Baseline Report

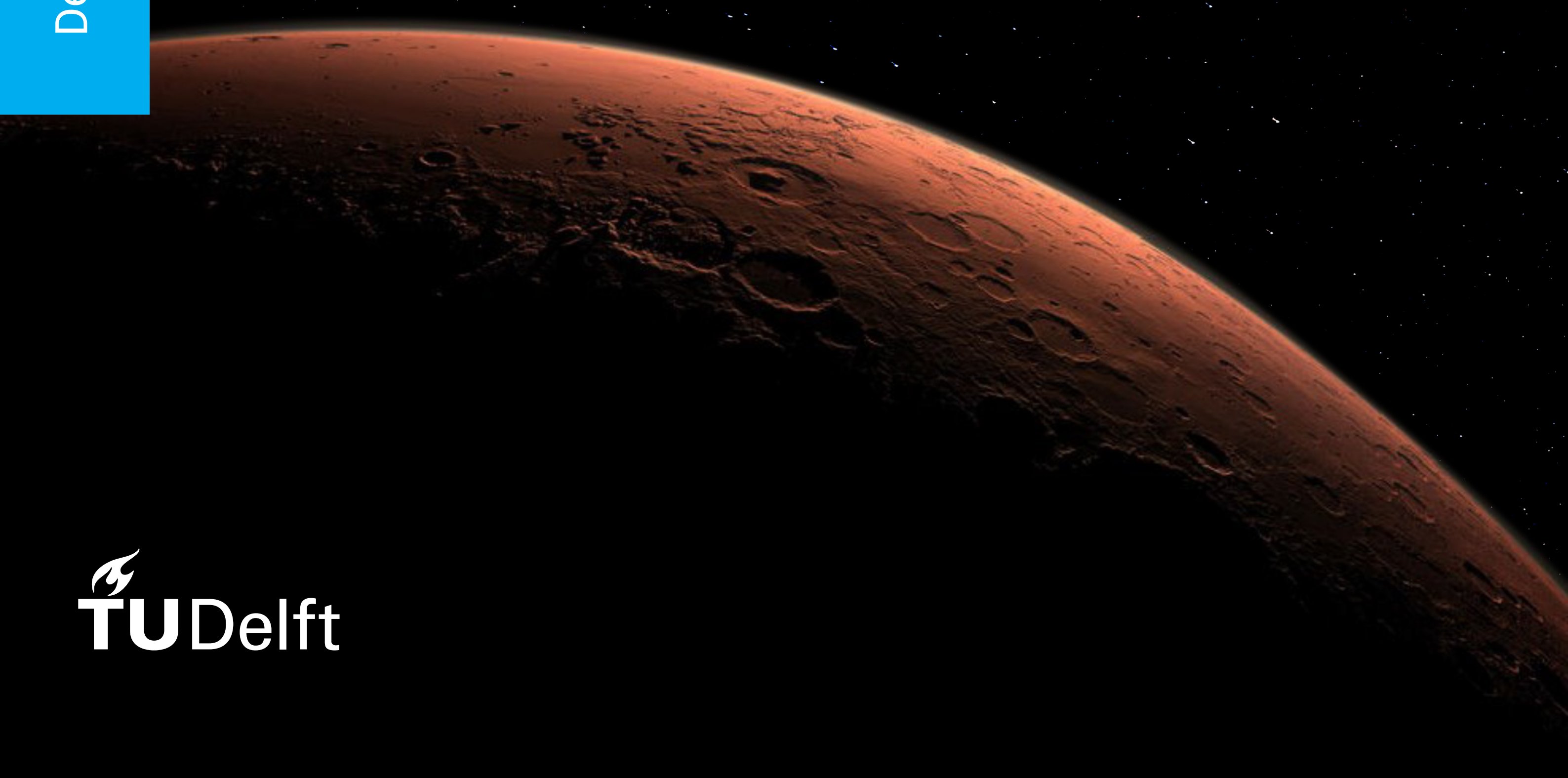
Design Synthesis Exercise

Group 15 - Manned Martian Aircraft

May 4, 2023

Javier Alonso Garcia	5228530	Adrian Beňo	5338514
Freek Braspenning	5291526	Joachim Bron	5259754
Pedro Coimbra Dos Santos	4682335	Sebastian Harris	5277418
Timo de Kemp	5310474	Patrick Kostelac	5238676
Thomas van de Pavoordt	5312329	Dominik Stiller	5253969

Delft University of Technology



TU Delft

Baseline Report

Design Synthesis Exercise

by

Group 15 - Manned Martian Aircraft

May 4, 2023

Javier Alonso Garcia	5228530	Adrian Beňo	5338514
Freek Braspenning	5291526	Joachim Bron	5259754
Pedro Coimbra Dos Santos	4682335	Sebastian Harris	5277418
Timo de Kemp	5310474	Patrick Kostelac	5238676
Thomas van de Pavoordt	5312329	Dominik Stiller	5253969

Version Control			
Version	Date	Author(s)	Description
1.0	04-05-2023	All	First draft

Project duration:	April 24, 2023 – June 30, 2023	
Thesis committee:	Dr. A. Sciacchitano,	TU Delft, tutor
	Dr. S. J. Paardekooper,	TU Delft, coach
	Dr. ir. J. A. Pascoe,	TU Delft, coach

Cover image credit: Pam van Schie (accessed April 2023 and adapted)

TU Delft

Executive Overview

Humans have been exploring Earth for centuries, and as technology advanced, this curiosity extended beyond our planet. The most promising target for making humanity interplanetary is our neighbor Mars. For astronauts going to Mars and exploring the planet in the next decade, rapid transportation between different locations on the surface of Mars is crucial. The mission statement is the following:

MS: Transport two astronauts with payload quickly over a long range on Mars.

A system should be designed that will fulfill the mission statement and everything that it entails.

E.1. Market analysis & cost estimation

The current rovers that are present on Mars are limited in range, due to their speed and obstacles that might be between landing location and science location. Even if rovers improve in the future in terms of speed and range, they are still limited in the types of terrains that they can explore. Manned aircraft will be a very efficient way of transporting astronauts over the Martian surface and thus exploring a new conceptual design is warranted.
The cost for this project is derived from the cost that was made to develop and manufacture the Perseverance rover. The cost per mass for this vehicle is being used to scale up the costs for this project. The total cost for the development and manufacturing of a manned Martian aircraft of 3000 kg is estimated at 6.6 bil. USD.

E.2. Mission description and requirements

The mission is described through the previously mentioned mission statement. Thus our main goal is the transport of the astronauts and payload on Mars. The DSE itself is responsible for the conceptual design, after which it goes into detailed design and is then manufactured and tested. After testing, the aircraft is launched towards Mars. Once on Mars, ground operations are performed, which are preparing the aircraft for its mission. Once the ground operation is finished, the mission described in the mission statement begins. The aircraft performs its desired flight profile while at the same time performing the necessary support functions. After the lifetime has ended, the appropriate end-of-life procedures are done.

The mission description is used to identify all the stakeholders and their needs. Those needs are then used to create a requirement discovery tree, which is finally used to develop a detailed set of requirements. From the detailed set of requirements, the key requirements and the driving requirements were identified and can be seen in Table E.1 and Table E.2 respectively. There are no killer requirements.

Table E.1: *Key requirements*

Identifier	Description
REQ-SAG-LF-03	The system shall obtain power from sources available in Mars.
REQ-LCD-LVEH-SIZE-01	The system shall have a volume of less than <TBD>m^3
REQ-LFSP-AIR-01	The system shall provide breathable air to the astronauts
REQ-CRUS-05	The nominal cruise speed shall be 111 m/s.

Table E.2: *Driving requirements*

Identifier	Description
REQ-ASTR-SAFE-01	The system shall not produce more than <TBD>positive gs in any direction.
REQ-SAG-REUS-03	The system's assembly process shall be repeatable
REQ-GOPS-ACT-ASS-01	The system shall be able to be assembled by 2 astronauts
REQ-AERO-LFT-02	The aerodynamic system shall have a maximum lift coefficient of <TBD>.
REQ-AERO-LFT-04	The aerodynamic system shall have a stall angle of <TBD>degrees.
REQ-STG-PAY-02	The system shall be able to hold 100 kg of payload
REQ-PWR-ELEC-01	There shall be <TBD>Watts of power available to power all essential systems
REQ-ETHC-02	The system shall not pollute the Martian environment.
REQ-CLMB-01	The climb rate at take-off altitude shall be at least <TBD>m/s.

E.3. Risk Assessment & sustainable development strategy

There are various risks to be considered in a project of this size. Organizational risks concerning scheduling issues, team member conflicts, or external factors affecting team members all pose continuous problems. These risks are continuously mitigated. As the project moves towards the more detailed design phase, it is important to identify the technical risks associated with system and subsystem design.

Technical risks have been identified concerning the functions of the system as well as the design process. These include but are not limited to missing requirements, missing design options, failure to take-off, dust storms leading to damage, life support failure, or structural failure. Every risk underwent a risk assessment to determine its probability and impact. For the design risks, impact, and probability values were determined by experience and engineering judgment. For technical risks, the probability is assessed in the same way. However, the impact is based on **?**].

Once all risks had been assessed, a risk mitigation plan was created, and risk mitigation measures were generated. Any risk is unwanted, and therefore, every risk is mitigated. The final result for all risks were plotted in a risk matrix. This matrix showed that no risk poses a serious threat anymore.

E.4. Trade-off

Many options for aircraft configuration have been thought of, after some brain storming and visualization in a design option tree. Then, based on the requirements presented on Section E.2, the design possibilities have been narrowed down to a few options, each with its own unique configuration possibilities. These options can be seen in the summarized design tree below:

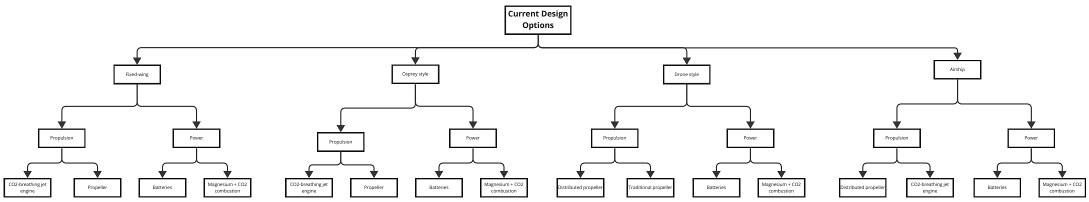


Figure E.1: *Summarized design option tree*

Through the figure, it can be seen that there are basically four final general aircraft types as design possibilities, namely a fixed wing aircraft and its different propulsion and power possibilities, an aircraft with propulsion units near its wingtips resembling a Boeing V-22 Osprey, a quad-copter resembling a standard drone design (could use more than 4 propellers) and an airship filled with either hydrogen or helium. These were the result of the trade-off performed by the team and will be used for further development.

E.5. Conclusions and further development

Each of the four general design possibilities presented at the end of Section E.4 will be further studied in detail by a subgroup, responsible for considering the different possible configurations for that particular aircraft type and analyzing its pros and cons, resulting in an optimal configuration for that specific preliminary concept.

For the next phase of the design process, the aforementioned strategy of dividing the general design possibilities between subgroups will be used. After the optimal configuration for each possibility is derived, these will be presented in detail in the next report.

It is worth mentioning that two subgroups will be assigned to the fixed wing general concept and look into different subsystem combinations. This has been decided based on the fact that such aircraft design is the most flight proven on Earth and is quite robust in handling many possible configurations.

Finally, by the end of those three weeks, one design will be chosen, setting a start for the final design phase, in which this design will be fully developed for 5 weeks resulting in this project's final design and final presentation.

Contents

1
Introduction

By Freek Braspenning, Dominik Stiller

Private and public organizations have the goal of making humanity a multi-planetary species. Mars as our next neighbor will be our first destination in as soon as a decade. The first astronauts will be scientists, which will explore wide regions of the red planet. Currently, no feasible solution exists for human transportation on Mars over vast ranges and in a fast manner. While surface rovers may be adapted for human transportation, only airborne transportation will be able to meet the needs for true mobility. This baseline report is the second in a series of reports to describe the conceptual design of a two-astronaut Martian aircraft.

Previously, the project plan showed the organizational aspects of this project, including task division and scheduling. This baseline report represents the first technical report of the project. The goal for this phase is to discover the design scope and requirements, then propose a range of likely feasible design options. These design options form the basis of the upcoming midterm report, which will evaluate the options quantitatively and decide on the preferred one.

This baseline report is structured as follows. First, the environment of Mars is described in Chapter 2 to inform the requirements and key design challenges. Next, the functional flow of the mission is provided in Chapter 3. These diagrams describe the function of each subsystem of the mission, and their logical interrelation and chronological order to one another. The functional diagrams, in addition to stakeholder needs, form the basis of the requirements, which are listed and organized in Chapter 4. Then, the market is analyzed for potential customers in Chapter 5, which serves as a justification for further development of the project. Furthermore, a preliminary cost estimation is included to inform the client about initial costs and future investments. Following the market analysis, a design option tree is constructed, in Chapter 6. All options are considered and systematically evaluated on feasibility, technology readiness, and requirements. Five different concepts remain to be investigated further. Next, generic mass and power budgets are set up based on statistics in Chapter 7, after which the process and design risks are identified and mapped in Chapter 8. Finally, a sustainable development strategy including manufacturing and operational aspects is presented in Chapter 9.

2
Environment of Mars

By Dominik Stiller, Javier Alonso García, Timo de Kemp

Before exploring possible design options surrounding flight and transportation on Mars, it is important to realize the constraining environment that has to be dealt with. This chapter explores all aspects of Mars and its properties. Section 2.1 describes the Martian gravity field. Section 2.2 investigates the atmosphere of Mars, its composition, and its features. Section 2.3 discusses the radiation received on the surface from the Sun and cosmic background radiation. Finally, Section 2.4 describes the terrain of Mars, the soil it has, and its properties.

2.1. Gravity field

By Javier Alonso García

Unlike the lower atmospheric density that will make it harder to fly the aircraft, the gravity field on Mars only generates an acceleration of 3.71 m/s^2 [1], meaning that all objects will weigh 2.64 times less than on Earth.

Orbital data from the Mars Global Surveyor (MGS), Mars Odyssey, and Mars Reconnaissance Orbiter (MRO) missions have been used to analyze variations in the gravity field. The analysis showed that the most significant variation in the gravity field was of 1600 mGal, which represents 0.43% of the average value [2]. For this reason, it was decided that the value for the gravitational acceleration can be considered constant in further calculations.

The gravity field is also used to define the altitude datum on Mars. We use the post-2001 definition of zero elevation as “the equipotential surface (gravitational plus rotational) whose average value at the equator is equal to the mean radius” [1]. The Mars Orbiter Laser Altimeter experiment determined the mean radius.

2.2. Atmosphere

By Dominik Stiller

Knowledge of the expected atmospheric conditions is crucial for airborne vehicles, especially those using air for lift and propulsion. The atmosphere on Mars has some similarities with Earth’s but also significant differences, which are described subsequently. All information is due to Haberle et al. [2] if not indicated otherwise. Fundamental properties are summarized in Table 2.1.

Table 2.1: *Properties of the Martian atmosphere. The density and temperature ranges correspond to the extremes from Figure 2.1.*

Property	Symbol	Value	Unit
Density at 0 km	ρ	1.0×10^{-2} to 2.1×10^{-2}	kg/m^3
Density at 15 km		2.3×10^{-2} to 4.0×10^{-3}	kg/m^3
Temperature at 0 km	T	145 to 284	K
Temperature at 15 km		134 to 264	K
Wind speed (no dust storm)[5]	u	2 to 10	m/s
Wind speed (dust storm)[5]		17 to 30	m/s
Specific gas constant	R	191	$J\,K^{-1}\,kg^{-1}$
Ratio of specific heats	γ	1.2	-

Compared to the nitrogen- and oxygen-rich air on Earth, the Martian atmosphere is composed of 96 % carbon dioxide, 1.9 % argon, 1.9 % nitrogen and 0.15 % oxygen. The CO_2 fraction decreases seasonally at high latitudes as it condenses onto the polar ice caps. Also, the lower gravity leads to a more shallow hydrostatic pressure gradient, which translates to a much lower density than on Earth (about 80 times). Clouds on Mars can consist of water vapor or condensed CO_2. Weather forecasts for Mars exist, such

[1] URL: https://mars.nasa.gov/all-about-mars/facts/ [cited 2023-05-01]
[2] URL: https://pgda.gsfc.nasa.gov/products/57 [cited 2023-05-01]

as daily measurements taken by Curiosity [3] or ESA's Space Weather Service Network [4], and may be used operationally.

Significant variations in temperatures and densities occur due to diurnal, seasonal, and terrain variations as well as dust storms. The average temperature is about 15 K higher during the perihelion season than during the aphelion season. At night, the atmosphere is stably stratified. Just after sunrise, there is a steep temperature gradient, with differences of up to 20 K in the lowest meters above the surface and a warming rate of up to 10 K/min in the lowest 100 m. Throughout the day, there is intense convection in the boundary layer (up to 10 km high), which may be leveraged to conserve energy, similar to how gliders use convective plumes. Temperature gradients reverse towards the evening. The terrain leads to spatial variations due to surface albedos, thermal inertia, and shadowing.

