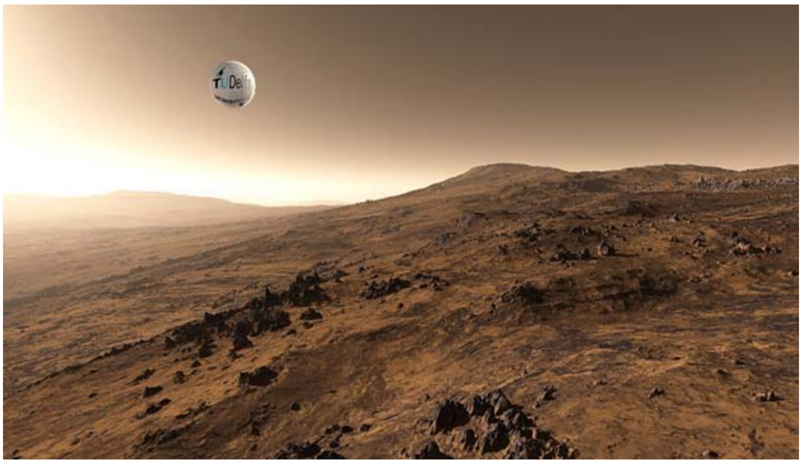
Delft2Mars Balloon

Midterm Report

Design Synthesis Exercise 2010



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Preface

The most extensive project of the BSc Aerospace Engineering programme at TU Delft is the Design Synthesis Exercise (DSE). This 10 week project is a collaborative design task shared by 10 students and takes place during the 3rd year of studies. This report contains the midterm report of the Delft2Mars project. The main purpose of the Delft2Mars project is to prove that it is possible for a university like the Delft University of Technology to supply the European Space Agency's Entry Descent and Landing Sytem (EDLS) mission to Mars with an extremely low-risk yet useful scientific payload. This payload will be in the form of a balloon containing sensors capable of analyzing the Martian atmosphere. Special attention is given to the possibility of using a tether to keep the balloon at one location in the atmosphere, which would allow the sensors to collect unique data for the scientific community.

Contents

List of abbreviations

Abbreviation	Description
COSPAR	Committee on Space Research
COTS	Commercial off-the shelf
DID	Deliverable item description
DOT	Design option tree
DSE	Design synthesis exercise
EDL	Entry descent landing vehicle
EDLS	Entry, descent and landing system
ESA	European Space Agency
ESTEC	European Space Research and Technology Centre
IR	Infra red
LLDPE	Linear low density polyethylene
MLI	Multi layer insulation
MNS	Mission need statement
NASA	National Aeronautics and Space Administration
POS	Project objective statement
RHU	Radioisotope heater unit
RTG	Radioisotope thermoelectric generator
sols	Martian day
TCS	Thermal control system
WBS	Work breakdown structure
WFD	Work flow diagram
WIP	Work in progress

Summary

This report will show the first part of a feasibility study for a balloon mission to Mars. It was preceded by a project planning stage, which is partially described in this report, and a baseline phase which contains background information on which this report is built. In this baseline report the requirements that are used in this report were defined.

To determine the structure of the whole project several system engineering tools are used. This use of tools resulted in a road map of the project which is constantly updated and used for planning. It is also used to keep the readers informed about the status and progress of the project.

The baseline requirements determined from literature studies and group discussions are the drivers behind the concepts shown in this report. For each sub-system, i.e. balloon shape, balloon configuration, communication, balloon construction, power supply and deployment, multiple concepts are generated based on brainstorm sessions and researching existing solutions. These ideas were structured in a Design Option Tree (DOT) for later use. Because it is important to see whether the mission is feasible a risk assessment is made to determine possible risks that can endanger the lander or the balloon itself.

In parallel the interactions between the functions of the vehicle are defined. Identifying these interactions can help during the design because they show what functions, and thus systems, are interfering with each other.

Furthermore the first design ideas are produced using the DOT as a source for ideas. Three ideas were generated because the available time limited more concept generation. The first design incorporated a tethered elliptical balloon filled with one gas. Through the cable the necessary energy is transported from the lander on the surface. This design uses the same cable for data transmission. By using the power and communications system of the lander this design would be extremely light-weight. Unfortunately a short study showed that a lot of power is lost in a long cable, so an alternative to communication and power through a cable has to be developed. Deploying this system would take place using a smaller secondary balloon, that would pull the main balloon out of the lander.

The second design uses a free-flying pumpkin-shaped balloon with multiple compartments to enable the balloon to float day and night. The gas in one compartment would keep the balloon floating at night, the other gas would produce lift at day. An initial plan was to use wind power for energy generation, but this turned out to be impossible on Mars due to the low air density. Ultimately solar cells were chosen as the power generators. This design incorporates a mid-air deployment system in which a parachute pulls-out the balloon during descent.

The third design is also a free-flying balloon. This concept uses a simple spherical balloon filled with one gas. As with the second design, solar energy is used for the power generation and mid-air deployment is used. Because this balloon is more fragile than the pumpkin balloon another deployment mechanism is incorporated. Deployment takes place using a pressurised canister which opens in the air, gently letting the balloon out.

