related to the presence of human beings on board.
A second important activity would be the development of the software chain to integrate complete project traceability into CAD. The methodology should be further developed to evolve it into a flexible product to allow its industrial use, even with the ad-hoc development of code or portions of software. This would allow to standardize the interfaces of the methodology and thus make its use simple within companies and teams already focused on existing projects in specific fields of research and industry.

Appendix A: Payload example - SUBORBITAL FLIGHT ENVIRONMENT MONITOR (SFEM)



It is an Equipment capable of detecting environmental conditions inside the container where it is stored, for example a Middeck Locker integrated to a suborbital spaceplane. It is very interesting, because it allows the experimental characterization of the flight framework where other payloads will operate.
It is made up of COTS components to detect and record acceleration shock, vibration, temperature, pressure and moisture.

Program Status	active
Successful accomplished flights	2 parabolic, 2 SRLV
Weight	2.2 kg
Read for flight	yes
Operator required	no
Technology maturation comments	it requires a 100 km altitude suborbital flight to change from TRL 8 to TRL 9
Requirements	Completely autonomous

Source: [https://flightopportunities.nasa.gov/technologies]

Appendix B: IMAGES AND DRAWINGS

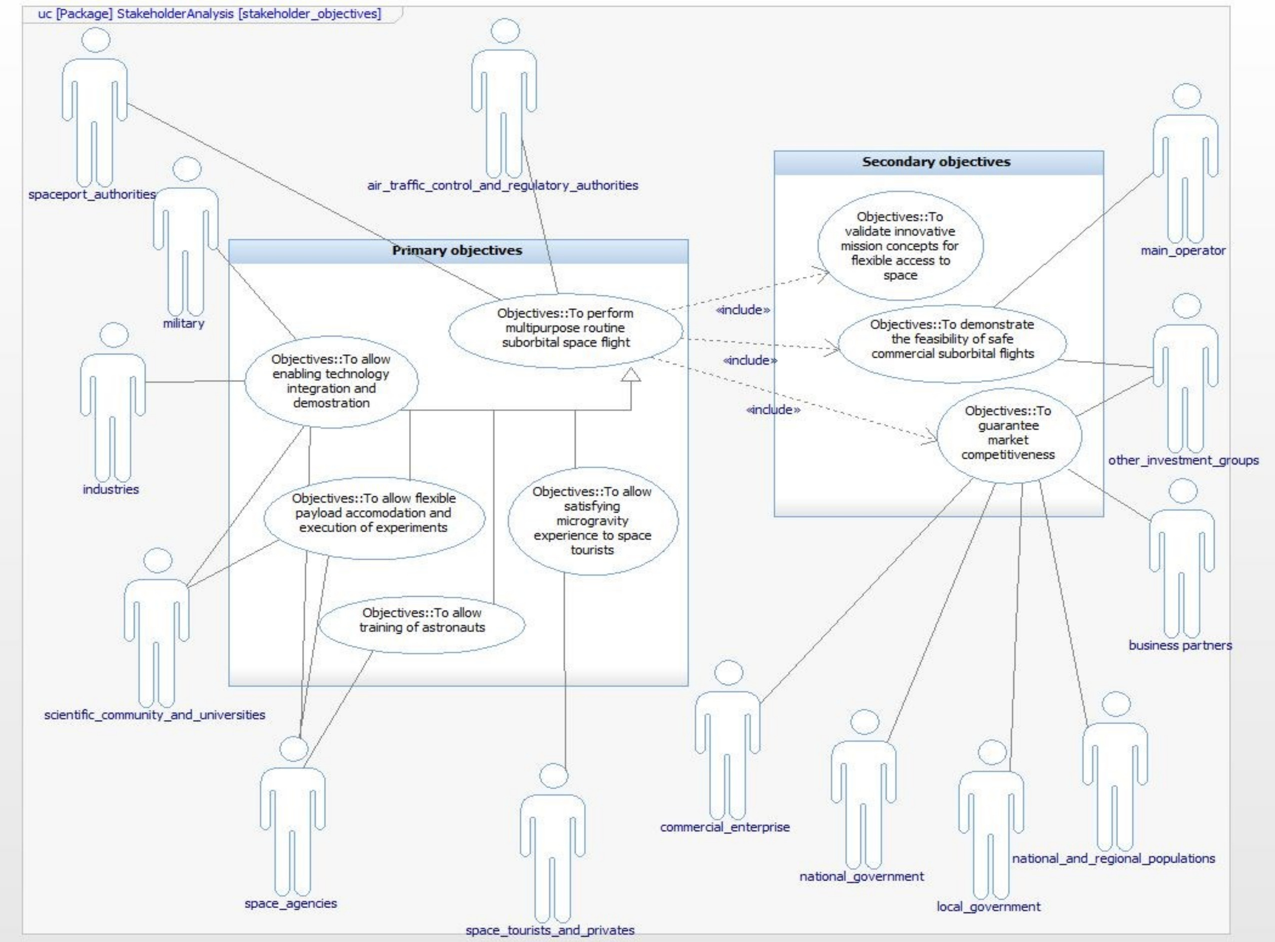


