Team Tumbleweed

Systems Engineering Team

Report

Initial Mission Baseline Report

Initial Pre-Phase A study of the Tumbleweed Demonstrator Mission

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Responsible Team Members

Julian Rothenbuchner	James Kingsnorth	Kristián Cuervo
Markus Renoldner	Mihir Kapadia	Paul Wiesen
Sebastian Harris	Mick Resinck	

Team Tumbleweed

Change Log

Version	Changes Implemented	Contributor
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Summary

This report covers the subsystem requirements derivation of the Tumbleweed rover. After discussing the operational analysis, addressing science objectives and stakeholder requirements, the logical analysis is presented. It covers the Functional Analysis at mission level, the mission architecture as well as the function interface analysis. In the next section, mission requirements are discovered and analysed, followed by a design trade study exploring various mission concept options. Finally, the winning concept is described in the last section.

The science objectives (chapter 2) can be summarized in three categories

1. Atmospheric science objectives
2. Internal planetary structure objectives
3. Surface geology objectives

Next to that, the following stakeholders were classified as "key":

1. **Space agencies**, that enable the mission organisation
2. **Mission scientists**, that act as a customer for science data
3. **Science objectives**, that must be performed to prove scientific value of the mission
4. **Team Tumbleweed**, the organisation developing and conducting the mission.

Both science objectives as well as requirements produced by stakeholders will define all future work on the mission, as every single detail being added to the Tumbleweed mission shall contribute to fulfill these objectives and requirements.

In chapter 3 the mission architecture is being presented. It contains all mission segments and how they relate to each other. Exemplary segments include

- Launch, Entry, Landing and Rolling Trajectories
- Launch, Transfer, Entry & Descent Vehicle and Orbiter
- The mission
- Spacecraft Bus (=the Tumbleweed rover)
- Communications, Relay satellites
- Mission Operations, Users
- Planet Mars

The functional analysis results in a functional flow diagram, that defines how functions (e.g. Development, Manufacturing AIT, Launch, Transfer, ...) relate to each other. I.e. it explains the order of the

functions and what has to happen in order to "initialize" and "finish" a function. Finally, the mission interface analysis is being conducted based on a functional and a non-functional N2-diagram.
It is important to note, that this analysis is only done for the base, i.e. the case of a spacecraft bus that is integrated into the entry & descent vehicle.

Then, a requirements discovery tree has been used to answer what capabilities are needed to fulfil the science goals, what and under what constraints the operations have to be conducted. Based on these results, the mission requirements were derived and formulated.

Subsequently, a mission concept options are being compared to one another, based on a quantitative score (from 0 to 3) applied to a range of criteria/properties of the concepts. These criteria include technical performance, costs and risks. These mission-level trades have been done for the following functions (the winning concepts are included in parentheses):

1. **F4 - Transfer to Mars** (Spacecraft bus integrated with parent mission in entry & descent vehicle)
2. **F5.5 - Reach Mars Surface** (Spacecraft bus descent at terminal velocity, using drag of spacecraft bus only.)
3. **F6.4 - Position Payload** (A swarm of several rovers distinguishing themselves based on non-hardware differences is being sent to Mars.)
4. **F6.6 - Handle Payload Data** (Onboard Processing)
5. **F6.4 - Spacecraft bus control method** (Stop/Start - the spacecraft bus can halt its trajectory at will.)
6. **F6.3.1 - Energy generation** (Lithium Sulphur Batteries)
7. **F6.3.12 - Location determination** (no winner identified)

Moving on the mission design is presented in more detail: The mission concept is a singular SCB within a dedicated EDV, which is packaged onto the side of the parent mission. The SCB itself is controllable through deliberately stopping its motion, and it is powered by thin-film GaAs solar panels and a lithium-ion battery.

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Glossary

AIT Assembly, Integration and Testing. i, 52, 62

BoL Beginning-of-Life. 52, 55, 56

CDH . 9

ECSS European Corporation for Space Standardization. 54, 59

EDL . 5, 11

EDV Entry & Descent Vehicle. i, ii, 13, 16, 26, 27, 50–53, 58, 59, 61–63

EoL End-of-Life. 34, 35, 56

EPS Electrical Power System. 9, 57

FMI Finnish Meteorological Institute. 46

GaAs Gallium Arsenide. ii, 51, 62

IMU Inertial Measurement Unit. 43, 44

MARSIS Mars Advanced Radar for Subsurface and Ionosphere Sounding. 4

MSL Mars Science Laboratory. 46, 47

PLD Payload. 52

RAMS Reliability, Availability, Maintainability, Safety. 22, 41

RDT Requirements Discovery Tree. iii, v, 18, 19

REMS Rover Environmental Monitoring Station. 46–48

RSL Recurring slope line. 4

SCB Spacecraft Bus. i, ii, iv, vi, vii, 13, 16, 17, 25–31, 34, 36, 43, 44, 46, 50–54, 57–59, 61–63

SOI Sphere of Influence. 27

SVLCM Spacecraft/Vehicle Level Cost Model. 27, 59

TDM Tumbleweed Demonstrator Mission. v, 19, 52

TRL Technology Readiness Level. 23, 24, 27, 30, 38, 43

TTW Team Tumbleweed. 10

1 | Introduction

Martian surface exploration has been performed using similar Martian rover designs in the past, such as Curiosity or Perseverance. These rover concepts have proven to be successful, however, their design is not able to meet the increasing needs of the space industry. An alternative rover concept is the Tumbleweed rover, which aims to use the Martian winds as a method of locomotion. The Team Tumbleweed organization has been exploring this concept since 2017. However, it is now, at the publishing of this document, that the fundamentals of the concept have been revisited to improve the foundation of the technology development. The results are used in design concept generations and for systems and sub-systems development for the other technical teams of Team Tumbleweed.

The goal of this report is to firstly redefine the need of the mission, and to realign it with current science goals of the European space exploration. It aims to identify stakeholders in the mission, and to derive the stakeholder requirements which must be met for the mission to be successful. Furthermore, it provides the basis of the different mission constituents, how they relate to each other, and how they are tradeable. From this, the mission requirements are derived from the stakeholder requirements and science goals. Furthermore, initial trade-off studies are made to determine the best performing options for different mission constituents. Finally, the report suggests a design option which follows from the best performing design concepts.

The report firstly outlines the Operational Analysis in chapter 2. This addresses and confirms the science objectives and needs of the mission through a literature study. In addition, a Stakeholder Analysis is performed to identify and understand the relevant importance of stakeholders of Team Tumbleweed. The Logical Analysis, in chapter 3, includes the Mission Architecture, Mission Functional Analysis and Mission Interface Analysis. In chapter 4 it outlines the Mission Requirements through a Requirements Discovery tree and its written counterpart. In chapter 5 it outlines multiple mission-level trade studies with the approached methodology and workflow used. Furthermore, chapter 6 describes the Winning Concept Design, with relevant budgets. Finally, the Conclusion and Recommendations are presented in chapter 7.

2 | Operational Analysis

2.1 Mission Need Literature Studies and Market Analysis

To pinpoint the need of the Tumbleweed mission, literature studies and market analysis were performed. The literature study identified the prominent Martian research goals and their relation to the needs of different industry stakeholders, such as academia or European Space Agency, as well as the market needs for each field of research. Following that, a market analysis was performed in order to determine the existing competition with regard to the relevant research field, and the areas in which the Tumbleweed mission can outperform its competitors. The following section serves as a summary of the main findings of this review.

2.1.1 Atmosphere & Climate Investigation

Understanding the Martian atmosphere and climate is crucial not only to the success of future manned missions, but also to understanding the dynamics of the planet better. Moreover, Mars' atmosphere can serve as a model for Earth's atmosphere, and understanding it can lead to improved understanding of our own planet.

The key market gaps relate to the resolution of data, and the wide spread of that data over a large surface area. The key hurdle for the Tumbleweed mission is to carry instruments which are able to perform the desired measurements. For atmospheric measurements, however, the orientation of the instrument does not create a problem, which means that the composition can be accurately studied with any instrumentation that can resist the shock loads of the final design. This will end up being a design constraint. For widespread data, the Tumbleweed mission is able to meet that market need perfectly. The feasibility for vertical measurements is, as yet, unclear. The surface level is however feasible due to the key strength of the Tumbleweed - its mobility, allowing regional/global mapping of the relevant factors over a significant amount of time. There are alternatives to do it from orbit, with upcoming missions potentially investigating some aspects, but there is a clear scope for a distributed weather station network to complement these measurements.

To determine research goals, resources have been used as references to what important goals are in the science community. These resources include MEPAG goals [2], those set in the FAHRENHEIT report, and documentation previously published internally such as C.SC1 and the Mission Study report. The market analysis showed that there is a need to not only find data over a large area, but also to find data over a longer time span in important locations. This has indicated the possible need for the Tumbleweed to have a stationary phase. The inclusion of a stationary phase supports the goals of the FAHRENHEIT report, which aims to find the requirements necessary for a weather station on Mars.

2.1.2 Interior Structure Investigation

Mars has an intermediate size between the Moon and Earth, and can therefore provide invaluable insights into planet formation. While the Moon, due to its small size, cannot provide a good model to gain such data, Mars, with its larger size, has processes much more akin to larger terrestrial planets such as Earth. At the same time, its surface is arrested in more or less its original state due to its relatively smaller size when compared to Earth leading to a rapid cool-down of the primordial surface Geodetic data, from radio beacons and laser retroreflectors, can provide crucial insights for the Mars Interior, such as Planetary Precession, Nutation and Love number for the J2 harmonic [3], [17], [8]. In addition, Planetary Gravimetry, Mantle Plume Strength and Surface Support Mechanisms can be gained from this data to understand the temporal evolution of mantle properties. For example, recently it has been proposed that the Tharsis region is rising in elevation. Investigating this potential rise could lead to an understanding of the planetary mantle dynamics on the whole, and can be helped by precise gravimetry data over time [17][19].Thus, understanding Martian interior structure and formation is key to understanding the formation of planets in the whole. In addition, further measurements that can be conducted with these instruments include atmospheric measurements, e.g. atmospheric densities, mass exchange, dust concentrations and much more.

Many of the measurements required for the above goals are contingent on measurements from more than one point [5], [3]. Therefore, the gap in knowledge pertains to all measurements that can be achieved using one singular instrument compatible with direct Earth - Mars measurements, namely Nutation. Consequently, the capability gap is the ability to generate RF and light-based geodetic data with cm-level precision over a large (>5) number of points, ideally distributed over the order of thousands of kilometres. Another consideration is that ideally, more than one radio beacon should be reachable at the same time from the orbiter used.

From the Market Analysis, it showed when it comes to alternative mission concepts to achieve alternative investigations, orbital missions are relevant for their capability to indirectly measure the gravity field of Mars. Furthermore, conventional landers could provide seismology similar to Mars InSight [17], and deployment of singular radio beacons such as RISE already has flight heritage [8]. However, the Market Analysis showed that The Tumbleweed mission is preferable for this application compared to conventional impactors due to its relatively benign mechanical environment during landing. On the one hand, impact acceleration for impactors are on the order of $10^5 m/s^2$, whereas the Tumbleweed rover's impact acceleration is on the order of $10^1 m/s^2$ [16]. Furthermore, the Tumbleweed mission concept gives the opportunity to distribute beacons over a large area in the vicinity of the initial landing location, leading to a more performant network. This means that the mechanical environment, distribution ability (both in distance and control of final location) and time to full deployment of the radio beacon are the main factors of interest from this investigation. This means that the network can operate for a longer time within the design life of components, and it returns data sooner. As the length of observations are critical for returning usable data. This is all in consideration to the research goals that are currently important in the science community, as outlined in the MEPAG goals [2].

2.1.3 Surface Geology Investigation

The Mars topology has been shaped by impacts. The craters left behind contain valuable information regarding the geology and internal geology of the planet. With the use of cameras it allows for Crater observation, Fluid observation and Recurring slope lineae (Recurring slope line) observation. Where crater observation provides the determination of suitable samples as well as clues to the topological and geological processes sustained in old craters [11]. Fluid observation provides observation of areas suspected to have once contained water and Recurring slope lineae observation could help with identifying the source of these geological features, which has a huge impact on habitability assessments. Therefore, through surface observation of geological elements, it will be possible to further understand the history of the Martian surface.

The key market gaps relate to the origin of Recurring slope line as it has yet to be determined. If liquid water is responsible for the phenomena, the source of this water must be determined. Recurring slope line are 0.5 - 5 meter wide, dark lines that lengthen downhill on slopes in warmer seasons, fade in colder seasons and reoccur each Mars year. Some studies propose liquid water as the source of recurring slope lineae while other studies point towards liquid-free mechanisms. The liquid-water-involving hypotheses suggest that salt may lower the melting point of water, enabling lineae. One study suggests that such a “brine” could be flowing just beneath the surface, and that some of this liquid is wicking up to the surface. According to a study published in 2017, Coprates Montes in Valles Marineris may have the highest areal density of Recurring slope line found on Mars [18], [13], [22].

From the Market Analysis, it is shown that competing mission concepts include orbiting missions. The Mars Advanced Radar for Subsurface and Ionosphere Sounding (Mars Advanced Radar for Subsurface and Ionosphere Sounding) onboard the Mars Express spacecraft has previously performed measurements that indicate the presence of a large body of liquid water below the ice of the South Polar Layered Deposits. However, smaller bodies of water cannot be detected by this mission concept. In addition, FREND is a neutron telescope onboard ExoMars Trace Gas Orbiter, and it has measured hydrogen abundance in the shallow subsurface but has a very low resolution of 200 km [14]. The major investigation is through imaging and with current orbiters a lack of resolution and perspective limits this and landers are limited by inclination and area they can observe. Using the Tumbleweed mission as the basis of an imaging investigation has several advantages. For example, the investigation itself is simple and only requires a camera. In addition, the use of multiple Tumbleweed rovers makes it possible to investigate many local areas at a high resolution to detect smaller geological features that may indicate liquid water. Furthermore, under preferable wind conditions, the Tumbleweed rovers can travel up steep inclinations and provide close up images of e.g. recurring slope lineae. Also, the perspective of the Tumbleweed at ground-level is preferable when observing steep slopes.

2.2 Science Objectives

As mentioned previously, three groups of science objectives have been identified as key research points for the Tumbleweed mission to focus on. These include atmospheric sciences, internal geology, and surface geology. These groups were derived from a literature study, and following that a market and competition analysis on what market gap which the Tumbleweed mission can fill. Once this analysis was performed, science objectives were derived from each research theme. The science objectives can be seen in Table 2.1.

Science Objectives	
Objective ID	**Objective Description**
Atmospheric Science	
SCI-OBJ-A01	Provide imaging of transient Mars weather phenomena.
SCI-OBJ-A02	Improve understanding of Martian climate and weather and provide constraints to computational models thereof.
SCI-OBJ-A03	Characterize the visible and near-visible light radiation environment on the Martian surface.
Internal Structure	
SCI-OBJ-I01	Constrain Mars mantle properties through measurements of nutation, precession and tidal deformation.
Surface Geology	
SCI-OBJ-S01	Determine areas of interest for sample return missions.
SCI-OBJ-S02	Investigate the landform modification processes on Mars
Opportunistic/Secondary Goals	
SCI-OBJ-O01	Expand knowledge needed for human exploration missions through radio science investigations of Martian Ionosphere.
SCI-OBJ-O02	Determine the aspects of the atmospheric state that affect orbital capture and for human scale missions to Mars.
SCI-OBJ-O03	Assess landing-site characteristics and environment related to safe landing of human-scale landers.
SCI-OBJ-O04	Constrain temporal evolution of mantle properties through measurements of surface deformation and support of measurements of temporal evolution of Mars' gravity field.
SCI-OBJ-O05	Investigate mantle plume strength through direct measurements of surface deformation.
SCI-OBJ-O06	Search for structures associated with life in surface or subsurface environments.
SCI-OBJ-O07	Identify the geologic evidence for the location, volume, and timing of ancient water reservoirs.
SCI-OBJ-O08	Link geologic evidence for local environmental transitions to global-scale planetary evolution.
SCI-OBJ-O09	Observe impact of fluids on the topology, be it magma or water, to rebuild the history of the Martian Surface.
SCI-OBJ-O010	Observe geological features that may indicate present liquid water.

Table 2.1: Science Objectives

2.3 Mission Statement

Open up access to deep space by proving crucial technologies and science applications of the Tumbleweed rover on Mars by 2030.

2.4 Need Statement

Pushing Mars exploration further along towards human exploration requires increased access to the Martian surface in terms of mission cost, risk and timeline. Moreover, scientists are in need of data from large areas of the surface to augment current datasets and improve models of the Martian climate and interior, as well as its surface geology. It would moreover be desirable, albeit not crucial, to provide basic visual surveying capabilities, together with the ability to process large datasets in-situ. To address these needs, the Tumbleweed mission architecture has to be demonstrated on Mars through an in-situ demonstrator before it can be used to address the scientific applications of the ultimate mission. This will also allow for potential commercial avenues to be evaluated.

The data obtained from the Mars demonstrator mission will be used by Team Tumbleweed to verify, validate and further develop the design of their wind-driven rover. Furthermore, the results of the mission are used by Team Tumbleweed to increase their legitimacy vis-à-vis future customers such as scientists and space agencies, as well as funding sources. The data generated by the demonstrator mission will be used by space researchers in order to improve the understanding of the Martian climate and weather, as well as interior structure and surface geology.

2.5 Stakeholder Analysis

In this section, the Stakeholder Analysis is outlined. This analysis includes the identification, assessment and prioritization of people and organizations that influence Team Tumbleweed. Allowing the categorization of the stakeholders into a matrix, as shown in Figure 2.1.

2.5.1 Stakeholder Identification & Matrix

The stakeholders were identified by first considering every person, investor, organization, employee, customer, supplier and regulatory body that can affect Team Tumbleweed. Following this, each stakeholder was separated into a category of Key Player, meet their Needs, Show Consideration or Least Important dependent on their respective power and interest. This is visually represented in the Stakeholder Matrix and is shown in Figure 2.1. The Key Players are listed below, with their justification.

Key Player stakeholders:

- **Space Agencies**: They enable the mission to be flown and are the primary customer.
- **Mission scientists**: The direct customer of the science return from the mission.
- **Science Objectives**: The scientific investigations required to meet the mission's science goals.
- **Team Tumbleweed**: The organization is responsible for the overall mission.

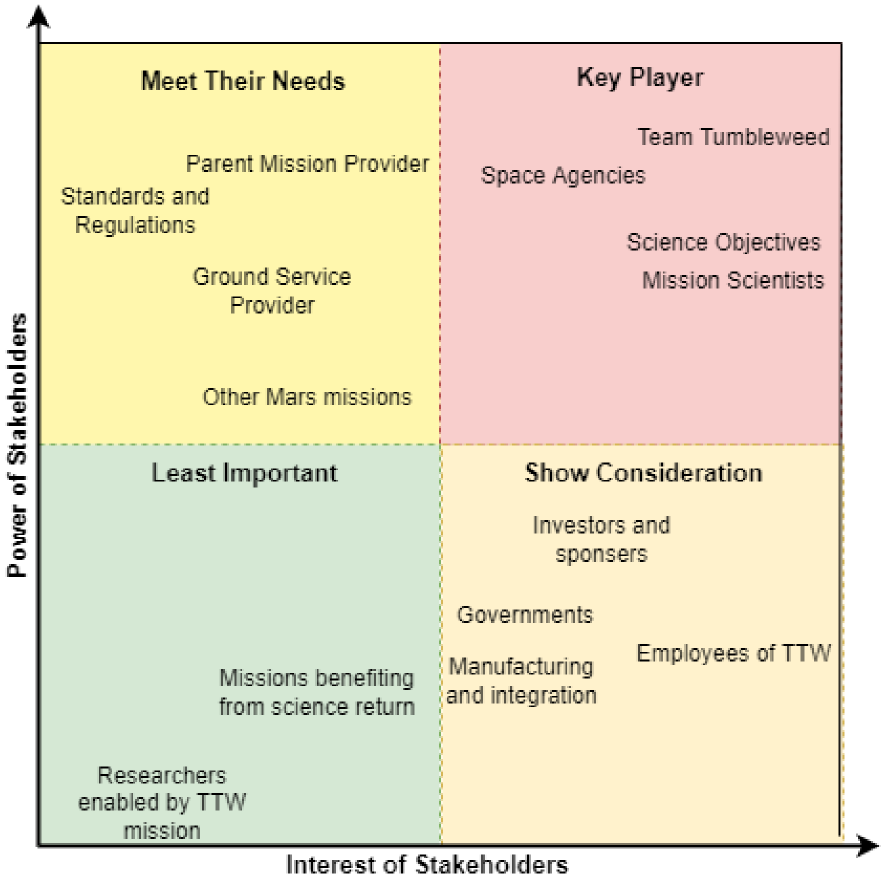


Figure 2.1: Stakeholder Matrix showing all stakeholders, in relation to their relative power and interest to Team Tumbleweed.

2.5.2 Science goals & Stakeholder Requirements

The science goals have been derived from the science objectives in section 2.2. Furthermore, the stakeholders have been brainstormed and iterated upon, together with the science goals, to derive the capabilities of the mission. Consequently, stakeholder requirements which relate to the stakeholders have also been added. Table 2.2 shows the aforementioned goals and stakeholders, their respective requirements, their role and what mode they have.