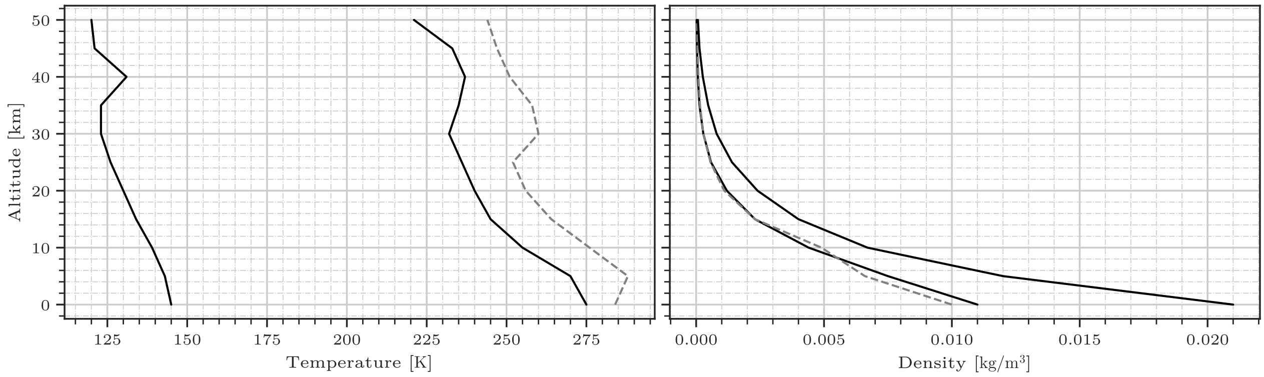


Figure 2.1: *Extreme temperatures and densities on Mars for low-temperature and high-temperature conditions. Note that these do not necessarily correspond to the same locations due to the influence of pressure. The dashed line corresponds to a global dust storm and high-temperature conditions.*

The extreme temperatures and densities expected on Mars as a function of altitude is shown in Figure 2.1. The temperature will be relevant for thermal expansion and constraints on fuel and life support; the density is critical for lift generation and may determine the cruise altitude. The values were found from the Mars Climate Database Version 6.1 [3, 4]. The low temperature corresponds to aphelion (solar longitude $L_s = 71°$) during solar minimum and a clear sky at the winter pole at 05:00 local solar time. The high temperature corresponds to perihelion ($L_s = 251°$) during solar maximum and a dusty sky (but no dust storm) at the summer pole at 15:00 local solar time. 05:00 and 15:00 correspond to the daily minimum/maximum temperature as found in [2, Figure 7.8a]. The temperature extremes agree with [2, Figure 4.11].

A unique feature of Mars is its dust storms. Most of them are regional but can grow to a planetary scale. While global dust storms are irregular (in some years, there are none), they can last for months, and atmospheric temperatures can increase by more than 20 K, which leads to lower densities (see dashed line in Figure 2.1). Atmospheric dust is linked to particular seasonal windows. There are low levels of dust during northern spring and summer ($L_s = 0°$ to $135°$), while the dusty season corresponds to northern autumn and winter ($L_s = 135°$ to $360°$). Extensive regional and global dust storms only occur during the dusty season.

2.3. Radiation and irradiance

By Javier Alonso García

Solar panels are a prevalent and sustainable method to power systems in outer space. This is, however, harder to do on Mars as opposed to Earth since solar irradiance decreases with the square of the distance towards the Sun. Mars is located at 1.52 [AU] from the Sun, therefore solar irradiance will be 586.2 [W/m^2], which is 2.32 times less intense than at Earth [5]. This implies that this option is still feasible, but the collecting area must be larger to provide the same power.

Another aspect that would make it challenging to have manned missions on Mars is the absence of a

[3]URL: https://mars.nasa.gov/msl/weather [cited 2023-05-12]
[4]URL: https://swe.ssa.esa.int/current-space-weather [cited 2023-05-12]
[5]URL: https://nssdc.gsfc.nasa.gov/planetary/factsheet/marsfact.html [cited 2023-05-01]

magnetic field around the planet and the absence of a protective ozone layer, which allows radiation to reach the planet's surface. This radiation can be categorized into two groups: Galactic Cosmic Rays (GCR) and Solar Energetic Particles (SEP) [5]. GCR consists of nucleic ions of elements, ranging from hydrogen to nickel, and their impact can be assumed to be constant over time. SEP, on the other hand, is associated with solar flares, which vary between solar maximums and minimums [5].

Exposure to either of these types of radiation would have severe health implications and eventually result in the death of the astronauts. Therefore, a protective system will be necessary.

SEP carry lower energy, so the energy they deposit upon impact can be securely reduced to non-harmful levels easily [5]. On the other hand, GCR may have very high energy, depending on the particular ion in question (the heavier the element, the more energy it will carry). For this reason, any structure in which humans are expected to be present in for long periods of time will need to be covered by a protective coating layer, explicitly designed to intercept these particles. Common elements in the aerospace industry, such as aluminum, polymers such as polyethylene, hydrides, and carbon-fiber composites, were tested to see how much protection they provide. The result of this investigation was that hydride provided the most protection, followed by polyethylene (although it was 20% less mass efficient than $Li^{10}BH_4$) [5, 6]. Regarding load-bearing materials, composite materials such as CFRP and SiC composite plastics offered 1.9 times the dose reduction of aluminum while maintaining high mechanical strengths when exposed to Fe ions [6].

2.4. Terrain

By Timo de Kemp

To take off and land, it is essential to know the terrain on Mars. To design the landing system, the roughness of the terrain as well as the softness of the terrain, and the number of rocks present are vital knowledge.

The roughness of the terrain is essential for both landing and for accessibility of ground vehicles adding to the need for an aircraft on Mars. According to **?**], it can be seen that asteroid impacts have shaped the terrain on Mars. However, the surface seems relatively flat apart from the boundaries of the asteroid impacts. Furthermore, Valles Marineris, a 4000 km wide, 200 km wide, and 7 km deep canyon, can be seen; this could be a compelling location to fly to as this canyon can probably not be accessed with a ground-based transportation system due to the steep slopes.

The softness of the terrain is a critical parameter to determine the size of the landing gear needed in case of horizontal landing. The mechanical properties of Mars can be modeled off the Mojave desert as done in [7]; this could also be a possible testing location for designing take-off and landing.

Finally, the rocks that can be found on the Martian surface must be considered when designing an aerial vehicle landing and taking off from the ground. The rocks should not interfere with the landing system and either cause a tip-over or break the landing gear. According to Golombek et al. [8], the size of rocks and their presence per area are analyzed for several landing sites on Mars. From these findings, it can be concluded that only one rock of more than 10 cm is present on 1 m^2. However, many landings were done in rocky areas, which were interesting for research. Therefore this research might be biased to more rocks present, leading to a conservative design.
It can thus be said that landing is not significantly restricted by Mars' terrain as derived from the initial research. The landing gear will need to be designed such that it can withstand rock impacts and the softness of the terrain, but enough landing distance will be available.

3 System Function Flowdown

In this chapter, descriptions of the process used to generate the Project design & development logic (PDDL) (Section 3.1), Functional Breakdown Diagram (FBD) (Section 3.2) and the Functional Flow Diagram (FFD) (Section 3.3) are given. The PDDL was derived from the phases of any generic engineering project. Then, both the FBD and FFD were designed concurrently, as many of their parts depend on each other. To design these two diagrams, first a brainstorm session was held, in which as many functions as possible were identified. After this, to make sure no functions were forgotten, feedback from other group members was gathered and the functions were reviewed. Functions of the mission/system are given from the launch on Earth up to the end-of-life (EOL) on Mars. An effort was made to generate and phrase the functions in the diagrams in a general way, to avoid constraining the design space and limiting future designs, i.e. the functions were written in a "solution-free" way. Only the most essential tasks known to date were added since the design process is still in its early phase and not much is known about which design will be chosen. A more detailed version of both diagrams will be included in the final report, once a preliminary design has been chosen and functions become more design specific.

3.1. Project design & development logic

By Dominik Stiller, Timo de Kemp

The Project Design & Development Logic (PDDL) describes all post-DSE phases, starting with the preliminary design produced in the DSE and ending with the end of life of the system. The logic is kept at a high level, since the FFD dives into more detail. The preliminary/detailed design and testing phases are tightly entangled since verification and validation may lead to revisions. Prototype manufacturing is also part of this loop, while the manufactured final product will be transported to the launch site, then launched to Mars for operation. The PDDL is shown in Figure 3.1.

3.2. Functional breakdown diagram

By Joachim Bron, Patrick Kostelac, Freek Braspenning, Pedro Santos, Adrian Beňo

The FBD provides a hierarchical view of the functions to be performed by the system in the form of an AND tree. This means that any block is made up of the sum of the blocks under it. The advantage of the FBD is that it can display functions that are difficult to include in the FFD, since these are inherently in some kind of chronological order, i.e. in a "flow". The FBD thus allows to showcase functions that are time-independent or that need to be fulfilled at all times, such as providing power or ensuring structural integrity. The FBD does not provide information on the flow of functions, which is done by the FFD. The FBD is shown in Figure 3.2. Each function is given a unique ID for identification.

3.3. Functional flow diagram

By Joachim Bron, Patrick Kostelac, Freek Braspenning, Pedro Santos, Adrian Beňo

The FFD shows the logical flow of the functions of the system/mission. Contrary to the FBD, the steps in which the functions are performed matter. Functions can be in series, in parallel using AND gates, or optional based on a certain criterion using an OR gate. Each function is given a unique ID, related to the functions in the FBD. Some functions are split up into lower-level functions; this is done for up to a maximum of 5 levels deep, but on average functions are detailed up to 3 levels deep. The FFD is shown in Figure 3.3. The functions followed from the brainstorming sessions on what the system should perform. It consists of pre-launching phases such as manufacturing and testing, mission phases, during which the system should fulfill its mission, and the end-of-life phase. The mission phase is subdivided into functions before arrival on Mars, ground operations on Mars, and the flight profile. It is important to note that the functions that were time-independent and easily shown in the FBD are also here. These continuous functions are grouped into the "4. Perform support functions" block and are shown in parallel to other functions in the FFD, to display the fact that these functions are performed at all times.

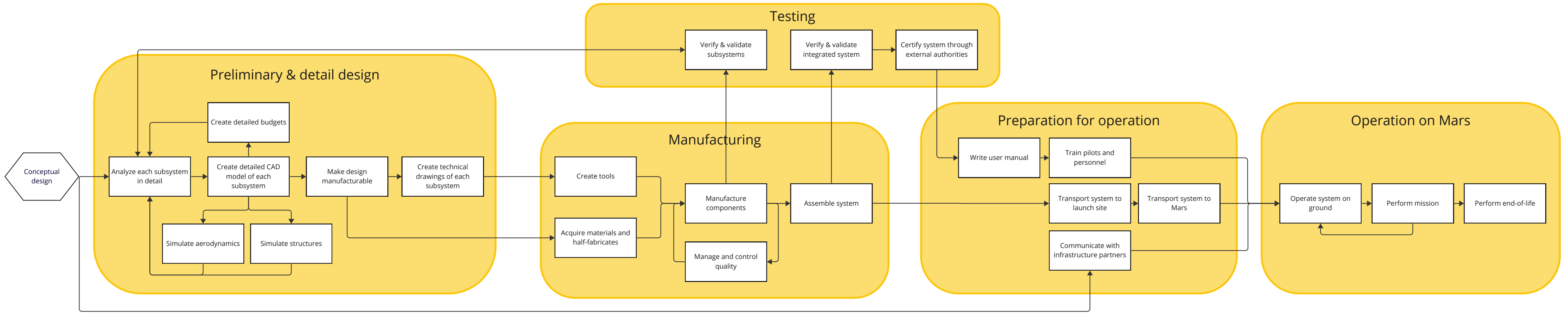


Figure 3.1: *Project design & development logic*

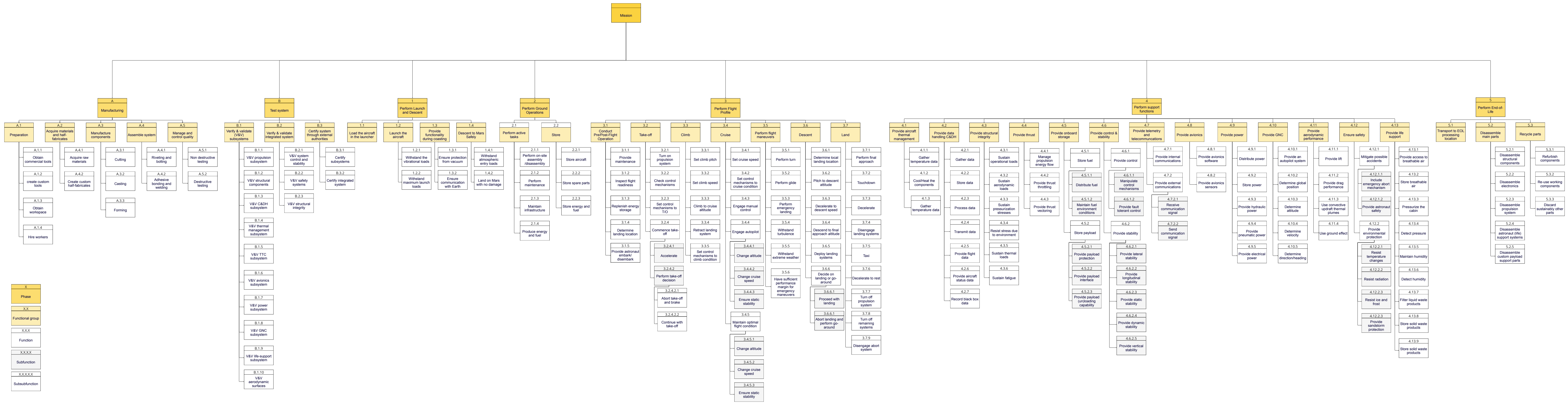


Figure 3.2: *Functional breakdown diagram*

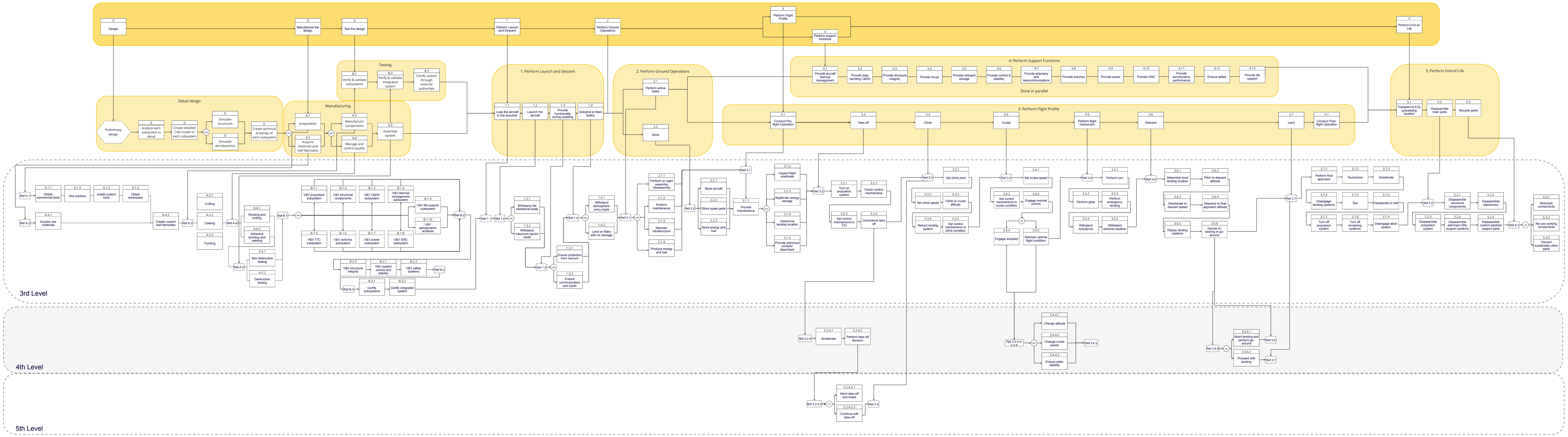


Figure 3.3: *Functional flow diagram*

4
Requirements and constraints

In this chapter, the stakeholder and the system requirements are discussed. First, the previously derived mission need and project objective statements will be analyzed, and possible requirements will be extracted. Secondly, all project stakeholders will be gathered, and their needs will be assessed and formulated into requirements; once they are known, the requirement discovery tree can be created. Finally, the requirement discovery tree lists the top-level system functions for formulating the system and subsystem needs and requirements.

4.1. Mission statement and project objective statement

By Patrick Kostelac

The project can be defined through a mission statement and a project objective statement. These two statements summarize the mission's goal and impose requirements and constraints on the mission. The mission statement (MS) and the project objective statement (POS) are:

> *MS: Transport two astronauts with payload quickly over a long range on Mars.*
>
> *POS: With 10 people in 10 weeks, design an aerial vehicle that is capable of transporting two astronauts for at least* 1000 km *on Mars.*

Several requirements can be extracted from the mission statement. Firstly, it specifies that two astronauts and a payload should be transported. Secondly, it specifies that they should be transported quickly, and lastly, it specifies that they should be transported over a long range. The project objective statement adds numbers to the mission statement and specifies the range of 1000 km. The project objective statement also constrains the project as 10 people should complete the project in 10 weeks.

4.2. Top level requirements specification

By Patrick Kostelac, Thomas van de Pavoordt

Along with the mission statement and the project objective statement, a set of top-level user requirements was given to the group, which can be seen below:

- **REQ-USER-PERF-01:** The system shall have a range of at least 1000 [km].
- **REQ-USER-PERF-02:** The system shall have a cruise speed of at least 400 [km/h].
- **REQ-USER-SARE-01:** The system shall be able to perform all its functions in the Mars atmosphere.
- **REQ-USER-SARE-02:** The system shall be able to take-off and land on Mars soil.
- **REQ-USER-SUST-01:** The system shall be able to use in-situ resources to function.
- **REQ-USER-ENGB-01:** The system shall have a Maximum Take-Off Mass (MTOM) of less than 3000 [kg].
- **REQ-USER-ENGB-02:** The system shall be able to transport 2 astronauts with a maximum mass of 250 [kg].
- **REQ-USER-ENGB-03:** The system shall be able to carry a payload of at least 100 [kg].
- **REQ-USER-OTHR-01:** The system shall be able to be assembled on Mars.