After determining which criteria would be used to rate the concepts, a trade-off was carried out. One design will be chosen in the next phase to develop further.

To keep the readers up to date a chapter is included describing the work in progress. This work has not produced reliable results yet, but the results will be presented in the next report about four weeks from now.

Introduction

This report presents the results of the Delft2Mars project on the midterm milestone. The midterm milestone defines the point in time during this project at which the design options are clear. The design possibilities of the overall balloon system, as well as the possible designs of the required subsystems are now set. The next step in this project is to choose the most suitable concept during a trade-off. After reading this report, the reader will have a clear overview of the decisions that have to be made during the trade-off session which will follow soon after the publishing date of this document.

This midterm report starts with a review of the project planning and organisation in chapters 1 to 3. What follows are the actual design options of the balloon mission at Mars. The various concepts for the subsystems are introduced, described and finally summarised in the Design Option Tree in chapter 4. Chapter 4 also contains a risk assessment based on the various subsystems. This chapter is followed by an identification and systematic sorting of the interfaces of the system in chapter 5. In chapter 6, the three most promising combinations of subsystem designs are derived from the Design Option Tree. These three designs will form the possible options which will be compared during the trade-off. Chapter 7 contains the method and criteria used to guide the trade-off in an effective and efficient way. Finally, the writers of this report deemed it necessary to show other work done, which is not directly related to the upcoming trade-off. This work can be found in chapter 8 and includes preparation for the upcoming prototype, a description of the strategy and a dynamic model of a balloon flight on Mars.

Chapter 1

Project approach

To successfully complete the project, an approach must be specified. This chapter describes the approach to the project. First a Mission Need Statement (MNS) is set up together with the Project Objective Statement (POS) to get a good guideline and a clear direction for this project. After that the sustainability in the project is discussed.

1.1 Project Objective Statement and Mission Need Statement

To get a proper guideline for the team a MNS and POS are set up. The goal of this project is described by the POS:

> Design a low-cost balloon system to explore the Martian atmosphere and surface using Commercial Of The Shelf components to show the feasibility of such a mission, and build a prototype, with a group of 10 students in 10 weeks.

The project objective from the project guide is used as a basis for the POS and is extended with the specific constraints of the Design Synthesis Exercise (DSE). After discussion with the project's tutors and coaches regarding the goal of the project, the feasibility has been explicitly emphasised in the POS. For the end product the following MNS is defined:

> Explore the Martian atmosphere and surface for at least 90 Martian days (sols) with a self-contained, low risk balloon system, capable of piggy-backing with the Entry Descent Landing System (EDLS).

The MNS is composed of the constraints which are mentioned in the project guide.

1.2 Sustainability

The committee on space research (COSPAR) has issued a planetary protection policy in which it is stated that:

> "Although the existence of life elsewhere in the solar system may be unlikely, the conduct of scientific investigations of possible extraterrestrial life forms, precursors, and remnants must not be jeopardized" [42].

To prevent the contamination of other planets with organic material from Earth, space probes have to be cleaned thoroughly. Different categories are distinguished based on the likeliness of life on the investigated body.

For Mars, category IV applies. Category IV missions consist of certain types of missions to a target planet for which biological contamination could jeopardize future scientific research on the presence of life. For Mars, category IV is subdivided in missions which search for life, past or present, and missions that do not search for life. Taking these subdivisions into account category IVa applies to our balloon mission which states:

> "Lander systems not carrying instruments for the investigations of extant Martian life are restricted to a biological burden no greater than Viking lander presterilization levels" [42]

This means that the total bioburden is restricted as follows: fewer than $3 \cdot 10^5$ spores are allowed on the surface with a maximum of 300 spores per square meter [35].

Next to these organic contamination risks and regulations there are also ethical problems with contamination that have to be addressed [46]. The system which will be deployed on Mars will be left on the planet, resulting in contamination of the Martian surface. At least some form of contamination is impossible to avoid if one wants to advance knowledge about Mars. However, the contamination on Mars should be minimised. This includes using a lifting substance that either is already present on Mars or can be shown not to harm the environment. The balloon material should be degradable if possible. How these contamination issues will further be addressed is not clear at this moment and will have to be addressed in the future of this project.

Chapter 2

Planning diagrams

In order to get an overview of the complete planning three diagrams are created. These give the team the opportunity to assess where they are in the project. This chapter contains these diagrams.

The first of these diagrams is the Work Flow Diagram (WFD). This is followed by Work Breakdown Structure (WBS). Finally, the Gantt chart is presented.

2.1 Work flow diagram

To determine the overall course of the project a Work Flow Diagram is made [43]. For each project phase the necessary actions and deliverables are grouped and arranged in a hierarchy. This enables the project group to find, at each moment in time during the project, what needs to be accomplished.

2.1.1 Project Plan

The whole Work Flow Diagram is broken up in four parts. Each part is separated by an official review moment. The first part is shown in figure 2.1 on page 5. As can be seen in the flow diagram it is first determined what the mission is about. The Mission Need Statement (MNS) and the Project Objective Statement (POS), found in the project approach section, summarise this. The source for both the MNS and the POS are the Project Guide, Deliverable Item Descriptions (DID's) and lectures.