.2

Table 2.2: Stakeholder Requirements

Stakeholder (Sci.Obj)	**Stk.req. ID**	**Goal / requirement description**
Atmospheric science		
Key-player		Mode: Interact
SCI-OBJ-A02	ATM-REQ-001	The mission shall provide surface level measurements of atmospheric and ground temperature.
SCI-OBJ-A02	ATM-REQ-002	The mission shall provide surface level measurements of ambient pressure.
SCI-OBJ-A02	ATM-REQ-003	The mission shall provide surface level measurements of the 3D wind field.
SCI-OBJ-A02	ATM-REQ-004	The mission shall provide surface level measurements of optical depth/light diffusion in the atmosphere.
SCI-OBJ-A02	ATM-REQ-005	The mission shall provide surface level measurements of humidity through the mission duration
SCI-OBJ-A03	ATM-REQ-006	The mission shall provide measurement of surface-level solar irradiation.
SCI-OBJ-A01	ATM-REQ-007	The mission shall detect and categorize weather phenomena such as clouds, precipitation or dust devils.
Internal structure		
Key-player		Mode: Interact
SCI-OBJ-I01	INT-REQ-001	The mission shall measure the precession of Mars.
SCI-OBJ-I01	INT-REQ-002	The mission shall measure the nutation of Mars.
SCI-OBJ-I01	INT-REQ-003	The mission shall determine the Love number for the J2 harmonic.
Surface geology		
Key-player		Mode: Interact
SCI-OBJ-S01	SUR-REQ-001	The mission shall provide high resolution images of several Martian craters located in different areas.

SCI-OBJ-S02	SUR-REQ-002	The mission shall provide high resolution imagery of Martian volcanic regions
SCI-OBJ-S02	SUR-REQ-003	The mission shall provide high resolution imagery of the mass ejected during meteoric impacts
Mission scientists		
Key-player		Mode: Interact
-	MSC-REQ-001	The mission shall return all scientific data required for the science objectives before 2033
-	MSC-REQ-002	The mission shall provide scientifically relevant data to all entities with appropriate and simple access abilities
Space Agencies		
Key-player		Mode: Active
-	SPA-REQ-001	The mission shall support the development of promising and novel deep-space missions by setting a precedent for wind powered extra-terrestrial exploration
-	SPA-REQ-002	The mission shall aid in realizing the Terrae Novae 2030+ roadmap by investigating the viability of a weather network, demonstrating novel mobility solutions and preparing for future human missions through the use of the Tumbleweed Rover
Team Tumbleweed		
Key-player		Mode: Active
-	TTW-REQ-001	The mission shall prove scientific potential and application of ultimate mission: 1) Relevant science instruments 2) Science operations
-	TTW-REQ-002	The mission shall prove technologies needed for a subsequent mission: 1) adcs; Location Determination 2) Electrical Power System; Power Generation 3) ; Data processing 4) TT&C; Communications 5)Structures; Physical deployment of the rover

-	TTW-REQ-003	The mission shall prove the viability of the business model for a subsequent mission: 1) Tokenized access to in-situ data and computing resources
-	TTW-REQ-003	The mission shall demonstrate that the Tumbleweed Rover is capable of being a viable and competitive deep-space commercial service
-	TTW-REQ-004	The mission shall increase the financial and intellectual network of the Team Tumbleweed organization for a subsequent mission
-	TTW-REQ-005	The mission cost including operations shall not exceed <TBD> FY2022 €
-	TTW-REQ-006	The mission shall have a probability of 90% of achieving all demonstration goals.
-	TTW-REQ-006	The mission shall have a probability of 70% of achieving all science goals.
Governments		
Show consideration		Mode: active
-	GOV-REQ-001	The mission shall retain economic rewards through jobs creation, creation of expertise, economic activity of mission operator and suppliers
-	GOV-REQ-002	The mission shall represent the scientific community of their nation
-	GOV-REQ-003	The mission shall provide access to valuable spin-off technologies
-	GOV-REQ-004	The mission shall remain within international treaties
Investors and Sponsors		
Show consideration		Mode: passive
-	INV-REQ-001	The mission shall provide its successes for international recognition
-	INV-REQ-002	The mission shall demonstrate value and potential for a subsequent full-scale mission
Employees/Members of Team Tumbleweed		

Show consideration		Mode: active
-	MEM-REQ-001	The mission shall prove an innovative design
-	MEM-REQ-002	The mission shall prove the mission concept
-	MEM-REQ-003	The mission shall demonstrate value and potential for a subsequent full-scale mission
Manufacturing and integration		
Show consideration		Mode: active
	MAN-REQ-001	The mission shall make use of established aerospace industry manufacturing techniques.
	MAN-REQ-002	The mission shall maximize use of COTS products
Parent Mission Provider		
Meet their needs		Mode: active
-	PMP-REQ-001	The mission shall use unused mission budgets in an existing mission to provide a future mission with more proven technology.
-	PMP-REQ-002	The mission shall increase primary mission relevance and funding.
-	PMP-REQ-003	The mission shall be compatible with the parent mission launch, transfer and stage
-	PMP-REQ-004	The mission shall minimize risk influence on the parent mission
-	PMP-REQ-005	The mission shall meet the time constraints of the parent mission
Ground Service Provider		
Meet their needs		Mode: active
-	GSP-REQ-001	Be compatible with the ground service provider's infrastructure
-	GSP-REQ-002	The mission shall use the same communication system during the mission lifetime

Standards and Regulations		
Meet their needs		Mode: passive
-	STA-REQ-001	Adhere to Standards and Regulations for space exploration
Other Mars missions		
Meet their needs		Mode: passive
-	OMI-REQ-001	The mission shall not interfere with other Mars missions
-	OMI-REQ-002	The mission shall communicate with a present Mars orbiter to relay data
Researchers who will be enabled by the Tumbleweed mission		
Least important		Mode: passive
-	PRE-REQ-001	Provide inspiration for new research to be conducted in the subsequent mission
ESA Sample Return / Missions that will benefit from the science returns		
Least important		Mode: passive
-	FMI-REQ-001	The mission shall capture photographic imagery of critical areas in the context of an ESA return mission
-	FMI-REQ-002	The mission shall gather data regarding dust storms to aid in reliability of future missions

3 | Logical Analysis

3.1 Mission Architecture

In order to begin the logical analysis of the Tumbleweed demonstrator mission, the logical constituents of the mission must be defined. This includes both the constituents of the mission itself, and the segments that the mission will interact with to fulfil its objectives. Furthermore, for the purpose of the current analysis, the tradeability of the segments must be established. The architecture, showing these elements, is presented in Figure 3.1:

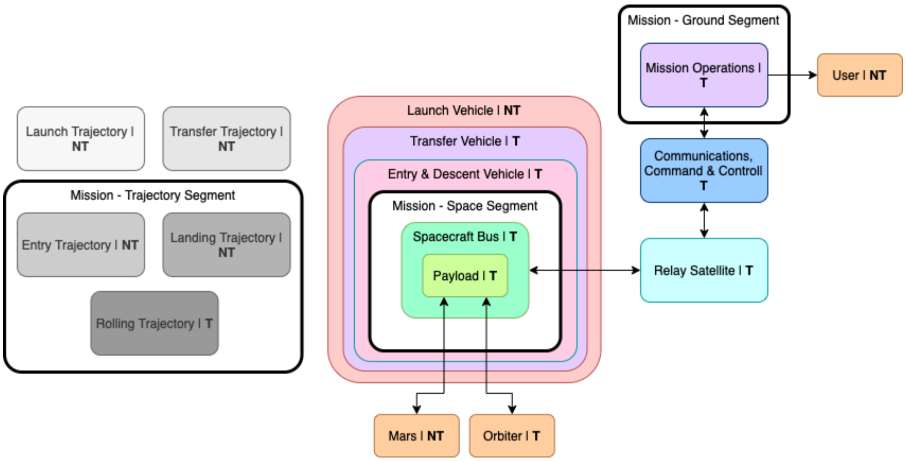


Figure 3.1: The logical architecture of the rover-only mission concept of the Tumbleweed Demonstrator Mission.

Here, the thick black lines show the systems boundary of the mission, and T stands for tradeable, whereas NT stands for non-tradeable. As shown, the mission consists of a space segment, including the payload which interacts with the mission subjects to fulfil the mission objectives, and the Spacecraft Bus (SCB), supporting the payload. The space segment of the mission is integrated into the EDV of the parent mission, which also includes the transfer and launch vehicles. Furthermore, the space segment interacts with the relay satellite to transmit data and receive commands, which in turn interacts similarly with the communications, command and control segment. As a result, the mission ground segment, consisting of mission operations, receives the data and passes commands to the communications, command and control segment, and interacts with the end user.

Furthermore, the mission trajectory segment consists of the entry trajectory, landing trajectory and rolling trajectory. Also, the launch and transfer trajectory of the parent mission need to be taken into account as they influence the design of the Demonstrator mission.

3.2 Mission Functional Analysis

In the following section, the initial releases of mission functional and data flow diagrams are presented. These diagrams are fundamental to the initial derivation of mission requirements, and further form the foundation of the trade studies presented in chapter 5.

3.2.1 Mission Functional Flow Diagram

To support mission requirements formulation, a functional flow must be established which is aimed at determining the required steps to satisfy stakeholder needs. In order to systematically identify the required functions of the Tumbleweed Demonstrator Mission, a functional flow diagram is established down to the second level, with a specific function being further broken down to the third level. First up, Figure 3.2 shows the first-level functions, hereafter called mission phases:

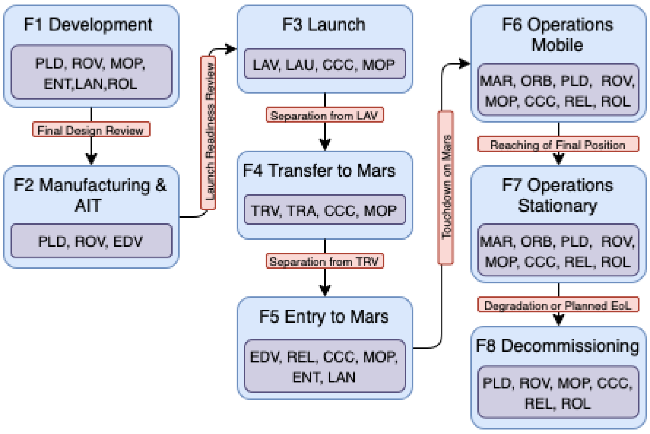


Figure 3.2: The mission phases of the Tumbleweed Demonstrator Mission.

As can be seen, the phases include development, manufacturing & AIT, Launch, Transfer, Entry, Operations while Mobile, Operations while Stationary and Decommissioning. Next up, Figure 3.3 shows the second-level functional flow block diagram, expanding on the missions phases F4-F7. The other mission phases are omitted at this moment due to the early stage of the design work.

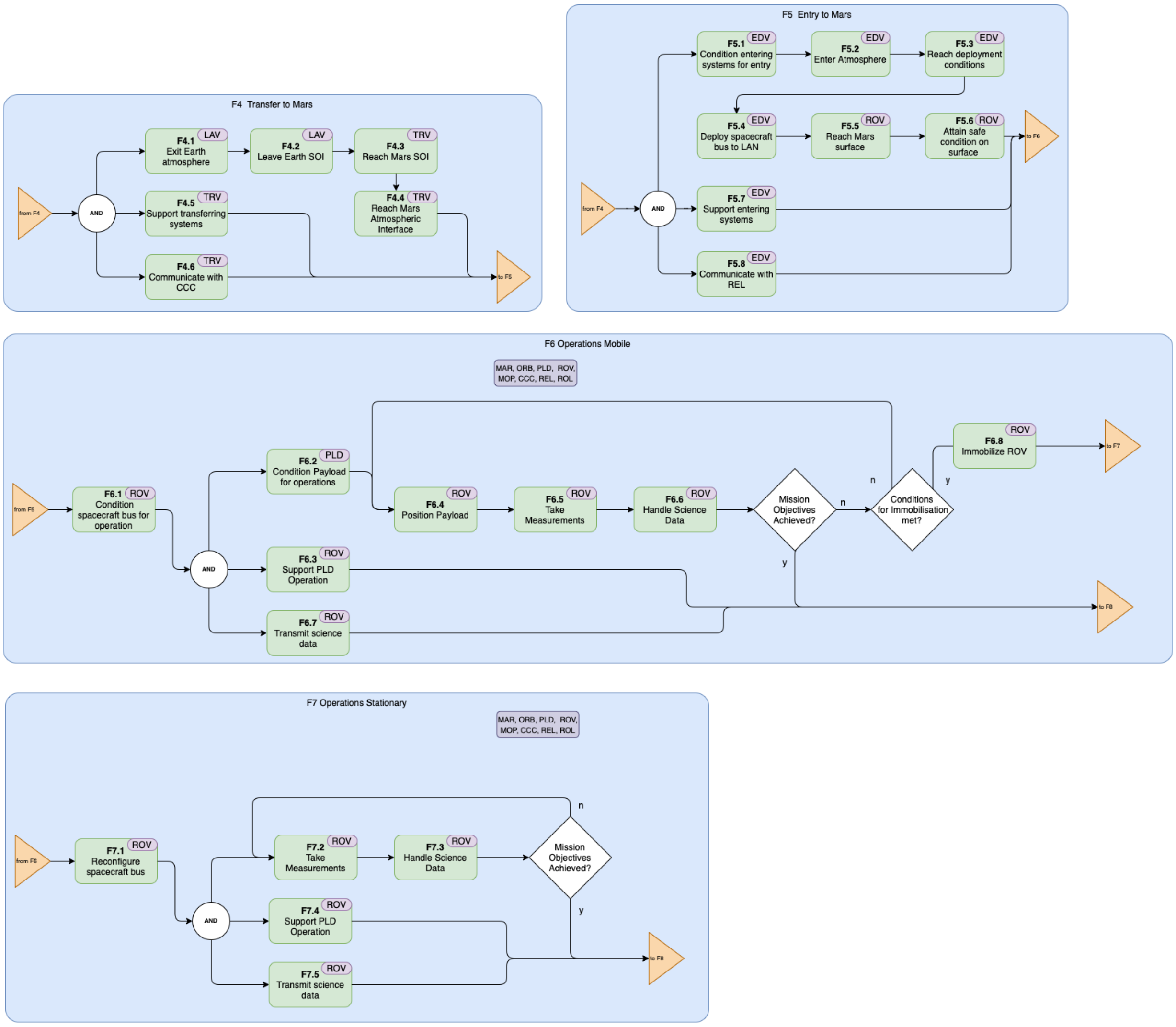


Figure 3.3: The second-level mission functions of the Tumbleweed Demonstrator Mission.

Lastly, Figure 3.4 shows the third-level functional breakdown of function F6.3. This is done as this function contains within several major mission trades, which are described in chapter 5.

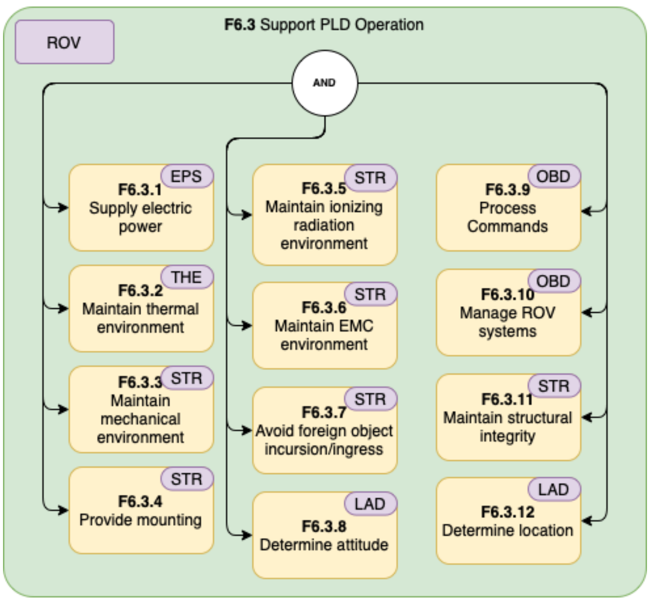


Figure 3.4: The third-level functions of function F6.3 of the Tumbleweed Demonstrator Mission.

3.2.2 Mission Data Flow and User Interaction Diagram

In the following, the mission data flow diagram is presented. This shows the propagation of data from its source (the payload) to the end user, including important intermediate steps. Creating an initial version of this diagram is crucial at this early stage, as the generation of data is central to the fulfilment of mission objectives. Figure 3.5 shows this data flow:

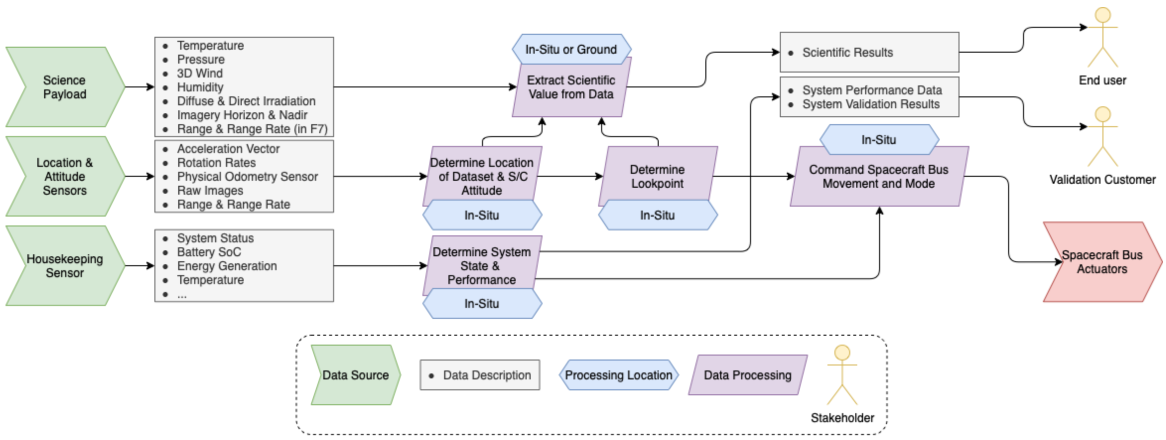


Figure 3.5: The data flow diagram of the Tumbleweed Demonstrator Mission.

Furthermore, it is important to conceptualize the interaction between the mission and its end user at this point. This is shown in Figure 3.6:

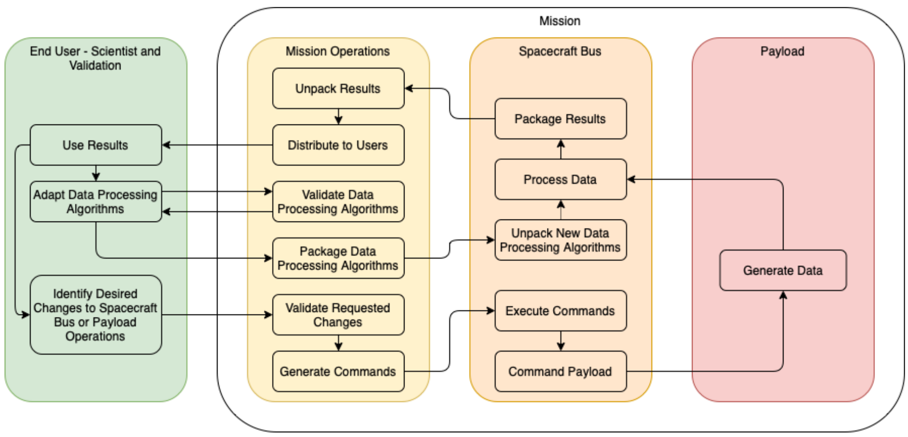


Figure 3.6: The user interaction diagram of the Tumbleweed Demonstrator Mission.

3.3 Mission Interface Analysis

Now, the interfaces of the Tumbleweed Demonstrator Mission with other parts of the mission architecture are presented. This is done through the creation of two N2 charts, one for functional and one for non-functional interfaces. This analysis is done for the base case of the SCB being integrated within the Entry & Descent Vehicle (EDV). For other concepts described in subsection 5.2.1, the interfaces between the SCB and the EDV move to the transfer vehicle. In this case, functional interfaces are defined as being related to the fulfilment of functions and therefore capabilities, whereas non-functional interfaces include the generation and propagation of constraints through the interaction of the segments. First up, the functional N2 chart is presented in Figure 3.7:

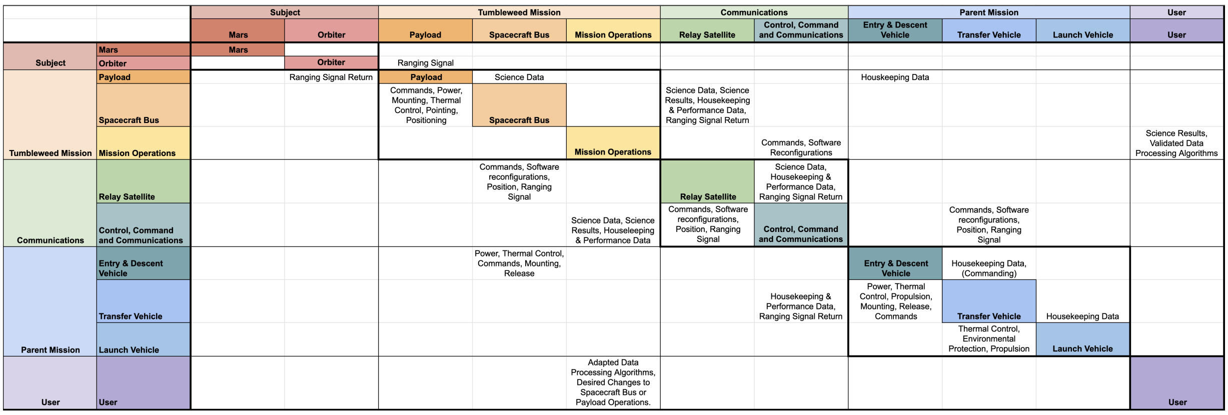


Figure 3.7: Functional N2 chart of the Tumbleweed Demonstrator Mission.