Where the abbreviations are as follows: PERF - performance, SARE - safety and reliability, SUST - sustainability, ENGB - engineering budgets, OTHR - other, these top-level requirements are provided by the user. They should be considered as leading requirements. Later a detailed set of system and mission requirements will be created based on the provided user requirements, requirement discovery trees, and requirement flow down. Those requirements can be found in Section 4.4.1 and Section 4.4.2, respectively.

4.3. User and stakeholder needs

By Patrick Kostelac, Sebastian Harris, Javier Alonso García, Thomas van de Pavoordt, Dominik Stiller

The project users and stakeholders can be identified from the mission statement, project objective statement, and top-level requirements. The stakeholders were identified as Astronauts (ASTR), Space agencies

(SAG), Customers (CUST), Manufacturers (MNFCT), the Scientific community (SCNCE), and the Launch provider (LAU), where the astronauts are considered as users and the rest as stakeholders. Once the users and stakeholders are identified, their needs were assessed in Table 4.1 below:

Table 4.1: *Overview of the stakeholders and their needs*

(a) *Needs of the astronauts*

ID	Astronauts	ID	Astronauts
1	Safety	6	Able to see their surroundings
2	Able to manually control the aircraft	7	Able to travel from one place to another
3	Simple to use	8	Easy and quick ingression and egression
4	Basic level of comfort	9	Simple assembly process
5	Able to transport payload	10	Simple maintenance and repairs

(b) *Needs of the space agencies*

ID	Space agencies
11	No interference with concurrent missions
12	Re-usability of the system by different missions
13	Long lifetime of the system
14	Compatibility of the system with already existing infrastructure
15	Ability of the system to be transported by an already existing launcher

(c) *Needs of the tutors/customers*

ID	Customers
16	Design is innovative
17	Design process is successful
18	Final design fulfills the requirements
19	Design process is done as fast as possible
20	Costs are as low as possible

(d) *Needs of the manufacturers*

ID	Manufacturers
21	Materials employed are not toxic
22	Manufacturing is profitable

(e) *Needs of the scientific community*

ID	Scientific community
23	No damage is done to collected payload
24	No damage is done to scientific instruments
25	Provide access to scientifically interesting areas

(f) *Needs of the launch provider*

ID	Launch provider
26	System components are attached to the launcher
27	System fits within the payload bay
28	System can withstand prescribed loads

4.3.1. User and Stakeholder requirements

The user and stakeholder requirements are created from the needs in Section 4.3. From the astronaut needs, three main categories can be explored. The astronaut safety (SAFE), the astronaut control over the aircraft and visibility of their surroundings (CNTRL), and lastly, the astronaut comfort (CMFRT).

Table 4.2: *Astronaut requirements*

Identifier	Description
REQ-ASTR-SAFE-01	Astronauts shall be transported safely by the system.
REQ-ASTR-SAFE-02	The system shall not produce more than <TBD> positive [g] in any direction.
REQ-ASTR-SAFE-03	The system not produce more than <TBD> negative [g] in any direction.
REQ-ASTR-SAFE-04	In a crash situation, the system shall not induce more than <TBD> [g] over <TBD> [s] in spineward direction.
REQ-ASTR-SAFE-05	In a crash situation, the system shall not induce more than <TBD> negative [g] over <TBD> [s] in spineward direction.
REQ-ASTR-SAFE-06	In a crash situation, the system shall not induce more than <TBD> [g] over <TBD> [s] in the tailward direction.
REQ-ASTR-SAFE-07	In a crash situation, the system shall not induce more than <TBD> negative [g] over <TBD> [s] in the tailward direction.
REQ-ASTR-SAFE-08	The system shall extinguish fires in <TBD> [s].
REQ-ASTR-SAFE-09	The system shall allow for a maximum exposure of 1 [Sv] for <TBD> [s].
REQ-ASTR-SAFE-10	Astronauts shall be able to exit the aircraft in under <TBD> [s].
REQ-ASTR-CNTRL-01	Astronauts shall be able to control the system manually.
REQ-ASTR-CNTRL-03	Astronauts shall have an upward field of view of <TBD> [deg].
REQ-ASTR-CNTRL-04	Astronauts shall have a downward field of view of <TBD> [deg].
REQ-ASTR-CNTRL-05	Astronauts shall have a lateral field of view of <TBD> [deg].
REQ-ASTR-CMFRT-01	The system shall maintain the astronauts at a temperature of <TBD> [K].
REQ-ASTR-CMFRT-02	The system seat shall be within <TBD> [m] of all controls.
REQ-ASTR-CMFRT-03	The astronauts shall be able to enter the aircraft in under <TBD> [s].

The next stakeholder was the manufacturer. The first manufacturer's need is to remain profitable (COST). The second manufacturer's need is to ensure the safety of the workers by not using toxic material (TXIC).

Table 4.3: *Manufacturer requirements*

Identifier	Description
REQ-MNFCT-COST-01	The cost of manufacturing and materials should be less than <TBD> % of the development cost.
REQ-MNFCT-TXIC-01	The system shall not utilize toxic materials, unable to be handled by protected employees.
REQ-MNFCT-TXIC-02	The system shall not utilize materials comprised of toxic raw ingredients, unable to be handled by protected employees.

The scientific community has two needs, the scientific samples should not be damaged (PAYL), and scientific instruments should not be damaged (INSTR).

Table 4.4: *Scientific community requirements*

Identifier	Description
REQ-SCNCE-PAYL-01	The integrity of the collected scientific payload shall be preserved.
REQ-SCNCE-INSTR-01	The scientific instruments shall not be disturbed by more than <TBD> [g].
REQ-SCNCE-INSTR-02	The scientific instruments shall not have the same eigenfrequency as the aircraft.

The next stakeholder is the space agencies. The space agency can be divided into interference with concurrent missions (INT), re-usability of the system (REUS), compatibility of the system with existing infrastructure (COMP), the lifetime of the system (LIFE), operational aspects of the system (OPE) and the compatibility with existing launchers (LCH).

Table 4.5: *Space agencies requirements*

Identifier	Description
REQ-SAG-INT-01	The system shall not interfere with current missions.
REQ-SAG-INT-02	The system shall not utilize the same transmission frequency as current missions.
REQ-SAG-INT-03	The system shall not impede other missions' operations.
REQ-SAG-REUS-01	The aircraft shall have standardized payload storage.
REQ-SAG-REUS-02	The system shall be able to be stored for <TBD> years without use or maintenance.
REQ-SAG-REUS-03	The system's assembly process shall be repeatable.
REQ-SAG-COMP-01	The system shall be compatible with already existing infrastructure.
REQ-SAG-COMP-02	The system shall be able to communicate with already existing spacecraft.
REQ-SAG-COMP-03	The system shall be able to utilize already existing forms of recharging/refueling.
REQ-SAG-LIFE-01	The system shall have an operational life of <TBD> years.
REQ-SAG-LIFE-02	The system shall have an operational lifetime of at least <TBD> flight hours.
REQ-SAG-LIFE-03	The system shall obtain power from sources available on Mars.
REQ-SAG-OPE-01	The system shall be operational in all periodical conditions.
REQ-SAG-OPE-02	The system shall be operated independently of the season.
REQ-SAG-OPE-03	The system shall be operated independently of the day-night cycle.
REQ-SAG-OPE-04	The system shall be operational during sand storms.
REQ-SAG-OPE-05	The system shall be operational in all parts of the planet.
REQ-SAG-OPE-06	The system shall not need runways to take-off and land.

The next stakeholder is the launch provider. The launch provider needs the system attached to the launcher to fit within the payload bay and withstand prescribed loads.

Table 4.6: *Launch provider requirements*

Identifier	Description
REQ-LAU-01	The system components shall remain attached to the launcher during launch.
REQ-LAU-02	The system components shall be able to fit in the selected launcher.
REQ-LAU-03	The system components shall be able to withstand the loads specified.
REQ-LAU-04	The system shall comply with all requirements set by the manual of the chosen launcher vehicle.

The next stakeholder is the customer. The customer, first and foremost, needs the design to be successful (SUCC). The second customer need is for the design to be done as fast as possible (FAST), and the third is for the design to be innovative (INNO). The fourth customer need is for the design to have low costs (COST). The fifth customer need is for the design to fit the requirements (REQ). Finally, the last customer need is for the team working on the project to distribute the work evenly (RESC).

Table 4.7: *Customer requirements*

Identifier	Description
REQ-CUST-FAST-01	The conceptual design shall be finished within 3600 working hours.
REQ-CUST-FAST-02	The project schedule shall be reevaluated in case of competition.
REQ-CUST-INNO-02	The design shall improve upon state of the art.
REQ-CUST-COST-01	The project cost shall be minimized.
REQ-CUST-COST-02	The design cost shall be at most <TBD> mil. FY2023 USD.
REQ-CUST-COST-03	The manufacturing cost shall be at most <TBD> mil. FY2023 USD per vehicle.
REQ-CUST-COST-04	The operating cost shall be at most <TBD> mil. FY2023 USD per year.

4.4. Requirements discovery tree

By Adrian Beňo, Dominik Stiller

A requirements discovery tree is a systems engineering design tool that identifies all the requirements in a structured way. It is an AND tree in which each parent leaf requirement is the sum of its child leaf requirements. The dichotomous approach was used not to leave any requirements. The top binary splitting point separates the requirements into technical and non-technical. The second level lists aircraft life stages, and the third level provides a detailed analysis. The leaves were generated based on the functional diagrams, created first, and extended with non-technical constraints. The requirements discovery tree is shown in Figure 4.1.

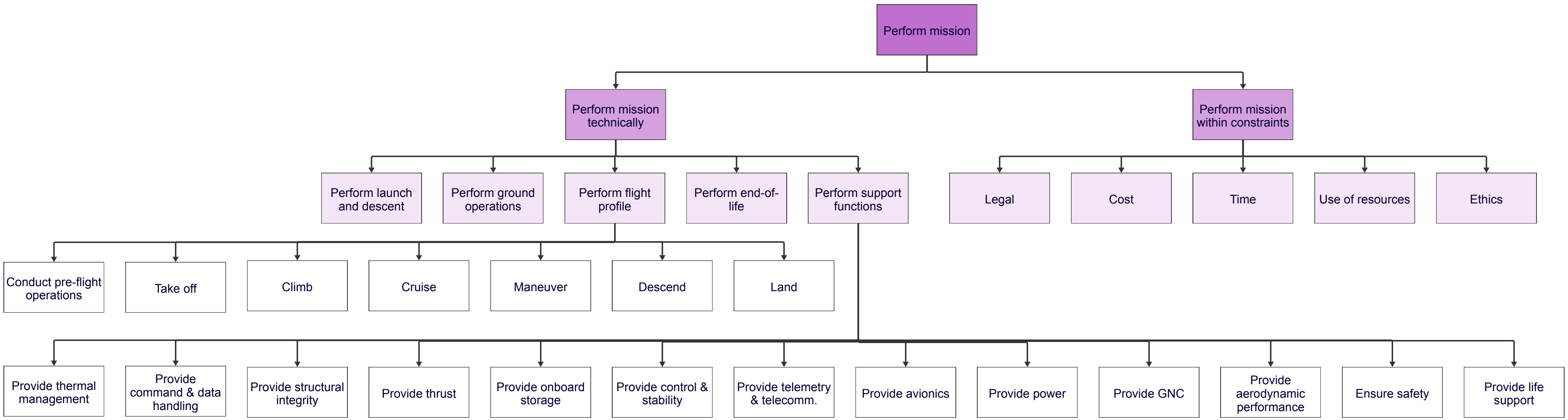


Figure 4.1: *Requirements discovery tree*

4.4.1. System requirements
By Group

This chapter lists a breakdown of all the system requirements. The system requirements are obtained by further developing the requirements discovery tree. The "Perform mission within constraints" and "Perform support functions" functions are considered system requirements as those are not specific to the mission profile but are requirements that must always be satisfied for a successful mission. Each of those functions is further developed into the system's needs to fulfill that function which are then developed into sets of requirements that can be seen below.

Successful launch, coast, and descent (LCD) of the aircraft to Mars is crucial to the mission. The aircraft will be created on Earth while its mission is on Mars. Thus, the transportation of the aircraft is crucial. The aircraft is first constrained by the launch vehicle (LVEH), by its size (SIZE), adapter (ADAPT), eigenfrequencies (EIGEN), and vibrations (VIBR). The vehicle is constrained by the launch (LNCH) as it needs to withstand the launch loads (LOAD). The vehicle then coasts to Mars (COAST) while being protected from the environment (PROT) and keeping communication with Earth (COMM). Finally, the vehicle descends (DSCNT) into the Martian atmosphere (ATMOS) and touches down on the Mars surface (TCHDWN).

Table 4.8: *Launch, coasting and descent requirements*

Identifier	Description
REQ-LCD-LVEH-SIZE-01	The system, in launch configuration, shall have a volume of less than <TBD> [m^3].
REQ-LCD-LVEH-SIZE-02	The system, in launch configuration, shall have a height of less than <TBD> [m].
REQ-LCD-LVEH-SIZE-03	The system, in launch configuration, shall have a width of less than <TBD> [m].
REQ-LCD-LVEH-SIZE-04	The system, in launch configuration, shall have a depth of less than <TBD> [m].
REQ-LCD-LVEH-EIGEN-01	The system shall have an eigenfrequency higher than <TBD> [Hz] (of the launch vehicle).
REQ-LCD-LVEH-EIGEN-02	The payload shall have an eigenfrequency higher than <TBD> [Hz] (of the system).
REQ-LCD-LNCH-VIBR-01	The system shall be able to withstand vibrational loads of <TBD> [g].
REQ-LCD-LNCH-LOAD-01	The system shall be able to withstand longitudinal loads of <TBD> [g].
REQ-LCD-LNCH-LOAD-02	The system shall be able to withstand lateral loads of <TBD> [g].
REQ-LCD-COAST-PROT-01	The system shall be able to withstand <TBD> [Sv] of radiation.
REQ-LCD-COAST-COMM-01	The system shall remain in communication with Earth throughout the coasting phase.
REQ-LCD-COAST-COMM-02	The system shall use <TBD>-band to communicate with Earth.
REQ-LCD-DSCNT-ATMOS-01	The system shall withstand atmospheric entry temperatures of up to <TBD> [K].
REQ-LCD-DSCNT-ATMOS-02	The system shall withstand longitudinal atmospheric entry loads of up to <TBD> [g].
REQ-LCD-DSCNT-ATMOS-03	The system shall withstand lateral atmospheric entry loads of up to <TBD> [g].
REQ-LCD-DSCNT-ATMOS-04	The system shall withstand vibrational atmospheric entry loads of up to <TBD> [g].
REQ-LCD-DSCNT-TCHDWN-01	The system shall withstand longitudinal touchdown loads of up to <TBD> [g].
REQ-LCD-DSCNT-TCHDWN-02	The system shall withstand lateral touchdown loads of up to <TBD> [g].
REQ-LCD-DSCNT-TCHDWN-03	The system shall withstand vibrational touchdown loads of up to <TBD> [g].

Ground operations (GOPS) are performed once the aircraft lands on Mars. First, several active tasks (ACT) need to be performed. The vehicle must first be assembled (ASS); once assembled, it must be maintained (MAINT). To be assembled, some existing infrastructure (INFRA) is needed. The infrastructure must provide energy to the aircraft (PROD) to ensure multiple flights. When on the ground, the aircraft needs a storage system (STORE). The storage system protects the aircraft (SYS) and provides spare parts (PART) and energy (ENRG).

Table 4.9: *Ground operations requirements*

Identifier	Description
REQ-GOPS-ACT-ASS-01	The system shall be able to be assembled by at least 2 astronauts.
REQ-GOPS-ACT-ASS-02	The assembly process shall only use tools available in-situ.
REQ-GOPS-ACT-ASS-03	The assembly process shall not use more than <TBD> hours.
REQ-GOPS-ACT-MAINT-01	The system shall allow for visual checks every <TBD> flights.
REQ-GOPS-ACT-MAINT-02	The system shall allow for system diagnostic checks every <TBD> flights.
REQ-GOPS-ACT-MAINT-03	The system shall allow for Non-Destructive Testing every <TBD> flights.
REQ-GOPS-ACT-INFRA-01	The infrastructure supporting the system shall allow for maintenance every <TBD> days.
REQ-GOPS-ACT-INFRA-02	The energy replenishment system shall allow for maintenance every <TBD> days.
REQ-GOPS-ACT-INFRA-03	The main take-off site shall allow for maintenance every <TBD> days.
REQ-GOPS-ACT-INFRA-04	Any storage facility of the system shall allow for maintenance every <TBD> days.
REQ-GOPS-ACT-PROD-01	The energy replenishment system shall have energy available for <TBD> flights.
REQ-GOPS-ACT-PROD-02	The energy replenishment system shall produce energy at a rate of <TBD> [W/hr].
REQ-GOPS-STORE-SYS-01	The system shall be able to be stored in a protective and non-damaging environment.
REQ-GOPS-STORE-PART-01	The system shall have spare parts available at all times for <TBD> number of components.
REQ-GOPS-STORE-ENERG-01	The infrastructure supporting the system shall have energy storage for <TBD> flights.

The Avionics subsystem (AVNC) consists of the appropriate instrument flight conditions (IFC), which are needed for the autopilot to follow the selected flight plan. In addition to the IFR, an appropriate navigation system (NAV) is needed to provide the astronauts with all the relevant flight information.