Figure 1 - Stakeholders - Mission objective relationships

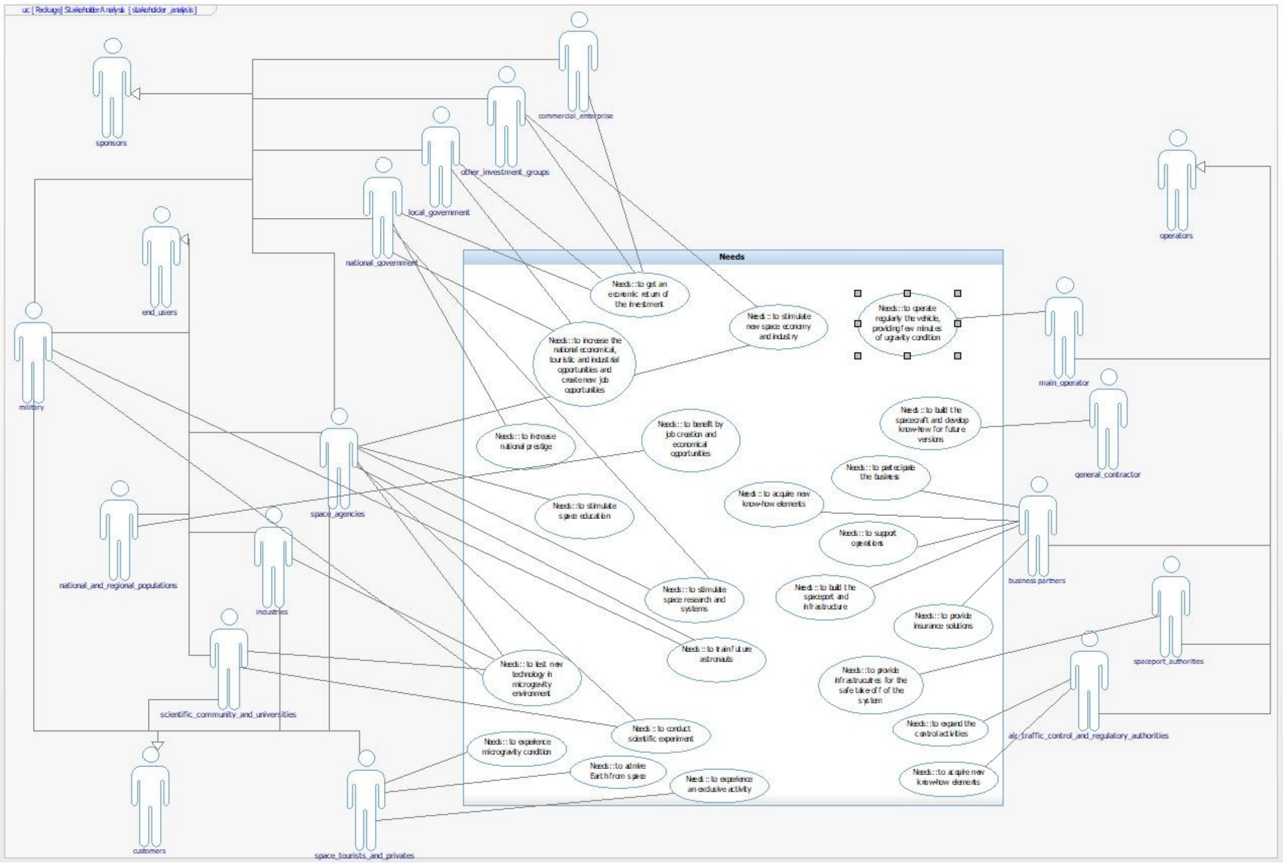


Figure 2 - Stakeholders's needs

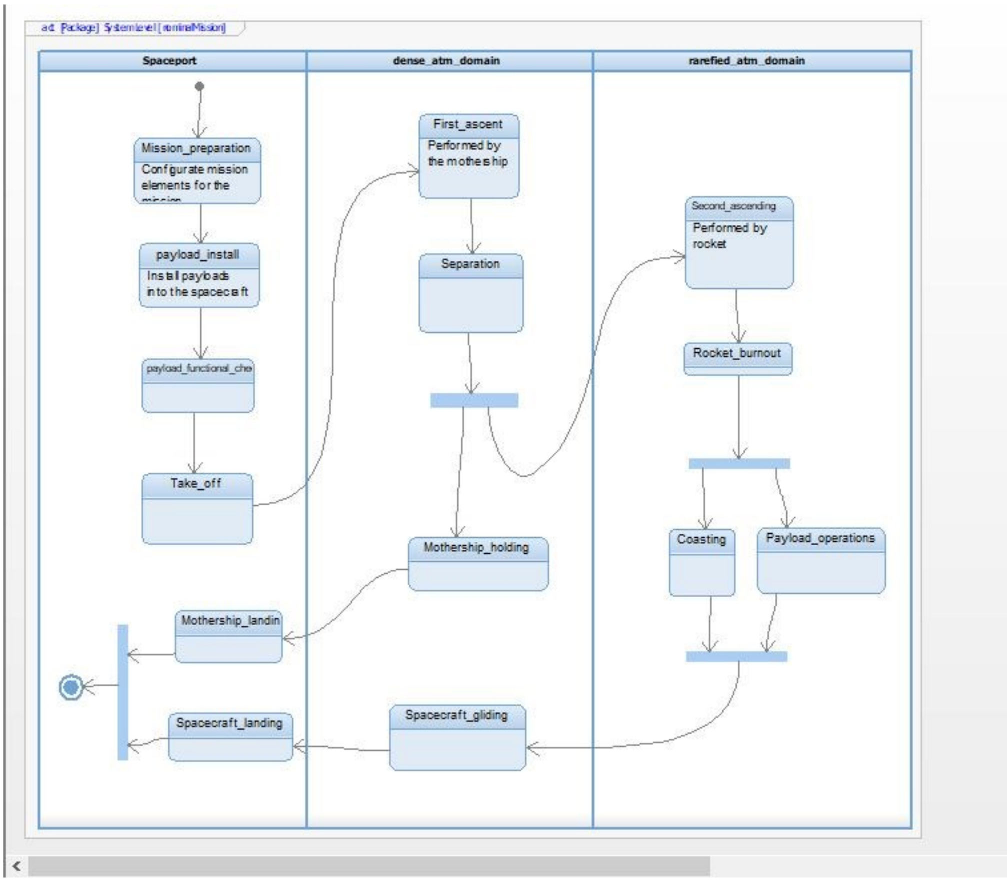


Figure 3 - Activity diagram at system level

To: Block **Scope:** Products

From: Block **Scope:** Functions

	Mothership	Spacecraft	Spaceport	Flight_operations_center	Payload_data_center
To_accomodate_payloads		Spacecraft			
To_guarantee_the_survival_of_payload_if_requested		Spacecraft			
To_guarantee_the_payload_functioning		Spacecraft			
To_handling_payload_locally		Spacecraft			
To_receive_telemetry_from_the_spacecraft				Flight_operations_center	
To_monitor_spacecraft_trajectory_and_attitude				Flight_operations_center	
To_perform_a_post_mission_checklist			Spaceport		
To_recover_payloads			Spaceport		
To_handling_payload_command_and_data_remotely				Flight_operations_center	
To_take_off	Mothership				
To_climb_to_the_release_altitude	Mothership				
To_perfom_release	Mothership				
To_climb_to_the_target_altitude		Spacecraft			
To_assume_TBD_attitude_profile		Spacecraft			
To_stop_propulsive_force_at_the_burnout_altitude		Spacecraft			
To_configure_system_elements			Spaceport		
To_integrate_the_system			Spaceport		
To_perform_a_pre_takeoff_checklist			Spaceport		
To_send_commands_to_the_spacecraft				Flight_operations_center	
To_elaborate_payload_data					Payload_data_center
To_elaborate_telemetry_after_mission				Flight_operations_center	
To_install_payloads		Spacecraft			