After determining the goal of the project the different items has to be put in the correct order. Because the WFD, schedule and Gantt chart all address this issue they are worked out in parallel. The Work Breakdown Structure (WBS) is created during the development of the WFD and partly uses this as a source, therefore, these are also parallel and interdependent processes. The four charts are a guideline during the project which show what needs to be done at which moment in time.

The report template design and the set-up of the IT-structure occur independent of the content of the project and therefore they are shown as individual processes. After the important wire-frame of the project is set-up the rest of the necessary structure and agreements are determined. The agreements are summarised in the team rules and the team structure is described in the organogram. Finally, a risk assessment is added as well as considerations about sustainability.

2.1.2 Baseline report

As the goal of the project is clear at this point it is now important to determine the baseline requirements. These requirements can be obtained from different sources shown in the hexagons at the beginning of the flow chart in figure 2.2. After all these requirements are obtained they can be divided in four groups, **1)** the requirements which are set by the ESA, **2)** the requirements that are set by the MNS and POS, **3)** the constraints that are set by the physical properties of the Entry Descent Lander (EDL) and **4)** the constraints that are set by the Martian environment. The division is made because this makes it easier to assign the requirements to the systems.

From the different external requirements and constraints the minimal system requirements are determined for the sensor, the balloon and the system bus. All the minimum specifications are summarised in the requirement discovery tree.

From the requirements the system functions can be deduced. For a clear overview these functions will be ordered in a functional flow diagram, which shows the functions usage in time, and a functional breakdown structure, which orders the functions in a hierarchical way, just as is done with the work flow and work breakdown structure. The final product of this phase is a set of requirements, which is used as input for the concept generation that takes place after this phase.

2.1.3 Mid-Term report

As can be seen in figure 2.3 on page 7 this phase uses the baseline requirements to create several design options. All possible design options are structured in a tree and serve as a source for different concepts. Parallel with the concept generation different criteria are determined to which the designs should comply. These criterian will later be used in the trade-off. At this moment the prototype design should have started. This ensures that the prototype will be ready during the final phase of the project.

After several concepts are generated they will all be analysed to determine resource usage and possible risk factors. The results from these analyses will be used to improve the design in an iterative way. These factors will also play a role during the trade-off. After the trade-off one concept will remain which will be designed in detail in the following phase. One or multiple aspects of this final concept will also be tested with the prototype.

2.1.4 Final report

The final phase, shown in figure 2.4, mainly consists of working out the details of the chosen concept such that it can be made into a detailed design. Simultaneously with the detailed design, the prototype construction will start. During the finishing of the detailed design the exact scaling method is determined such that the results obtained on Earth can be used for the Martian vehicle. Because only limited real-life testing is allowed, a simulation will also be made to perform tests. The result from the simulation and from the prototype measurements will be used to alter the design. These alteration will again be tested in the simulation to see if the desired results are obtained. This iterative process will then lead to a final design.

The final design then will be visualised on a poster such that it can be presented on the International Planetary Probe Workshop. The final two weeks of the projects are dedicated to preparing a presentation and making a poster for the Design Synthesis Exercise Symposium.