Table 4.10: *Avionics requirements*

Identifier	Description
REQ-AVNC-GNRL-01	The system shall have an avionics subsystem.
REQ-AVNC-IFC-01	The avionics subsystem shall include all instruments needed for IFC navigation.
REQ-AVNC-IFC-02	The avionics subsystem shall include an airspeed indicator.
REQ-AVNC-IFC-03	The avionics subsystem shall include an altimeter indicator.
REQ-AVNC-IFC-04	The avionics subsystem shall include a fuel gauge indicator.
REQ-AVNC-IFC-05	The avionics subsystem shall include position lights.
REQ-AVNC-IFC-06	The avionics subsystem shall include anti collision lights.
REQ-AVNC-IFC-07	The avionics subsystem shall include a gyroscopic rate-of-turn indicator.
REQ-AVNC-IFC-08	The avionics subsystem shall include a slip-skid indicator.
REQ-AVNC-IFC-09	The avionics subsystem shall include an attitude indicator.
REQ-AVNC-IFC-10	The avionics subsystem shall include a heading indicator.
REQ-AVNC-IFC-11	The avionics subsystem shall gather measurements on total atmosphere pressure.
REQ-AVNC-IFC-12	The avionics subsystem shall gather measurements on static atmosphere pressure.
REQ-AVNC-IFC-13	The avionics subsystem shall gather measurements on inertial acceleration.
REQ-AVNC-IFC-14	The avionics subsystem shall gather measurements on global system position.
REQ-AVNC-IFC-15	The avionics subsystem shall measure fuel level.
REQ-AVNC-NAV-01	The avionics subsystem shall have navigation instruments.
REQ-AVNC-NAV-02	The avionics subsystem shall include a <TBD> Band Radar.
REQ-AVNC-NAV-03	The avionics subsystem shall include a Short-Wave Infrared sensor.
REQ-AVNC-NAV-04	The avionics subsystem shall include a Terrain Awareness and Warning System.
REQ-AVNC-NAV-05	The avionics subsystem shall include a Heads Up Display.
REQ-AVNC-NAV-06	The avionics subsystem shall include a Traffic Alert and Collision Avoidance System.
REQ-AVNC-NAV-07	The avionics subsystem shall include a Night Vision System.
REQ-AVNC-ICE-01	The avionics subsystem shall include a de-icing system.

The transport of the astronauts and the payload through the air is possible because of the aircraft's aerodynamic performance (AERO). The aircraft will need to produce lift (LFT) in order to sustain flight while at the same time minimizing drag (DRG) to reduce the amount of thrust required.

Table 4.11: *Aerodynamics requirements*

Identifier	Description
REQ-AERO-LFT-01	The aerodynamic system shall provide lift.
REQ-AERO-LFT-02	The aerodynamic system shall produce more than <TBD> [N] of lift.
REQ-AERO-LFT-03	The aerodynamic system shall have a maximum lift coefficient of <TBD>.
REQ-AERO-LFT-04	The system shall have an induced drag coefficient of no more than <TBD>.
REQ-AERO-LFT-05	The aerodynamic system shall have a stall angle of <TBD> [deg].
REQ-AERO-LFT-06	The aerodynamic system shall have a stall speed of <TBD> [m/s].
REQ-AERO-LFT-07	The aerodynamic system shall have a maximum speed of <TBD> [m/s].
REQ-AERO-DRG-01	The aerodynamic system shall have parasitic drag coefficient in cruise of less than <TBD>.
REQ-AERO-DRG-02	The aerodynamic system shall have a parasitic drag coefficient during take-off and landing of less than <TBD>.

The thermal control of the aircraft is necessary as the temperatures on Mars can range from $-140°$ Celsius to $20°$ Celsius. In addition, thermal control is vital as appropriate thermal insulation (INS) should keep the astronauts and payloads at appropriate temperatures. Also, heat will need to be generated (HTCL), as perfect insulation is impossible. Lastly, there is a need to detect the temperature (DTCT) to know when heating is needed.

Table 4.12: *Thermal requirements*

Identifier	Description
REQ-THRM-01	The system shall have a thermal control system.
REQ-THRM-INS-02	The system shall have an overall emissivity lower or equal to <TBD>.
REQ-THRM-INS-03	The system shall have an overall absorptivity lower or equal to <TBD>.
REQ-THRM-HTCL-02	The system shall be able to generate <TBD> [W] of heat.
REQ-THRM-HTCL-03	The system shall be able to exhaust <TBD> [W] of heat.
REQ-THRM-HTCL-04	The system shall be able to distribute heat within the vehicle.
REQ-THRM-DTCT-01	The system shall be able to detect the temperature of different parts of the vehicle with an accuracy of <TBD> [K].

The storage capabilities (STG) of the aircraft are essential as the primary use of the aircraft is to transport astronauts and a payload and to do so, it needs to store the astronauts and payload inside it (PAY).

Additionally, the energy source used for thrust must be stored on board (PRP) to provide constant thrust during the mission.

Table 4.13: *Storage requirements*

Identifier	Description
REQ-STG-PAY-01	The system shall be able to store payload.
REQ-STG-PAY-02	The system shall be able to hold at least 100 [kg] of payload.
REQ-STG-PAY-03	The payload bay shall have a minimum volume of <TBD> [m^3].
REQ-STG-PAY-04	The payload bay shall be airtight.
REQ-STG-PAY-05	The payload bay shall be able to maintain a minimum temperature of <TBD> [K].
REQ-STG-PAY-06	The payload bay shall be able to maintain a maximum temperature of <TBD> [K].
REQ-STG-PAY-07	The payload bay shall be accessible from the outside.
REQ-STG-PRP-01	The system shall be able to hold propellant.
REQ-STG-PRP-02	The system shall be able able to hold <TBD> [kg] of fuel.
REQ-STG-PRP-03	The system shall be able able to hold <TBD> [kg] of oxidizer.
REQ-STG-PRP-04	The system shall be able to provide <TBD> [kg/s] of fuel to propulsion subsystem.
REQ-STG-PRP-05	The system shall be able to provide <TBD> [kg/s] of oxidizer to propulsion subsystem.
REQ-STG-PRP-10	The system shall be able to store fuel at a pressure of at most <TBD> [Pa].
REQ-STG-PRP-11	The system shall be able to store oxidizer at a pressure of at most <TBD> [Pa].
REQ-STG-PRP-12	The system shall ensure the fuel is kept in a temperature range of <TBD> - <TBD> [K].
REQ-STG-PRP-13	The system shall ensure the oxidizer is kept in a temperature range of <TBD> - <TBD> [K].

In addition to keeping the astronauts at an appropriate temperature, a life support system must be in place (LFSP). The astronauts need to be provided with oxygen (AIR), water (WTR), and appropriate humidity levels (HMD) in order to survive the flight. Additionally, a waste disposal system (WST) is needed.

Table 4.14: *Life support requirements*

Identifier	Description
REQ-LFSP-01	The system shall include life support capabilities.
REQ-LFSP-AIR-01	The system shall provide breathable air to the astronaut.
REQ-LFSP-AIR-02	The system shall ensure a minimum oxygen level of <TBD> %.
REQ-LFSP-AIR-03	The system shall store <TBD> [kg] of O_2.
REQ-LFSP-AIR-04	The system shall detect air pressure within the cabin with an accuracy of <TBD> [Pa].
REQ-LFSP-WTR-01	The system shall store <TBD> [kg] of drinkable water.
REQ-LFSP-WST-01	The system shall have waste-disposal capabilities.

The structural integrity of the aircraft is critical to ensuring that the aircraft can complete its mission without sustaining damage (STR). The structure should withstand the loads experienced during the flight (LD). Additionally, if the cabin needs to be pressurized, additional loads will be due to pressure (PRS). The harsh Martian environment will present an additional challenge as additional loads are present (ENV). The aforementioned temperature changes will cause thermal loads (THR), and fatigue (FTG) should be accounted for.

Table 4.15: *Structures requirements*

Identifier	Description
REQ-STR-LD-01	The system shall sustain a maximum load factor of <TBD> for the MTOM configuration.
REQ-STR-LD-02	The system shall sustain a minimum load factor of <TBD> for the MTOM configuration.
REQ-STR-LD-03	The system shall ensure damping of all vibrational loads.
REQ-STR-PRS-03	The payload bay shall sustain a pressure of <TBD> [Pa].
REQ-STR-PRS-04	The fuel tank shall sustain a pressure of <TBD> [Pa].
REQ-STR-PRS-05	The oxidizer tank shall sustain a pressure of <TBD> [Pa].
REQ-STR-ENV-01	The system shall be suitable for the Martian environment.
REQ-STR-ENV-03	The system shall have a corrosion rate smaller than <TBD> microns per year when exposed to the Martian environment.
REQ-STR-ENV-04	The system shall sustain impacts of objects with an energy of at most <TBD> J.
REQ-STR-THR-01	The system's structure shall be viable in the temperature range found on Mars.
REQ-STR-THR-02	The system shall satisfy all other requirements at an external temperature between <TBD> [K] and <TBD> [K].
REQ-STR-THR-03	The system shall sustain thermal loads induced by a temperature change of <TBD> [deg].
REQ-STR-FTG-01	The system shall have a fatigue life of <TBD> flights.

While flying to the desired destination, the plane must be controllable and stable (CS). The pilots need to be able to control the aircraft in order to reach the desired destination. The aircraft also needs to be stable to ensure that the aircraft does not crash.

Table 4.16: *Control and stability requirements*

Identifier	Description
REQ-CS-01	The aircraft shall have control mechanisms that are capable of satisfying the maneuver requirements.
REQ-CS-02	The aircraft shall have a fault-tolerant (fail-safe) control mechanism.
REQ-CS-03	The aircraft shall be statically stable in the lateral directions.
REQ-CS-04	The aircraft shall be statically stable in the longitudinal direction.
REQ-CS-05	The aircraft shall be dynamically stable in the lateral direction.
REQ-CS-06	The aircraft shall be dynamically stable in the longitudinal direction.
REQ-CS-07	The aircraft shall be dynamically stable in vertical direction.
REQ-CS-08	The aircraft shall be statically stable in the vertical direction.
REQ-CS-09	The aircraft maximum stick force shall not exceed <TBD> [N].
REQ-CS-10	The aircraft shall have a positive stick force curve.

The guidance navigation and control system on board (GNC) consists of an autopilot (APS). The autopilot operates based on gathered information on velocity (DV) and attitude (DA) and adjusts the flight plan accordingly (DDH) while simultaneously transmitting the said data (DGP)

Table 4.17: *Guidance navigation and control requirements*

Identifier	Description
REQ-GNC-APS-01	The autopilot system shall be operable in low visibility conditions.
REQ-GNC-APS-02	The autopilot shall be fault tolerant to <TBD> extent.
REQ-GNC-DGP-01	The communication system shall transmit position data.
REQ-GNC-DGP-02	The communication system shall receive position data.
REQ-GNC-DGP-03	The communication system shall send current position data every <TBD> [s].
REQ-GNC-DGP-04	The guidance system shall be able to determine location based on a non-GPS way.
REQ-GNC-DV-01	The velocity shall be determined with error less than <TBD> [m/s].
REQ-GNC-DV-02	The velocity shall be determined in at least 2 independent ways.
REQ-GNC-DA-01	The attitude shall be determined with error less than <TBD> [deg].
REQ-GNC-DA-02	The attitude shall be determined in at least 2 independent ways.
REQ-GNC-DDH-01	Local flight plan shall be adjusted to avoid locally detected terrain.
REQ-GNC-DDH-03	The state-space data shall be communicated to autopilot and PFD.

The data gathered by the aircraft is processed by the command and data handling system (CDH). The CDH system shall gather the data from onboard instruments (DAT) and use that data to send controls and manage the aircraft based on that information (CMD) while taking up as little space and mass budgets as possible (PRO).

Table 4.18: *Command and data handling requirements*

Identifier	Description
REQ-CDH-DAT-01	The C&DH subsystem shall be able to manage all the systems data.
REQ-CDH-DAT-02	The C&DH subsystem shall be able to manage a minimum data throughput of <TBD> [MB/s].
REQ-CDH-DAT-03	The C&DH subsystem shall be able to manage the flight computer data.
REQ-CDH-DAT-04	The C&DH subsystem shall be able to manage the payload data.
REQ-CDH-DAT-05	The C&DH subsystem shall be able to manage the astronaut health data.
REQ-CDH-DAT-06	The C&DH subsystem shall be able to manage the aircraft subsystems status data.
REQ-CDH-DAT-07	The C&DH subsystem shall be able to manage the black-box data.
REQ-CDH-DAT-08	The C&DH subsystem shall be able to manage the data from any external communications.
REQ-CDH-DAT-09	The C&DH subsystem shall be able to manage the data from internal communications.
REQ-CDH-DAT-10	The C&DH subsystem shall be able to manage the data from the GNC subsystem.
REQ-CDH-DAT-11	The C&DH subsystem shall manage the data transmission between different subsystems.
REQ-CDH-PRO-02	The C&DH subsystem shall use a peak power of less than <TBD> [W].
REQ-CDH-PRO-03	The C&DH subsystem shall have a mass less than <TBD> [kg].
REQ-CDH-PRO-04	The C&DH subsystem combined hardware shall fit in a volume of <TBD> [m^3].
REQ-CDH-PRO-05	The C&DH subsystem shall transmit data with an error rate less than <TBD>.
REQ-CDH-CMD-01	The C&DH subsystem shall manage commands.
REQ-CDH-CMD-02	The C&DH subsystem shall autonomously manage any problems or anomalies that occur in any subsystems based on the data received.
REQ-CDH-CMD-03	The C&DH subsystem shall manage astronaut commands.
REQ-CDH-CMD-04	The C&DH subsystem shall manage external communication commands.
REQ-CDH-CMD-05	The C&DH subsystem shall manage the power usage.

The telecommunications subsystem (TTC) handles the communications between the aircraft and the ground base. The astronauts shall be able to communicate with the base (INT), and individual subsystems whose data is collected with the CDH shall be communicated to the ground base (EXT). The telecommunications system also has its mass, volume, and cost budget, which needs to be adhered to (PRO).

Table 4.19: *Telecommunications requirements*

Identifier	Description
REQ-TTC-01	The system shall provide a TTC subsystem.
REQ-TTC-INT-01	The astronauts shall be able to communicate without their suits on.
REQ-TTC-INT-02	The astronauts shall be able to communicate with their suits on.
REQ-TTC-EXT-01	The TTC subsystem shall periodically transmit a signal to its environment with a power of <TBD> [W].
REQ-TTC-EXT-02	The TTC subsystem shall communicate with the Mars ground segment.
REQ-TTC-EXT-03	The TTC subsystem shall communicate with the space segment.
REQ-TTC-EXT-04	The TTC subsystem shall communicate with other aerial vehicles.
REQ-TTC-EXT-05	The TTC subsystem shall communicate with other ground vehicles.
REQ-TTC-EXT-06	The TTC subsystem shall operate on the <TBD>-band of frequencies.
REQ-TTC-EXT-07	The TTC subsystem shall have bandwidth of <TBD> [Hz].
REQ-TTC-EXT-08	The TTC subsystem shall have a maximum bit error rate of <TBD>.
REQ-TTC-EXT-09	The TTC subsystem shall be able to detect incoming signals with a minimum of <TBD> [W].
REQ-TTC-EXT-10	The TTC subsystem shall operate at a weather availability of <TBD>%.
REQ-TTC-PRO-02	The TTC subsystem shall have a mass less than <TBD> [kg].
REQ-TTC-PRO-04	The TTC subsystem combined hardware shall fit in a volume of <TBD> [m^3].

Thrust must be provided to the aircraft at all times (THR) to compensate for the atmospheric drag that will be experienced throughout the mission.

Table 4.20: *Thrust requirements*

Identifier	Description
REQ-THR-01	The system shall provide <TBD> [W] of excess power for take-off.
REQ-THR-02	The system shall provide <TBD> [W] of excess power to climb.
REQ-THR-03	The system shall provide <TBD> [N] of thrust to cancel out drag during cruise.
REQ-THR-04	The system shall allow for throttling as low as <TBD> % of nominal thrust for ground operation.
REQ-THR-05	The system shall ensure thrust direction is optimal.
REQ-THR-07	The system shall have a thrust margin of <TBD> [N] for emergency maneuvers.

The power subsystem (PWR) is responsible for distributing all electrical power in the system (ELEC).

Table 4.21: *Power requirements*

Identifier	Description
REQ-PWR-01	There shall be <TBD> [W] of power available to power all essential systems.
REQ-PWR-ELEC-01	There shall be <TBD> [W] of power available for thermal management.
REQ-PWR-ELEC-01	There shall be <TBD> [W] of power available for data handling.
REQ-PWR-ELEC-01	There shall be <TBD> [W] of power available for avionics.
REQ-PWR-ELEC-01	There shall be <TBD> [W] of power available for GNC.
REQ-PWR-ELEC-01	There shall be <TBD> [W] of power for life support.
REQ-PWR-02	There shall be <TBD> [W] of excess power available in case of system failure.
REQ-PWR-03	There shall be a power storage unit providing a peak power of <TBD> [W].
REQ-PWR-04	There shall be a power storage unit providing <TBD> [W] of power for <TBD> hours.
REQ-PWR-05	There shall be a means to produce <TBD> [W] of power.