Figure 4 - Functions-Product Matrix at system level

To: Block **Scope:** Products

From: Block **Scope:** Functions

	Cabin	Electrical_power_system	Command_and_data_handling_system	External_exposition_system
To_contain_payloads_in_a_controlled_environment	Cabin			
To_prevent_unwanted_payload_movements	Cabin			
To_control_moisture_level				
To_control_temperature				
To_control_internal_pressure				
To_provide_protection_against_fire	Cabin			
To_provide_protection_against_overcurrents		Electrical_power_system		
To_isolate_payloads_from_vibrations	Cabin			
To_feed_payloads_with_electrical_power		Electrical_power_system		
To_feed_payloads_with_fluidical_power				
To_feed_payloads_with_pneumatic_power				
To_remove_waste_gases_or_substances				
To_feed_payloads_with_substances				
To_receive_commands_from_ground_station			Command_and_data_handling_system	
To_manage_payloads_data_and_telemetry_locally			Command_and_data_handling_system	
To_control_attitude_pointing				
To_physically_manipulate_payloads	Cabin			
To_restart_payloads_and_solve_first_level_problems			Command_and_data_handling_system	
To_send_payload_data_and_telemetry_to_ground_segment				
To_expose_payloads_to_external_environment				External_exposition_system

To: Block **Scope:** Products

From: Block **Scope:** Functions

	Environmental_control_system	Hydraulic_system	Pneumatic_system	Communications_system
To_contain_payloads_in_a_controlled_environment				
To_prevent_unwanted_payload_movements				
To_control_moisture_level	Environmental_control_system			
To_control_temperature	Environmental_control_system			
To_control_internal_pressure	Environmental_control_system			
To_provide_protection_against_fire				
To_provide_protection_against_overcurrents				
To_isolate_payloads_from_vibrations				
To_feed_payloads_with_electrical_power				
To_feed_payloads_with_fluidical_power		Hydraulic_system		
To_feed_payloads_with_pneumatic_power			Pneumatic_system	
To_remove_waste_gases_or_substances	Environmental_control_system			
To_feed_payloads_with_substances	Environmental_control_system			
To_receive_commands_from_ground_station				
To_manage_payloads_data_and_telemetry_locally				
To_control_attitude_pointing				
To_physically_manipulate_payloads				
To_restart_payloads_and_solve_first_level_problems				
To_send_payload_data_and_telemetry_to_ground_segment				Communications_system
To_expose_payloads_to_external_environment				

To: Block **Scope:** Products

From: Block **Scope:** Functions

	Pneumatic_system	Communications_system	Attitude_determination_and_control_system
To_contain_payloads_in_a_controlled_environment			
To_prevent_unwanted_payload_movements			
To_control_moisture_level			
To_control_temperature			
To_control_internal_pressure			
To_provide_protection_against_fire			
To_provide_protection_against_overcurrents			
To_isolate_payloads_from_vibrations			
To_feed_payloads_with_electrical_power			
To_feed_payloads_with_fluidical_power			
To_feed_payloads_with_pneumatic_power	Pneumatic_system		
To_remove_waste_gases_or_substances			
To_feed_payloads_with_substances			
To_receive_commands_from_ground_station			
To_manage_payloads_data_and_telemetry_locally			
To_control_attitude_pointing			Attitude_determination_and_control_system
To_physically_manipulate_payloads			
To_restart_payloads_and_solve_first_level_problems			
To_send_payload_data_and_telemetry_to_ground_segment		Communications_system	
To_expose_payloads_to_external_environment			

Figure 5 - Functions-Product Matrix at subsystem level

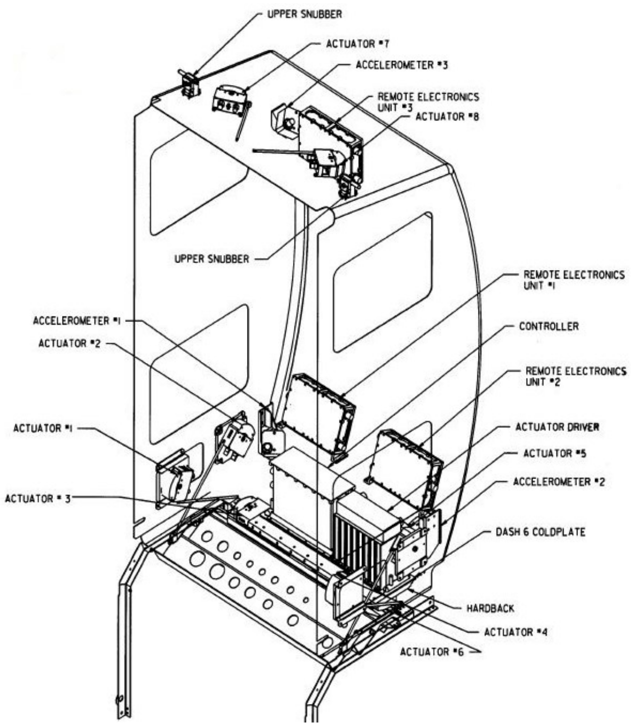


Figure 6 - ARIS components attached to an ISPR (source: 5.12)

The ARIS is a system aimed to suppression of vibrations.