The N2 Chart shows that most interfaces are related to data transmission and navigation of the SCB. Furthermore, the SCB and the payload are closely interfaced as expected. Next up, Figure 3.8 shows the non-functional interfaces of the Tumbleweed Demonstrator Mission, including the trajectory segments. These were omitted in the functional N2 chart, as they do not perform any functions in the conventional sense.

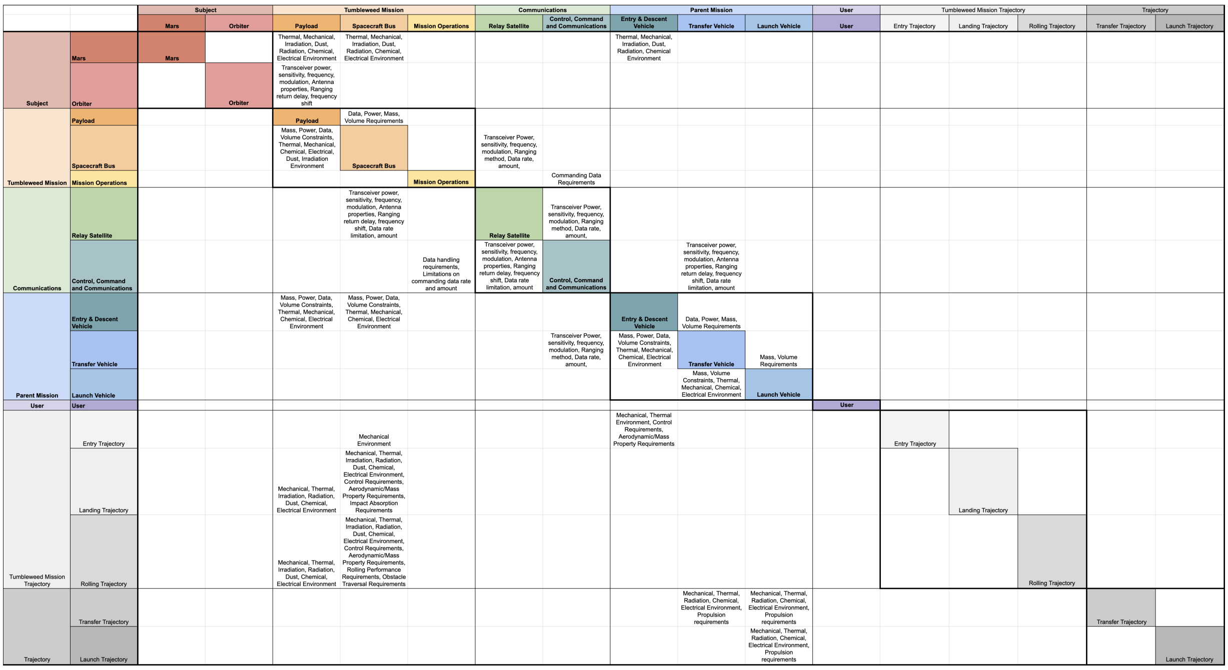


Figure 3.8: Non-functional N2 chart of the Tumbleweed Demonstrator Mission

In this figure, it can be seen that the constraints of mass and volume originally posed by the launch vehicle are propagated down to the SCB through two intermediate steps. This makes the specification of fundamental constraints of the mission contingent on a myriad of factors, posing a significant risk factor during development. This is further discussed in subsection 5.2.1.

4 | Mission Requirements

In order to determine available design options for the Tumbleweed rover, mission requirements are derived The mission requirements serve to specify each system's required capabilities, and what constraints it must follow. The mission requirements were first derived using a RDT, which is documented in section 4.1. From these, the initial mission requirements were organized and linked back to their stakeholders in a summarizing table, as presented in section 4.2.

4.1 RDT

To derive the mission requirements, a Requirements Discovery Tree (RDT) is generated. The purpose of the RDT is to create an overview over the mission's capabilities and constraints. Furthermore, the operational constraints and capabilities have been set. The following list indicates the questions that the RDT aims to answer:

- **Capabilities**
  - What is needed to fulfil the science goals?
  - What is needed to prove the Tumbleweed rover as a viable technology for Mars exploration?
  - What is needed to prove the Tumbleweed mission as a viable business case?
- **Operations**
  - How must the Tumbleweed mission supply science data to its customers?
- **Constraints**
  - Under what time constraints must the Tumbleweed mission be performed?
  - Under what cost constraints must the Tumbleweed mission be performed?
  - What regulations must the mission Tumbleweed adhere to?
  - How can the Tumbleweed mission be sustainable?
  - How unlikely must it be for the Tumbleweed mission to interfere with other Mars missions?
  - What constraints does the parent mission set on the Tumbleweed mission?

These questions relate the mission to its stakeholders, which were derived in chapter 2. From these questions, the RDT was used to derived mission requirements. The full RDT and its derived requirements can be seen in Figure 4.1

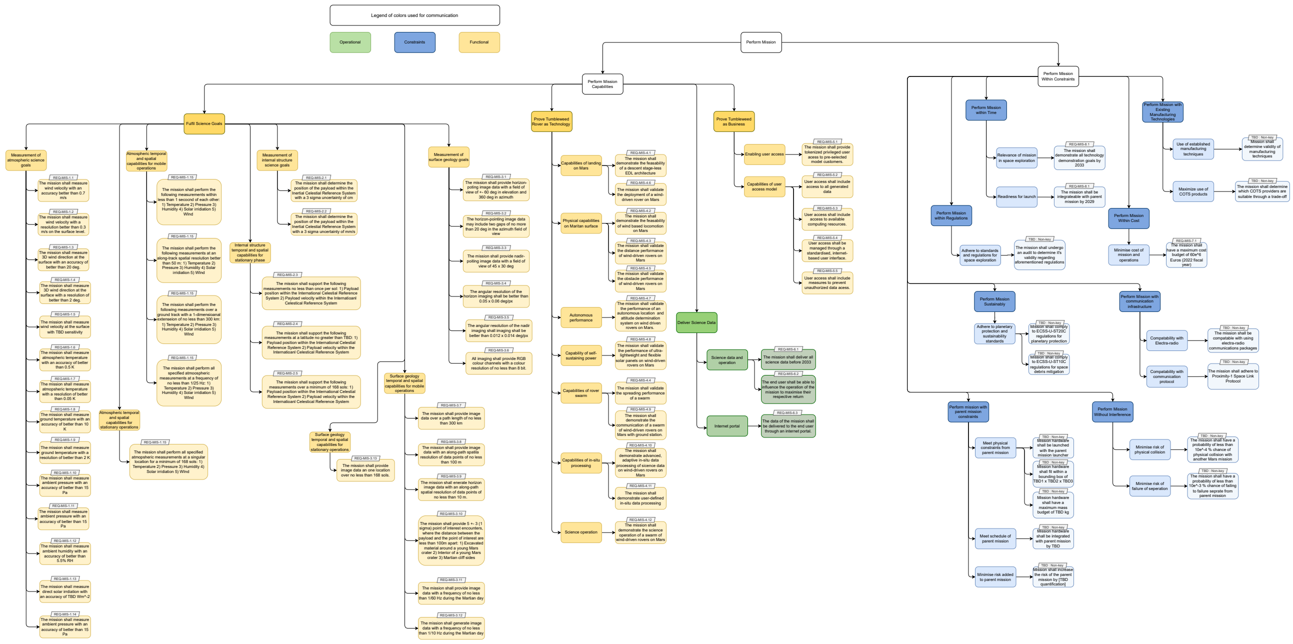


Figure 4.1: The RDT of the Tumbleweed Demonstrator Mission (TDM).

4.2 Initial Mission Requirements

From the RDT, the initial mission requirements were derived and formulated. The requirements are then reviewed and rationale is given for each derived requirement, as well as their parent requirement. Furthermore, justification analysis of any quantification is provided. From this, a condensed table which summarizes the mission requirements, and their parent requirements, is generated made. The requirements can be seen below?

Mission Requirements

Higher-Level Requirement	Requirement ID	Key Words	Requirement description	Rationale - General	Rationale - Quantification
Capabilities					
Atmospheric Science - Measurements					
ATM-REQ-003	REQ-MIS-1.1	Wind velocity, accuracy	The mission shall measure wind velocity with an accuracy better than 0.7 m/s.	The mission requirement must have synonymous to better accuracy of similar devices.	An accuracy of better than 0.7 m/s is taken from the Miniature 3D Wind sensor which has a perfomance accuracy (1 sigma) of 0.7 m/s
ATM-REQ-003	REQ-MIS-1.2	Wind velocity, resolution	The mission shall measure wind velocity with a resolution better than 0.3 m/s on the surface level.	The mission requirement must have synonymous to better accuracy of similar devices.	A resolution of better than 0.3 m/s is taken from the Miniature 3D Wind sensor which has a resolution of 0.3 m/s.
ATM-REQ-003	REQ-MIS-1.3	Wind direction, accuracy	The mission shall measure 3D wind direction at the surface with an accuracy of better than 20 deg.	Required to fulfil atmospheric science goals.	An accuracy of better than 20 deg is taken from the Miniature 3D Wind sensor which has a perfomance accuracy (1 sigma) of 20 deg.
ATM-REQ-003	REQ-MIS-1.4	Wind direction, resolution	The mission shall measure 3D wind direction at the surface with a resolution of better than 2 deg.	Required to fulfil atmospheric science goals.	An accuracy of better than 20 deg is taken from the Miniature 3D Wind sensor which has a resolution of 2 deg.
ATM-REQ-003	REQ-MIS-1.5	Wind velocity, sensitivity	The mission shall measure wind velocity at the surface with TBD Sensitivity.	The sensitivity is the total accuracy of similar devices.	Quantification outstanding.
ATM-REQ-001	REQ-MIS-1.6	Atmospheric temperature, accuracy	The mission shall measure atmospheric temperature with an accuracy of better than 0.5 K	Required to fulfil atmospheric science goals.	An accuracy of better than 0.5 K is taken from the Mars MetNet Temperature sensor.
ATM-REQ-001	REQ-MIS-1.7	Atmospheric temperature, resolution	The mission shall measure atmospheric temperature with a resolution of better than 0.05 K	Required to fulfil atmospheric science goals.	A resolution of better than 0.05 K is taken from the Mars MetNet Temperature sensor.
ATM-REQ-001	REQ-MIS-1.8	Ground temperature, accuracy	The mission shall measure ground temperature with an accuracy of better than 10 K	Required to fulfil atmospheric science goals.	An accuracy of better than 10 K is taken from the Curiosity GTS.
ATM-REQ-001	REQ-MIS-1.9	Ground Temperature, resolution	The mission shall measure ground temperature with a resolution of better than 2 K.	Required to fulfil atmospheric science goals.	A resolution of better than 2 K is taken from the Curiosity GTS.
ATM-REQ-002	REQ-MIS-1.10	Pressure, accuracy	The mission shall measure ambient pressure with an accuracy of better than 15 Pa.	Required to fulfil atmospheric science goals.	An accuracy of better than 15 Pa is taken from the Mars MetNet pressure sensor.
ATM-REQ-002	REQ-MIS-1.11	Pressure, resolution	The mission shall measure ambient pressure with a resolution of better than 0.2 Pa.	Required to fulfil atmospheric science goals.	A resolution of better than 0.2 Pa is taken from the Mars MetNet pressure sensor.
ATM-REQ-005	REQ-MIS-1.12	Humidity, accuracy	The mission shall measure ambient humidity with an accuracy of better than 5.5% RH.	Required to fulfil atmospheric science goals.	An accuracy of better than 5.5% RH is taken from the Mars MetNet humidity sensor.
ATM-REQ-006	REQ-MIS-1.13	Direct solar irradiation, accuracy	The mission shall measure direct solar irradiation with an accuracy of TBD W/m2.	Required to fulfil aerosol detection and quantification goals.	Quantification outstanding.
ATM-REQ-006/ ATM-REQ-004	REQ-MIS-1.14	Diffuse solar irradiation, accuracy	The mission shall measure diffuse solar irradiation with an accuracy of TBD W/m2	Required to fulfil aerosol detection and quantification goals.	Quantification outstanding.
Atmospheric Science - F6 Mobile Operational Phase - Temporal and Spatial					
ATM-REQ-001...007	REQ-MIS-1.15	Measurements, temporal	The mission shall perform the following measurements within less than 1 second of each other: - Temperature - Pressure - Humidity - Solar Irradiation - Wind	Allows for the generation of coherent data points.	Quantity is an estimate with the objective of keeping variations small over measurement duration while not putting undue requirements on data handling.
ATM-REQ-001...007	REQ-MIS-1.16	Measurements, along-track spatial resolution	The mission shall perform the following measurements at an along-track spatial resolution better than 50 m: - Temperature - Pressure - Humidity - Solar Irradiation - Wind	Allow for the data to be used in the generation of both microscale (< 1km) and mesoscale circulation models (1-1000 km).	The specified resolution is set to produce 20 data points within one microscale simulation cell, generating datapoints at the resolution of the model.
ATM-REQ-001...007	REQ-MIS-1.17	Measurements, ground track, 1-dimensional extension	The mission shall perform the following measurements over a ground track with a 1-dimensional extension of no less than 300 km: - Temperature - Pressure - Humidity - Solar Irradiation - Wind	Allow for the data to be used for the generation/validation of common mesoscale circulation models.	The specified distance spans the largest grid size used by Forget & Spiga (2009).
ATM-REQ-001...007	REQ-MIS-1.18	Perform atmospheric measurements, frequency	The mission shall perform all specified atmospheric measurements at a frequency of no less than 1/25 Hz: - Temperature - Pressure - Humidity - Solar Irradiation - Wind	Allow for regular data to be generated.	The selected time span is equal to the second-largest time step used in the mesoscale model of Forget & Spiga (2009).
ATM-REQ-001...007	REQ-MIS-1.19	Generate atmospheric measurements, frequency	The mission shall generate all specified atmospheric measurements at a frequency of no less than 1/5 Hz: - Temperature - Pressure - Humidity - Solar Irradiation - Wind	Allow for the data to be used in the generation of both microscale (< 1km) and mesoscale circulation models (1-1000 km). Furthermore, allows for the detection of transient weather phenomena.	The specified resolution is set to produce 100 data points within one microscale simulation cell, generating datapoints at the resolution of the model.
Atmospheric Science - F7 Stationary Operational Phase - Temporal and Spatial					
ATM-REQ-001...007	REQ-MIS-1.20	Atmospheric measurements, singular location, 168 sols	The mission shall perform all specified atmospheric measurements at a singular location for no less than 168 sols: - Temperature - Pressure - Humidity - Solar Irradiation - Wind	Allow for the investigation of temporal evolution of the Martian climate and weather.	The selected time span is a first-order estimate, based on 1/4 of a Mars year. This is dictated by the geodesy instrument - 1/4 year allows for the measurement of one oscillation caused by C4 term in Mars precession. It also allows for change in relay overpass geometry covering one quarter wave of the tidal deformation.
Internal Structure					
INT-REQ-001...003	REQ-MIS-2.1	Position, ICRS	The mission shall determine the position of the payload within the Inertial Celestial Reference System with a 3 sigma uncertainty of TBD cm.	Required to measure nutation, precession and tidal deformation.	Quantification outstanding.
INT-REQ-001...003	REQ-MIS-2.2	Velocity, ICRS	The mission shall determine the velocity of the payload within the Inertial Celestial Reference System with a 3 sigma uncertainty of TBD mm/s.	Required to measure nutation, precession and tidal deformation.	Quantification outstanding.
Internal Structure - F7 Stationary Operational Phase - Temporal and Spatial					
INT-REQ-001...003	REQ-MIS-2.3	Measurments once per sol	The mission shall support the following measurements no less than once per sol: - Payload position within the International Celestial Reference System - Payload velocity within the International Celestial Reference System	Allow for the demonstration of Geodesy and measurement of Nutation, Precession and J2 Love number.	The selected time period is a first-order estimate based on the performance of the RISE instrument on Mars InSight, which performed measurements approximately once every 1.5 days.
INT-REQ-003	REQ-MIS-2.4	Measurements at no greater latitude	The mission shall perform the following measurements at a latitude no greater than TBD: - Payload position within the International Celestial Reference System - Payload velocity within the International Celestial Reference System	Maximise the observable deformations caused by equatorial tidal bulge.	Quantification outstanding.
INT-REQ-001...003	REQ-MIS-2.5	Measurements, 168 sols	The mission shall perform the following measurements over no less than 168 sols: - Payload position within the International Celestial Reference System - Payload velocity within the International Celestial Reference System	Allow for the measurement of the precession, nutation and J2 deformation	The selected time span is a first-order estimate, based on 1/4 of a Mars year. This is dictated by the geodesy instrument - 1/4 year allows for the measurement of one oscillation caused by C4 term in Mars precession. It also allows for change in relay overpass geometry covering one quarter wave of the tidal deformation.
Surface Geology					
SUR-REQ-001...003	REQ-MIS-3.1	Horizon-pointing image data, field of view	The mission shall provide horizon-pointing image data with a field of view of ±60 deg in elevation and 360 deg in azimuth.	Required for imaging, lacking pointing ability of the spacecraft bus.	Initial assumption - Field of View of ±60 deg allows for views of the ground and the sky, allowing for compensation of spacecraft bus movement.
SUR-REQ-001...003	REQ-MIS-3.2	Horizon-pointing image data, gaps	The horizon-pointing image data may include two gaps of no more than 20 deg in the azimuth field of view.	Allow for the requirement to be met using only two camera positions.	Assuming 160 deg Field of View per camera, two cameras will result in two 20 deg gaps.
SUR-REQ-002	REQ-MIS-3.3	Nadir-pointing image data, field of view	The mission shall provide nadir-pointing image data with a field of view of 45 x 30 deg.	Allows for in-depth mm-scale imaging of the ground. Subject to further investigation.	Initial assumption based on heritage imagers such as the engineering cameras on Perseverance Mars rover.
SUR-REQ-001...003	REQ-MIS-3.4	Horizon-imaging, angular resolution	The angular resolution of the horizon imaging shall be better than 0.05 x 0.06 deg/px.	Imaging must have sufficient resolution in order to discern details and generate usable data.	Initial estimation - using specified field of view and Ingenuity Science Camera resolution. Results in resolution of <10 cm at 100 m distance.
SUR-REQ-002	REQ-MIS-3.5	Nadir imaging, angular resolution	The angular resolution of the nadir imaging shall be better than 0.012 x 0.014 deg/px.	Imaging must have sufficient resolution in order to discern details and generate usable data.	Initial estimation - using specified field of view and Ingenuity Science Camera resolution. Results in resolution of <1 mm at 2 m distance.
SUR-REQ-001...003	REQ-MIS-3.6	RGB colour channels, colour resolution	All imaging shall provide RGB colour channels with a colour resolution of no less than 8 bit.	Colour imaging allows for simpler identification of features and has higher scientific relevance.	8 bit is selected as typical color resolution.
Surface Geology - F6 Mobile Operational Phase - Temporal and Spatial					
SUR-REQ-001...003	REQ-MIS-3.7	Image data, path length	The mission shall provide image data over a path length of no less than 300 km.	Allows for the detection of rare features on the Martian surface.	Quantification is an initial assumption based on other mission constraints and expected mission performance
SUR-REQ-001...003	REQ-MIS-3.8	Image data, spatial resolution	The mission shall provide image data with an along-path spatial resolution of data points of no less than 100 m.	Required for reliable detection of rare features.	Initial assumption based on expected feature size of larger features and baseline maximum range of imaging system to retain <10 cm resolution.
SUR-REQ-001...003	REQ-MIS-3.9	Generate horizon image data, along-path spatial resolution	The mission shall generate horizon image data with an along-path spatial resolution of data points of no less than 10 m.	Required to have full coverage to support feature detection.	Initial assumption based on distance required to maintain <1 cm resolution.