The end-of-life operations (EOL) include the transportation of the aircraft to the disposal location (TRANSP), the disassembly of the aircraft (DISS), and possible re-usability of parts (REPURP)

Table 4.22: *End of life requirements*

Identifier	Description
REQ-EOL-TRANSP-01	The system shall be able to be transported to <TBD> location at EOL.
REQ-EOL-DISS-01	The structural components of the system shall be able to be disassembled with tools available in-situ.
REQ-EOL-DISS-02	The electrical components of the system shall be able to be disassembled with tools available in-situ.
REQ-EOL-DISS-03	The propulsion system components of the system shall be able to be disassembled with tools available in-situ.
REQ-EOL-DISS-04	The life support system components of the system shall be able to be disassembled with tools available in-situ.
REQ-EOL-DISS-05	The payload components of the system shall be able to be disassembled with tools available in-situ.
REQ-EOL-REPURP-01	Broken components shall be repaired until it has reached a life expectancy of less than <TBD> flights.
REQ-EOL-REPURP-02	Repaired components shall be refurbished until it has reached a life expectancy of less than <TBD> flights.
REQ-EOL-REPURP-03	Working components shall be re-used until it has reached a life expectancy of less than <TBD> flights.
REQ-EOL-REPURP-04	Components with a life expectancy of less than <TBD> flights shall be discarded without impact to Mars' environment.

The safety of the onboard astronauts (SAF) is an additional requirement. There should be an emergency abort plan and equipment (EMR) as well as equipment that should protect the astronauts from the environment (ENV)

Table 4.23: *Safety requirements*

Identifier	Description
REQ-SAF-EMR-01	The system shall provide an emergency abort option.
REQ-SAF-EMR-02	The system shall be designed for crashworthiness.
REQ-SAF-ENV-01	The system shall protect the inside from radiation.
REQ-SAF-ENV-02	The system shall provide breathable air for <TBD> [hr].
REQ-SAF-ENV-03	The system shall provide an air pressure of <TBD> [atm].
REQ-SAF-ENV-05	The system shall provide temperatures within range <TBD>.

Ethical use (ETHC) of the aircraft ensures that the aircraft is used for the mission it is designed and it ensures that the aircraft does not pollute Mars.

Table 4.24: *Ethics requirements*

Identifier	Description
REQ-ETHC-01	The system shall not be weaponizable.
REQ-ETHC-02	The system shall not pollute the Martian environment.
REQ-ETHC-03	The system shall not harm any potential indigenous Martian species.
REQ-ETHC-04	The manufacturing process shall be safe for workers.
REQ-ETHC-05	The manufacturing process shall be fair towards workers.
REQ-ETHC-06	Discrimination towards working in the supply chain shall be prevented.

4.4.2. Mission requirements

This chapter lists a breakdown of all the mission requirements. The mission requirements are developed from the requirements discovery tree. The mission requirements are those requirements that relate to the performance of the mission itself Section 4.1. Those can be seen in the requirement discovery tree under the block perform mission technically.

The requirements related to the specific act of the transportation of the astronauts and payload on Mars using the aircraft are thus considered here.

The mission begins with a series of pre-flight operations and ends with a series of post-flight operations (PPFO). First, the astronauts must be able to enter the aircraft (EMB). Next, the system needs to receive terrain data in order to find a landing spot (LND); the system needs to be maintainable (MNT) and inspectable (FRD). Lastly, the system must be rechargeable (ENS) to increase its lifetime.

Table 4.25: *Pre- and post-flight requirements*

Identifier	Description
REQ-PPFO-EMB-01	The system shall provide accessibility for astronauts to embark from the outside.
REQ-PPFO-EMB-02	The system shall provide accessibility for astronauts to disembark from the inside.
REQ-PPFO-LND-01	The system shall receive terrain data with a resolution of <TBD>.
REQ-PPFO-LND-02	The system shall provide a landing location with rocks no bigger than <TBD> [m].
REQ-PPFO-LND-03	The system shall provide a landing location with a softness above <TBD>.
REQ-PPFO-LND-04	The system shall provide a landing location which has a flatness of more than <TBD>.
REQ-PPFO-LND-05	The system shall provide a landing location that has a slope of less than <TBD> [deg].
REQ-PPFO-MNT-01	The system shall be accessible for maintenance purposes.
REQ-PPFO-MNT-02	The system shall have tooling available for maintenance.
REQ-PPFO-MNT-03	The system shall provide sufficient power for maintenance tooling.
REQ-PPFO-FRD-01	The system shall be easily accessible for inspection.
REQ-PPFO-FRD-02	The system shall be inspectable without dust contamination.
REQ-PPFO-FRD-03	The system shall have inspection tooling present.
REQ-PPFO-FRD-04	The system shall provide safety during inspection.
REQ-PPFO-FRD-05	The system shall provide sufficient power for inspection tooling.
REQ-PPFO-ENS-01	The system shall provide full energy replenishment within <TBD> [hr].

After the pre-flight operations, the aircraft should take off (TOFF). The aircraft should be able to self-start (PPS). Once the aircraft is started, it needs to detect and remove icing (CMCH), find a take-off location (CTOFF), and accelerate to take-off speed (ACC).

Table 4.26: *Take-off requirements*

Identifier	Description
REQ-TOFF-PPS-01	Engines shall provide self-start possibility without external power supply.
REQ-TOFF-PPS-02	Engines shall be able to monitor their functioning.
REQ-TOFF-PPS-03	Aircraft shall be able to provide remaining energy information.
REQ-TOFF-CMCH-01	Aircraft shall be able to detect icing.
REQ-TOFF-CMCH-02	Aircraft shall provide de-icing system.
REQ-TOFF-TOM-01	Aircraft shall provide take-off aiding mechanism.
REQ-TOFF-CTOFF-01	The aircraft shall scan the local surface to determine the most optimal take-off location.
REQ-TOFF-CTOFF-02	The aircraft shall be able to take-off in low-visibility conditions.
REQ-TOFF-CTOFF-03	The propulsion system shall be able to exert its full thrust capability during take-off.
REQ-TOFF-ACC-01	The aircraft shall accelerate with at least <TBD> [m/s^2].

Once the aircraft takes off from the ground, it must climb to the desired altitude (CLIMB).

Table 4.27: *Climb requirements*

Identifier	Description
REQ-CLMB-01	The climb rate at take-off altitude shall be at least <TBD> [m/s].
REQ-CLMB-03	The climb angle at take-off altitude shall be at least <TBD> [deg].
REQ-CLMB-04	The climb angle at take-off altitude shall be at most <TBD> [deg].
REQ-CLMB-05	The landing system shall be retracted once a steady climb is achieved.

For the aircraft to reach the desired location, it will need to perform a series of maneuvers (MAN). The aircraft needs to maneuver around the Martian terrain and dust storms on its desired flight profile.

Table 4.28: *Maneuver requirements*

Identifier	Description
REQ-MAN-01	The aircraft shall be able to perform a horizontal turn in the Martian atmosphere at the rate of <TBD> [deg/min].
REQ-MAN-02	The aircraft shall be able to glide in the Martian atmosphere at a glide angle of <TBD> [deg].
REQ-MAN-03	The aircraft shall not stall in the Martian atmosphere before the angle of attack of <TBD> [deg].
REQ-MAN-04	The aircraft shall not exceed the load factor of <TBD> [g] during maneuvers.
REQ-MAN-05	The aircraft shall be able to fly with a sideslip angle <TBD> [deg].
REQ-MAN-06	The aircraft shall be able to perform an emergency landing on Martian soil.
REQ-MAN-07	The aircraft shall be able to withstand gust loads of <TBD> [N] from an arbitrary directions.
REQ-MAN-08	The aircraft shall not be damaged by local dust storms.
REQ-MAN-09	The aircraft shall be able to fly through the dust storm with maximum winds of <TBD> [m/s].
REQ-MAN-10	The aircraft shall be able to avoid dust storms with maximum winds of more than <TBD> [m/s].
REQ-MAN-11	The aircraft shall be able to withstand extreme temperature changes of up to <TBD> [K/h].

When the cruise altitude is reached, the aircraft should cruise toward the desired location (CRUS).

Table 4.29: *Cruise requirements*

Identifier	Description
REQ-CRUS-01	The system shall continuously cruise at the optimal altitude for the mass.
REQ-CRUS-02	The nominal cruise altitude shall be <TBD> [m].
REQ-CRUS-04	The system shall continuously cruise at the optimal speed.
REQ-CRUS-05	The nominal cruise speed shall be at least 111 [m/s].
REQ-CRUS-06	The cruise speed shall not be less than <TBD> [m/s].
REQ-CRUS-07	The cruise speed shall not exceed <TBD> [m/s].
REQ-CRUS-08	The cruise Mach number shall not exceed 0.7.
REQ-CRUS-09	The system shall have a service ceiling of at least <TBD> [m].

The aircraft must descend (DSCT) towards the previously selected landing spot shortly before reaching the desired location.

Table 4.30: *Descent requirements*

Identifier	Description
REQ-DSCT-01	The approach speed shall not exceed <TBD> [m/s].
REQ-DSCT-02	The descent path angle shall be at least <TBD> [deg].
REQ-DSCT-03	The descent path angle shall be at most <TBD> [deg].

Lastly, the aircraft needs to land (LDG) on the Martian terrain in most conditions (FAPP). The touchdown (TDWN) must be safe for the astronauts and the equipment. That is ensured with the braking system (DLRT), which minimizes the loads experienced. Finally, after landing, the aircraft must be able to self-start (TOFF) and return to the base.

Table 4.31: *Landing requirements*

Identifier	Description
REQ-LDG-FAPP-01	The system shall be able to scan the ground and detect rocks larger than <TBD> diameter.
REQ-LDG-FAPP-02	Autopilot shall provide automatic landing mode.
REQ-LDG-FAPP-03	The aircraft shall be able to land in low-visibility conditions.
REQ-LDG-FAPP-04	<TBD> [N] of landing force shall be ensured at finals.
REQ-LDG-TDWN-01	Use of ground effect shall be made to ensure soft landing.
REQ-LDG-TDWN-02	The aircraft shall not exert more than <TBD> pressure on ground during touchdown.
REQ-LDG-TDWN-03	Structural integrity shall be ensured up to <TBD> [g] during touchdown impact.
REQ-LDG-TDWN-04	The aircraft shall provide pilot and equipment safety during landing.
REQ-LDG-DLRT-01	The aircraft shall have braking systems.
REQ-LDG-DLRT-02	The aircraft shall decelerate with at least <TBD> [m/s^2].
REQ-LDG-DLRT-04	The aircraft shall provide steering capability on the ground.

4.4.3. Driving and key requirements

From the system requirements mentioned in Section 4.4.1 and mission requirement mentioned in Section 4.4.2 the driving requirements have been identified in Table 4.32 and the key requirements have been identified in Table 4.33. There were no killer requirements found in the list.

Table 4.32: *Driving requirements*

Identifier	Description
REQ-ASTR-SAFE-01	The system shall not produce more than <TBD> positive gs in any direction.
REQ-SAG-REUS-03	The system's assembly process shall be repeatable.
REQ-GOPS-ACT-ASS-01	The system shall be able to be assembled by 2 astronauts.
REQ-AERO-LFT-02	The aerodynamic system shall have a maximum lift coefficient of <TBD>.
REQ-AERO-LFT-04	The aerodynamic system shall have a stall angle of <TBD> degrees.
REQ-STG-PAY-02	The system shall be able to hold 100 kg of payload.
REQ-PWR-ELEC-01	There shall be <TBD> Watts of power available to power all essential systems.
REQ-ETHC-02	The system shall not pollute the Martian environment.
REQ-CLMB-01	The climb rate at take-off altitude shall be at least <TBD> m/s.

Table 4.33: *Key requirements*

Identifier	Description
REQ-SAG-LF-03	The system shall obtain power from sources available on Mars.
REQ-LCD-LVEH-SIZE-01	The system shall have a volume of less than <TBD> [m^3].
REQ-LFSP-AIR-01	The system shall provide breathable air to the astronauts.
REQ-CRUS-05	The nominal cruise speed shall be 111 m/s.

These requirements will likely drive the design process from now on and will be critical when deciding on one design concept at the end of the midterm report.

5
Market analysis

When conducting market analysis for any product, one of the first aspects considered must be the potential customer. Hence the question of justification of the need for a Manned Martian Aircraft (MMA) must be answered. This section provides the reasons for the need of an MMA and from it derives the potential customers in Section 5.1. Designs similar to an MMA are listed in Section 5.2. Cost estimation is discussed in Section 5.3.

5.1. Customer

By Adrian Beňo

In the early stages of Mars exploration it would be mainly research institutions that are interested in scientific information about the planet. Although rovers provide some capability of exploring the surface and can carry the required scientific equipment, they are limited in speed and range. Mars Perseverance Rover has top speed of 4.2 cm/s and has traveled total of 18 [km] so far [1]. Moreover, their range is limited by too large obstacles, such as canyons or rocks. The need for long range transportation (~1000 km) on Mars within reasonable amount of time (few hours) is thus necessary for future scientific exploration on Mars. Aircraft in general, manned or unmanned, is a possible solution to this need.

Although unmanned aircraft would be sufficient in the early stages of flight on Mars, manned aircraft becomes necessary as soon as the first astronauts reach the planet. Unmanned flight can represent the first steps towards flight, for example, to collect atmospheric properties, but is an insufficient long-term concept. Even more so, as Mars planet becomes more commercialized via private companies, the increased accessibility to the public would require enhanced transportation capabilities.

5.2. Existing aircraft designs

By Adrian Beňo

There have been several concepts of an aircraft for Mars already developed, but almost exclusively unmanned. These include ARES 2 [9], ARGO 7 [9], PRANDTL-M [2] and Ingenuity [3]. The only manned aircraft concept found is Raymer Manned Mars Airplane [10]. Unfortunately, none of these concepts except for Ingenuity have been developed, nor was any cost analysis ever performed for them.

5.3. Cost estimation

By Adrian Beňo

There is great difference in costs of missions on Mars. While Ingenuity only cost 85 Million to build [3], the Perseverance rover development costs were approximately 2.2 billion [4]. At this point we must disregard the development and manufacturing costs of Ingenuity as this two propeller drone has a mass smaller than 2 kg and in no way compares to 3000 kg manned aircraft. Hence we continue our analysis with statistics about Perseverance rover.

The Perseverance rover's mass is 1025 kg [5]. The MMA mass can be at most 3000 kg, which is 3 times as much. This would translate to about 3 times as much technology needed on the aircraft, which comes from the balance between novel technology development and manufacturing. We justify this with the fact that even though substantial part of the development cost of the Perseverance rover was used to develop the scientific instruments on board (which our aircraft would not have), the aircraft would require more complex systems for basic mission goals, such as movement, than a rover. Also, the fact that additional safety hazards come into play due to the crew on the aircraft, the price would increase substantially. We suppose that these aspects are together comparable to the complexity of the scientific instruments on board of the Perseverance rover. The development cost estimate is $3 \cdot 2.2[B] = 6.6[B]USD$.

[1] URL: https://mars.nasa.gov/mars2020/spacecraft/rover/wheels/ [cited 2023-05-03]
[2] URL: https://www.nasa.gov/centers/armstrong/features/mars_airplane.html [cited 2023-05-03]
[3] URL: https://www.planetary.org/space-missions/ingenuity [cited 2023-05-03]
[4] URL: https://www.planetary.org/space-policy/cost-of-perseverance [cited 2023-05-03]
[5] URL: https://www.jpl.nasa.gov/news/press_kits/mars_2020/launch/mission/spacecraft/perseverance_rover [cited 2023-05-04]

6
Design options

For a conceptual design to take shape, various options must be considered. These options are formed in brainstorming sessions as they allow for unconstrained thinking of possible solutions to the project objective statement. Based on the literature found in Section 6.1, the brainstormed ideas from Section 6.2 are filtered based on criteria as shown in Section 6.3. After eliminating unfeasible concepts, simple ideas and design combinations can be formed. These are stated in Section 6.4, of which the final concept design options worth further development are listed in Section 6.5.

6.1. Literature review

By Freek Braspenning, Adrian Beňo, Patrick Kostelac

Various parties have developed concepts, such as those presented for manned Martian missions by Lunar and Planetary Institute [11] and the flying wing by Guynn et al. [12]. There are various ways to design an aircraft, and this literature review gives an in-depth analysis of the possibility and feasibility of several designs. Besides design configurations, propulsion is also a vital element of the mission. The harsh Martian atmosphere is depleted of oxygen, making combustion almost impossible. In Subsection 6.1.2, alternatives to oxygen deflagration and alternative power sources such as electrical and nuclear are researched.

6.1.1. Aircraft configuration

There are many concepts of aerial transport on Mars. These categorize as either heavier-than-air vehicles, such as flying wings and drones, to lighter-than-air vehicles, such as airships.

The fixed-wing offers a lot of advantages over other alternatives as the design ends up being less complex. Developed concepts of fixed-wing aircraft include crewless aircraft such as the tail-less aircraft from Kwiek [13], and the Aerial Regional-scale Environmental Survey developed by Guynn et al. [12], and manned missions such as the Raymer Manned Martian Aircraft by Raymer et al. [10]. Due to the low Reynolds number of the Martian atmosphere, the use of conventional airfoils needs to be reconsidered.[14][15] Extensive research has been done on the optimization of airfoil shape for Martian missions.[16]

Rotary aircraft offer advantages over fixed wings, such as hover capabilities and vertical take-off or landing. However, these usually come with more complexity. Nevertheless, extensive research proves the viability of using rotary aircraft in the Martian atmosphere. [17] The low density and low Reynolds Number give the rotary blades almost nothing to push up against. To still produce enough lift, the rotational speed must increase considerably, which complicates structural components[18] and airfoil selection[19].