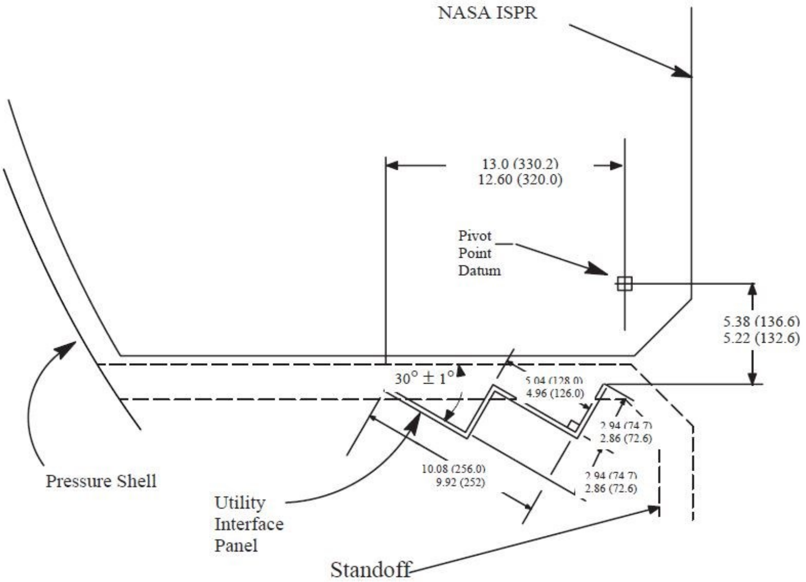


Figure 7 - ISPR-to-module interface with measures of the Utility Interface Panel [5.11]

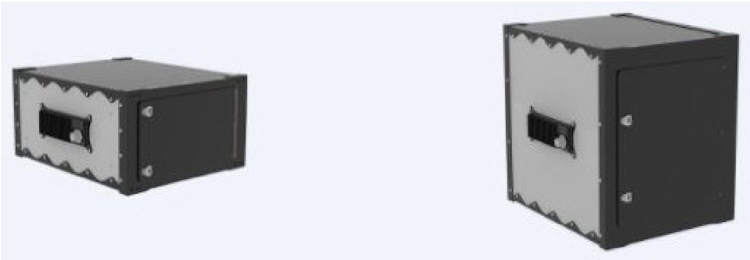


Figure 8 - Blue Origin Lockers [Source: Blue Origin]

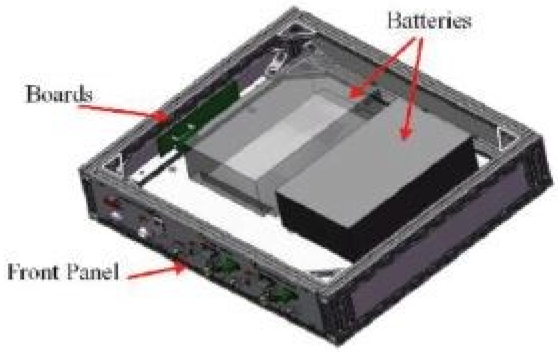


Figure 9 - FASTRACK support drawer [2.2]

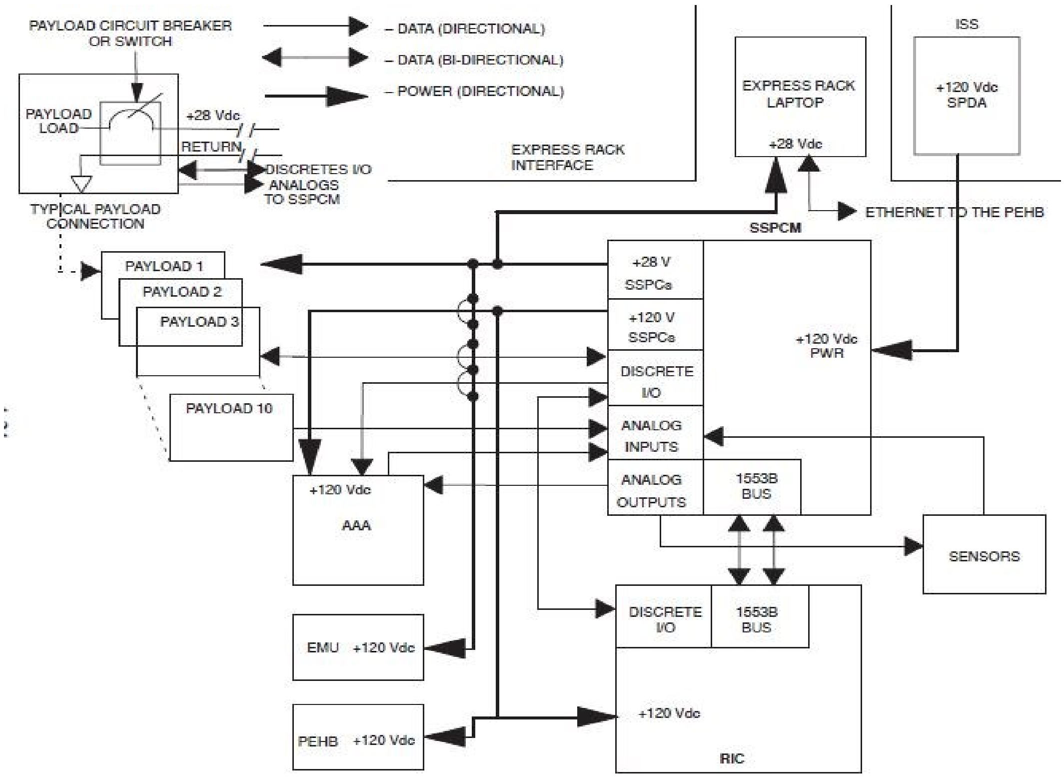


Figure 10 - Power distribution diagram of the standard EXPRESS Rack [5.7]