Mission Requirements

Higher-Level Requirement	Requirement ID	Key Words	Requirement description	Rationale - General	Rationale - Quantification
SUR-REQ-001	REQ-MIS-3.10	Point of interest encounters, Mars crater	The mission shall provide 5 ± 3 (1 sigma) point of interest encounters, where the distance between the payload and the point of interest are less than 100m apart: - Excavated material around a young Mars crater - Interior of a young Mars crater - Martian cliff sides	Required to achieve surface geology science objectives.	Initial assumption of number of point of interest encounters, distance based on imaging performance.
SUR-REQ-003	REQ-MIS-3.11	Provide image data, frequency	The mission shall provide image data with a frequency of no less than 1/60 Hz during the Martian day.	Required to record transient phenomena when stationary.	Initial assumption of frequency to take image once per minute.
SUR-REQ-003	REQ-MIS-3.12	Generate image data, frequency	The mission shall generate image data with a frequency of no less than 1/10 Hz during the Martian day.	Required to detect transient phenomena when stationary.	Initial assumption of frequency to take image once every 10 seconds.
Surface Geology - F7 Stationary Operational Phase - Temporal and Spatial					
ATM-REQ-007	REQ-MIS-3.13	Image data, 168 sols	The mission shall provide image data at one location over no less than 168 sols.	Stationary phase serves goals of observing weather phenomena.	168 sols is 1/4 Martian year which allows for the observation of seasonal changes in weather.
Technology Demonstration					
SPA-REQ-001	REQ-MIS-4.1	Descent stage-less EDL architecture.	The mission shall demonstrate the feasibility of a descent stage-less EDL architecture.	Key function of ultimate mission to be validated.	-
SPA-REQ-001	REQ-MIS-4.2	Wind-based locomotion	The mission shall demonstrate the feasibility of wind-based locomotion on Mars.	Key function of ultimate mission to be validated.	-
SPA-REQ-001	REQ-MIS-4.3	Distance performance	The mission shall validate the distance performance of wind-driven rovers on Mars.	Key function of ultimate mission to be validated.	-
SPA-REQ-002	REQ-MIS-4.4	Spreading performance	The mission shall validate the spreading performance of a swarm of wind-driven rovers on Mars.	Key function of ultimate mission to be validated.	-
SPA-REQ-001	REQ-MIS-4.5	Obstacle performance	The mission shall validate the obstacle performance of wind-driven rovers on Mars.	Key function of ultimate mission to be validated.	-
SPA-REQ-001	REQ-MIS-4.6	Deployment	The mission shall validate the deployment of a wind-driven rover on Mars.	Key function of ultimate mission to be validated.	-
SPA-REQ-001	REQ-MIS-4.7	Autonomous location and attitude determination system	The mission shall validate the performance of an autonomous location and attitude determination system on wind-driven rovers on Mars.	Key function of ultimate mission to be validated.	-
SPA-REQ-001	REQ-MIS-4.8	Ultra light-weight and flexible solar panels	The mission shall validate the performance of ultra-light-weight and flexible solar panels on wind-driven rovers on Mars.	Key function of ultimate mission to be validated.	-
SPA-REQ-002	REQ-MIS-4.9	Communication of a swarm	The mission shall demonstrate the communication of a swarm of wind-driven rovers on Mars with ground station.	Key function of ultimate mission to be validated.	-
SPA-REQ-001	REQ-MIS-4.10	In-situ data processing	The mission shall demonstrate advanced, adaptive in-situ data processing of science data on wind-driven rovers on Mars.	Key function of ultimate mission to be validated.	-
SPA-REQ-001	REQ-MIS-4.11	User-defined in-situ data processing	The mission shall demonstrate user-defined in-situ data processing.	Key function of ultimate mission to be validated.	-
TTW-REQ-001	REQ-MIS-4.12	Science operation	The mission shall demonstrate the science operation of a swarm of wind-driven rovers on Mars.	Key function of ultimate mission to be validated.	-
TTW-REQ-006	REQ-MIS-4.13	Probability, technology	The mission shall have a probability of 90% of achieving all demonstration goals.	Key function of ultimate mission to be viable.	
TTW-REQ-007	REQ-MIS-4.14	Probability, science goals	The mission shall have a probability of 70% of achieving all science goals.	Key function of ultimate mission to be viable.	
Business Demonstration					
TTW-REQ-003	REQ-MIS-5.1	Tokenized privileged user access	The mission shall provide tokenized privileged user access to pre-selected model customers.	Key business model for progressive commercialization of Mars exploration.	-
MSC-REQ-002	REQ-MIS-5.2	Access to all generated data	User access shall include access to all generated data.	Key business model for progressive commercialization of Mars exploration.	-
MSC-REQ-002	REQ-MIS-5.3	Access to available computing resources	User access shall include access to available computing resources.	Key business model for progressive commercialization of Mars exploration.	-
MSC-REQ-002	REQ-MIS-5.4	Standardised, internet-based user interface	User access shall be managed through a standardised, internet-based user interface.	Key business model for progressive commercialization of Mars exploration.	-
MSC-REQ-002	REQ-MIS-5.5	Unauthorized data access	User access shall include measures to prevent unauthorized data access.	Key business model for progressive commercialization of Mars exploration.	-
Operational					
MSC-REQ-001	REQ-MIS-6.1	Science data	The mission shall deliver all science data before 2033.	Required for this mission to be useful strategically.	-
MSC-REQ-002	REQ-MIS-6.2	Influence operation, maximise respective return	The end user shall be able to influence the operation of the mission.	Key to the tokenized access business strategy, and for every user to maximize their return.	-
MSC-REQ-002	REQ-MIS-6.3	Internet portal	The data of the mission shall be delivered to the end user through an internet portal.	Required for simple access to the data.	-
Constraints					
Parent Mission Integration					
PMP-REQ-001	REQ-MIS-7.1	Parent mission, budgets, mass	The mission hardware shall not exceed TBD kg	The mission hardware will be given a mass budget from the parent mission	Quantification outstanding.
PMP-REQ-001	REQ-MIS-7.2	Parent mission, budgets, volume	Mission hardware shall fit within a bounding box of TBD1 by TBD2 by TBD3 meters	The mission hardware will be given the volumetric dimensions which it must fit to be suited for integration and launch	Quantification outstanding.
PMP-REQ-004	REQ-MIS-7.3	Parent mission, budgets, risk	Mission should minimise the risk added to the parent mission	The mission shall not significantly increase the risk of the parent mission for it to be viable as piggyback	Quantification outstanding.
PMP-REQ-003	REQ-MIS-7.4	Parent mission, physical	Mission hardware shall use the parent mission launch vehicle	Must be able to resist vibrational constraints and pre-launch constraints to integration	-
Standards and Regulations					
STA-REQ-001	REQ-MIS-8.1	Regulations, ECSS, sustainability	Mission shall comply to ECSS-U-ST20C regulations for planetary protection	Must follow planetary protection regulalations set by ECSS	-
STA-REQ-001	REQ-MIS-8.2	Regulations, ECSS, sustainability	Mission shall comply to ECSS-U-AS-10C regulations for space debris mitigation	Must follow space debris mitigation regulalations set by ECSS; is still important to state despite TTW not being transfer vehicle provider	-
Cost					
TTW-REQ-005	REQ-MIS-9.1	Cost, budget	The mission shall total cost shall not exceed TBD FY2022 MEUR	Mission must be financeable.	-
Time					
SPA-REQ-002	REQ-MIS.10.1	Budget, time, schedule	The mission shall demonstrate all technology demonstration goals by 2033	To ensure relenvancy in the deep space exploration plan, the Tumbleweed mission must maintain a schedule	-
TTW-REQ-003	REQ-MIS.10.2	Budget, time, schedule	The mission shall be integrateable with parent mission by 2029	To ensure that the vehicle can be launched, the mission must be integrated with the parent mission	-

5 | Mission Trade Studies

5.1 Trade Methodology

In [12] two major kinds of trades are identified: the first type trades cost against performance, whereas the second type trades design concepts against each other. As the objective of this section is to lay the foundation of design decisions, only the latter trade-off type is performed. In the following, the trade-off workflow, showing the individual steps taken and the trade-off methodology, discussing the method employed in the trade itself, are presented.

5.1.1 Trade-off Workflow

The trade-off workflow is aimed at a) exhaustively identifying design trades, b) exhaustively identifying all design options for each trade, c) minimizing the required analysis and d) providing consistent results with well-understood reliability. Therefore, a multistep process is defined based on workflows presented in [7] and [12]. Figure 5.1 shows this workflow:

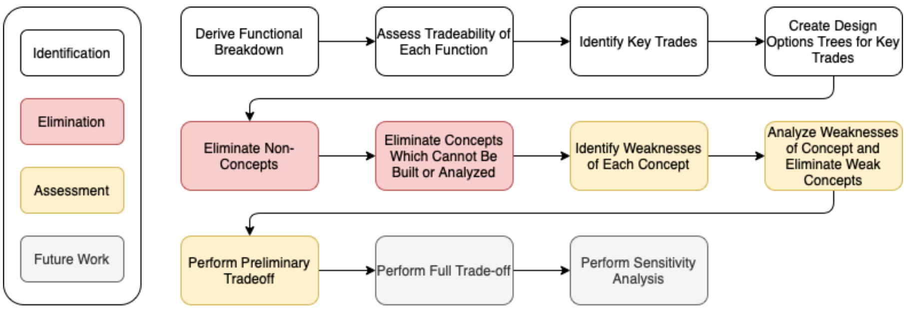


Figure 5.1: The trade workflow, showing the phases already performed and future work.

As can be seen above, the trade-off process begins with the identification of functions, which is discussed in **??**. Therein, functional flow and data flow diagRAMSare generated in order to identify required design decisions. Then, the tradeability of each function is assessed: if there is strong design heritage for a specific solution, or the solution is straightforward, or the function does not lend itself to a straightforward trade (such as F6.3.11 Maintain structural integrity). Then, the trades with the largest impact on performance or design are identified, and design options trees are generated. Subsequently, non-concepts (concepts which are logically inconsistent) and concepts which cannot be built (such as nuclear fusion) are eliminated. Then, each concept is probed for weaknesses and these weaknesses are analysed by themselves. This is done to further reduce the number of concepts which need to be traded. Then, a preliminary trade-off is performed which is based on high-level analysis in order to once again narrow down the options. Finally, the surviving concept will be entered into a full-scale trade-off, which will analyse the performance of individual concepts in detail. During this step, trade studies may also be merged to trade combined design concept (such as a singular ride-share-to-atmosphere rover versus two rovers which separate ahead of encountering the Mars atmosphere interface - cf subsection 5.2.1).

5.1.2 Trade-off Methodology

The trade methodology applied has the goal of evaluating all options on the basis of consistent high-level figures of merit, based on which a decision is made. These figures of merit are based on the 'systems engineering universe' (cf. Figure 5.2) and are as follows:

- **Performance:** Ability of the concept to achieve the desired capability. On mission-level trades, this is related to stakeholder requirements and mission objectives. On system and subsystem level, the performance is taken both from functional and non-functional system or subsystem requirements.
- **Cost:** Monetary cost of the concept. This is consistently based on the development, manufacturing and operations cost incurred by the concept as applicable.
- **Schedule:** Required development schedule. Here, proxies for development schedule such as Technology Readiness Level (TRL) of design options or number of subsystems are used at this stage.
- **Risk:** Overall risk of the mission. This is divided into program risk, development risk and technical risk. The first category relates to sensitivity to external factors, the second item is the internal risk to be expected during development and the latter is the straightforward technical risk of the design solution.

Figure 5.2: The systems engineering universe, showing the four major figures of merit applied to the presented trade-offs [7]

In order to arrive at a trade-off result, the high-level figures of merit are split up into criteria, which are then further bifurcated into sub-criterion. Table 5.1 shows the flow between figures of merit and criteria:

Table 5.1: High-level figures of merit with trade criteria.

Risk	Program Risk
	Development Risk
	Technical Risk
Performance	Science Output
	Technology Demonstration
Schedule	Development Schedule
	Manufacturing Schedule
	Mission Schedule
Cost	Development Cost
	Manufacturing Cost
	Operations Cost

While the overall score is a weighted average of the figures of merit, the figures of merit are the weighted average of the criteria, and the same holds true for the sub-criterion. The scoring is then performed as follows: a scoring scheme going from 0 to 3 is introduced:

Table 5.2: Four-point scoring method used in all trade-offs.

0	Non-correctable deficiencies
1	Correctable deficiencies
2	Meets requirements
3	Exceeds requirements

The sub-criterion are initially scored on a scale most appropriate for the respective criterion (such as 1-9 for TRL, or M€ for Cost) and then converted to the scale through defining one baseline option which is given an initial score, and all other options are scored based on their relative performance. The initial score of the baseline is adapted iteratively until all options fit within the 0-3 scoring interval.

5.2 Mission-Level Trades

The mission-level trades performed relate to trades on how various segments interact to achieve the mission capability. These trades have far-reaching concepts on the design of the mission and strongly interrelate with other analyses presented in this report. For the following functions, key mission concept trades are identified:

- **F4 - Transfer to Mars:** Trading integration with parent mission - which elements of F4 are to be performed by elements within the Tumbleweed Demonstrator Mission system boundary.

- **F5.5 - Reach Mars Surface:** Trading landing systems, and whether landing on Mars is to be performed by the Tumbleweed Demonstrator Mission or the parent mission.
- **F6.4 - Position Payload:** Trading the number of SCBes.
- **F6.6 - Handle Payload Data:** Trading the location of data processing: in-situ or on-ground.

Furthermore, several key trades on systems and subsystems level must be considered as they have considerable impact on overall mission performance and characteristics:

- **F6.4 - SCB Control Method:** How does the SCB control its trajectory?
- **F6.3.1 - Energy Generation:** How does the SCB supply its systems and the payload with electric energy?
- **F6.3.12 - Location Determination:** How does the SCB determine its location?

Note that no trade on the fundamental design of the SCB is performed, as only wind-driven rovers are considered to be able to fulfil the goal of demonstrating key technologies of wind-driven Mars rovers (cf. stakeholder requirements TTW-REQ-001 and 002).

5.2.1 Trade 1: F4 Transfer To Mars - Transfer Strategy

In this subsection, the trade-off regarding the Mars transfer of the Tumbleweed Demonstrator Mission is presented. The goal of this study is to identify no more than two best-performing concepts which will be subject to full on trade-off as discussed in subsection 5.1.1. Firstly, assumptions are presented. Then the trade tree is shown and eliminated concepts are discussed. Lastly, the preliminary trade-off method and results are presented.

A. Assumptions

The assumptions made during the analysis are as shown below in Table 5.3:

Table 5.3: Assumptions made for F4 Transfer to Mars trade-off

Identifier	Assumption	Justification	Effect
MIS-ASS-201	Wind-driven rover is the chosen design for mobile and stationary part of the SCB.	Only way to fulfil TTW-REQ-001 & 002	Other surface locomotion concepts are discarded
MIS-ASS-515	The functional breakdown of the ultimate mission is the same as the one of the demonstrator mission.	Lacking the exact functional breakdown and understanding of the ultimate mission, it is assumed to be similar to the demonstrator mission.	

B. Design Options Tree

The Design Options Tree is shown below in Figure 5.3:

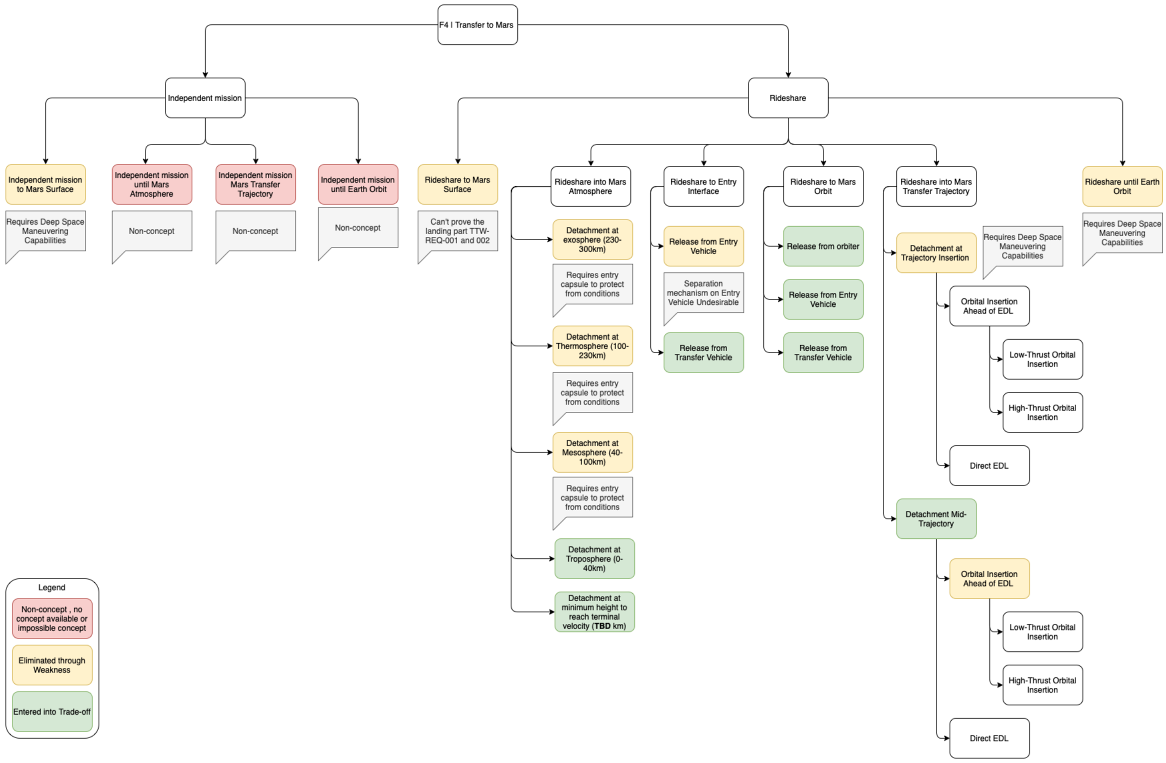


Figure 5.3: Design options/trade tree for the function F4 Transfer to Mars.

All independent mission types are discarded either due to them being a non-concept (an independent mission until, for example, Mars Atmosphere, is illogical) or due to the mission concept requiring significant capabilities going far beyond the technology demonstration of the wind-driven rover. Detachment of the rover from the parent mission at high altitudes will require the SCB to have additional thermal protection, which, everything else being equal, is inferior to deployment from the parent mission in the lower atmosphere. The concept of separating from the parent mission at the atmospheric interface of Mars will require an additional entry vehicle for the SCB. Here, separation from the EDV has significant drawbacks against release from the transfer vehicle due to the potential incompatibility of the separation mechanism. Release from the transfer vehicle is therefore preferred. It is important to note that this concept has design heritage with the Deep Space 2 microprobes [16]. Rideshare to Mars orbit further trades added complexity to the mission concept for a higher number of compatible parent mission.

Ultimately, three concepts were entered into the trade-off study:

Table 5.4: Transfer Concepts considered for the F4 trade-off

Identifier	Description
F4-CON1	SCB is integrated with parent mission in EDV.
F4-CON2	SCB with dedicated EDV is integrated on parent mission transfer vehicle, separates ahead just before atmosphere interface.
F4-CON3	SCB with dedicated entry & descent and transfer vehicle is integrated on parent mission, separates as mission enters Mars acrlongsoi (SOI) or from Mars orbit.

C. Method and Results

As discussed in subsection 5.1.2, sub-criterion were defined which are to be scored. These sub-criterion are shown in Figure 5.4 which shows an exemplary trade table:

	Total Score	Weights	Score	Figure of Merit	Weights	Score	Criterion	Weights	Normalized Score	Score	Subcriterion
Performance of Mission Concept 2: Mars Aerial Deployment					30%	2	Science Output	100%	2	3	Number of Science Goals Achieved
								100%	1.25	10	Number of critical functions from ultimate mission validated
		30%	1.48	Performance	70%	1.25	Technology Demonstration				Number of business cases validated
		20%	2.87	Cost	100%	2.87	Cost	100%	2.87	55.03	Cost [FY2022 MEUR]
											TRL of subsystems
					70%		Development Schedule				Number of subsystems
		10%	0	Schedule	30%		Mission Schedule				Mission Schedule
								70%	1.89	9	Number of subsystems
								30%	1.6	10	Number of critical functions performed by mission
					30%	1.80	Technical Risk				Average TRL of subsystems
											Average TRL of subsystems
					21%	1.89	Development Risk		1.89	9	Number of subsystems
								10%	2.87	55.03	Cost [FY2022 MEUR]
								30%	1	1	Risk to Parent Mission
								30%	1	2	Number of compatible parent missions
	1.81	40%	1.52	Risk	49%	1.19	Program Risk	30%	1	1	Design Sensitivity to Parent Mission

Figure 5.4: Exemplary trade-off table snippet showing the criteria considered, together with weighting and result

As can be seen in Figure 5.4, science output is measured by the number of science goals achieved, and technology demonstration is based on the critical functions fulfilled by the hardware included in the demonstrator mission which needs to be demonstrated by the ultimate mission. Number of business cases is omitted based on current lack of exhaustive list of business cases formulation for this purpose. Cost was based on a weighted average on a variety of systems-level costing models, namely NASA Spacecraft/Vehicle Level Cost Model (SVLCM) for interplanetary mission and orbital spacecraft, and statistical relations found in [4]. While the cost figure produced has a very high uncertainty, it is deemed sufficiently accurate to show differences in cost between the concepts. Schedule is omitted, as further analysis on exact development timelines is required. For the technical risk, the number of subsystems and critical functions performed by the mission are used as proxies for actual risk, which, while insufficient for an accurate quantification of risk, is shown to produce usable comparative results. For development risk, only the number of subsystems is considered. Average TRL of subsystems is omitted, as it was found that this figure leads to the counterintuitive result that it deems more complex missions less risky as low TRL of some subsystem is averaged out. Risk to parent mission is chosen as a sub-criterion for program risk, together with cost and compatible parent missions. The first figure is the result of a preliminary risk analysis using a likelihood-consequence risk matrix, and the last was derived by considering the following mission types:

- Surface Mission - Stationary

- Surface Mission - Mobile
- Orbiter Mission
- Flyby Mission
- Dedicated Transfer Mission

Lastly, design sensitivity to parent mission was scored as follows: 0 if change of parent mission requires mission redesign beginning at concept design, 1 if change of parent mission requires mission redesign beginning at detailed design, 2 if change of parent mission requires redesign of subsystems and 3 if a change of parent mission does not require any change in design. The preliminary trade-off ultimately yielded the following scores for the three concepts:

Table 5.5: Results of preliminary trade-off for F4 - Mars Transfer

Concept	Performance (30%)	Cost (20%)	Schedule (10%)	Risk (40%)	Total (100%)
F4-CON1	1.48	2.87	/	1.52	1.81
F4-CON2	2	2	/	1.49	1.77
F4-CON3	2.1	1.6	/	1.34	1.65

As Table 5.5 shows, F4-CON1 performs the best, however the difference between its score and the one of F4-CON2 is only 2.2 %, which gives reason for concern regarding the reliability of the results of this trade-off. Sensitivity analysis with respect to figure of merit weights showed that if the weight of performance is increased by 4%, the results reverse and F-CON2 wins the trade-off. Therefore, the result of the trade-off is to eliminate F4-CON3, however, more detailed analysis must be performed in the full trade-off too in order to make a confident design decision.