As seen in the literature, the Martian climate challenges the fixed wing and rotary wing. The low air density and low Reynolds make both mentioned design options aerodynamically less efficient than their on-Earth counterpart. Extensive research has been done into lighter-than-air aircraft, such as airships.[20][18] They would excel on Mars as previously ruled-out design options can be reconsidered for the Martian atmosphere. The use of hydrogen as a lighter-than-air gas can be used in Martian air as the atmosphere has an absence of oxygen.[21]

The concept of hybrid design options, such as a fixed-wing rotary aircraft hybrid, also arises from literature. This concept has advantages of both the fixed wing and the rotary aircraft, as it has tiltable rotors attached to a fixed wing. Disadvantages include a significant increase in complexity. Another proposed design is a two-stage aircraft, which uses a first-stage rocket booster, bringing the aircraft to altitude, after which it detaches and glides to the final destination.[22]

6.1.2. Propulsion

The absence of oxygen in the Martian atmosphere makes combustion close to impossible. However, several different propulsion concepts shown in the literature could be viable for usage on an aircraft, as mentioned by Colozza [23].

The low-density atmosphere makes the design of a propeller blade as tricky as the design of propellers for aircraft taking flight in the higher stratosphere.[24] At these altitudes, the atmospheric conditions on Earth and Mars have many similarities, making the design process quite similar.

Electric aircraft on Earth is a step toward a more sustainable industry. It has been researched extensively and gives useful insight into the design of the power unit for Martian aircraft. Ways of electricity generation include solar[25], nuclear[26], and fuel cells [27].

On Earth, deflagration is used in almost all propellant systems. However, with the absence of oxygen as an oxidizer, alternatives must be used. A promising alternative is the reduction reaction between magnesium and carbon dioxide.[28] This is an exothermic reaction that can occur in the low pressures of the Martian atmosphere. The use of magnesium as fuel has a relatively low technology readiness level and has only recently seen promising proofs of concept.[29][30]

Another innovative propulsion system is the use of detonation instead of deflagration. Detonation shows an increase of 15% in efficiency compared to regular combustion. A pulsing detonation engine has been proven to work but does not utilize the detonation optimally. A recent development has shown a great increase in efficiency. The rotating detonation engine is proof of using detonation in propulsion.[31] A detonation engine could also be combined in a hybrid of deflagration and detonation engines.[32]

6.1.3. Life support

Life support is essential to consider when considering a crewed extraterrestrial mission. There are four ways to ensure the well-being of an individual on such a mission, as mentioned by Drysdale et al. [33]. The four ways are: supply, physicochemical (PC) regeneration, bio-regeneration, and in-situ resource utilization (ISRU). The author believes that a cost-effective hybrid will come from these four.

The supply contains the resupply of a deep space mission. This is because, at first, there might need to be an infrastructure to have a self-sufficient food supply. However, future technology could account for food generation. This is where PC regeneration comes in handy. This is a chemical process to generate food from waste material. The next step in life support is the availability of bio-regeneration. Bio-regeneration is attractive due to it also replenishing food and water. Last step to being fully self-sufficient on Mars, would be full usage of the raw materials Mars has to offer.

6.2. Creating the Design Option Tree

By Javier Alonso García, Pedro Santos, Sebastian Harris, Thomas van de Pavoordt

Creating the design options tree is complex, as it is necessary to ensure all options are included. To maximize the ideas available, brainstorming sessions were used in which general categories were given to lead the various design splits. Within these splits, a color system was used to indicate the status of each option. For example, a green box marked with a G in the upper left corner indicates accepted options that can later be designed. Orange boxes, marked with an O in the top left corner, indicate options not worth investigating, either due to their cost or far-fetched ness. Next, red boxes, marked with an R in the top left corner, indicate options that violate the design requirements and are thus not feasible.

The first split created was linked to the type of lifting device utilized. For this, the categories *Fixed Wing*, *Moving Wing*, *No Wing* were used. The first category refers to conventional aircraft, similar to those found on Earth, with sub-options such as Biplanes, flying wings, gliders, and more. Next, within the *No Wing* category, design options such as rockets, airships, hovercrafts, and more can be found. Finally, the *Moving Wing* category contains both conventional rotorcraft and hybrid concepts, mainly tilt-rotors similar to V-280s and V-22s designed by Bell.

The next split regards the propulsion system. The primary separation for the brainstorming session was between systems utilizing sci-fi-inspired and those that did not. Both conventional propellers and sci-fi-inspired flapping wing mechanism options are found within the first category. Opposingly, the propellerless systems contain CO2-breathing jet engines, rockets, wind-powered solutions, electrical propulsion, ion and plasma engines, and post-detonation systems.

Following this split, all propeller options require a system to provide torque. These systems can originate from an electric engine powered by batteries, radioisotope thermogenerators, fuel cells, radiation harvesting, dynamos, laser transmission, integrated solar panels, fusion reactors, or fission reactors. Regarding torque generation through combustion engines, these can originate from Stirling engines, conventional internal combustion engines, or turboshaft-inspired magnesium and carbon dioxide engines. For non-propeller-driven systems, the system producing thrust already produces its energy and, as such, does not require an external power generation system.

Regarding landing types, the first decision is regarding the deceleration method, mainly split between rocket-based deceleration, aerodynamic braking, reverse thrust, and arresting wires. These landing systems are also considered for take-off, regarding vertical rockets, thrust, and catapults similar to aircraft carriers. Next, it must be chosen between Vertical and Horizontal landing. In the first case, the landing system could utilize skids, retractable legs, tower capture, inflatable cushions, and wheels or have no landing gear and land on the aircraft's belly. Next, the horizontal landing could utilize the identical skids, wheels, and belly landing as the vertical landing systems.

Although valuable and necessary to keep in mind when developing detailed solutions, additional design options regarding control and structures are not included in the design options tree. This is because their impact on the overall structure of the design is limited and implies more detailed choices, which will be included in the next steps of the design process. Nonetheless, the brainstormed design options and their relevant trees are still included in Figure 6.5.

6.3. Rejected design options

By Javier Alonso García, Pedro Santos, Sebastian Harris, Thomas van de Pavoordt

After the design options tree had been completed, less optimal options were eliminated, using filters such as technology level readiness, unfeasibility due to physics, and safety.

Options for lift devices such as two-stage planes, rockets, hoppers, ballistic flight devices, gliders, and hovercraft were discarded based on requirements violation. The first four were thought to violate, by a wide margin, the maximum speed requirement of Mach 0.7 at certain stages of the flight envelope. The last two were rejected on the grounds of being only able to operate at pre-defined routes or needing excessive pre-existing infrastructure, not allowing for an extended range of exploration.

Options for propulsion mechanisms such as flapping wings, asymmetric propellers, non-nuclear explosions, kite, sail, compressed gas, and ion and plasma engines were filtered out based on physical unfeasibility. Rationales for such filtering involved material stress limitations, lack of power or range in thin atmospheres, and significant gravitational fields. At the same time, traditional and distributed rocket engines were again thought to violate the maximum speed requirement of Mach 0.7.

Nuclear fusion and fission as means of powering the aircraft were deemed unsafe for the astronauts onboard in case of accidents, taking into account that if eventually built and operated, this would be the first product of its kind. Furthermore, a conventional internal combustion engine has yet to be considered due to its need for large quantities of oxygen. Finally, the radioisotope thermoelectric generators, fuel cells, and Stirling engines were thought to have an insufficient specific power, i.e., Watt per kilogram (W/kg).

For landing mechanisms, belly landing has been deemed structurally unfeasible, while arresting wire and tower capturing require too much infrastructure, limiting exploration flexibility. Furthermore, vertical rocket landing has been deemed not sustainable since the need for carrying "landing fuel" would limit the number of take-offs that could be performed and drastically increase aircraft weight.

6.4. Accepted design combinations

By Javier Alonso García, Pedro Santos, Sebastian Harris, Thomas van de Pavoordt

After eliminating all the unfeasible concepts and all the concepts not worth investigating, all remaining combinations were listed and analyzed. The following constraints were applied to the possible combinations:

- Concepts that utilize a fixed wing and traditional or distributed propellers do not have vertical landing capabilities.
- Use of inflatable cushions was discouraged since a puncture would lead to severe risks during landing.
- Only concepts that use a fixed-wing configuration have the necessary surface area and structural integrity to be powered by integrated solar panels.
- Tilted rotor aircraft, helicopters, and drone-type vehicles are incompatible with distributed propellers.
- Helicopter and drone-type vehicles cannot utilize aerodynamic breaking (use of parachutes or similar technologies) during the landing phase.
- Helicopter and drone-type vehicles cannot utilize a magnesium and carbon dioxide engine as a propulsion method.
- The required size for the airship will imply high values of required thrust. Therefore, the traditional propeller was deemed unfeasible.
- Airships will take off and land vertically, so wheels are unsuitable for landing gear.

After these constraints were applied, a total of 56 design options remained.

It is essential to mention that although the engines based on magnesium and carbon dioxide ($Mg + CO_2$) combustion are still in the phase of development, there are prototypes. This brings some uncertainties regarding its performance potential, which will be further researched and assessed in the subsequent design phase. However, the reason for going forward with this option is that, if proven feasible, it would provide significant advantages over other propulsion options and represent the best one available.

6.5. Final concepts to develop

By Group

Detailed calculations would be needed to decide on fewer design concepts. Therefore, that process will be left for the midterm report. Within that report, general characteristics from within the 56 design options remaining from 6.4 were extracted, resulting in the following five concepts to investigate:

1. A flying wing that utilizes wheels for landing and take-off.
2. A conventional aircraft with a fixed-wing and tail configuration.
3. A tilted-rotor aircraft with undetermined propulsion and VTOL capabilities.
4. An aircraft that utilizes an undetermined number of propellers (so helicopter or drone-like) with VTOL capabilities.
5. An airship with VTOL capabilities and undetermined lifting or propulsion methods.

A first artist's impression was made for the final 5 concepts to develop to introduce a sense of familiarity with the designs. These are shown in Figure 6.1:

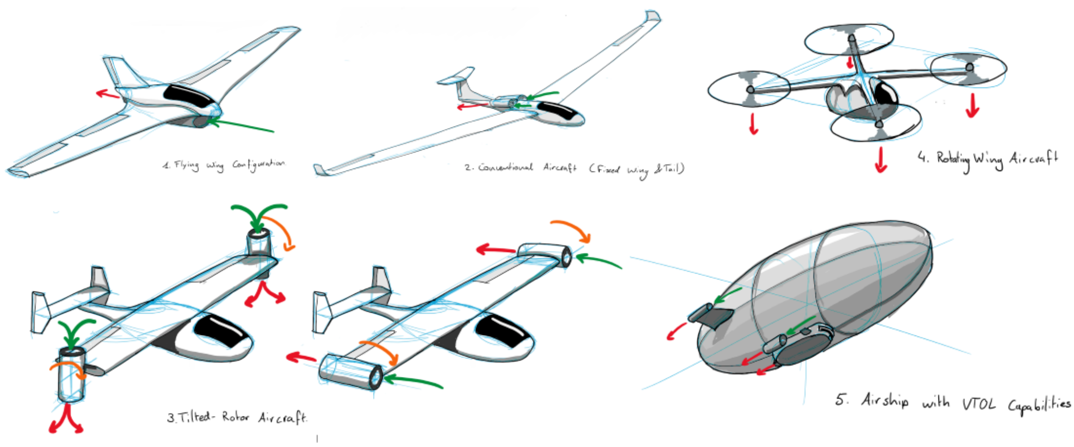
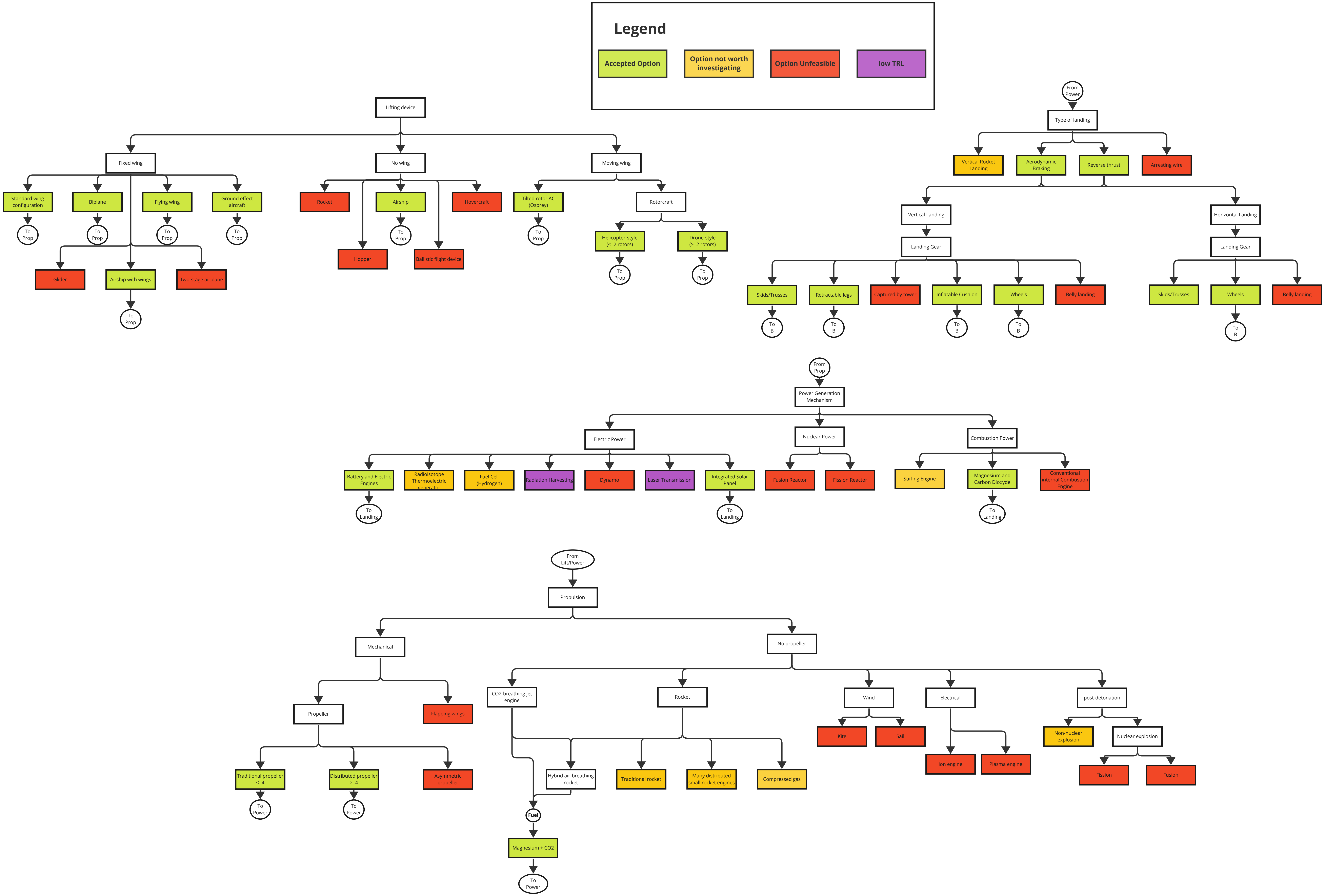


Figure 6.1: *Artist's impression of the final 5 design concepts*


Legend
Accepted Option
Option not worth investigating
Option Unfeasible
low TRL
Lifting device
Fixed wing
No wing
Moving wing
Standard wing configuration
Biplane
Flying wing
Ground effect aircraft
To Prop
Glider
Airship with wings
Two-stage airplane
Rocket
Airship
Hovercraft
Hopper
Ballistic flight device
Tilted rotor AC (Osprey)
Rotorcraft
Helicopter-style (<=2 rotors)
Drone-style (>=2 rotors)
From Power
Type of landing
Vertical Rocket Landing
Aerodynamic Braking
Reverse thrust
Arresting wire
Vertical Landing
Horizontal Landing
Landing Gear
Skids/Trusses
Retractable legs
Captured by tower
Inflatable Cushion
Wheels
Belly landing
To B
From Prop
Power Generation Mechanism
Electric Power
Nuclear Power
Combustion Power
Battery and Electric Engines
Radioisotope Thermoelectric generator
Fuel Cell (Hydrogen)
Radiation Harvesting
Dynamo
Laser Transmission
Integrated Solar Panel
Fusion Reactor
Fission Reactor
Stirling Engine
Magnesium and Carbon Dioxyde
Conventional internal Combustion Engine
To Landing
From Lift/Power
Propulsion
Mechanical
No propeller
Propeller
Flapping wings
Traditional propeller <=4
Distributed propeller >=4
Asymmetric propeller
To Power
CO2-breathing jet engine
Rocket
Wind
Electrical
post-detonation
Hybrid air-breathing rocket
Traditional rocket
Many distributed small rocket engines
Compressed gas
Kite
Sail
Ion engine
Plasma engine
Non-nuclear explosion
Nuclear explosion
Fission
Fusion
Fuel
Magnesium + CO2

7
Resource allocation and budget breakdown

With several design options in mind, it is possible to make a very high-level preliminary budget breakdown. This chapter will explore what mass could be allocated to what subsystems (Section 7.1), the amount of power that can be expected (Section 7.2), the cost target (Section 7.3) and the contingency management (Section 7.4).

7.1. Mass budget

By Freek Braspenning

The mass budget is done to ensure that the sum of all masses of each system shall not exceed the predetermined MTOM. Due to little being known about the aircraft configuration, a rough estimate is made for each system, which may be altered for each concept as they might lay the focus on different subsystems. The mass was based on the limited research available, as seen in [10]. From this, various mass fractions are computed. These mass fractions give the masses as seen in Table 7.1. There is a reserve of 10% included as a margin. The payload includes the mass of each astronaut with a spacesuit of 45 kg and 100 kg of payload, where the mass of the spacesuit is based on research by Carr [34].