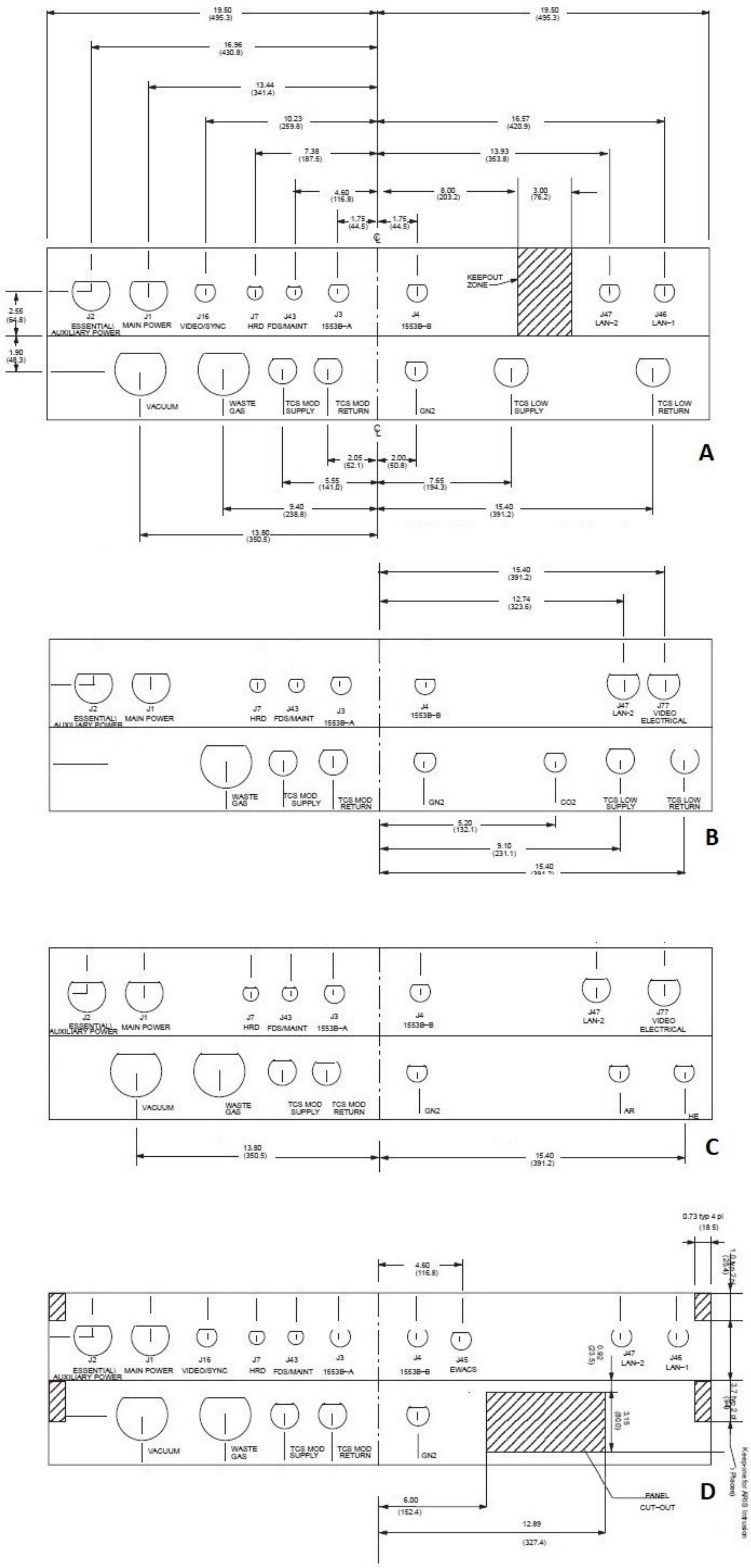


Figure 11 - Utility Interface Panels for different customized ISPR

As well as the global arrangement of each ISPR is different from others, also the UIP shows differences between “models”. The figure shows four examples from source [2.22]:

A) NASA Racks;

B) NASDA Material Processing Racks;

C) NASDA Life Sciences Rack;

D) ESA Racks;

Repeated measures are not showed.

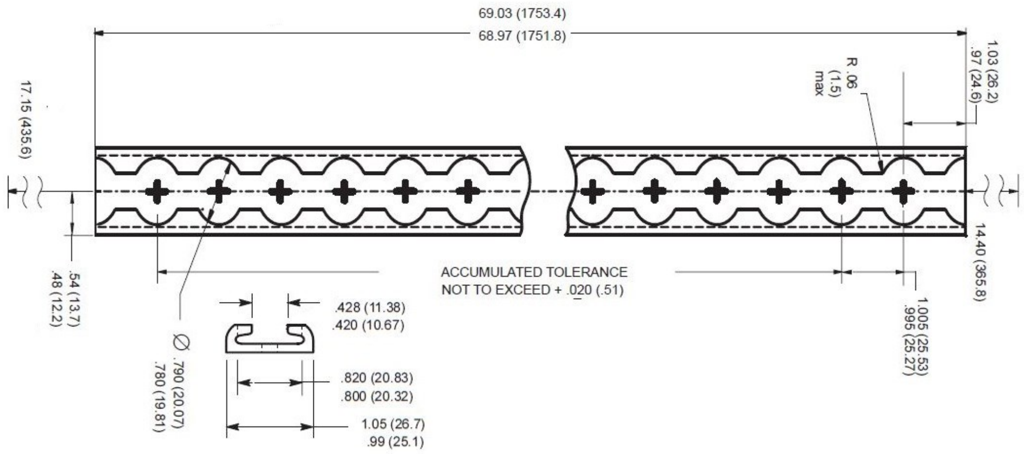


Figure 12 - ISPR front holes for secondary structures [5.11]
The pattern, localized on the front of front posts, allows mounting of front plates or notebooks.

Figure 13 – FASTRACK used on a parabolic airplane (source: NASA)
Note the foam coating of internal surfaces: it is a safety requirement for crewed flight.

Figure 14 - ESA astronaut Alexander Gerst with a biologic experiments on ISS (source: NASA)
The experiment is related to activation of T-cells of immune system

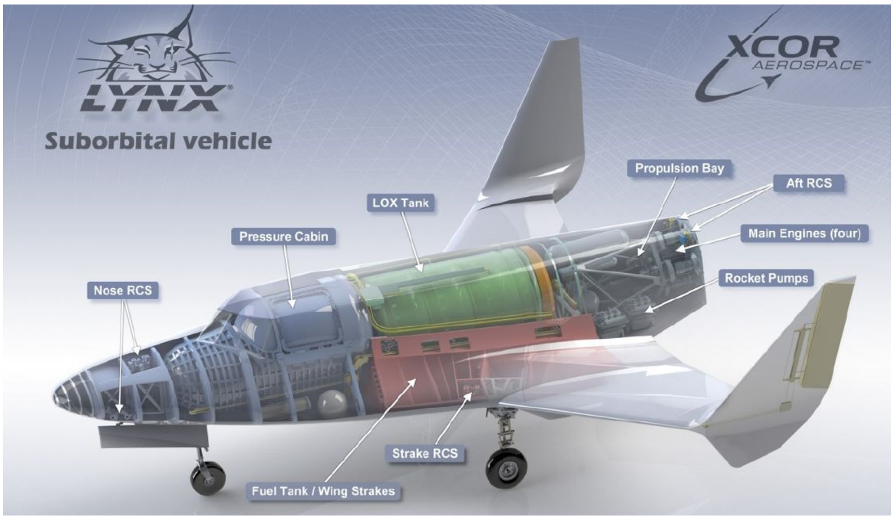


Figure 15 - Lynx suborbital vehicle with propulsion and life support systems highlight (source: XCOR)