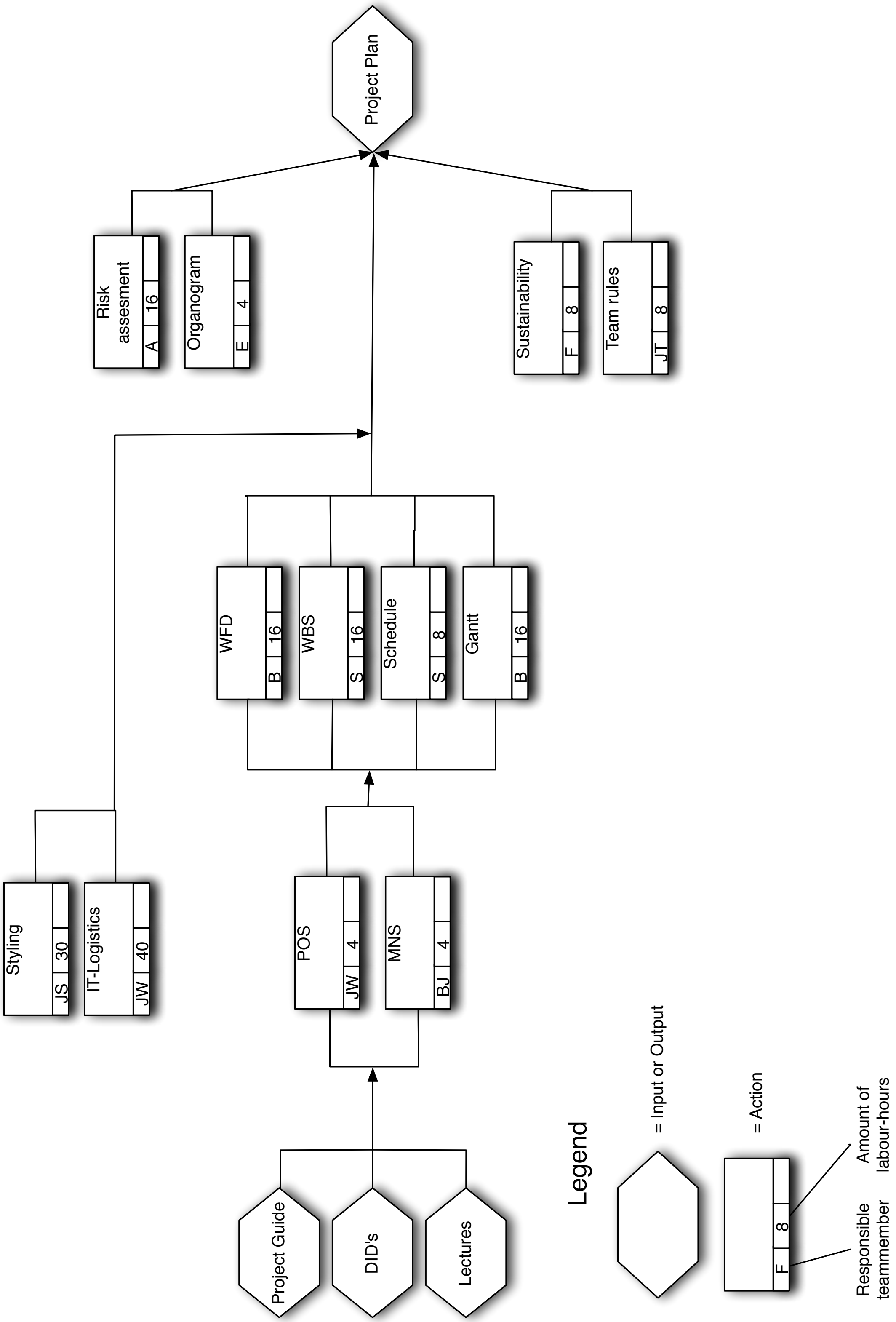


Figure 2.1: Work Flow Diagram: Project Plan phase, an outline for the complete project is derived from the project objective statement (POS) and the mission need statement (MNS)