Table 7.1: *Mass budget with mass percentages taken from Raymer et al. [10]*

Aircraft System	Mass [kg]	Mass percentage
Lift System	755	48% OEM
Control & Stability System	12	1% OEM
Fuselage	213	13% OEM
Propulsion System	281	18% OEM
Landing Gear	61	4% OEM
Equipment	198	12% OEM
Power System	60	4% OEM
OEM	1580	59% MTOM
Payload	350	-
Propellant	770	28% MTOM
MTOM	2700	

7.2. Power budget

By Thomas van de Pavoordt

According to the requirements for the power system, various subsystems will require an amount of power that is still to be determined. Since the design options left range from drone-style aircraft to fixed-wing options with propeller or jet propulsion systems, defining statistical relations that will span all these options is unfeasible. Therefore, it is too early to estimate how many Watts of power will be allocated to which subsystem. However, based on the preliminary mass budget and various power generation systems from literature [35], it can be assessed what different design solutions can produce in terms of power. This is shown in Table 7.2:

Table 7.2: *Power budget calculated with Specific Power values from [35]*

Power System	Specific Power [W/kg]	Power [W]
Solar Photovoltaic	10.78-86.21[1]	646.55-5172.41
Radio-isotope	5-20	300-1200
Nuclear Reactor	2-40	120-2400
Fuel cell	275	16500

Even though some of these power options are deemed unfeasible due to either safety or sustainability issues, they are incorporated into this budget since power generation is a significant issue on Mars and a

[1] Calculated with solar irradiance correction factor for Mars from Section 2.3

possible reassessment could be considered.

7.3. Cost target

By Timo de Kemp

In Section 5.3 the final cost of the project was determined to be 6.6 bil. USD, including design and manufacturing. As the design is in a very preliminary design phase come margins need to be taken into account to make sure that the project does not go over price and to make sure costs are kept low. Therefore a margin of 10% is included, which makes the targeted cost the mission 6 bil. USD.

7.4. Contingency management

By Timo de Kemp

The margins set for the mass, power and cost budgets have to be managed throughout the execution of the design. The management of these budgets is done in a similar manner which will be described shortly. The contingency management begins with the start of the detailed design after the midterm milestone. Before the midterm, members working on the concepts should be keeping track of their own budgets as this is done in small groups it is easily doable. However, in the concept development phase, individuals work on one part of the aircraft, which can result in less overview, and thus the need arises to be controlled by the budget manager.

The concept development phase will take five weeks, when the design is being worked out more certainty on mass, power and cost budgets can be given, therefore the margins can be lowered in these weeks. At the end of the concept development phase still, a margin will be left as the final detailed design still needs to be worked out. It was chosen to have an update from each subsystem each week, this includes all fluctuations in the budgets. Furthermore, two and four weeks into the design milestones are set on the margins. For example, the mass margin at the start is 300 kg which goes down to 200 kg after 2 weeks and to 100 kg after 4 weeks.

Finally, to ensure that the budgets do not go over during a week, subsystem designers should always contact the budget manager when they cannot meet their budget. The team should demonstrate convincingly to the budget manager that they cannot meet the set target. The budget manager can then decide to give this subsystem some more budget or deny their proposal if not found convincingly enough. The subsystem teams should then update their proposal and propose to the budget manager again, who could also reshuffle the budget at the weekly meeting.

8
Technical risk assessment

Risk is present throughout any project, and starting a new phase requires a new look at the risks. Naturally, all organizational risks identified in the project plan still remain present, and their mitigation plan should be maintained throughout the rest of the project. In addition to the organizational risks, the baseline phase of the project comes with new risks. In Section 8.1, the various risks linked to the Operational processes will be investigated and handled. Next, the design risks are analyzed, ranked, and handled in Section 8.2.

8.1. Risks from processes

By Sebastian Harris, Thomas van de Pavoordt, Javier Alonso García

The Organizational Risks discovered in the Project plan are still present, along with the proposed mitigation measures. Furthermore, certain general risks can be added and must be assessed. First, it must be reiterated that scheduling is of the utmost importance. Following the timelines and regularly reworking them will ensure the timely execution of all deliverables. Impact and probability for this section are based on experience and engineering judgment.

Table 8.1: *Risks linked to the general project*

Risk ID	Description	Probability (1-5)	Impact (1-5)
R-GR-01	Project falls behind schedule	3	3
R-GR-02	Member fails to fulfill role	1	3

8.1.1. Investigative risks

Determining the environment in which the aircraft will be moving is a critical step in determining the associated risks and requirements. As such, a thorough investigation is led on the atmosphere, the terrain, and ground structure, as well as the gravitational and magnetic properties of the planet. As such, there is a set of risks associated with this progress. These risks are identified and listed in Table 8.2.

Table 8.2: *Risks linked to the investigative process*

Risk ID	Description	Probability (1-5)	Impact (1-5)
R-IV-01	Information is contradicting	3	5
R-IV-02	Information is erroneous	3	5
R-IV-03	Lack of information	4	3
R-IV-04	Information is lost	2	4

First, the information found between varying sources could have significant discrepancies. As Mars is still in the early stages of exploration, there is still much to discover about the planet. This leads to a risk of using contradicting or even erroneous information, which could have disastrous effects on the success of the mission. Furthermore, it is highly likely that certain information will simply not be known due to the large knowledge gaps present. From a more group-oriented perspective, improper classification of sources will lead to a delay in work until that source can be found, or worse lead to the total loss of the source in case it cannot be found.

8.1.2. Functional risks

When developing the Functional Description of the design, further risks can be discovered. These risks are summarized in Table 8.3.

Table 8.3: *Risks linked to the Functional Breakdown Process*

Risk ID	Description	Probability (1-5)	Impact (1-5)
R-FU-01	Functional Flow is incomplete	2	4
R-FU-02	Functional Flow is design-oriented	3	3

Regarding the creation of the Functional Flow and Functional Breakdown Diagram, the associated risks are linked mainly to the incompleteness of both. Missing functions will heavily impact the mission's success and prevent the production of a complete design. Next, having a design-oriented functional flow could prevent the analysis of potentially better-performing options due to the sub-conscious removal of those design options.

8.1.3. Requirements risks

Requirements are a key part of the design process, and any inaccuracies in this phase could lead to significant issues in the detailed design phase. Requirements should be complete, correct, optimal, verified, and validated. These risks are summarized in Table 8.4:

Table 8.4: *Risks linked to Requirement Discovery Process*

Risk ID	Description	Probability (1-5)	Impact (1-5)
R-RQ-01	Missing Requirement	3	5
R-RQ-02	Wrong Requirement	4	4
R-RQ-03	Overconstrained Requirement	2	3
R-RQ-04	Underconstrained Requirement	2	2
R-RQ-05	Requirement not verified	1	4
R-RQ-06	Requirement not validated	1	4

The most significant risk during requirement discovery is overlooking a requirement. This will lead to a design that might not satisfy all requirements and will thus be suboptimal. The discovery of a new requirement during a later phase, such as the detailed design phase, will cause scheduling issues, and a possible redesign with all consequences implied. A wrong requirement is more likely to occur than a missing requirement, but will impact the design less, since it will not require a full redesign, but can likely be incorporated in subsystem design. Requirement verification and validation should be performed and can be easily checked. However, when not performed, it can have serious consequences on the correctness of the design and the detailed design phase. It could also be possible that a requirement is either too constraining or leaves too much design space, which should be watched out for.

8.1.4. Design options risks

During the creation of the design options tree, a few risks can arise. This is more a brainstorming phase rather than a detailed technical phase and thus the risks are of lesser impact. The risks are summarized in Table 8.5:

Table 8.5: *Risks linked to the Design Option Process*

Risk ID	Description	Probability (1-5)	Impact (1-5)
R-DO-01	Missing Design Options	3	3
R-DO-02	Incorrect Design Option Eliminated	3	3

There are two main risks associated with the design options tree. The first one relates to missing a design option. Naturally, there are infinitely many design options, but the trick is to identify the ones that are useful for further investigation. Infeasible or not-yet-developed concepts can be included, but more attention should be paid to including conventional or already-tried solutions to make sure no design options are missed. If, during the preliminary eliminations of truly infeasible and unavailable concepts, the wrong design option is eliminated, this might lead to a suboptimal winning design in the end.

8.1.5. Risk map and mitigation

With all process risks identified, a risk mitigation plan can be created. Table 8.6 shows the current risk map, where R-IV-01, R-IV-02, R-RQ-01 and R-RQ-02 are the most critical. However, since any risk is unwanted, a risk-handling approach is generated for every risk. This way, every possible risk event is anticipated and accounted for. Table 8.7 shows the approach for every risk.

Table 8.6: *Risk matrix*

		Probability				
		Very Low (1)	Low (2)	Moderate (3)	High (4)	Very High (5)
Impact	Catastrophic (5)		R-DO-02	R-IV-01, R-IV-02, R-RQ-01		
	Critical (4)	R-RQ-05, R-RQ-06	R-IV-04, R-FU-01		R-RQ-02	
	Moderate (3)		R-RQ-03	R-GR-01, R-FU-02, R-DO-01, R-DO-03	R-IV-03	
	Marginal (2)		R-RQ-04			
	Negligable (1)					

Table 8.7: *Summary of Risk Mitigation approaches and their impact*

Risk ID	Mitigation Measure	Probability (1-5)	Impact (1-5)
R-GR-01	Updating the Gantt Chart and including time margins	2 (-1)	2 (-1)
R-IV-01	Choose most trust-worthy source	3	2 (-3)
R-IV-02	Verify information through various sources	2 (-1)	2 (-3)
R-IV-03	Contact experts in the field to search for unreleased information	3 (-1)	2 (-1)
R-IV-04	Maintain source filing procedures	1 (-1)	2 (-2)
R-FU-01	Thoroughly brainstorm with other team members	1 (-1)	3 (-1)
R-FU-02	Review blocks and verify they are design-free	2 (-1)	2 (-1)
R-RQ-01	Thoroughly go through Requirement Discovery processes	1 (-2)	5
R-RQ-02	Experts can be consulted to ensure the feasibility of the requirements	1 (-3)	4
R-RQ-03	Expertscan be consulted to ensure the feasibility of the requirements	1 (-1)	3
R-RQ-04	Further develop the requirement discovery tree	1 (-1)	2
R-RQ-05	Implementation of Verification procedures	1	2 (-2)
R-RQ-06	Implementation of Validation procedures	1	2 (-2)
R-DO-01	Thorough brainstorming of design options within team	1 (-2)	3
R-DO-02	Search for feedback and external advice	2	2 (-3)
R-DO-03	Removal of design options will be approved by the entire team	1 (-2)	3

Following these mitigations, the risk matrix can be updated. The resulting Table 8.8 shows all risks are in a safer zone.

Table 8.8: *Updated risk matrix*

		Probability				
		Very Low (1)	Low (2)	Moderate (3)	High (4)	Very High (5)
Impact	Catastrophic (5)	R-RQ-01				
	Critical (4)	R-RQ-02				
	Moderate (3)	R-FU-01, R-DO-01, R-DO-03, R-RQ-03				
	Marginal (2)	R-IV-04, R-RQ-04, R-RQ-05, R-RQ-06	R-GR-01, R-IV-02, R-FU-02, R-DO-02	R-IV-01, R-IV-03		
	Negligable (1)					

8.2. Design risks

By Javier Alonso García, Sebastian Harris, Thomas van de Pavoordt

When it comes to the more technical side of the project, the design is also subjected to several risks. These can be separated based on which functions the aircraft has to fulfill. The probability of these risks is based on experience and engineering judgment, and the impact of the risks is based on **?**].

8.2.1. Pre-operational risks

Before the aircraft is in use and operational, it is already exposed to risks during, for example, manufacturing or assembly. These risks are listed in Table 8.9:

Table 8.9: *Risks linked to the Pre-Operational Phase*

Risk ID	Description	Probability (1-5)	Impact (1-5)
R-PREOP-01	Imperfections in manufacturing	2	4
R-PREOP-02	Damage during transport	2	4
R-PREOP-03	Errors in Assembly	2	4
R-PREOP-04	Missing items in package	2	4
P-PREOP-05	Launcher fails	1	5

8.2.2. Stationary risks

Once the aircraft is operational, but not yet flying, several risks can be identified when it is stationary on the ground. Winds, dust storms, or radiation exposure are among these risks. All stationary risks are listed in Table 8.10:

Table 8.10: *Risks linked to the Stationary Phase*

Risk ID	Description	Probability (1-5)	Impact (1-5)
R-STAT-01	Dust Storm leading to aircraft damage	3	3
R-STAT-02	Damage due to strong winds	3	3
R-STAT-03	Damage due to Radiation	3	3
R-STAT-04	Incident when refueling/recharging	3	3
R-STAT-05	Pre-flight procedures fail	3	3
R-STAT-06	Unable to refill energy storage	2	4
R-STAT-07	Failure to assemble on sight	2	5

8.2.3. Operational risks

Operational risks are linked to all risks that can occur during the entire operational performance of the aircraft. These are listed in Table 8.11:

Table 8.11: *Risks shared by all operational phases*

Risk ID	Description	Probability (1-5)	Impact (1-5)
R-OP-01	Life support failure	1	5
R-OP-02	On-board fire	1	4
R-OP-03	Compromised thermal insulation	2	3
R-OP-04	Astronauts unable to operate the aircraft	2	5
R-OP-05	Power system failure	2	4
R-OP-06	Improper maintenance	2	3

8.2.4. Take-off risks

During take-off, several risks can occur. Engines can fail, control surfaces can fail or external factors could influence the take-off. These risks are listed in Table 8.12:

Table 8.12: *Risks linked to take-off*

Risk ID	Description	Probability (1-5)	Impact (1-5)
R-TO-01	Engine failure	2	2
R-TO-02	Control surface failure	2	3
R-TO-03	Dust clogs any air intake	3	3
R-TO-04	Corrupted on-board computer	1	2
R-TO-05	Structural failure	2	3
R-TO-06	Insufficient runway length	2	5
R-TO-07	Insufficient lift produced	1	5

8.2.5. Cruise risks

Several risks are present during the cruise phase. Some of them may be shared by other phases but the severity of said failures may differ. An overview of the in-cruise risks can be seen in Table 8.13:

Table 8.13: *Risks linked to cruise phase*

Risk ID	Description	Probability (1-5)	Impact (1-5)
R-CR-01	Engine failure	2	4
R-CR-02	Dust clogs any air intake	1	3
R-CR-03	Control surface failure	2	4
R-CR-04	Corrupted on-board computer	1	3
R-CR-05	Structural failure	2	4
R-CR-06	Strong turbulence	1	3

8.2.6. Landing risks

Several risks are present during the landing phase. Some of them may be shared by other phases but the severity of said failures may differ. An overview of the risks during landing can be seen in Table 8.14:

Table 8.14: *Risks linked to landing*

Risk ID	Description	Probability (1-5)	Impact (1-5)
R-LD-01	Engine failure	2	2
R-LD-02	Dust clogs any air intake	3	3
R-LD-03	Control surface failure	2	4
R-LD-04	Non-functional landing gear	2	4
R-LD-05	Corrupted on-board computer	1	2
R-LD-06	Structural failure	2	3
R-LD-07	Need multiple approaches	3	2
R-LD-08	Landing site is to small	3	3
R-LD-09	Landing gear failure	2	4

8.2.7. Risk mitigation

Once the risks have been identified, they can be combined into a risk matrix and ranked accordingly. This has been done in Table 8.16.

Table 8.15: *Design risk matrix*

		Probability				
		Very Low (1)	Low (2)	Moderate (3)	High (4)	Very High (5)
Impact	Catastrophic (5)	R-OP-01, P-PREOP-05, R-STAT-07, R-TO-07, R-TO-08	R-OP-04			
	Critical (4)	R-OP-02	R-PREOP-01, R-PREOP-02, R-PREOP-03, R-PREOP-04, R-STAT-06, P-OP-4, R-CD-05, R-LD-03, R-LD-04, R-LD-09	R-OP-07		
	Moderate (3)	R-CR-06	R-TO-02, R-TO-05, R-LD-06	R-STAT-01, R-STAT-02, R-STAT-03, R-STAT-04, R-STAT-05, R-OP-03, R-TO-03, R-LD-02, R-LD-03		
	Marginal (2)	R-TO-04, R-LD-05	R-TO-01, R-LD-01	R-LD-07		
	Negligable (1)					

The risks can be mitigated by a variety of measures, some of which will lead to the creation of requirements in the next phase. These additional requirements will ensure these risks are lowered to a level deemed acceptable, thus improving the success of the mission. A summary of these mitigations and their effect can be found in Table 8.17.