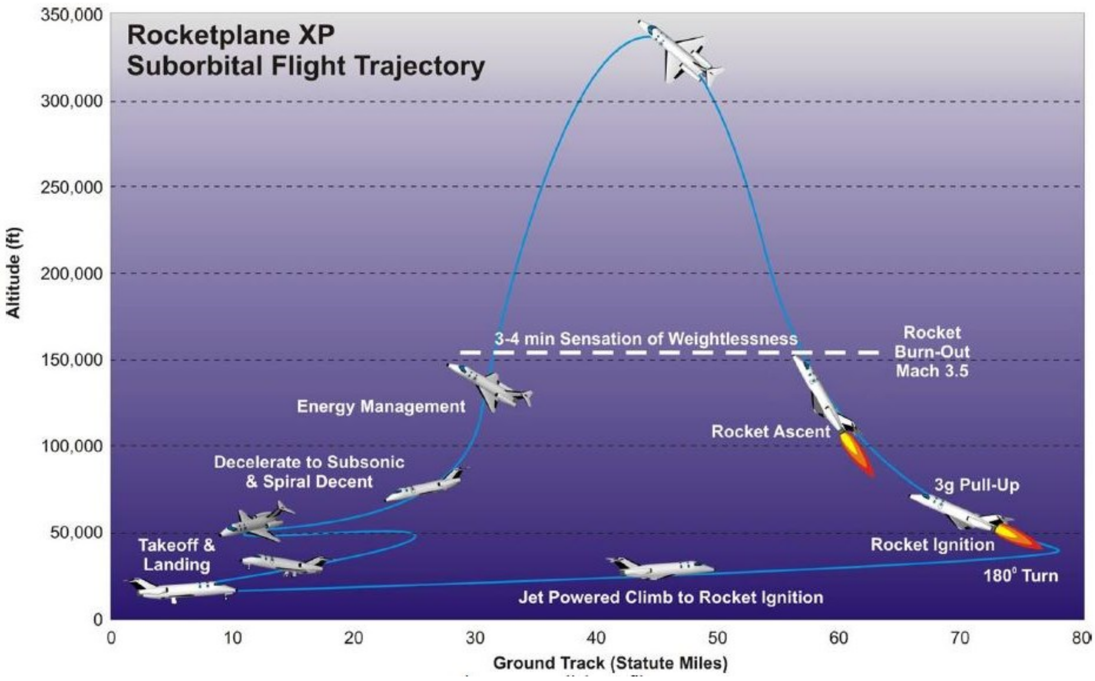


Figure 16 - Rocketplane XP mission profile [2.16]

It is a suborbital single stage to orbit mission. Note that before igniting the rocket, the spaceplane executes a 180° pointing back manoeuvre to direct heading towards the spaceport.

The spiral descent is performed during re-entry to dissipate kinetic energy for the landing.

Figure 17 - X-15 Cockpit [source: https://www.avgeekery.com/x-15-world/]

Figure 18 - SpaceShipOne cockpit (Source: Virgin Galactics)

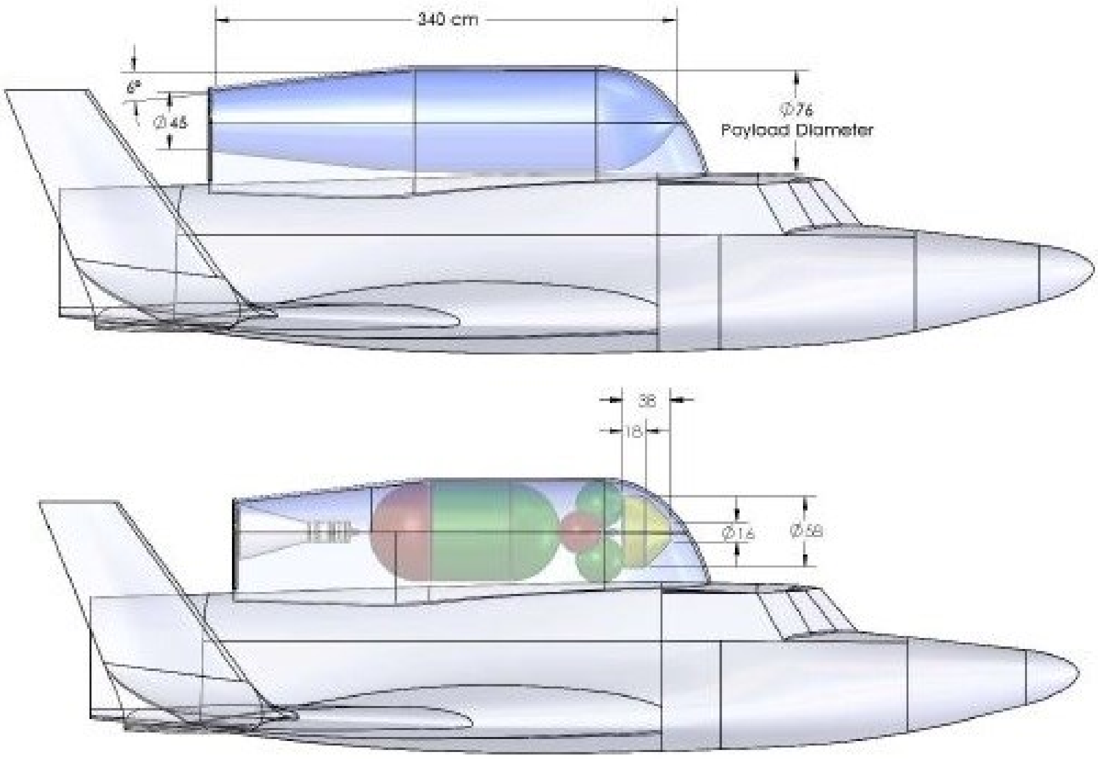


Figure 19 - Lynx dorsal pod dimensions [source: Lynx Payload User Guide 2012]
In the upper figure are highlighted dimension of container for remote sensing or sampling payloads.
In the lower, the stage with and example payload for a launch mission into LEO are showed .