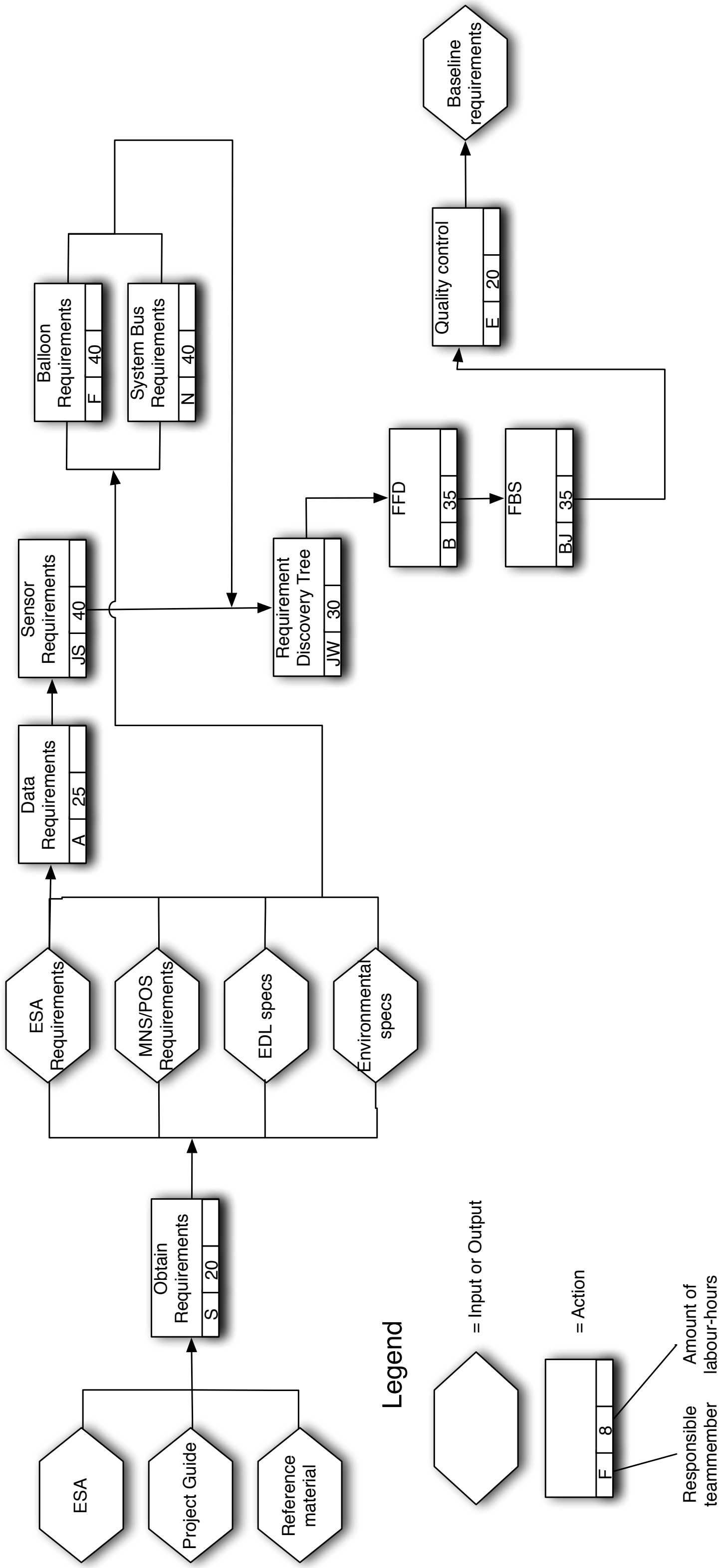


Figure 2.2: Work Flow Diagram: Baseline Requirements phase, requirements are formulated from constraints and requirements with which the system has to comply

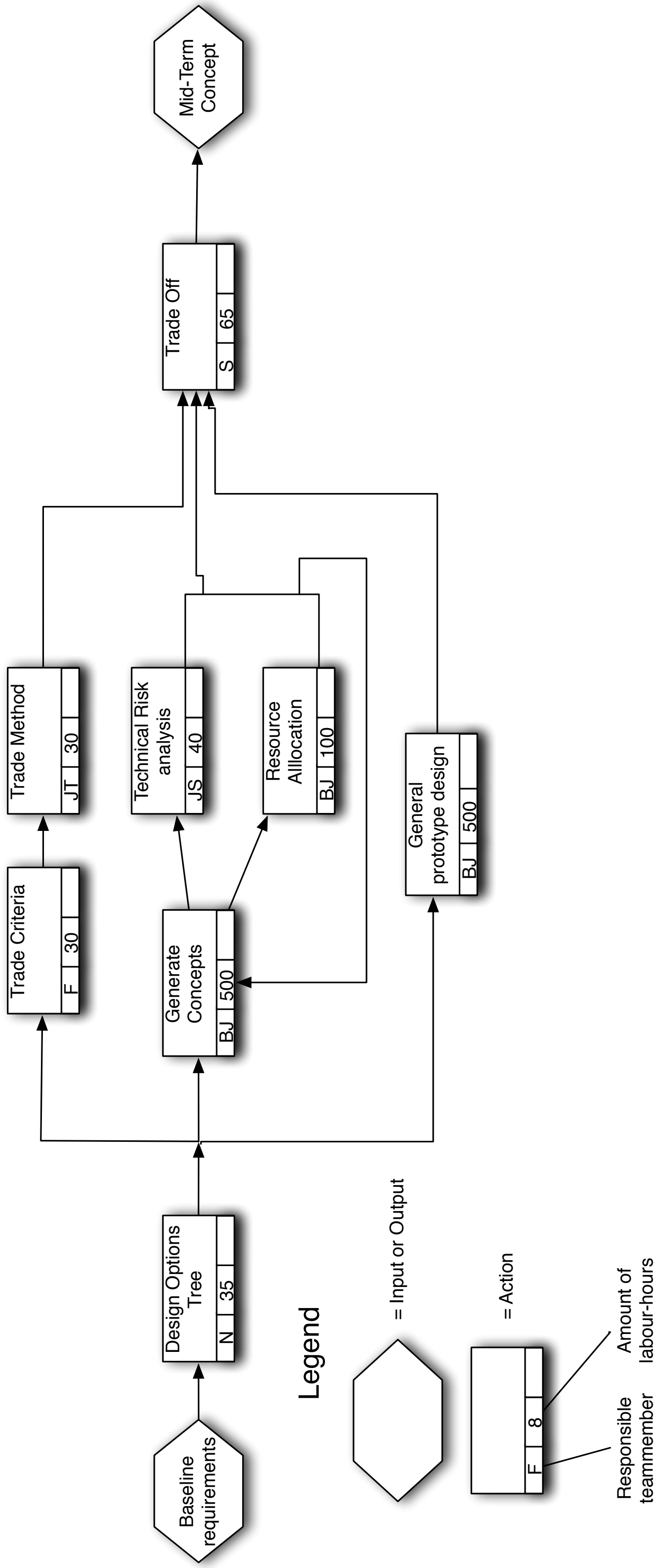


Figure 2.3: Work Flow Diagram: Mid Term review phase, concepts are generated from the requirements and a trade-off is prepared and carried out