5.2.2 Trade 2: F5.5 Reach Mars Surface - Descent Strategy

In the following, the trade-off regarding the descent of the SCB within the Martian atmosphere is presented. This function incorporates both the reduction in velocity to achieve acceptable entry accelerations and reaching the surface of Mars starting at an altitude of several kilometers. The goal of this trade-off is not so much to generate an optimized final design solution, but to support the generation of a baseline design.

A. Assumptions

In the following Table 5.6, the assumptions made during this analysis are presented.

Table 5.6: Assumptions made for F4 Transfer to Mars trade-off

Identifier	Assumption	Justification	Effect
MIS-ASS-516	The coefficient of drag of the SCB is equal to a finite flat plate of the same dimensions.	As the sails are flat, this assumption is made as no exact aerodynamic analysis is performed at this moment.	Potential deviation in terminal velocity.
MIS-ASS-517	The SCB has an elongation coefficient of 0.2.	This elongation coefficient was found in previous studies to result in acceptable rolling stability.	Potential deviation in terminal velocity.
MIS-ASS-518	Potential deviation in terminal velocity.	As most parent missions cannot exceed this altitude, and most of Mars is below this altitude, this assumption is made to provide limits on atmospheric properties.	Put limitations on operational environments
MIS-ASS-519	The SCB structure behaves similarly to an undamped mass-spring system for one impact.	This is a worst-case analysis of the impact - lacking exact information on the deformation of each element of the rover, this assumption is made.	May mischaracterize the impact acceleration experienced by some parts of the structure as it deforms.

B. Design Options Tree

The design options tree is shown in Figure 5.5:

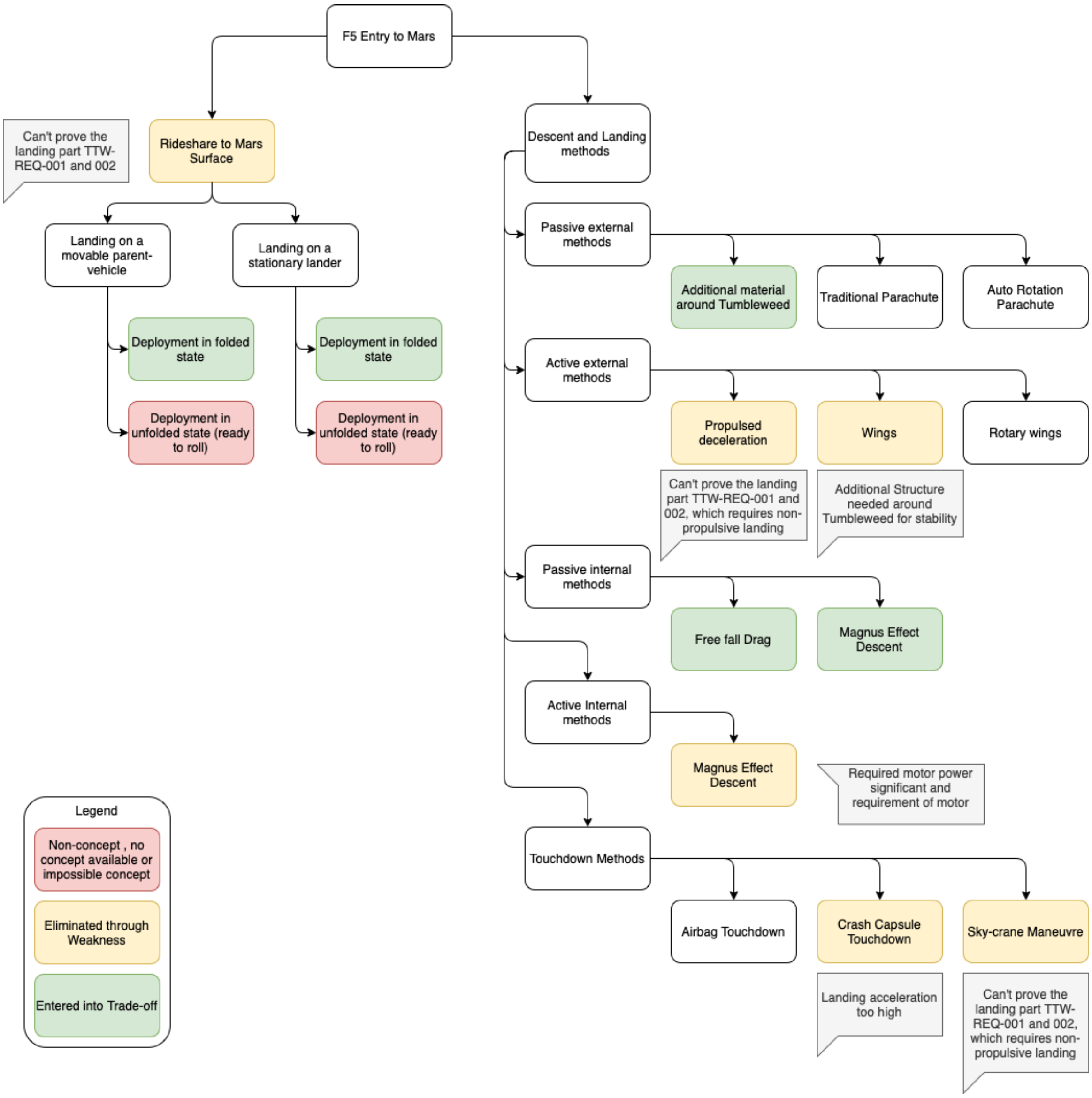


Figure 5.5: Design options/trade tree for the function F5.5 Reach Mars Surface.

As can be seen above, to reach the Martian surface, ridesharing with the parent mission until the surface or independent landing were considered. This cross-cuts to the design options shown in the previous trade in Figure 5.3. For independent landing, propulsed deceleration, wings and rotary winds and active Magnus effect were eliminated due to the fact that it either cannot fulfil the required technology demonstration requirements (as the touchdown without extraneous hardware is one of the key enabling technologies of the ultimate mission) or due to their low TRL. This leaves only free-fall drag and magnus effect descent, as well as descent using extra drag-inducing structures as viable methods:

Table 5.7: Transfer Concepts considered for the F4 trade-off

Identifier	Description
F5.5-CON1	SCB with additional drag-inducing material for descent
F5.5-CON2	SCB descent at terminal velocity, using drag of SCB only.
F5.5-CON3	SCB designed to generate lift through the Magnus effect, using autorotating aerodynamic configuration

C. Method and Result

Lacking the resources and required design maturity to analyse all these concepts in detail, the decision is taken to showing the feasibility of the most simple design solution. This design solution considered the simplest base case is F5.5-CON2, as this is based on pure drag and uses the already-existing aerodynamic properties of the SCB for controlling the descent.

In order to show the feasibility, an analysis of the impact acceleration and forces is performed. This is done for a worst case where the restoring force of the structure is related to its deformation purely linearly, and the best case where the force is constant. The former case is purely elastic deformation, whereas the latter case is purely plastic deformation. In reality, as the structure of the SCB is complex, it will have a force-deformation curve that is in between these two cases, even though the deformation of each individual structural element is purely elastic. Then, the maximum impact acceleration is computed for a variety of deformation lengths-the interval chosen is between 0.5 meters (a quarter of the SCB' radius) and 2 meters (the SCB' radius). The results are plotted in Figure 5.6.

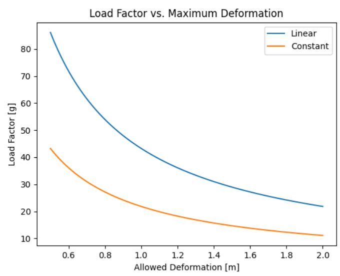


Figure 5.6: Worst- and best-case impact acceleration for pure drag-based landing at 4 km altitude

The results of the analysis are validated against previous work shown in [21], showing deviations in the terminal velocity which are a result of a switch to flat-plate aerodynamics and due to the higher altitude. The results in terms of acceleration are as follows:

Table 5.8: Results of impact analysis for worst- and best-case scenarios and minimal and maximal acceleration

Max. Deformation [m]	Best-Case Load Factor	Worst-Case Load Factor
0.5	43.26	86.14
2	11.10	21.82

As Table 5.8 shows, the impact load factors stay within 10^1s of g's, which is significantly lower than with comparable mission concepts (Deep Space 2: >30000 g [16], Mars MetNet: 500 g [10]). In fact, considering the upper end of allowed deflections, the load factors even approach those typically experienced during entry-descent and landing.

The conclusions to be drawn from this analysis are not only that the landing accelerations of the simplest-possible descent concept are within acceptable limits for the systems and payload, but that the stress-strain curve and maximum deformation of the structure will be key system requirements further down the line.

5.2.3 Trade 3: F6.4 Position Payload - Number of Rovers

In this subsection, the trade-off regarding the multiplicity of the space bus (i.e. the number of rovers) of the Tumbleweed Demonstrator Mission is being discussed. The goal of this study is to identify no more than two best-performing concepts which will be subject to full on trade-off as discussed in subsection 5.1.1. After presenting assumptions, the trade tree is shown and eliminated concepts are discussed. Lastly, the preliminary trade-off method and results are presented.

A. Assumptions

It is assumed, that a swarm of rovers consists of two single rovers. The design options that are entered into the trad-off are a single rover, and a swarm of two either identical or different rovers.

B. Design Options Tree

The Design Options Tree is shown below

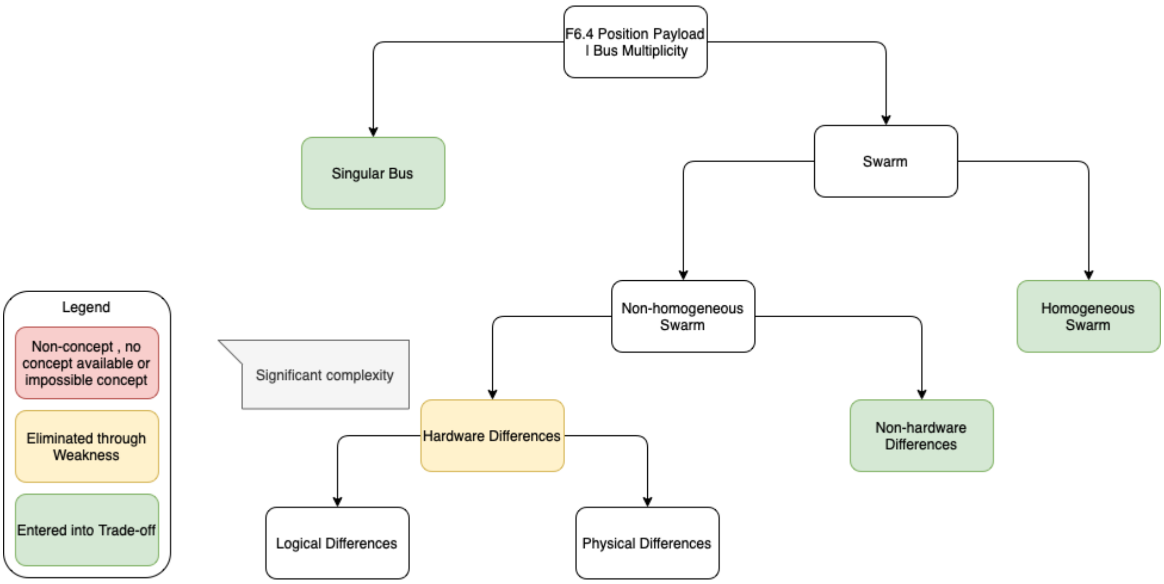


Figure 5.7: Design options/trade tree for the function F6.4 Number of Rovers.

All swarm-based mission concepts are being eliminated due to the unfeasible development effort and system complexity. Producing a swarm of rovers, based on the same hardware configuration, reduces the complexity and susceptibility to errors significantly.
The alternative to a heterogeneous swarm based on non-hardware differences is a completely homogeneous (including non-hardware properties of the rover) swarm of rovers.
The third design option in terms of bus multiplicity is a single rover.

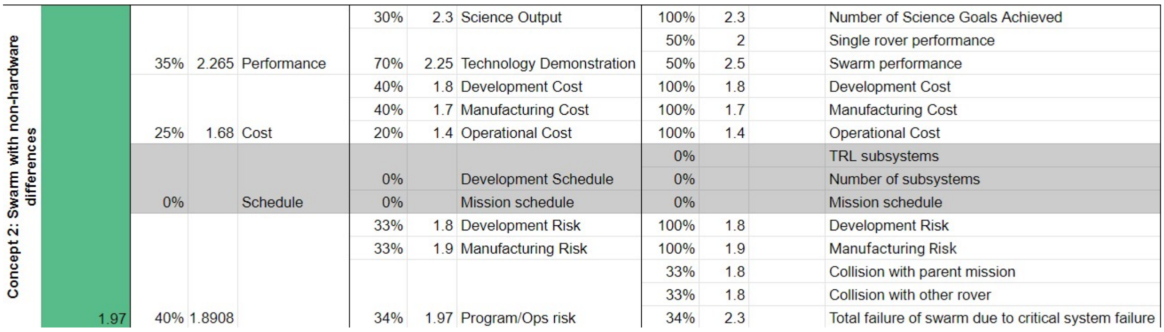
Ultimately, three concepts were entered into the trade-off study:

Table 5.9: Transfer Concepts considered for the F6.4 "Number of rovers" trade-off

Identifier	Description
F6.4A-CON1	A single space bus (i.e. rover) is being used on the Martian surface.
F6.4A-CON2	A swarm of several rovers distinguishing themselves based on non-hardware differences is being sent to Mars.
F6.4A-CON3	A swarm of several identical rovers is being sent to Mars.

C. Method and Results

As discussed in 5.1.2, sub-criterion were defined which are to be scored. These sub-criterion are shown in 5.8 which shows an exemplary trade table.



Concept	Score	Weight	Score	Category	Weight	Score	Criterion	Weight	Score	Sub-criterion
Concept 2: Swarm with non-hardware differences					30%	2.3	Science Output	100%	2.3	Number of Science Goals Achieved
								50%	2	Single rover performance
		35%	2.265	Performance	70%	2.25	Technology Demonstration	50%	2.5	Swarm performance
					40%	1.8	Development Cost	100%	1.8	Development Cost
					40%	1.7	Manufacturing Cost	100%	1.7	Manufacturing Cost
		25%	1.68	Cost	20%	1.4	Operational Cost	100%	1.4	Operational Cost
								0%		TRL subsystems
					0%		Development Schedule	0%		Number of subsystems
		0%		Schedule	0%		Mission schedule	0%		Mission schedule
					33%	1.8	Development Risk	100%	1.8	Development Risk
					33%	1.9	Manufacturing Risk	100%	1.9	Manufacturing Risk
								33%	1.8	Collision with parent mission
								33%	1.8	Collision with other rover
	1.97	40%	1.8908		34%	1.97	Program/Ops risk	34%	2.3	Total failure of swarm due to critical system failure

Figure 5.8: Exemplary trade-off table snippet showing the criteria considered, together with weighting and result.
Remark: Schedule is not included, therefore the other category scores only add up to 90% which are then normalized to 100%.

As can be seen in 5.8, science output is measure by the number of science goals achieved as well as the ability to successfully demonstrate usage of innovative technology.
Greyed out areas (with a weight of 0%) are not being taken into account, due to lacking data at this stage of development.
Having a swarm of rovers allows a higher precision irradiation measurement, leading to an exceeded mission requirement REQ-MIS-1.13 including the subsequent requirements. This is why the performance score of concept 2 and 3 are higher than for the single bus not only for the achievement of science objectives but also for the demonstration of technology.
The risk evaluation has a higher uncertainty, as the physical properties of the rover systems are not clear yet. Generally speaking: more rovers have a lower risk of a total failure of the entire swarm. On the other hand, there is a higher risk of colliding with a possible lander vehicle (see 5.2.2). Furthermore, the development of a hardware related non-homogeneous swarm of rovers is more complex and therefore creates a higher development risk.

Table 5.10: Results of preliminary trade-off for F6.4 - Number of rovers.

Concept	Performance (30%)	Cost (20%)	Schedule (10%)	Risk (40%)	Total (100%
F6.4A-CON1	1.30	2.00	/	2.05	1.79
F6.4A-CON2	2.27	1.68	/	1.89	1.97
F6.4A-CON3	2.06	1.78	/	1.88	1.92

Clearly, concept 2 wins, due to a comparatively high performance as well as risk. Again, the risk score has a relatively high uncertainty and the cost and schedule scores are still to be determined.

5.2.4 Trade 4: F6.4 Position Payload - Rover Control Method

As the estimation of performance as a function of control method represents a complex engineering problem, with performance not only dependent on the concept itself, but the behaviour of the rovers, a quantitative trade-off is difficult to perform at this moment. Still, a design options tree is presented, concepts generated and evaluated as precise as possible.

A. Design Options Tree

In Figure 5.9 the trade-off regarding rover controllability is shown:

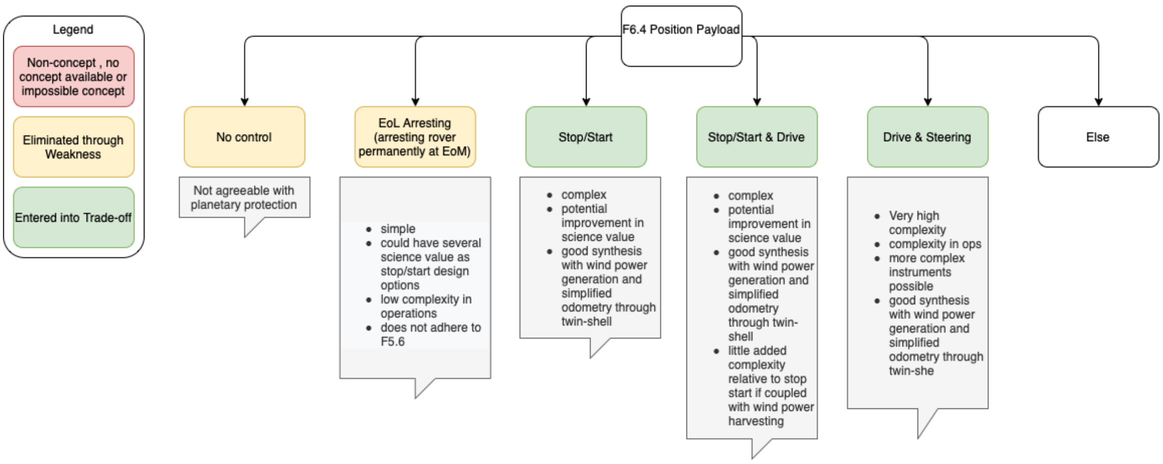


Figure 5.9: Design options/trade tree for the function F6.4 Rover Controllability.

This results in the following design concepts shown in Table 5.11:

Table 5.11: Transfer Concepts considered for the F4 trade-off

Identifier	Description
F6.4B-CON1	Stop/Start - the SCB can halt its trajectory at will.
F6.4B-CON2	Stop/Start & Drive - the SCB can halt its trajectory at will and can impart additional locomotion force that is independent of wind.
F6.4B-CON3	Drive & Steering - the SCB can control the direction of travel and can impart locomotion independent of the wind.

These concepts increase in expected performance, while also becoming more complex. While the first concept is quite close to the original idea of a Tumbleweed rover, whereas the latter concept is more akin to conventional rovers while using the wind as an additional power source.

B. Method and Results

The results of [15] as well as the previous design of the SCB which featured no controllability other than End-of-Life (EoL) arresting [20] is summarized as follows.

- Relative to the previous baseline of EoLarresting, all investigated concepts are expected to be around 30% heavier. However, this is outweighed by the improved aerodynamic performance which is a side effect of the control mechanism as it maintains constant attitude of the aerodynamic drag surfaces.
- Relative to the previous baseline of EoLarresting, all investigated concepts have significant advantages with respect to required system robustness of the data handling & transmission, power generation and location determination system.
- Advantages in terms of performance diminish as the amount of controllability is increased relative to the required additional system complexity.

The result of this trade-off is that the stop/start and stop/start & drive concepts perform similarly well, with a slight edge towards the stop/start concepts. This is therefore selected for this baseline, and for the subsequent budget analysis in chapter 6. This decision is based on the fact that this concept won the trade-off but also that this will simplify analysis. In future, however, the performance of all concepts should be further illuminated through detailed performance analysis.

In addition, a quantitative tradeoff was being conducted. sub-criterion were defined (see 5.1.2) which are to be scored. These sub-criterion are shown in an exemplary trade table 5.10.

Concept 1: Start/Stop					30%	1.80	Science Output	100%	1.80	Number of Science Goals Achieved
								50%	1.70	Maneuverability
		30%	1.66	Performance	70%	1.60	Technology Demonstration	50%	1.50	Dependence on wind speed
					40%	2.00	Development Cost	100%	2.00	Development Cost
					40%	2.00	Manufacturing Cost	100%	2.00	Manufacturing Cost
		20%	2.00	Cost	20%	2.00	Operational Cost	100%	2.00	Operational Cost
								0%		TRL subsystems
					0%		Development Schedule	0%		Number of subsystems
		0%		Schedule	0%		Mission schedule	0%		Mission schedule
					33%	2.00	Development Risk	100%	2.00	Development Risk
					33%	2.00	Manufacturing Risk	100%	2.00	Manufacturing Risk
								33%	2.50	System failure due to complexity
								33%	1.80	suboptimal wind conditions
	1.89	40%	2.00		34%	2.00	Program/Ops risk	34%	1.70	collisions with parent of other rovers of swarm

Figure 5.10: Exemplary trade-off table snippet showing the criteria considered, together with weighting and result.
Remark: Schedule is not included, therefore the other category scores only add up to 90% which are then normalized to 100%.