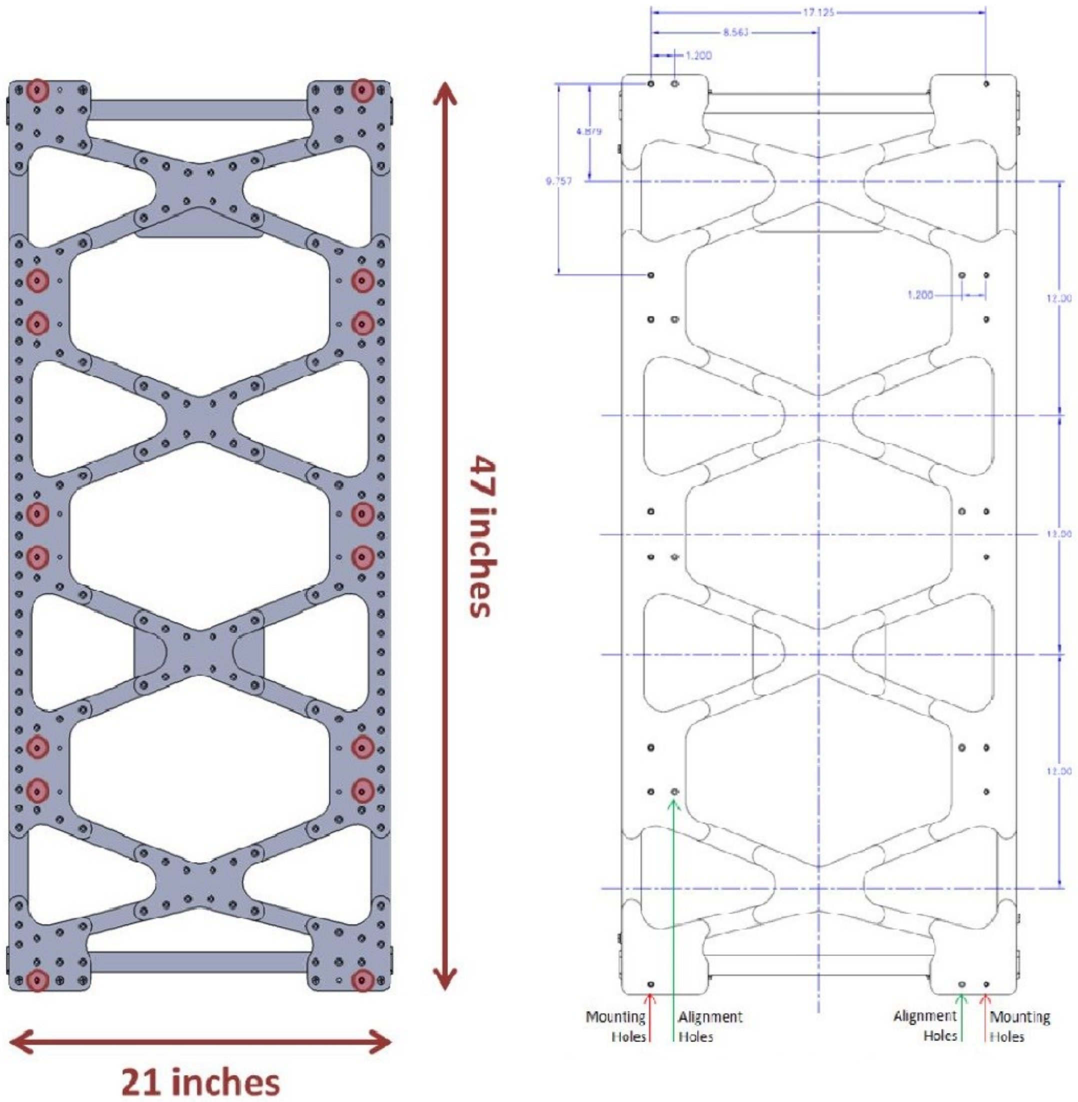


Figure 20 – SpaceShipTwo standard mounting plate with dimensions. [2.23]