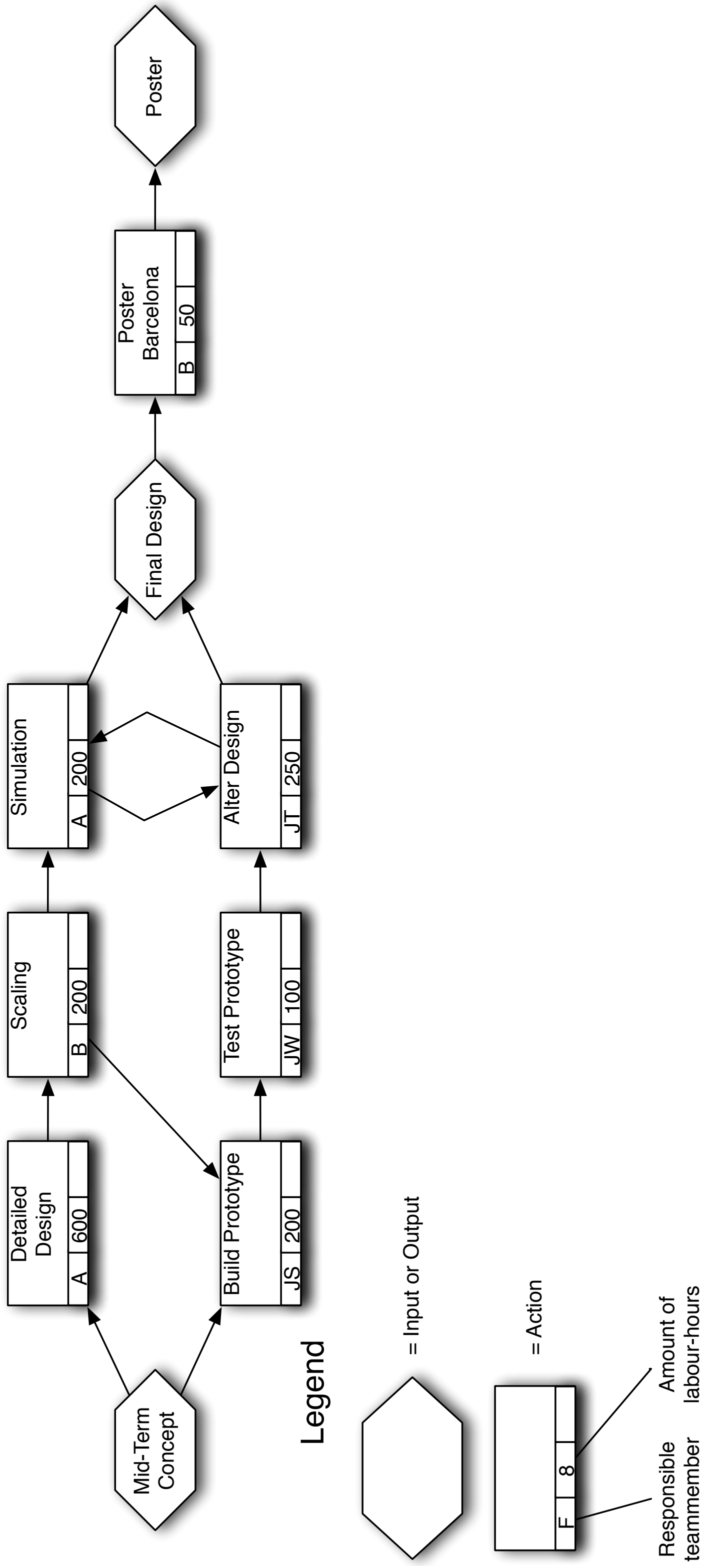


Figure 2.4: Work Flow Diagram: Final review phase, detailed designing which will be tested by prototype testing and simulating

2.2 Work break-down structure

The Work Break-down Structure (WBS) is shown in figure 2.5 on page 10. The main branches of this diagram are based on the most high-level tasks described in the Work Flow Diagram. These main branches are then divided into subtasks. The Work Break-down Structure will be used to track work packages and assign package responsibilities during the entire project. The time dimension of these work packages is displayed in the Gantt chart in the next section.

- **Project Planning**
  The tasks related to the planning of the project are gathered under this heading. These tasks are not directly related to the Delft2Mars project, but solely related to the organization of the working environment.

- **Requirements**
  The generation of requirements and other tasks related to requirements that are found in the WFD are put under the branch called Requirements.

- **Concepts**
  Tasks in this section have to do with the conceptual phase of the Delft2Mars project.

- **Trade-off**
  Items under this heading are related to the preparation and the actual trade-off of concepts.

- **Detail Design**
  The section detail design includes tasks that are done after the trade-off has taken place. These tasks are meant to add more detail to the designs made during the conceptual phase.

- **Experimental**
  The 'experimental' tasks are there to support the trade-off and detail design phases. Everything related to the trade-off, instrument selection and building of the prototypes is found here.

- **Document and present**
  This broad group of tasks includes every task related to the communication of the concepts and ideas generated during this project to the outside world. The main parts are the reports for our tutors and coaches, the European Space Agency (ESA), the final presentation in Delft and the presentation in Barcelona.

2.3 Gantt chart

The Gantt chart is displayed in Appendix B and shows the work packages listed in the work break-down structure in chronological order. A large copy of this document is placed at a prominent position in the workplace and will be used to track the long term progress of the group.