Finally, these design risk mitigation techniques will lead to the risk matrix present in Table 8.16

Table 8.16: *Updated design risk matrix*

		Probability				
		Very Low (1)	Low (2)	Moderate (3)	High (4)	Very High (5)
Impact	Catastrophic (5)	R-TO-06, R-TO-07, R-STAT-07				
	Critical (4)	R-PREOP-01, R-PREOP-03, R-PREOP-04, R-STAT-06				
	Moderate (3)	R-PREOP-02, R-STAT-01, R-STAT-04, R-OP-01, R-OP-02, R-CR-05, R-LD-02	R-OP-04			
	Marginal (2)	R-STAT-03, R-TO-03, R-CR-02, R-CR-06, R-LD-06	R-STAT-02, R-STAT-05, R-OP-03, R-OP-05, R-TO-05, R-CR-01, R-CR-03, R-LD-03, R-LD-04, R-LD-09			
	Negligable (1)	R-TO-04, R-CR-04	R-OP-06, R-TO-01, R-TO-02, R-LD-01, R-LD-05	R-LD-07, R-LD-08		

Table 8.17: *Summary of risk mitigation approaches and their impact*

Risk ID	Mitigation Measure	Probability (1-5)	Impact (1-5)
R-PREOP-01	Test all pieces before launch	1 (-1)	4
R-PREOP-02	Damp vibrations and use fairing to carry load	1 (-1)	3 (-1)
R-PREOP-03	Train astronauts in the assembly process	1 (-1)	4
R-PREOP-04	Make a detailed inventory before launch	1 (-1)	4
R-STAT-01	Ensure dust-storm resistance	1 (-2)	3
R-STAT-02	Secure aircraft when stationary	2 (-1)	2 (-1)
R-STAT-03	Employ radiation-shielding materials	1 (-2)	2 (-1)
R-STAT-04	Install redundancies in the energy replenishment system	1 (-2)	3
R-STAT-05	Train astronauts in correct procedures	2 (-1)	2 (-1)
R-STAT-06	Install redundancies in the energy replenishment system	1 (-1)	4
R-STAT-07	Ensure necessary tools are delivered with the system	1 (-1)	5
R-OP-01	Mandatory astronaut suits inside aircraft	1	3 (-2)
R-OP-02	Ensure fire extinguishing capabilities	1	3 (-1)
R-OP-03	Install thermal control capabilities	2	2 (-1)
R-OP-04	Install auto-pilot capabilities	2	3 (-2)
R-OP-05	Ensure backup power system for emergencies	2	2 (-2)
R-OP-06	Create and follow maintanance protocols	1 (-1)	2 (-1)
R-TO-01	Design with one-engine-out performance parameters	2	1 (-1)
R-TO-02	Ensure redundancy in control surfaces	2	1 (-2)
R-TO-03	Employ filters in the intake system	1 (-2)	2 (-1)
R-TO-04	Use back-up computers for redundancy	1	1 (-1)
R-TO-05	Design the structure to survive a crash	2	2 (-1)
R-TO-06	Ensure multiple take-off and landig sites are available	1 (-1)	5
R-TO-07	Install high lift devices for take-off and landing	1 (-1)	5
R-CR-01	Design for one-engine-out performance	2	2 (-2)
R-CR-02	Employ filters in the intake system	1	2 (-1)
R-CR-03	Ensure redundancy in control surfaces	2	2 (-2)
R-CR-04	Use back-up computers for redundancy	1	1 (-2)
R-CR-05	Ensure sufficient safety factors	1 (-1)	3 (-1)
R-CR-06	Ensure structural integrity and autopilot capabilities	1	2 (-1)
R-LD-01	Design for one-engine-out performance	2	1 (-1)
R-LD-02	Employ filters in the intake system	1 (-2)	3
R-LD-03	Ensure redundancy in control surfaces	2	2 (-2)
R-LD-04	Design for potential crash	2	2 (-2)
R-LD-05	Use back-up computers for redundancy	2	1 (-2)
R-LD-06	Ensure sufficient safety factors, inspections and redundancy	1 (-1)	2 (-1)
R-LD-07	Ensure sufficient energy margin	3	1 (-1)
R-LD-08	Ensure sufficient fuel for alternative landing site	3	1 (-2)
R-LD-09	Ensure structural integrity of the main body	2	2 (-2)

9 Sustainable development strategy

To design for sustainability, firstly, a definition of sustainability needs to be agreed upon. We define sustainability after Brundtland:

> "Meeting the needs of the present without compromising the ability of future generations to meet their own needs." [36]

Since the future of humanity may be multi-planetary, we need to consider the needs of future generations on both Earth and Mars. This means that both the manufacturing of the system on earth and the operations of the system on Mars should be sustainable.

9.1. Manufacturing sustainability

By Thomas van de Pavoordt

As manufacturing is done on Earth, sustainability legislation needs to be considered. Additionally, some other essential aspects of the team will be considered.

First and foremost, during manufacturing, it is essential to have no toxic materials. The EU has implemented a directive on the Restriction of Hazardous Substances [1], which prohibits using heavy metals, such as lead, cadmium, mercury, or hexavalent chromium. Furthermore, according to Bhat, following NASA guidelines, all spacecraft and ground supporting equipment materials should meet the criteria of NASA-STD-6001, which tests materials for odor, flammability, off-gassing, and fluid compatibility, depending on the environment to which the materials are exposed. Following these, all materials used in (the manufacturing of) our system will be safe and sustainable. Secondly, it should be kept in mind that as few materials as possible that are increasingly scarce on Earth should be used. The use of recycled materials will be encouraged for manufacturing, as well. Lastly the manufacturing methods themselves should be considered. The manufacture of the parts themselves should not emit any harmful material and should consider both the workers and the environment.

9.2. Operational sustainability

By Dominik Stiller, Timo de Kemp

Since the system will operate on Mars, operational sustainability has multiple dimensions. First, similarly to aircraft on Earth, our system should be reusable for a long time. This reduces the need to source materials, manufacture, and transport them from Earth. A longer lifetime may come with additional maintenance costs, but it reduces overall costs and is economical and sustainable.

A sustainable plan for the end-of-life of our system can also help other aspects of the human presence on Mars. It is important to have an EOL plan for the system. For example, transporting raw materials that do not exist on Mars from Earth is very costly; therefore, recycling the system's materials is much more economical than on Earth. However, some materials are much easier to recycle than others. Therefore, metals are preferable to carbon-fiber composites as they will be easily reusable. Additionally common components such as navigation systems, cockpit elements and so on shall be reused for other purposes.

Fuel will continuously have to be replenished, a critical aspect of sustainability. Shipping fuel from Earth is not sustainable. Thus, the fuel should be generated locally on Mars. Learning from the past century's lessons, fuels extracted from the planet (fossil fuels on our planet, possibly magnesium on Mars) are neither renewable nor pollution-free. Renewable energy sources such as sun and wind will always be available and preferable. Regarding pollution, while a greenhouse effect similar to Earth may not be induced on Mars since the atmosphere is already rich in CO_2 and dust aerosols, different chemical reactions may still lead to irreversible harmful atmospheric effects and thus the fuel used for the system shall produce

[1] URL: https://environment.ec.europa.eu/topics/waste-and-recycling/rohs-directive_en [cited 2023-05-04]

as little waste as possible in order to ensure that the Mars environment does not get damaged in the process.

While the probability of life on Mars is low, the possibility must be considered. Both from an ethical and scientific perspective, potential indigenous life should be protected from the impact of our system.

9.3. Strategy

By Dominik Stiller, Thomas van de Pavoordt

Summarizing the previous two sections, we set new sustainability goals:

- Achieve a lifetime of 10+ years
- Use non-toxic, abundant, recyclable materials
- Use in-situ, renewable fuels
- Evaluate the impact of pollution on the atmosphere and potential life
- Evaluate end-of-life plan

These goals will are then translated into new system sustainability requirements which shall apply to the finished product.

Table 9.1: *Sustainability requirements*

Identifier	Description
REQ-SUST-01	The system shall have a lifetime of 2000 flights of the range 1000 km.
REQ-SUST-02	The system shall be made out of non-toxic, abundant, recyclable materials.
REQ-SUST-03	The system shall use in-situ renewable fuels.
REQ-SUST-04	The system shall not pollute the Martian soil or atmosphere with its fuel.

The end of life plan was already evaluated in the end of life requirements which can be seen in Table 4.22. To achieve these goals, the sustainability manager will check every week what progress each subsystem has made to accomplish these five goals. For example, the structures subsystem shall be checked on the use of materials, their toxicity, and recyclability, and the propulsion subsystem shall be checked on the emissions of the engines and their impact.

Bibliography

[1] Smith, D. E., Zuber, M. T., Frey, H. V., Garvin, J. B., Head, J. W., Muhleman, D. O., Pettengill, G. H., Phillips, R. J., Solomon, S. C., Zwally, H. J., Banerdt, W. B., Duxbury, T. C., Golombek, M. P., Lemoine, F. G., Neumann, G. A., Rowlands, D. D., Aharonson, O., Ford, P. G., Ivanov, A. B., Johnson, C. L., McGovern, P. J., Abshire, J. B., Afzal, R. S., and Sun, X., "Mars Orbiter Laser Altimeter: Experiment summary after the first year of global mapping of Mars," *Journal of Geophysical Research: Planets*, Vol. 106, No. E10, 2001, pp. 23689–23722. doi:10.1029/2000JE001364.

[2] Haberle, R. M., Clancy, R. T., Forget, F., Smith, M. D., and Zurek, R. W. (eds.), *The Atmosphere and Climate of Mars*, 1st ed., Cambridge University Press, 2017. doi:10.1017/9781139060172.

[3] Forget, F., Hourdin, F., Fournier, R., Hourdin, C., Talagrand, O., Collins, M., Lewis, S. R., Read, P. L., and Huot, J.-P., "Improved general circulation models of the Martian atmosphere from the surface to above 80 km," *Journal of Geophysical Research: Planets*, Vol. 104, No. E10, 1999, pp. 24155–24175. doi:10.1029/1999JE001025.

[4] Millour, E., Forget, F., Spiga, A., Vals, M., Zakharov, V., Navarro, T., Montabone, L., Lefevre, F., Montmessin, F., Chaufray, J.-Y., Lopez-Valverde, M., Gonzalez-Galindo, F., Lewis, S., Read, P., Desjean, M.-C., and MCD/GCM Development Team, "The Mars Climate Database (MCD version 5.3)," *EGU General Assembly Conference Abstracts*, 2017, p. 12247.

[5] Simonsen, L. C., Wilson, J. W., Kim, M. H., and Cucinotta, F. A., "Radiation Exposure For Human Mars Exploration," *Health Physics*, Vol. 79, No. 5, 2000.

[6] Naito, M., Kodaira, S., Ogawara, R., Tobita, K., Someya, Y., Kusumoto, T., Kusano, H., Kitamura, H., Koike, M., Uchihori, Y., Yamanaka, M., Mikoshiba, R., Endo, T., Kiyono, N., Hagiwara, Y., Kodama, H., Matsuo, S., Takami, Y., Sato, T., and Orimo, S.-i., "Investigation of shielding material properties for effective space radiation protection," *Life Sciences in Space Research*, Vol. 26, 2020, pp. 69–76. doi:10.1016/j.lssr.2020.05.001.

[7] Johnson, A., Willson, R., Goguen, J., Alexander, J., and Meller, D., "Field Testing of the Mars Exploration Rovers Descent Image Motion Estimation System," *Proceedings of the 2005 IEEE International Conference on Robotics and Automation*, IEEE, Barcelona, Spain, 2005, pp. 4463–4469. doi:10.1109/ROBOT.2005.1570807.

[8] Golombek, M. P., Trussell, A., Williams, N., Charalambous, C., Abarca, H., Warner, N. H., Deahn, M., Trautman, M., Crocco, R., Grant, J. A., Hauber, E., and Deen, R., "Rock Size-Frequency Distributions at the InSight Landing Site, Mars," *Earth and Space Science*, Vol. 8, No. 12, 2021. doi:10.1029/2021EA001959.

[9] Walker, D. D., "Preliminar Design, Flight Simulation, and Task Evaluation of a Mars Airplane," Ph.D. thesis, University of Tennessee, Knoxville, Dec. 2008.

[10] Raymer, D. P., French, J., Finger, D. F., Gomez, A., Singh, J., Pillai, R. G., Monjon, M. M., Marcos De Souza, J., and Levy, A., "The Raymer Manned Mars Airplane: A Conceptual Design and Feasibility Study," *AIAA Scitech 2021 Forum*, American Institute of Aeronautics and Astronautics, VIRTUAL EVENT, 2021. doi:10.2514/6.2021-1187.

[11] Lunar and Planetary Institute, *Concepts and Approaches for Mars Exploration*, Part 2, NASA Headquarters, 2000.

[12] Guynn, M. D., Croom, M. A., Smith, S. C., Parks, R. W., and Gelhausen, P. A., "Evolution of a Mars Airplane Concept for the Ares Mars Scout Mission," *AIAA*, Vol. 2003, No. 6578, 2003. doi:10.251/6.2003-6578.

[13] Kwiek, A., "Conceptual design of an aircraft for Mars mission," *Aircraft Engineering and Aerospace Technology*, Vol. 91, No. 6, 2019, pp. 886–892. doi:10.1108/AEAT-08-2018-0231.

[14] Nagai, H., Numata, D., Suwa, T., and Asai, K., "Characteristics of Low-Reynolds Number Airfoils in a Mars Wind Tunnel," *AIAA*, Vol. 2013, No. 0073, 2013. doi:10.2514/6.2013-73.

[15] Jung, J., Yee, K., Misaka, T., and Jeong, S., "Low Reynolds Number Airfoil Design for a Mars Exploration Airplane Using a Transition Model," *TRANSACTIONS OF THE JAPAN SOCIETY FOR AERONAUTICAL AND SPACE SCIENCES*, Vol. 60, No. 6, 2017, pp. 333–340. doi:10.2322/tjsass.60.333.

[16] Selig, M. S., and Guglielmo, J. J., "High-Lift Low Reynolds Number Airfoil Design," *Journal of Aircraft*, Vol. 34, No. 1, 1997, pp. 72–79. doi:10.2514/2.2137.

[17] Young, L. A., Lee, P., Aiken, E., Briggs, G., Pisanich, G. M., Withrow-Maser, S., and Cummings, H., "The Future of Rotorcraft and other Aerial Vehicles for Mars Exploration," 2021.

[18] Vega, G., Paeres, D., Forteza, E., Claudio, E., Marcial, D., and Araya, G., "Aerodynamic assessment of a drone dirigible-based carrier for search and research purposes," *AIAA SciTech Forum*, 2023. doi:10.2514/6.2023-1735.

[19] Withrow-Maser, S., Johnson, W., Young, L., Koning, W., Kaung, W., Malpica, C., Balaram, J., and Tzanetos, T., "Mars Science Helicopter: Conceptual Design of the Next Generation of Mars Rotorcraft," , 2020.

[20] El-Gaaly, T., McMahan, B., and El Qursh, A., "Multi-Segment Zeppelin-Aided Robotic Rover For Ground-Based and Atmospheric Exploration," *Concepts and Approaches for Mars Exploration*, Vol. 4278, 2012.

[21] Li, Y., Nahon, M., and Sharf, I., "Airship dynamics modeling: A literature review," *Progress in Aerospace Sciences*, Vol. 47, No. 3, 2011, pp. 217–239. doi:10.1016/j.paerosci.2010.10.001.

[22] Underwood, C., and Collins, N., "Design and Control of a Y-4 Tilt-Rotor VTOL Aerobot for Flight on Mars," *IAC*, 2017.

[23] Colozza, A. J., "Comparison of Mars Aircraft Propulsion Systems," *NASA/CR*, Vol. 2003, No. 212350, 2003.

[24] Ma, R., Zhong, B., and Liu, P., "Optimization design study of low-Reynolds-number high-lift airfoils for the high-efficiency propeller of low-dynamic vehicles in stratosphere," *Science China Technological Sciences*, Vol. 53, No. 10, 2010, pp. 2792–2807. doi:10.1007/s11431-010-4087-0.

[25] Landis, G., Kerslake, T., Scheiman, D., and Jenkins, P., "Mars Solar Power," *2nd International Energy Conversion Engineering Conference*, American Institute of Aeronautics and Astronautics, Providence, Rhode Island, 2004. doi:10.2514/6.2004-5555.

[26] Colozza, A., "Preliminary Design of a Long-Endurance Mars Aircraft," *AIAA*, Vol. 90, No. 2000, 1990. doi:10.2514/6.1990-2000.

[27] Bradley, T. H., Moffitt, B. A., Mavris, D. N., and Parekh, D. E., "Development and experimental characterization of a fuel cell powered aircraft," *Journal of Power Sources*, Vol. 171, No. 2, 2007, pp. 793–801. doi:10.1016/j.jpowsour.2007.06.215.

[28] Wickman, J., "In-situ Mars rocket and jet engines burning carbon dioxide," *35th Joint Propulsion Conference and Exhibit*, American Institute of Aeronautics and Astronautics, Los Angeles,CA,U.S.A., 1999. doi:10.2514/6.1999-2409.

[29] Yuasa, S., and Isoda, H., "Carbon dioxide breathing propulsion for a Mars airplane," *25th Joint Propulsion Conference*, American Institute of Aeronautics and Astronautics, Monterey,CA,U.S.A., 1989. doi:10.2514/6.1989-2863.

[30] Foote, J., and Litchford, R., "Powdered Magnesium - Carbon Dioxide Combustion for Mars Propulsion," *41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, American Institute of Aeronautics and Astronautics, Tucson, Arizona, 2005. doi:10.2514/6.2005-4469.

[31] Wolanski, P., "Detonation Engines," *Journal of KONES Powertrain and Trasport*, Vol. 18, No. 3, 2011.

[32] Assad, M., Penyzkov, O., and Chernukho, I., "Symbiosis of deflagration and detonation in one jet system - A hybrid detonation engine," *Applied Energy*, Vol. 322, 2022. doi:https://doi.org/10.1016/j.apenergy.2022.119474.

[33] Drysdale, A. E., Ewert, M. K., and Hanford, A. J., "Life support approaches for Mars missions," *Advances in Space Research*, Vol. 31, No. 1, 2003, pp. 51–61. doi:10.1016/S0273-1177(02)00658-0.

[34] Carr, C. E., "Optimal space suit mass for Mars extravehicular activity," *2016 IEEE Aerospace Conference*, 2016, pp. 1–10. doi:10.1109/AERO.2016.7500869.

[35] Wertz, J. R., and Larson, W. J. (eds.), *Space mission analysis and design*, Space technology library, Kluwer Academic, Dordrecht ; Boston, 1991.

[36] Brundtland, G. H., *Report of the World Commission on environment and development: Our Common Future*, UN, 1987.

[37] Bhat, B. N. (ed.), *Aerospace Materials and Applications*, American Institute of Aeronautics and Astronautics, Inc., Reston ,VA, 2018. doi:10.2514/4.104893.