The quantitative trade-off results in the same design winner: Concept 1. Generally speaking, concept 2 and 3 are increasingly complex to develop and come with a higher risk of system failure. Their advantages, i.e. higher manoeuvrability does not outweigh the mentioned risk as well as their higher costs. The quantitative results from the trade table are summarized in the following table:

Table 5.12: Results of preliminary trade-off for F6.4 - Number of rovers.

Concept	Performance (30%)	Cost (20%)	Schedule (10%)	Risk (40%)	Total (100%
F6.4B-CON1	1.66	2.00	/	2.00	1.89
F6.4B-CON2	2.25	1.60	/	1.66	1.84
F6.4B-CON3	2.48	1.42	/	1.43	1.78

Concept 1 wins, mostly due to the relatively low cost and technical risk, and despite being less manoeuvrable.

5.2.5 Trade 5: F6.6 Handle Payload Data - Data Handling Concept

The Function F6.6 Handle Payload Data focuses on the processing and preliminary management of scientific data collected by the Tumbleweed payload instrumentation. This is a sub-function for the Rover vehicle while in F6 Operations Phase of the Mission.

Logically, this function follows after the scientific instruments, which are part of the Tumbleweed Rover payload, have obtained measurements. The function of obtaining measurements is a continuous process, considering the rover takes critical system performance data as well as scientific data during the entire duration of its trajectory and mission duration. The management of the collected scientific data, which is the end deliverable for the customers/stakeholders, is performed periodically. The volume of data collected drives the need for such periodic processing and transmission to the ground segment.

A. Assumptions

Table 5.13: Assumptions made for F4 Transfer to Mars trade-off

Identifier	Assumption	Justification	Effect
MIS-ASS-520	Look-point determination is performed on board of SCB.	This is a sub-function of determining location, which has to be done on board due to the high velocities that the SCB travels and the need to avoid certain areas. Furthermore, the data required to estimate position exceeds previously established communication limits.	No other options are considered.

The function *F6.7 Transmission of science data* is interleaved with this function, which is to be performed cyclically after F6.6 Handle science data.

B. Design Option Trees

The function F6.6 Handle Payload Data chiefly addresses the data processing requirements for the sensors of the Tumbleweed rover. The processing requirements can be identified from the characteristics of the sensing equipment, the data fidelity requirements of the Mission and the scientific goals arising from stakeholder requirements. The processing requirements are, therefore, part of the ability of rover to efficiently fulfil these objectives and satisfy the requirements with appropriate processing and memory capabilities.

Legacy rovers have been designed to perform exploration and scientific data collection, have relied on relaying the entire stream of data obtained to the ground segment on earth through the deep space network. However, the goal of the Tumbleweed rover is to advance these capabilities to a more commercialized data collection. This implies that the objectives of the Tumbleweed Rover are rather efficient relaying of scientific data as a Mars Sensor Laboratory. Therefore, the focus of data processing capabilities are measured against this metric of efficiency of delivering scientific data. Therefore, the design options for F6.6 Handle Science Data function is carried out by means of location of processing. The location of compute provides design options which result in different levels of processing and memory capabilities for the rover.

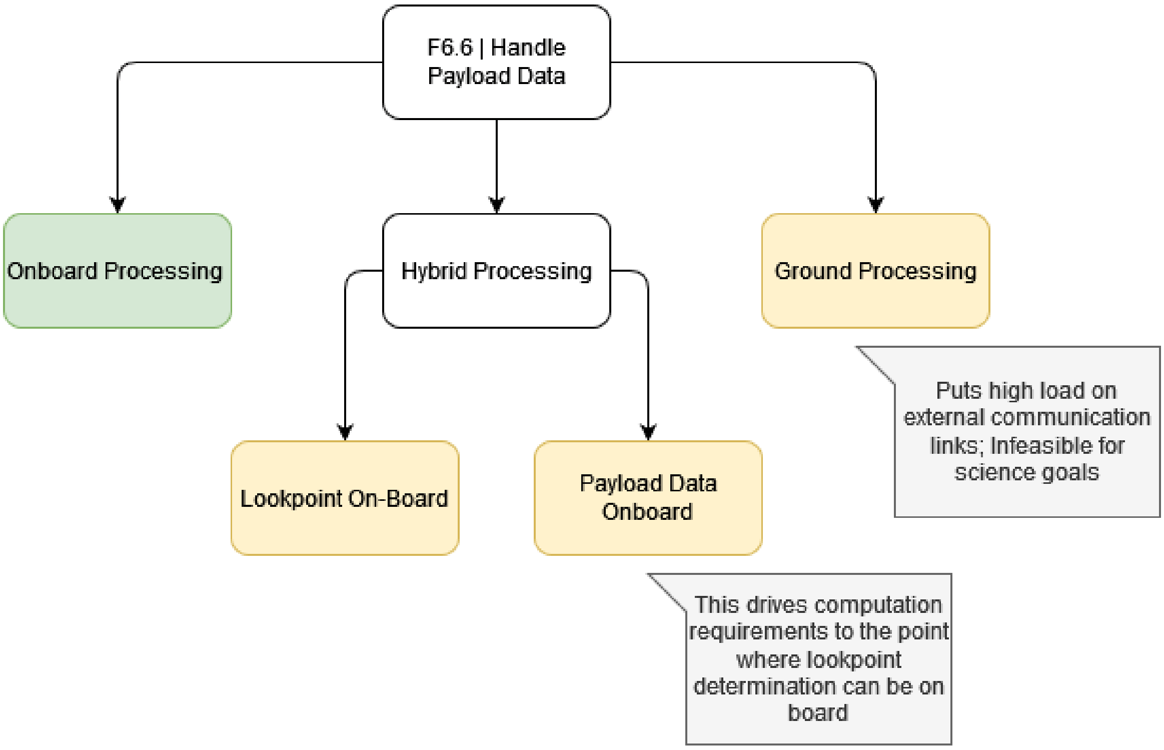


Figure 5.11: Design options/trade tree for the function F6.6 Handle Payload Data.

C. Methods and Results

The design options tree for this function is shown in Figure 5.11. The processing options include Ground Processing, Hybrid Processing and Onboard Processing. Ground Processing is the most conventional form of processing method prevalent in Mars Rover missions. This involves relaying the entire data stream of sensor data as-is with minimum in-situ processing on rover. The Hybrid processing approach is infeasible as the cost and design considerations for such an approach would already warrant and allow for an Onboad processing approach. Further, the utilization of communication links is almost similar for both Ground Processing as well as the Hybrid Processing approach since there is no apparent reduction in either the communication bandwidth requirements neither is there significant gain in design considerations with respect memory and power requirements of the processor.

Owing to these considerations, the design approach of Tumbleweed rover is to present a case for demonstration of the proposed Onboard processing approach. The arguments to choose this design approach to handling payload data, is multifold. Firstly, this would provide an opportunity for the Tumbleweed rover to prove the feasibility of such a technique which has already been studied and touted to be significantly efficient for data collection and exploration for deep space rovers. Secondly, the utilization of dedicated communication links as well as deep spac

5.2.6 Trade 6: F6.3.1 Supply Electric Power - Electric Power System Trade

The function F6.3.1 Supply Electric Power, is a sub-function under the parent function F6.3 Support PLD Operations, which represents all the payload associated operations. This sub-function relates to the operations of the Electric Power System (EPS). It follows attributes of its parent function, which is that it is triggered once conditions for bus operations of the Rover are activated and run in parallel to other functions of the rover payload.

The sub-function can be broken down further to the following:

- 1. F6.3.1.1 Generate Electrical Energy : This (sub-sub-) function deals with the task of generation of power necessary for the Rover vehicle as well as its associated on-board payload.
- 2. F6.3.1.2 Store Electrical Energy : This (sub-sub-) function : This (sub-sub-) function is associated with storing (surplus and reservoir) electrical energy generated by the previous sub-function on-board the rover for continuous, uninterrupted and fail-safe power supply for the payload.

In order to analyse the function F6.3.1, a trade analysis is therefore taken on each of its sub-functions. In the following sections, we analyse these sub-functions for design options, followed by performing a brief trade analysis on the possible technologies according to the criterion and methodology established in Section 5.1.2.

A. Assumptions

No specific assumptions are made regarding this sub-functions.

B. Design Option Trees

Functions (and sub-functions) associated with energy supply for the onboard payload of the Tumbleweed, are analysed for design options. For a feasibility check, a systematic three-fold check of the technologies is performed, finalizing potential candidates for further trade-off []. These are discussed below :

1. Source characteristic requirements []: Principal parameters of consideration - Energy density, structure mass per Wh/sol generation, specific energy.
2. Structural design of the Tumbleweed design : This includes the need for flexible, durable lightweight technologies, with specific mass constraints.
3. Mission considerations : The Mission parameters such as duration, payload capacity to be catered, Technology Readiness Levels (TRL), atmospheric and geographic considerations.

The Design Options Tree for the F6.3.1.1 Generate Electrical Energy sub-function is shown in Figure 5.12. From this design tree, technologies that are infeasible paths are ruled out, resulting in elimination of the branches representing *Thermal energy, Chemical Energy and Nuclear Energy* sources. It may be noted that despite the promising nature of Nuclear energy sources as well as considerably large energy density, the mass constraints of the tumbleweed as well as its complexity make this source infeasible.

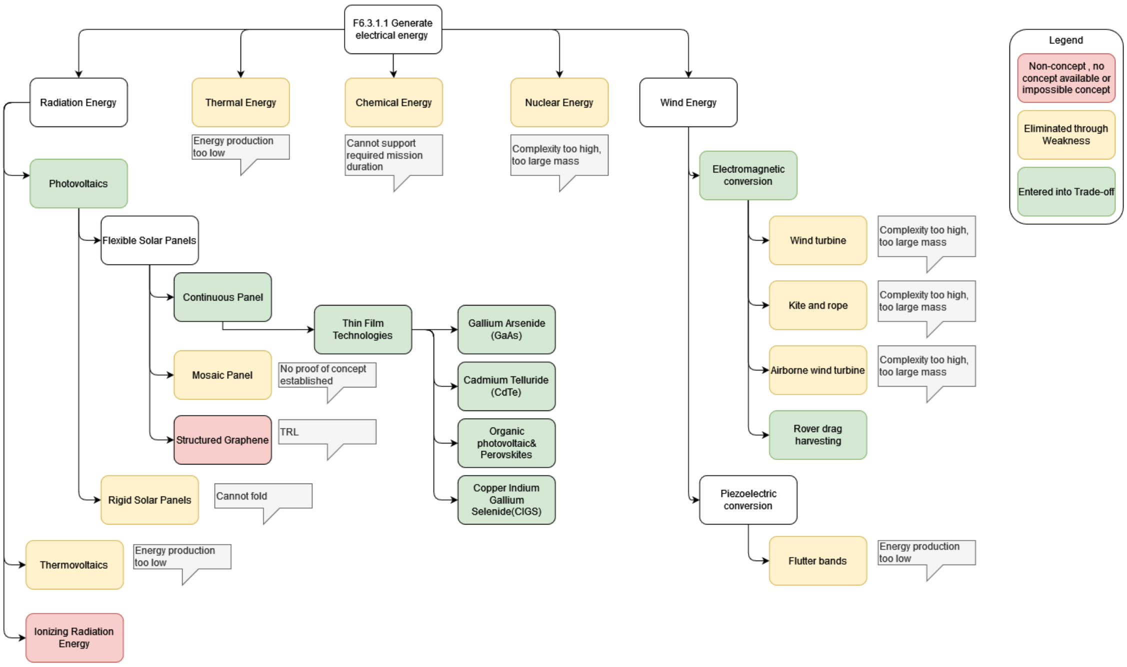


Figure 5.12: Design options/trade tree for the function F6.3.1.1 Generate electrical energy.

The design tree elicits two sub-branches of options - Flexible Thin-film photovoltaic technologies and Wind Drag harvesting rotor technologies, as shown below in Table 5.14. These technologies are entered in the trade-off for the sub-function of Generation of electrical energy.

Table 5.14: trade-off considered for the F6.3.1.1 "Generate Electrical Energy" Function

Identifier	Description
F6.3.1.1-CON1	Flexible Thin-Film Photovoltaics
F6.3.1.1-CON2	Wind Drag Harvesting

From Figure 5.13, the Design Options tree for the sub-function of F6.3.1.2 Store Electrical energy is presented. The energy storage technologies identified are potential energy storage, kinetic energy storage, chemical energy storage and thermal energy storage. Following the same principles discussed earlier, three of the technologies are deemed infeasible.

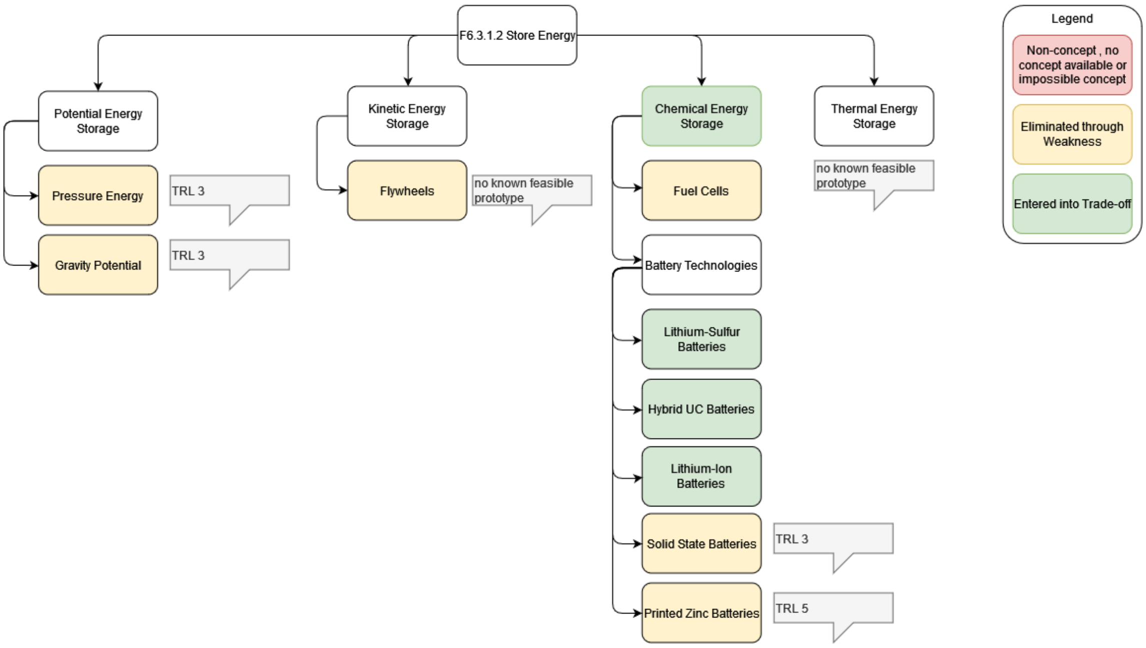


Figure 5.13: Design options/trade tree for the function F6.3.1.2 Store electrical energy.

Following this, three options are found feasible for this function - Lithium Sulphur Battery technologies, Lithium-ion Batteries and Hybrid Ultracapacitor batteries shown in Table 5.15.

Table 5.15: trade-off considered for the F6.3.1.2 "Store Electrical Energy" Function

Identifier	Description
F6.3.1.2-CON1	Lithium Sulphur Batteries
F6.3.1.2-CON2	Lithium-ion Batteries
F6.3.1.2-CON3	Hybrid Ultracapacitor Batteries

C. Methods and Results

Following the identification of promising technologies for the sub-functions from the design options tree from the previous section, a trade analysis is performed using the methodologies discussed in Section 5.1.2. For the two sub-functions, separate criterion are considered under each of the 4 major figures of merit.

Criterion for F6.3.1.1 Generate Electrical Energy

The figures of merit and corresponding criterion are elaborated into sub criterion. The chief sub-criterion examined are explained through the trade tables.

Firstly, Flexible thin-film Photovoltaic technologies are analysed in Figure. 5.14.

Function	Option	Total Score	Weights	Score	Figure of Merit	Weights	Score	Criterion	Weight	Score	Sub-criterion
Performance of Mission Concept 1: F6.3.1.1 Generate Electrical Energy	Radiation energy > Photovoltaics > Flexible Solar Panel technologies	2.35	30%	2.24	Performance	40%	2	Science Output	100.00%	2	Power System Mass
						60%	2.4	Technology Demonstration	30.00%	1	Geographical and Atmospheric Suitability
									30.00%	3	System Degradation
									40.00%	3	TRL
			20%	2.5	Cost	40%	2.5	Development Cost	100.00%	2.5	Availability of SOTA technologies; Novel R&D, V&V
						60%	2.5	Manufacturing Cost	100.00%	2.5	Availability of SOTA manufacturing; Novel T&V
			10%	2.5	Schedule	30%	2.5	Development Schedule	100.00%	2.5	
						70%	2.5	Mission schedule	100.00%	2.5	
			40%	2.32	Risk	30%	2.4	Technical Risk	30.00%	2	Design Complexity
									40.00%	3	Reliability, Availability, Maintainability, Safety
									30.00%	2	System Criticality
						20%	3	Development Risk	100.00%	3	Maturity of production
						50%	2	Program Risk	10.00%	2	Cost
									50.00%	2	Mass
									40.00%	2	Force majeure

Figure 5.14: trade-off table for F6.3.1.1 Generate electrical energy - A. Thin Film photovoltaics

Function	Option	Total Score	Weights	Score	Figure of Merit	Weights	Score	Criterion	Weight	Score	Sub-criterion
Performance of Mission Concept 1: F6.3.1.1 Generate Electrical Energy	Radiation energy > Photovoltaics > Flexible Solar Panel technologies	1.05	30%	1.36	Performance	40%	1	Science Output	100.00%	1	Power System Mass
						60%	1.6	Technology Demonstration	30.00%	3	Geographical and Atmospheric Suitability
									30.00%	1	System Degradation
									40.00%	1	TRL
			20%	1	Cost	40%	1	Development Cost	100.00%	1	Availability of SOTA technologies; Novel R&D, V&V
						60%	1	Manufacturing Cost	100.00%	1	Availability of SOTA manufacturing; Novel T&V
			10%	1	Schedule	30%	1	Development Schedule	100.00%	1	
						70%	1	Mission schedule	100.00%	1	
			40%	0.85	Risk	30%	1	Technical Risk	30.00%	1	Design Complexity
									40.00%	1	Reliability, Availability, Maintainability, Safety
									30.00%	1	System Criticality
						20%	0	Development Risk	100.00%	0	Maturity of production
						50%	1.1	Program Risk	10.00%	2	Cost
									50.00%	1	Mass
									40.00%	1	Force majeure

Figure 5.15: trade-off table for F6.3.1.1 Generate electrical energy - B. Wind Drag Harvesting

Table 5.16: Results of preliminary trade-off for F6.3.1.1 - Generate Electrical Energy.

Concept	Performance (30%)	Cost (20%)	Schedule (10%)	Risk (40%)	Total (100%
F6.3.1.1-CON1	2.24	2.5	2.5	2.32	2.35
F6.3.1.1-CON2	1.36	1	1	0.85	1.05

Table Table 5.16 elicits the results of the preliminary trade-off for this function. Thin-film photovoltaics outperform drag harvesting technologies on all parametric accounts. One of the key discriminators in performance characteristics is that of the mass of the system. For a rover with the payload requirements of the Tumbleweed, the mass of the drag harvesting technology exceed the mass constraints of the rover. Further, the drag harvesting technologies are not as mature and ready for deep space rover applications yet. Extensive R&D needs to be performed for establishing the readiness of this technology. Further, the increased number of moving parts associated with this technology increase risk of failure, and decrease the RAMSscores for this technology against that of photovoltaic panels, which are stationary and established in legacy rovers.

Criterion for F6.3.1.2 Store Electrical Energy

The figures of merit and corresponding criterion are elaborated into sub criterion. The chief sub-criterion examined are explained through trade tables.