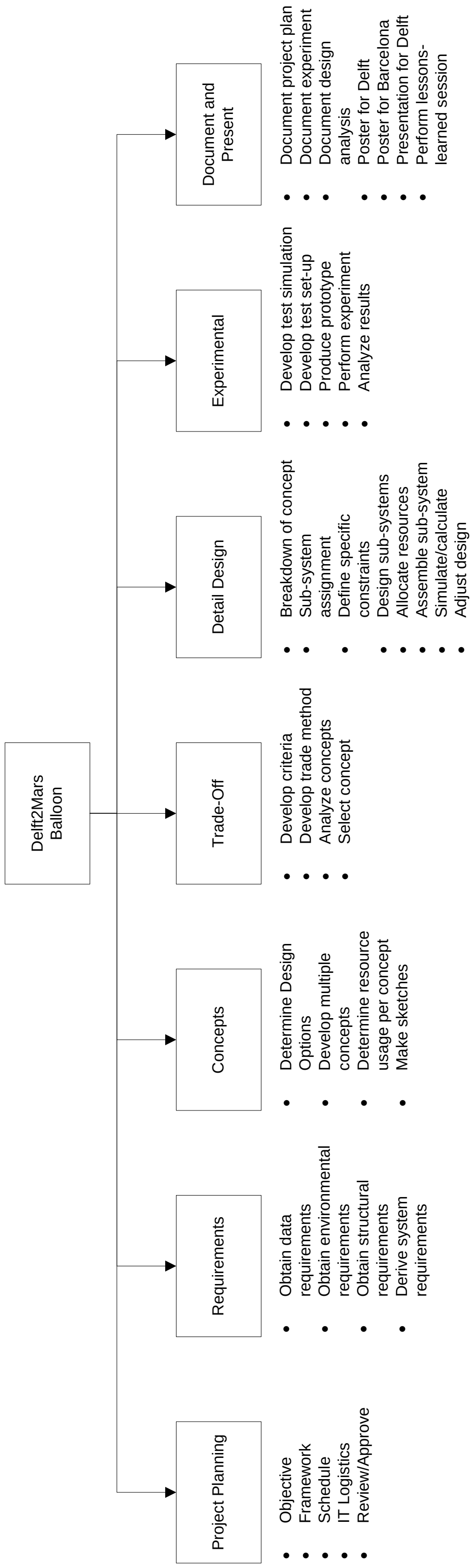


Figure 2.5: Work Break-down Structure

Chapter 3

Organisation and planning

This chapter will describe the way the group hierarchy is constructed using an organogram, including descriptions of each task within the group. Some rules are also mentioned which have been determined to ensure an efficient working environment. The team organisation will be discussed first. This includes organisation of meetings, tasks and organisation, and team rules. This is followed by project risk management, which also addresses issue tracking, which resembles a digital logbook.

3.1 Team organisation

As it needs to be clear in a group what everybody's responsibilities the team organisation structure will be shortly discussed.

3.1.1 Meeting structure

Meetings will take place daily at 9:30 AM. The topics discussed during the daily meetings will be listed on the whiteboard in the dedicated Agenda section. During the course of the day, team members will be able to add agenda points for the upcoming meeting to this section of the whiteboard. Further topics for the meeting will be gathered from DSE course documents and upcoming deadlines. If any other important topic will come up during the meeting, this topic will be added to the bottom of the agenda such that it can be discussed later.

3.1.2 Tasks and organisation

A breakdown of the task allocation within the group is given in Figure 3.1. The different tasks will be worked out below.

- Chairman
  The chairman will lead the daily meetings in an efficient way, this includes clearly indicating when every meeting starts and ends. During the meetings, the chairman will make sure everybody is involved in the discussion, that the topic of discussion is clear and that the laptop policy[1] is enforced.
- Secretary
  The secretary writes down all tasks, appointments and decisions discussed in the daily meetings and uploads the notes to the Dropbox folder. Furthermore, the secretary will take notes during lectures and upload them to the Dropbox folder as well.

[1] See team rules

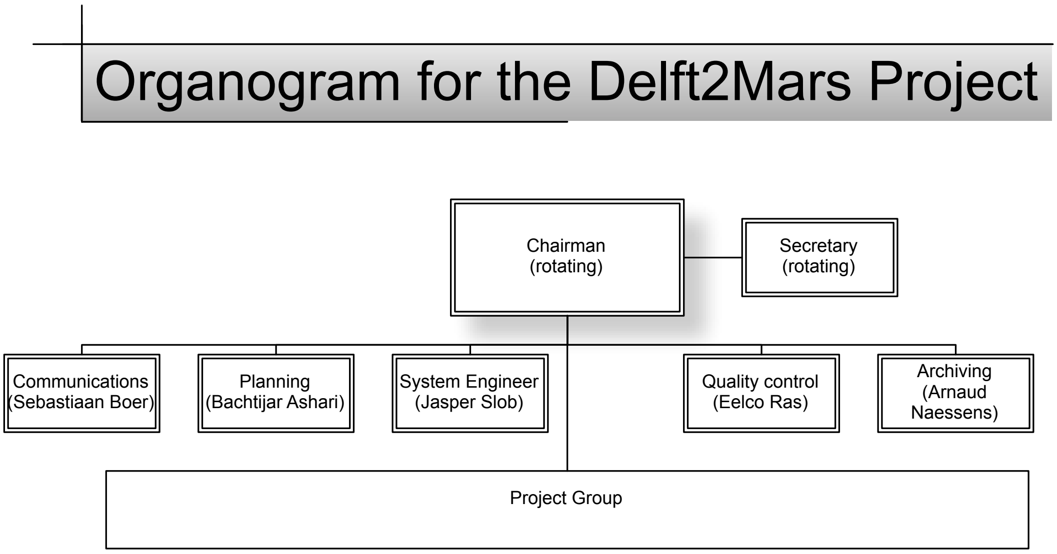


Figure 3.1: Organogram for the Delft2Mars project

- Quality Manager
  The quality manager will examine the process and deliverables to ensure that they meet certain quality standards. This includes, but is not limited to, verifying that argumentation is sound and sufficient, confirm that all required deliverables are included, ensuring a uniform style, and checking for spelling or grammar mistakes.