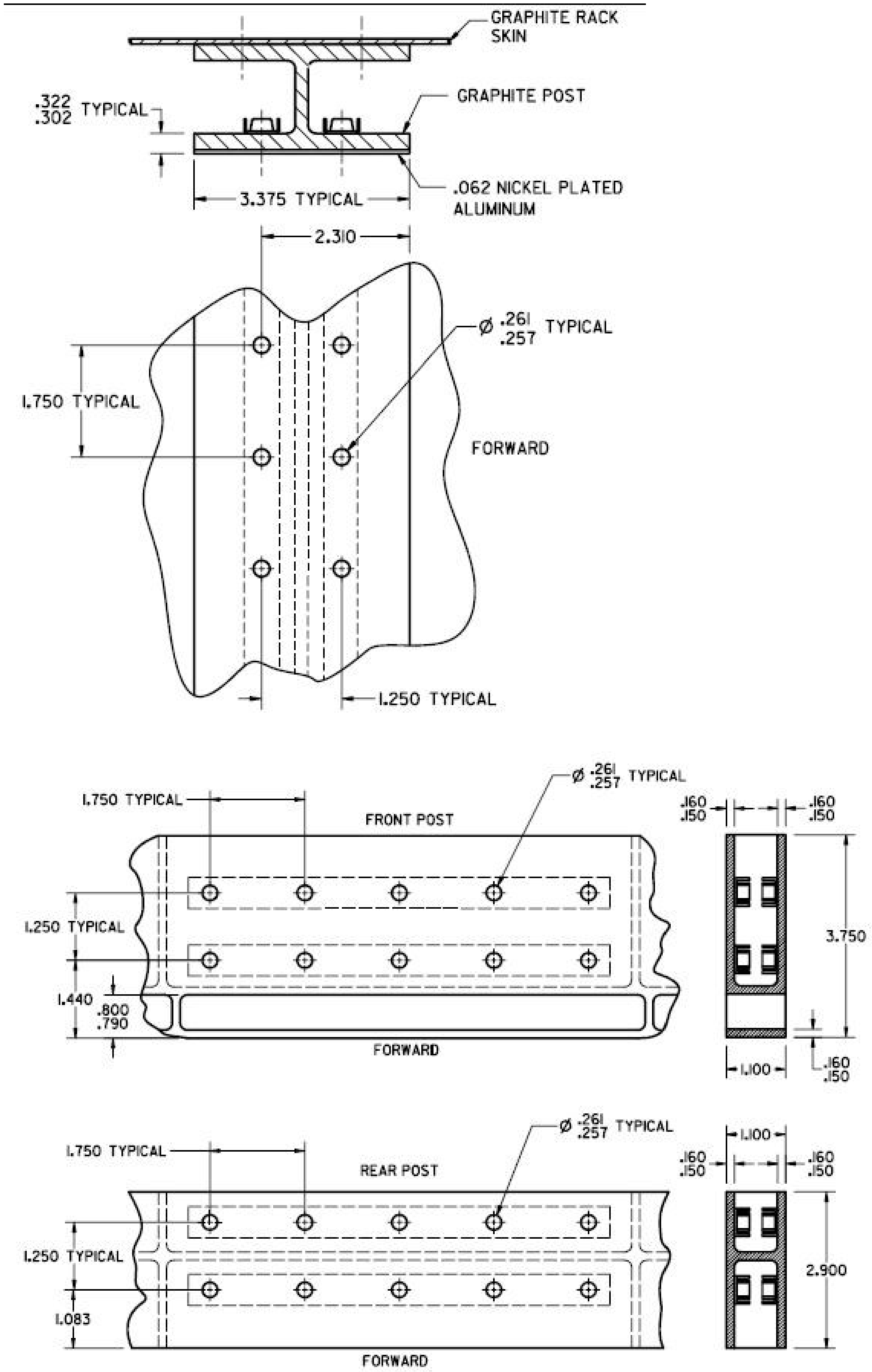


Figure 21 – Dimensions for IPSR posts [5.11]

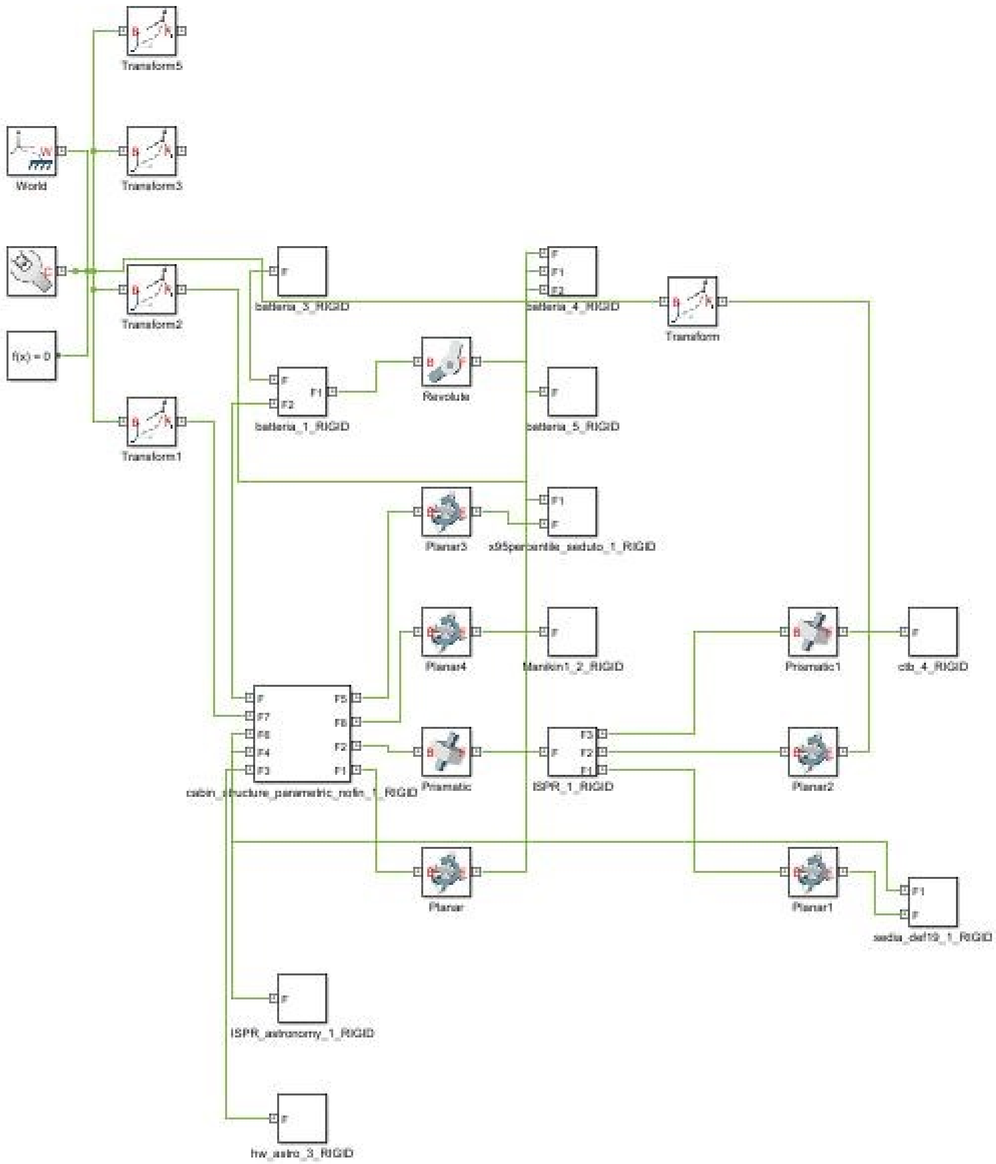


Figure 22 - Simulink model of the cabin CAD

All the elements and information introduced through Solidworks, such as position and mechanical constraints have been translated into this Simulink model. If there are parts with degrees of freedom it is possible to conduct dynamical analysis.

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- To my supervisors, prof. Nicole Viola, Dr. Roberta Fusaro and Dr. Davide Ferretto who gave me the possibility and support to work on a topic so interesting;

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