Function	Option	Total Score	Weights	Score	Figure of Merit	Weights	Score	Criterion	Weight	Score	Sub-criterion
Performance of Mission Concept 1: F6.3.1.2 Store Electrical Energy	Chemical Energy > Battery Technologies > Lithium Sulfur Battery	2.36	30%	2.74	Performance	40%	2.8	Science Output	100%	2.8	Energy Storage, Power Capabilities
						60%	2.7	Technology Demonstration	30%	2	Longevity of Storage
									30%	3	System Degradation
									40%	3	TRL
			20%	2	Cost	40%	2	Development Cost	100%	2	Availability of SOTA technologies; Novel R&D, V&V
						60%	2	Manufacturing Cost	100%	2	Availability of SOTA manufacturing; Novel T&V
			10%	2.15	Schedule	30%	2.5	Development Schedule	100%	2.5	
						70%	2	Mission schedule	100%	2	
			40%	2.31	Risk	30%	2.7	Technical Risk	30%	2	Design Complexity
									40%	3	Reliability, Availability, Maintainability, Safety
									30%	3	System Criticality
						20%	3	Development Risk	100%	3	Maturity of production
						50%	1.8	Program Risk	20%	2	Cost
									40%	1.5	Mass
									40%	2	Force majeure

Figure 5.16: trade-off table for F6.3.1.2 Store electrical energy - A. Lithium Sulphur Batteries

Function	Option	Total Score	Weights	Score	Figure of Merit	Weights	Score	Criterion	Weight	Score	Sub-criterion
Performance of Mission Concept 1: F6.3.1.2 Store Electrical Energy	Chemical Energy > Battery Technologies > Lithium Ion	2.50	30%	2.6	Performance	40%	2	Science Output	100%	2	Energy Storage, Power Capabilities
						60%	3	Technology Demonstration	30%	3	Longevity of Storage
									30%	3	System Degradation
									40%	3	TRL
			20%	3	Cost	40%	3	Development Cost	100%	3	Availability of SOTA technologies; Novel R&D, V&V
						60%	3	Manufacturing Cost	100%	3	Availability of SOTA manufacturing; Novel T&V
			10%	2	Schedule	30%	2	Development Schedule	100%	2	
						70%	2	Mission schedule	100%	2	
			40%	2.31	Risk	30%	2.7	Technical Risk	30%	2	Design Complexity
									40%	3	Reliability, Availability, Maintainability, Safety
									30%	3	System Criticality
						20%	3	Development Risk	100%	3	Maturity of production
						50%	1.8	Program Risk	20%	2	Cost
									40%	1	Mass
									40%	2.5	Force majeure

Figure 5.17: trade-off table for F6.3.1.2 Store electrical energy - B. Lithium-ion Batteries

Function	Option	Total Score	Weights	Score	Figure of Merit	Weights	Score	Criterion	Weight	Score	Sub-criterion
Performance of Mission Concept 1: F6.3.1.2 Store Electrical Energy	Chemical Energy > Battery Technologies > Hybrid Ultracapacitor	1.61	30%	1.78	Performance	40%	1	Science Output	100%	1	Energy Storage, Power Capabilities
						60%	2.3	Technology Demonstration	30%	3	Longevity of Storage
									30%	2	System Degradation
									40%	2	TRL
			20%	1	Cost	40%	1	Development Cost	100%	1	Availability of SOTA technologies; Novel R&D, V&V
						60%	1	Manufacturing Cost	100%	1	Availability of SOTA manufacturing; Novel T&V
			10%	2	Schedule	30%	2	Development Schedule	100%	2	
						70%	2	Mission schedule	100%	2	
			40%	1.69	Risk	30%	2.3	Technical Risk	30%	2	Design Complexity
									40%	2	Reliability, Availability, Maintainability, Safety
									30%	3	System Criticality
						20%	1	Development Risk	100%	1	Maturity of production
						50%	1.6	Program Risk	20%	2	Cost
									40%	1	Mass
									40%	2	Force majeure

Figure 5.18: trade-off table for F6.3.1.2 Store electrical energy - B. Hybrid Ultracapacitors

Table 5.17: Results of preliminary trade-off for F6.3.1.2 - Store Electrical Energy.

Concept	Performance (30%)	Cost (20%)	Schedule (10%)	Risk (40%)	Total (100%
F6.3.1.2-CON1	2.42	2	2.15	2.31	2.37
F6.3.1.2-CON2	2.60	3	2	2.31	2.50
F6.3.1.2-CON3	1.18	1	2	1.78	1.43

The trade-off for the F6.3.1.2 Store Electrical Energy sub-function is shown in Table 5.17. Lithium-ion battery technology outperforms hybrid ultracapacitor technologies and Lithium Sulphur technologies, significantly in the performance, cost and risk parameters. Lithium-ion and Lithium Sulphur technologies have dramatically higher energy density as compared to Hybrid ultracapacitor technology. It may be noted that the risk associated with the Lithium technologies is quite similar owing to their similarities in chemistry. Further, the longevity and system degradation characteristics of hybrid ultracapacitors is quite superior as compared to Lithium sulphur batteries, however their technology readiness is not as mature as lithium based technologies. Owing to these factors, the Lithium-ion batteries are selected as the candidate technology for this function.

5.2.7 Trade 7: F6.3.12 Determine Location - Location and Attitude Determination Trade

Determining the location of the SCB is essential not only to produce usable science data, but also to safely operate the spacecraft, staying compliant with planetary protection standards, scheduling tracking and communications with the relay, predicting power harvesting, and more. Therefore, generating a design solution for location determination is crucial. At the same time, the technology fulfilling this function within the requirements of the mission remains at low TRL, and requires extensive development. Therefore, the selection of a design solution is impossible at this point.

Instead the aim of this analysis is to identify all options and investigate the performance gap of the simplest solution in order to gain insight into the design problem and generate a preliminary baseline.

A. Assumptions

Table 5.18 shows the assumptions made during the subsequent analysis:

Table 5.18: Assumptions made for F4 Transfer to Mars trade-off

Identifier	Assumption	Justification	Effect
MIS-ASS-521	Dead-reckoning error is constant over time and equal to the sum of noise and bias instability of the Inertial Measurement Unit (IMU)	Conservative estimation of position error generated by dead-reckoning.	Overestimation of actual error
MIS-ASS-522	The IMU used is the VectorNAV LN110.	Miniature IMU which is certified for military and aviation use - no comparable space-based IMU could be found.	May constrain component selection later on.

B. Concepts

As a first step, a design options tree is generated, showing all design concepts - note that several of these options may be applied together. Figure 5.19 shows said tree.

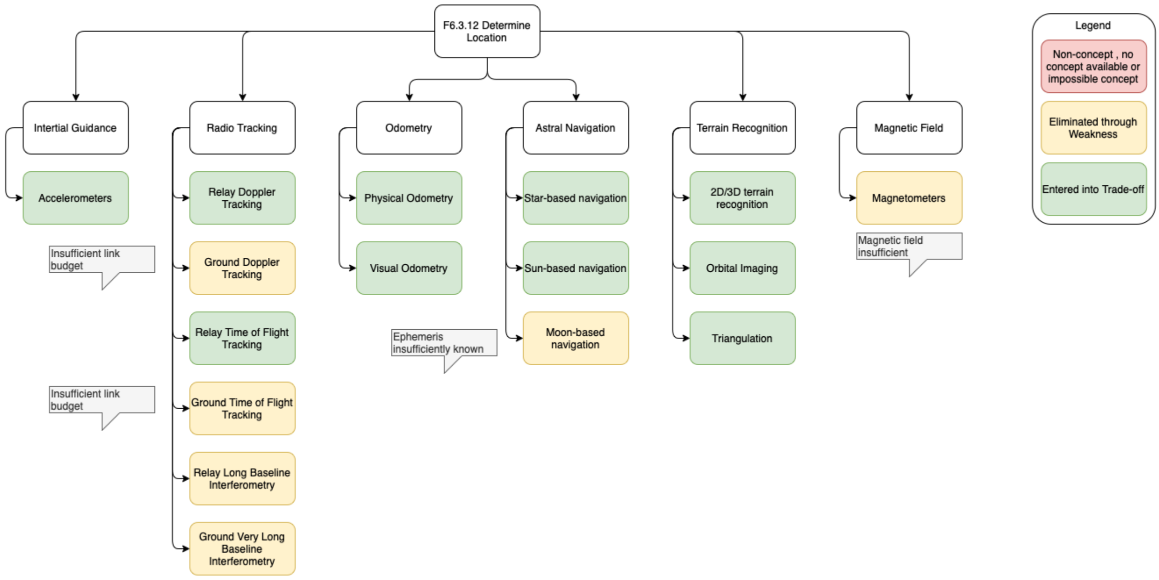


Figure 5.19: Design options/trade tree for the function F6.3.12 Location and Attitude Determination.

This figure shows that most options are deemed fundamentally viable options. However, ground-based radiometry tracking was eliminated based on insufficient link budget. This is based on previous analysis performed in [1] which showed the infeasibility of SCB to ground communications. Furthermore, the navigation based on the moons of Mars is eliminated, and magnetic field-based navigation due to the irregular and weak magnetic field. This leaves a plethora of options open to trade, which goes beyond the scope of this work.

Instead, a baseline based purely on dead reckoning from accelerometer data is investigated, as this represents the minimal solution from a hardware, computing and software complexity standpoint.

C. Method and Results

The method chosen to investigate the performance of dead reckoning is to consider the influence of constant bias on location determination performance. One crucial aspect to be considered is the use of frequent, deliberate stops to eliminate the build-up of velocity error. Therefore, the performance is investigated for various stopping frequencies. The results are shown in Figure 5.20 and Figure 5.21. As can be seen, using performance data from the VectorNav VN110 IMU, the velocity uncertainty reaches a maximum of 0.05 m/s and the position error is up to 250 meters after 10000 seconds. However, this analysis does not account for uncertainty in SCB orientation, a change in IMU bias and uncertainty thereof and measurement error of the actual acceleration. Therefore, it is estimated that the actual position drift is significantly greater than shown here.

On the other hand, this analysis shows that the velocity and position uncertainty decrease linearly with increasing stopping frequency, and therefore shows regular, controlled stopping to be an effective method to reduce position uncertainty. This means that this design solution performs significantly better than initially expected.

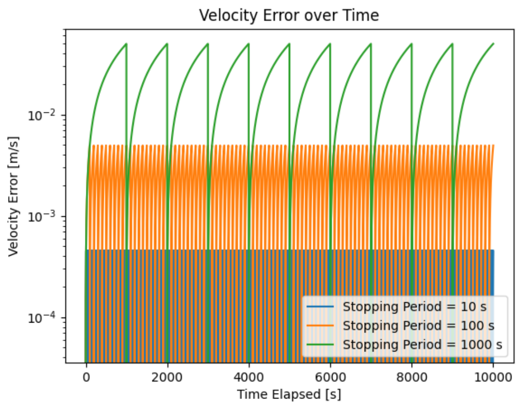


Figure 5.20: Theoretical velocity error over time

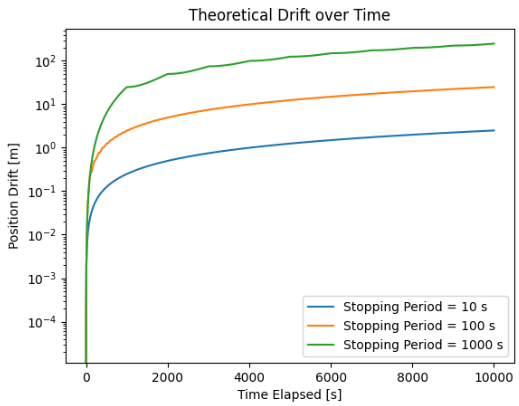


Figure 5.21: Position drift over time

6 Winning Concept - Baseline Design Description

In this chapter, the selection of a design concept of the space segment, based on the trades performed and the mission architecture, is presented. Furthermore, preliminary budgets are generated for the selected concept to assess its compliance with mission and technical constraints and support cost estimation. Finally, a preliminary program timeline is presented.

6.1 Design Choice Overview

6.1.1 Science Payload

In order to comply with the measurement requirements, payload instruments are selected in order to support sizing of the SCB and its subsystems. It is important to note that no trade-off has been performed on the instruments due to the lack of options. Instead, the goal is to identify miniaturized instruments with TRL > 6-7 that fit the science goals and the expected constraints of the demonstrator mission. This is done based on the mission requirements presented and through a survey of available instruments. The filter applied to all payload instruments is that they be miniaturized sufficiently, and that they be individual sensors as opposed to sensor packages. For example, the Mars Science Laboratory (MSL) instrument on the (MSL) mission is in actuality comprised of a multitude of sensors such as wind, humidity, pressure, ground temperature, ambient temperature and UV radiation. Based on these criteria, the following instrument candidates are identified:

A. Wind Sensors

For the wind sensors, two candidates are identified. The first instrument was developed for the proposed Mars MetNet mission by the Finnish Meteorological Institute (FMI) [10] based on hot film anemometry. The instrument itself consists of silicon cubes which are heated above ambient temperature and subsequently cooled down by the passing breeze. A very similar instrument is used in the Rover Environmental Monitoring Station (REMS) instrument on the MSL mission [9]. The other concept is presented in [6]: a spherical wind instrument based on very similar principles. However, this instrument allows for the measurement of 3D wind direction within just one sensor, and simplifies wind speed and direction extraction [6]. This led to the preliminary selection of this instrument. Table 6.1 shows an overview over the characteristics of the wind instruments:

Table 6.1: Overview over wind instrument candidates

Name	**Quantity**	**Accuracy** $[m/s]$, $[deg]$	**Resolution** $[m/s]$, $[deg]$	**Mass** $[g]$	**Dimensions** $[mm^3]$	**Avg. Power** $[W]$	**Source**
Mars Met-Net Wind Sensor	1	1, 20	0.5, 10	20	25 x 25 x 50	0.11	[10]
Miniature 3D Wind Sensor	2	0.7, 20	0.3, 2	22	230 x 35 x 10	0.768	[6]

The wind instrument supports the investigations specified by ATM-REQ-003.

B. Pressure Sensor

The selected pressure sensor was originally developed for the Mars MetNet mission by the FMI, and highly similar sensors were included as the Vaisala Thermocap and Barocap on the REMS instrument [9]. The pressure sensor's properties are shown below Table 6.2:

Table 6.2: Overview over pressure instrument candidates

Name	**Quantity**	**Accuracy** $[1sigma]$	**Resolution** $[px]$	**Mass** $[g]$	**Dimensions** $[mm^3]$	**Avg. Power** $[W]$	**Source**
Mars MetNet Pressure Sensor	1	15	0.2	45	20 x 62 x 55	0.015	[10]

The presence of the pressure sensor is a consequence of the science investigation laid out in ATM-REQ-002.

C. Temperature Sensors

For the temperature sensors, the candidate instrument considered are thermocouples intended for use on the Mars MetNet lander. Once again, this design is similar to the one used in legacy missions, with other past missions employing thermistors of type PT1000 [9]. Furthermore, for measuring the ground temperature, the ground temperature sensors (GTS) of the MSL mission is used. Table 6.3 shows the parameters are found for these sensors:

Table 6.3: Overview over temperature instrument candidates

Name	Quantity	Accuracy [$1sigma$]	Resolution [px]	Mass [g]	Dimensions [mm^3]	Avg. Power [W]	Source
Mars MetNet Temperature Sensor	/	0.5	0.05	3	50 x 50 x 3	/	[10]
Curiosity GTS	/	10	2	20	40 x 28 x 19	0.5	[9]

The temperature sensors gather data to achieve the science investigation specified in ATM-REQ-001.

D. Camera

While there are many camera options, ranging from cameras with space heritage on low Earth orbit missions to imagers designed for Mars missions such as Mars MetNet or Ingenuity. The following Table 6.4 shows currently identified promising camera candidates:

Table 6.4: Overview over wind instrument candidates

Name	Quantity	Accuracy [$1sigma$]	Resolution [px]	Mass [kg]	Dimensions [mm^3]	Avg. Power [W]	Source
Mars MetNet Camera	/	/	1280x1024	40	40 x 30 x 80	1.5	[10]
Ingenuity Engineering Camera	/	/	640x480	unknown	38 x 38 x 50	0.12	[10]
Ingenuity Science Camera	/	/	3840x2160	15	29 x 29 x 20	2	[10]
XCAM C3D	/	/	1280x1024	85	95 x 91 x 27	0.845	[10]
Infinity Avionics SelfieCam	/	/	1024x768	10	50 x 30 x 5	0.5	[10]

The data gathered by the cameras support a host of science investigations, namely SUR-REQ-001 to 003 and ATM-REQ-006 and 007.

E. Humidity Sensors

To measure humidity within the Martian atmosphere, a humidity sensor that was proposed for the Mars MetNet mission and later flown on the REMS instrument is selected. This instrument is also known as the FMI Vaisala Humicap. Table 6.5 shows its properties.

Table 6.5: Overview over humidity instrument candidates

Name	Quantity	Accuracy [$1sigma$]	Resolution [px]	Mass [g]	Dimensions [mm^3]	Avg. Power [W]	Source
Mars Met-Net/FMI Humidity Sensor	/	/	/	40	100 x 50 x 50	0.08	[10]

The data gathered by this instrument is used to gain insight into the properties of the Martian atmosphere in support of ATM-REQ-005.

F. Optical Sensors

The optical sensors measure and characterize the solar irradiation experienced by the payload. This is done by both gathering rudimentary spectroscopic information through the application of selective filters and measuring the distribution of direct and diffuse irradiation to infer information about the atmospheric optical depth and properties.

Table 6.6: Overview over optical instrument candidates

Name	Quantity	Accuracy [$1sigma$]	Resolution [px]	Mass [g]	Dimensions [mm^3]	Avg. Power [W]	Source
Mars MetNet Radiation Sensor	/	/	/	40	100 x 50 x 10	0.08	[10]

This instrument support the investigation outlined in ATM-REQ-004.

G. Retroflector

The retroreflector may be used as a target by Mars- or Earth-based systems to infer geodetic information of Mars. This is done by shining a laser at the reflector, which will then be reflected and can be analysed for its time-of-flight, spectrum/attenuation and frequency shift. This instrument is completely passive, and is complemented by a radio beacon, which is not included in the payload package as it is included with the transmit-receive module subsystem.

Table 6.7: Overview over retroflector candidates

Name	Quantity	Mass [g]	Dimensions [mm^3]	Avg. Power [W]	Source
INRRI	/	25	54 x 54 x 20	passive instrument	/

Together, these instruments achieve the mission science objectives which are required through INT-REQ-001 to 003.

6.1.2 Mission Concept Selection and Description

Here, the decisions for mission concept trades are discussed:

A. Transfer Concept

As discussed in subsection 5.2.1, the trade-off on the mission concept for transferring to Mars produced two strong contenders: F4-CON1 (SCB is integrated with parent mission inside the EDV) and F4-CON2 (SCB is housed within a dedicated EDV which is in turn integrated to the parent mission).

Looking at the trade-off, the cost and performance of F4-CON2 is higher as it represents the design solution which can prove more capabilities of the Tumbleweed Ultimate Mission, but at higher cost and complexity. In terms of risk, this solution provides higher internal technical risk, whereas it reduces program and development risk due to a reduction in interface complexity. This means that this design will be easier to design for on a systems level, as the likelihood of major requirements changes is reduced. Furthermore, this mission concept comes with a higher number of compatible missions and On the other hand, F4-CON1 is somewhat simpler and therefore more cost-effective.

What is not taken into account in this trade-off study are the integration costs, which will indubitably be higher for F4-CON1 as its integration is much tighter. As the parent mission budget likely does not account for these costs, this will be costs for the Tumbleweed Demonstrator Mission. Furthermore, the integration with the Parent Mission and the nature of its interaction (being in the Entry, Descent and Landing phase) will likely increase the complexity of validating and testing the design. Moreover, the cost estimation used likely strongly overestimated the cost of the EDV. Therefore, weighing factors omitted in the trade-off, F4-CON2 is deemed to be the superior design concept for this baseline, however, this decision can hardly be considered final, and more analysis is required to make a final decision:

Firstly, the implications of the introduction of an EDV on the development strategy must be considered in more detail. Furthermore, cost, mass, volume and other budget estimations must be improved and performed in detail for the EDV. Also, the compatibility of this concept with various missions must be verified further.

B. Descent Strategy

It was found in the analysis performed that a pure drag-based descent strategy of a Tumbleweed rover - type SCB results in acceptable impact load factors. Therefore, this concept is chosen as of this moment, however, some caveats must be considered: Firstly, while the impact may not be unacceptably harsh, it may still drive the structural design of the SCB to the point where adding additional landing hardware is preferable. Moreover, this trade-off did not consider attitude control during descent, which may be key for ensuring a safe landing. This needs to be studied further in additional analyses.

C. Number of Rovers

The decision between F6.4A-CON1 (single SCB), F6.4A-CON2 (several SCB with non-hardware differences) and F6.4A-CON3 (several spacecraft that are completely identical) is dictated by another trade-off between cost and performance: while F6.4A-CON1 has superior cost, its performance in validating the critical technologies is somewhat worse. On the other hand, F6.4A-CON2 fulfils the requirements, performing better than required on many fronts. The risk is similar across the board, with a slight edge to the singular SCB due to its lower program risk, caused by lower mass. On the other hand, the technical risk is reduced due to redundancy.

Overall, the decision is made to, in spite of its inferior score, go with F6.4A-CON1 (singular SCB). This is done in consideration of the decision to go with a dedicated EDV, as the package of EDV and SCB forms an easily scaleable mission concept that allows for the addition of a second package if the parent mission mass margins allow. At the same time, the minimum size of the mission is kept minimal, maximizing the number of candidate parent missions. It is important to mention that one critical function that this architecture cannot validate is the deployment of a multitude of rovers from one entry vehicle. At this moment, this is not deemed critical, but this must be kept in mind for future analysis. Should this prove more critical than assumed now, this would swing the favour towards a swarm architecture.

D. Science Data Handling

As a result of the trade-off, as much science data handling as possible will be done in-situ to minimize reliance on third-party communications infrastructure and as proving this capability is a major goal of the mission.

6.1.3 Selected SCB Concept

Now, the result of the design trades of the SCB are presented.

A. Rover Control Method

As winner of the trade-off, F6.4B-CON1 (start/stop control) is selected. It has the benefit of being low-cost and low-complexity. This result is in agreement with previous studies conducted in [15] which concluded the same result. Furthermore, it was found in this study, which focused more on qualitative assessment of relative strengths and weaknesses, that the performance gains afforded by higher maneuverability do not translate strongly into higher scientific output. Lastly, this concept has the benefit of being relatively simple to analyse and optimize.

B. Energy Generation & Storage

As a result of this trade, a simple architecture consisting of flexible thin-film GaAs solar cells and a Lithium-Ion battery is chosen for now. However, in the future, as Lithium-Sulfur batteries increase in maturity, they may offer an enticing alternative as a replacement with higher energy density, reducing battery mass. For now, however, Lithium-Ion is deemed preferable due to its design heritage on Mars.

C. Location Determination

It has been established that pure dead-reckoning, updated through radio tracking, likely offers insufficient performance. On the other hand, it is shown that by repeatedly stopping the rover, the accuracy of pure dead-reckoning-based tracking can be increased significantly. Therefore, it is recommended that more concepts are explored. For this baseline, building on work presented in [20, 21], this will consist of a mixture of visual and physical odometry. Here, the subdivision of the structure of the SCB into inner and outer structure will offer simplified physical odometry using a simple rotation counter.

6.2 Design Concept of Operations

The mission concept is envisioned to fulfil its mission through the following steps:

1. After development as well as manufacturing & AIT, the Tumbleweed Demonstrator Mission space segment is integrated onto the side of the parent mission: in case of a surface mission, this is likely the transfer/service module, for orbiting or flyby missions, the side of the main SCB.
2. The mission gets launched and put on a transfer trajectory to Mars. During that time, the Tumbleweed Demonstrator Mission space segment is dormant.
3. During approach to Mars, the TDM is separated from the parent mission. This is done either in conjunction with a maneuver that temporarily puts the perigee of the capture hyperBoLa within the Martian atmosphere, or through the separation velocity alone. In case of a surface mission, the TDM is separated when after the parent mission transfer/service module is separated to limit risk exposure of the parent mission.
4. After ballistic entry of the capsule, the backshell of the EDV is released. Subsequently, the SCB is deployed and unfolds. Potentially, a parachute is required in order to limit aerodynamic loads on the SCB.
5. The SCB impacts the Martian surface at terminal velocity. In its stopped mode, it awAITs signal acquisition.
6. Following system conditioning and verification that all systems are operating nominally, the SCB activates the PLD and begins its mobile phase of operations. During this phase, the SCB will be mobile during most of the Martian day, stopping periodically to minimize positioning uncertainty.
7. Once the final desired location has been reached, the SCB permanently disables its ability to roll - most likely through altering its structural characteristics - and begins the stationary phase of the mission. During the stationary phase, the instruments of the PLD specific to this phase are turned on and begin their operation.

8. Once all objectives are met and/or the system is degraded beyond acceptable limits, the space segment is shut down.

6.3 Physical Design and Configuration

Now, a draft of the physical shape and layout of the SCB and the EDV are presented. First up, Figure 6.1 shows a potential physical layout of the SCB.

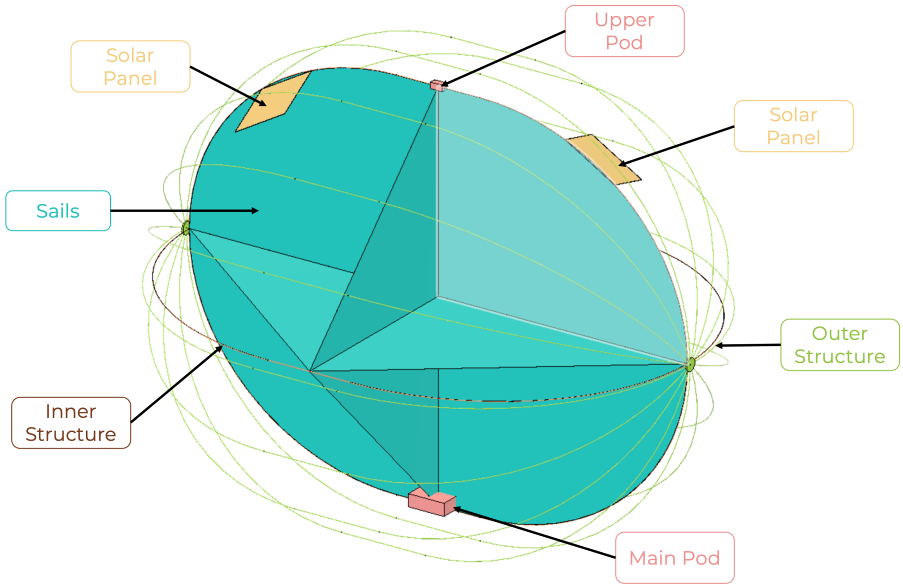


Figure 6.1: Conceptual design of the SCB concept with labelled subsystems

The figure shows a structure consisting of an outer structure and an inner structure which are connected through a rotating joint. Through the offset mass of the main pod, the inner structure stays upright while rolling and stabilizes the rolling axis. This is required for the stop/start functionality, which is realized through locking the rotating joint, impeding rotation. Furthermore, this has advantages with regard to solar panel mounting (allowing them to be continuously upwards-pointing, for cameras, allowing them to be pointing at the horizon continuously and for communications. The upper pod is envisioned to house said cameras, allowing them a clear view of the sky as required. The sails provide drag and therefore locomotive force. The current state of entry vehicle conceptual design is much more rudimentary and is shown in Figure 6.2:

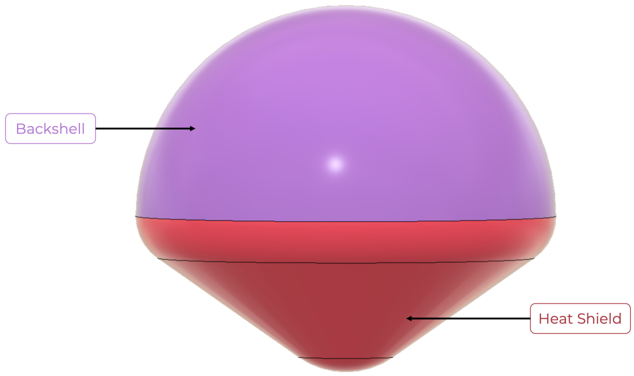


Figure 6.2: Conceptual design of the SCB concept with labelled subsystems

The image shows a hemispherical backshell and a sphere-cone heat shield, which is modelled after the Deep Space 2 entry vehicle [16].

6.4 Preliminary Budgets

In the following, the preliminary budgets generated as part of this report for the current baseline are presented. These include power and mass budgets on the technical side, and cost and schedule budgets on the programmatic side.

6.4.1 Power & Energy Budgets

This section discusses and presents a model Power and Energy Budget Calculation for the function F6.3.1 Supply Electric Power - Electric Power System. For this, two sub-system/ components need to be designed, each of which fulfil the sub-functions of F6.3.1.1 Generate electrical energy and F6.3.1.2 Store electrical energy. For the selected technologies, i.e. Flexible Thin-film photovoltaic panels and Lithium-ion batteries, their sizing and power requirements need to be performed. This is done in this section following the breakdown of power demand.

Breakdown of Power Requirements

The Power estimation is estimated using the suggestive power requirements for the sub-system components of the Tumbleweed Rover. This is shown in Table 6.8. A margin is included in the power calculations for each of the subsystem in line with the ECSS standards given by ECSS-E-TM-10-25A.

Table 6.8: Breakdown of power requirements for the tumbleweed rover payloads and systems

Sub-system	**Max Power**	**Duty Cycle**	**Quantity**	**Energy Sol^{-1} [Wh]**	**Margin (%)**	**Net Energy [Wh]**
PLD	3.454	0.5	1	42.5873	20	51.10
OBD-OBC	0.4	1	1	9.9863	20	11.84
OBD-DPC	7	0.7	1	120.8326	50	181.25
TRM	2	0.2	1	14.091	50	21.14
LAD-IMU	1	0.5	2	24.659	50	36.99
LAD-CAM	0.993	0.5	4	48.9742	20	58.77
THE	/	1	1	19.8	20	23.76
Total						384.85

The power budget breakdown gives an estimate aggregate of the total power requirements of the Tumbleweed Rover. This provides the basis for panel sizing. This requires some basic quantities, to be defined which establish Influx, Atmospheric ingress in the form of dust, mission duration and further technical parameters for the charging infrastructure such as charging efficiency. These assumptions are described in the table below:

Table 6.9: Assumptions and System Characteristics

Entity	**Characteristic**	**Value**
3*Irradiation and Atmospheric Characteristics	Length of Sol[h]	24.659
	Mars Solar Irradiation [Wm^{-2}]	29 []
	Mars Dust Deposition [% of BoL]	0.15 []
3*Solar Panel Characteristics	Efficiency [BoL]	210 []
	Density [gm^{-2}]	114 []
	Degradation [%/year]	5
3*Charging Characteristics	PCDU Efficiency [%]	90
	Charging Efficiency [%]	80
	Battery Energy Density [Whg^{-1}]	0.2

Sizing of the Solar Panel

This calculation reflects the functional requirement of F6.3.1.1 Generate Electrical Energy. The panel sizing is now calculated based on the assumptions from Table 6.9. This requires, calculation of input irradiation for a solar panel on Mars, adjusted to the degradation and ingress as well as the efficiency of the solar panel. This provides an estimate of the total expected power given the payload energy requirements of the rover obtained from Table 6.8. This calculation provides the approximate sizing of the panel as shown in the Table 6.10.

Table 6.10: Calculation for Panel Sizing

Quantity	**Value**
Energy Received per sq.m. over 1 Martian Day $[Wh]$ - BoL	4654.71
Energy Received per sq.m. over 1 Martian Day $[Wh]$ - EoL (Considering ingress)	3396.16
Efficiency of Solar Panel at End of Life [%]	0.282
Energy Produced by Solar Panel per sq.m. $[Wh]$ - BoL	1349.86
Energy Received by Solar Panel per sq.m. $[Wh]$ - EoL	956.24
Total Required Energy $[Wh]$	451.36
Panel Sizing for BoL $[m^2]$	0.472
Panel Mass $[Kg]$	53.80
Energy Produced $[Wh]$	637.15

Sizing of the Battery

It is assumed that the use of battery is restricted to the Martian nighttime, when direct solar irradiation is absent to fulfil the power demands of the onboard payload of the rover. For this purpose, the payload power requirements are distributed to Martian day-time and nighttime categories in Table 6.11.

Table 6.11: Payload Distribution during Day and Night time

Subsystem Payload $[Wh]$	**Night**	**Day**
PLD	0	51.10
OBD-OBC	5.918	5.918
OBD-DPC	51.785	129.46
TRM	0	21.14
LAD-IMU	0	36.99
LAD-CAM	0	58.77
THE	11.88	11.88
Total	96.64	350.291

The breakdown of power requirements for the payload during daytime and nighttime provides estimate for use of battery. Sizing of the battery is carried out in the Table 6.12.

Table 6.12: Calculations for Battery Sizing

Quantity	**Value**
Energy Required [Constant Duty cycle] for Martian Night-time payload $[Wh]$	213.80
Corresponding Battery Mass [Constant Duty Cycle] $[Kg]$	1069.01
Battery Mass - Average	776.118
Battery Mass - Adapted Duty cycle	483.220

6.4.2 Mass Budgets

Having sized the battery (a major part of the mass breakdown) and the solar panels, a subsystem-level mass budget is created for the SCB. This is done under the following assumptions shown in Table 6.13:

Table 6.13: Assumptions made for the generation of a mass breakdown of the SCB

Identifier	Assumption	Justification	Effect
MIS-ASS-504	Heater mass is 20 grams.	Ballpark figure, no exact figures are available and lacking thermal design.	Uncertainty in heater mass introduced.
MIS-ASS-505	Conduction path mass is 100 grams.	Ballpark figure, no exact figures are available and lacking thermal design.	Uncertainty in thermal system mass introduced.
MIS-ASS-506	Data storage mass is identical to OBC mass.	Ballpark figure, lacking exact data storage requirements - estimation based on qualitative similarity between the two subsystems.	Uncertainty in Data Storage Mass introduced.
MIS-ASS-509	Battery energy density is 200 Wh.	Based on typical energy density of lithium-ion cell.	Must be updated in future iteration
MIS-ASS-510	2 cameras are required for science objectives.	One nadir pointing, one horizon pointing.	Requires future adaptation
MIS-ASS-511	4 cameras are required for navigation	Required for near 360 deg, stereoscopic imaging; this is a very conservative approach.	Requires future adaptation
MIS-ASS-512	The breaking mechanism weights 200 grams.	Lacking a reference design, this assumption is based on the weight of the closest Earth-bound reference design: bicycle disc brakes.	Likely overestimation of brake mass.
MIS-ASS-513	The harness mass weighs 200 grams.	Lacking design fidelity, this is assumption is made.	Actual harness mass may be significantly different to this figure.

For other systems, the approach was to identify candidate subsystems, which has been done in previous analyses wherever possible. Some items are subject to sizing, such as the EPS. Others are based on statistical relations obtained, such as the structural masses. Overall, the following mass budget breakdown is obtained:

Table 6.14: Mass Budget for the SCB

System	Sub-system	Mass per Unit [g]	Quantity	Margin [%]	Mass with Margin [g]	Mass with Margin per sub-system [g]
Structural Mass						
SAI	SAI-SAI	194.9	1	20	233.8	233.8
CTR	CTR-BRK	200	1	20	240	240
HRN	HRN	200	1	20	240	240
3*STR	STR-OST	2923.6	1	20	3508.3	3*5375.9
	STR-IST	974.5	1	20	1169.4	
	STR-POD	581.7	1	20	698.1	
3*THE	THE-INS	150	1	20	180	3*324
	THE-HET	20	1	20	24	
	THE-CON	100	1	20	120	
7*PLD	PLD-TEM	3	3	100	18	3*506
	PLD-PRE	45	1	100	90	
	PLD-HUM	15	1	100	30	
	PLD-WIN	22	2	100	88	
	PLD-OPT	40	1	100	80	
	PLD-CAM	37.5	2	100	150	
	PLD-RET	25	1	100	50	
Total Structural Mass : 4259.2						
Non-Structural Mass						
3*EPS	EPS-SOA	52.8	1	50	79.2	3*1207.4
	EPS-BAT	776.1	1	20	931.3	
	EPS-PCD	164.1	1	20	196.9	
3*OBD	OBD-OBC	100	1	20	120	3*812.4
	OBD-DPC	452	1	20	542.4	
	OBD-STO	100	1	50	150	
2*TRM	TRM-TNC	90	1	50	135	3*262.5
	TRM-ANT	85	1	50	127.5	
2*LAD	LAD-IMU	12	2	20	28.8	3*208.8
	LAD-IMA	37.5	4	20	280	
Total Non-Structural Mass : 2491.1						
Total Mass : 9410.9						

This mass breakdown, due to its conservative margins, will likely prove conservative, especially due to the knock-on effects of overestimating mass as the size of the SCB can be reduced. Based thereon and statistical relations obtained from the mass breakdown of Deep Space 2 [16], an EDV mass of 1.80 kg is obtained, for a total mission mass of 11.2 kg.

6.4.3 Cost Budgets

Based on the mass budgets, cost budgets are now created. The structure of the cost breakdown consists of (estimated) program/development and manufacturing/operations costs to get an overall cost estimate on systems level. This is done by getting a weighted average from the following systems-level cost models:

- **NASA Spacecraft/Vehicle Level Cost Model (SVLCM) - Interplanetary**: 60 %
- **NASA Spacecraft/Vehicle Level Cost Model (SVLCM) - Orbital Unmanned**: 20 %
- **Zandbergen et al. Statistical Relations [4]**: 20 %

This weighting is done in order to balance aspects of strong congruence with the mass of the hardware (small-microsat) as well as with the mission type (interplanetary). Validating this against cost data from Ingenuity (90 M$) and Deep Space 2 (25 M$), this shows the cost model to be accurate to within the order of magnitude. Furthermore, cost margin is applied in accordance with ECSS-E-TM-10-25. The budget is shown in Table 6.15:

Table 6.15: Initial cost budget of the Tumbleweed Demonstrator Mission

Item	Cost [FY2022 M€]
SCB	45.87
EDV	20.03
Total Without Margin	65.90
Margin	20&
Total With Margin	79.08

It is important to consider that due to the high level at which the analysis is performed, the expected uncertainty is very high. Furthermore, as the cost models used are roughly linear and have a constant term (x^0), at low mission masses the cost model is likely to overestimate the actual cost somewhat. For future work, it is recommended that the cost estimation be repeated on subsystem level to gain a better understanding of the actual cost.

6.4.4 Schedule Allocation

The schedule allocation for the Tumbleweed demonstrator mission is taken from a method discussed in [12]. This allocation has been performed in previous work, and is repeated here [15]. Figure 6.3 shows the timeline allocated to the development, manufacturing and execution of the demonstrator mission.

As can be seen, this analysis is only preliminary as it is contingent on the finally chosen design concept, but it nevertheless gives an overview over what is required in order to meet the timeline requirements.

Phase	End defined by	Duration	Begin	End	Justification
Concept Exploration	Preliminary requirements release, proof of concept work complete	5y 9m	2017/03	2022/12	Volunteer phase strategy calls for end of PoC at 2022/12
Detailed Development					
Risk Reduction & Tech Development	Finishing of rover demonstrator	2y 7m	2022/12	2025/01	Volunteer phase strategy
Detailed Design and Development	Release of final specifications	1y 6m	2025/01	2026/06	Initial estimation
Production & Deployment					
Production and Testing	Shipping of rover for mission integration	3y 2m	2026/06	2029/08	First-order estimation based on SMAD - further detail needed
Integration with Parent Mission	Integration of entire mission to launch vehicle	0y 5m	2029/08	2030/01	First-order estimation based on SMAD - further detail needed
Launch, Transfer & EDL	Systems & instruments checkout on Mars	0y 9m	2030/01	2030/09	First-order estimation based on SMAD - further detail needed; CHECK FOR LAUNCH WINDOW
Operations & Support					
Operations - Mobile	Rover demobilized or stuck	0y 3m	2030/09	2030/12	based on mission requirements
Operations - Stationary	End of operations	0y 4m	2030/12	2031/04	based on mission requirements
Disposal	Safing & Turn-off of systems	0y 1m	2031/04	2031/05	Estimation

Figure 6.3: Program timescale of the Tumbleweed Demonstrator Mission

7 Conclusion and Recommendations

7.1 Conclusion

This report covers the subsystem requirements derivation of the Tumbleweed rover. After discussing the operational analysis, addressing science objectives and stakeholder requirements, the logical analysis is presented. It covers the Functional Analysis at mission level, the mission architecture as well as the function interface analysis. In the next section, mission requirements are discovered and analysed, followed by a design trade study exploring various mission concept options. Finally, the winning concept is described in the last section.

The science objectives (chapter 2) can be summarized in three categories

1. Atmospheric science objectives
2. Internal planetary structure objectives
3. Surface geology objectives

Next to that, the following stakeholders were classified as "key":

1. **Space agencies**, that enable the mission organisation
2. **Mission scientists**, that act as a customer for science data
3. **Science objectives**, that must be performed to prove scientific value of the mission
4. **Team Tumbleweed**, the organisation developing and conducting the mission.

Both science objectives as well as requirements produced by stakeholders will define all future work on the mission, as every single detail being added to the Tumbleweed mission shall contribute to fulfill these objectives and requirements.

In chapter 3 the mission architecture is being presented. It contains all mission segments and how they relate to each other. Exemplary segments include

- Launch, Entry, Landing and Rolling Trajectories
- Launch, Transfer, EDV and Orbiter
- The mission
- SCB (=the Tumbleweed rover)
- Communications, Relay satellites

- Mission Operations, Users
- Planet Mars

The functional analysis results in a functional flow diagram, that defines how functions (e.g. Development, Manufacturing AIT, Launch, Transfer, ...) relate to each other. I.e. it explains the order of the functions and what has to happen in order to "initialize" and "finish" a function. Finally, the mission interface analysis is being conducted based on a functional and a non-functional N2-diagram.
It is important to note, that this analysis is only done for the base, i.e. the case of a SCB that is integrated into the EDV.

In chapter 4, a requirements discovery tree has been used to answer what capabilities are needed to fulfil the science goals, what and under what constraints the operations have to be conducted. Based on these results, the mission requirements were derived and formulated.

In chapter 5, mission concept options are being compared to one another, based on a quantitative score (from 0 to 3) applied to a range of criteria/properties of the concepts. These criteria include technical performance, costs and risks. These mission-level trades have been done for the following functions (the winning concepts are included in parentheses):

1. **F4 - Transfer to Mars** (SCB integrated with parent mission in EDV)
2. **F5.5 - Reach Mars Surface** (SCB descent at terminal velocity, using drag of SCB only.)
3. **F6.4 - Position Payload** (A swarm of several rovers distinguishing themselves based on non-hardware differences is being sent to Mars.)
4. **F6.6 - Handle Payload Data** (Onboard Processing)
5. **F6.4 - SCB control method** (Stop/Start - the SCB can halt its trajectory at will.)
6. **F6.3.1 - Energy generation** (Lithium Sulphur Batteries)
7. **F6.3.12 - Location determination** (no winner identified)

Moving on, in chapter 6 the mission design is presented in more detail: The mission concept is a singular SCB within a dedicated EDV, which is packaged onto the side of the parent mission. The SCB itself is controllable through deliberately stopping its motion, and it is powered by thin-film GaAs solar panels and a lithium-ion battery.

7.2 Recommendations and Outlook

Based on the work outlined in this report, several recommendations are to be made: Firstly, when it comes to investigating the science cases, this analysis should be cross-referenced with professional scientists from all fields that are of interest, for example in a science definition workshop. Moreover, moving on to logical analysis, the depth of the functional flow should be extended to consistently reach the fourth level in preparation for detailed concept design. Furthermore, in support of this, the data flow diagram and user interaction diagram should both be increased in detail.

The requirements formulated here must be improved, especially with respect to their quantification based on more in-depth performance analysis. Furthermore, it is imperative that lower-level (system- and subsystem-level) requirements be derived. These should keep in mind the trades performed in this report. Before finalizing the design decision, however, the final trade-offs between the remaining, similarly performing options should be performed wherever applicable. These trades should be based on in-depth analysis and purely quantitative. For the trade-off on reaching the surface of Mars, emphasis must be put on higher-fidelity impact simulation and the results thereof are to be taken into account for the systems requirements formulation. The investigation into data handling and location determination must be continued to be treated as high priority. Furthermore, additional less significant trades should now be performed.

For the subsequent design phase, the deployment of multiple SCB from one EDV shall be investigated. Moreover, the baseline set in this report must be continually challenged in future work. Furthermore, the compatibility with parent mission and the interface must be investigated in greater detail, as well as the technical budgets.

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