- Archiving
  The archiver stores all documents, paper and digital, in a proper way such that the other team members are able to locate them when necessary. This will include, but is not limited to, placing documents into the right folders and taking care of references in the final report and management of version history. Finally, the archiver will make sure the contents of the whiteboard are not wiped out when they are not ought to be.

- Communications
  The person in charge of communications will obtain external contacts and maintain them during the course of the project. This person will make sure that external contacts are not overloaded with questions, and especially that the same questions are not submitted to the same person by different members of the team. Team members will check with the communications person before contacting outside contacts in order to avoid any disturbances.

- System Engineer
  The system engineer sees to it that all planning tools and diagrams are complete, consistent, up to date and non-conflicting. He will keep an eye on the long-term planning and alert the team when it is falling behind schedule.

3.1.3 Team rules

To accommodate an efficient and pleasurable working environment several rules have been set up which the team decided upon during the first few meetings. The team members are expected to follow these rules strictly, though a deviation from the rules for a good reason should never be discouraged, as is reflected by rule 7.

1. The project day starts at 9 AM.

2. Team members shall be on time. Failure to comply will result in the following measures:

   - Over 15 minutes late: the member in question is to buy everyone coffee or tea.

- Over 30 minutes late: the member in question is to buy everyone coffee and bring a cake the next project day.
- Over 60 minutes late: the group will decide on a measure by majority.

3. A meeting will be held on every project day at 9:30 AM. During these meetings all laptops are to be closed unless the situation dictates otherwise; one of the LCD screens may be used for informative purposes.
4. During the meetings each team member will briefly inform the team on his activities and progress of the previous day. Other topics team members want to discuss can be listed in the dedicated Agenda section on the whiteboard. The chairman will preside over the proceedings and ultimately decides on the topics to be discussed.
5. Absence is only possible when coordinated with the tutor(s), and the team can decide on assignments for the absent member to make up for the absence in his spare time.
6. Team members shall leave no earlier than 6 PM, unless an exception is made under rule 5.
7. Team members shall always be reasonable and fair in their interactions.

3.2 Project risk management

This section identifies the possible project management risks. For each individual risk event, precautionary actions and a contingency plan will be described. The risk event drivers below are sorted by priority.

- Inadequate organisation
  Impact: Chaotic work environment
  Solution: A clear definition of a distinct function structure known to all team members.

- Computer failure
  Impact: Loss of time and (partial) loss of project work.
  Solution: The use of backups and the revision control system 'Subversion' is a remedy to reduce the damage of a computer failure.
  Deficient work distribution, unanticipated tasks and uncoordinated concurrent engineering are of similar importance.

- Deficient work distribution
  Impact: Loss of efficiency due to work overload or lack of work for certain people
  Solution: A remedy for the risk driver 'deficient work distribution' is to have a common agreement about task distribution. Furthermore, a special function within Google Code is used to track work packages.
  This is discussed in more detail in the following section.

- Unanticipated tasks
  Impact: Last minute work when noticed, loss of quality when not noticed.
  Solution: Keep all planning tools up to date, and add new tasks as soon as their necessity becomes apparent.

- Uncoordinated concurrent engineering
  Impact: Parallel activities could lead to work done twice or to work that should have been done sequential.
  Solution: The main remedy against mishaps in coordination in concurrent Engineering is extensive communication within the project group. This means that, apart from the official communication, all persons involved should be aware of the project progress. If necessary, a meeting will be set up to clear up all confusions.

- Absence of personnel
  Impact: Time shortage, higher pressure and work overload
  Solution: The risk of absence of personnel can be averted by adjusting the project planning accordingly. The contingency plan is to have the absent person make up for their lost time outside of the project.

- External contacts
  Impact: Delay of information, conflicting information.
  Solution: A remedy for this risk is to timely send requests for information and this way be ahead of the game. In case this risk actually occurs and specific information is needed from external contacts within a short time frame, the team members will try calling the external contact. If this is not possible, the team can decide to make an assumption about the data at hand.

3.3 Issue tracking

The tasks shown in the Gantt chart (Appendix B) are split for issue tracking. Using the Google Code repository (http://code.google.com/p/delft2mars/) all the tasks that need doing, on a chapter level, are indexed in an online logbook. To be able to track the progress of these tasks a status can be assigned to them. Every status represents a different step in the process of performing and assuring the quality of tasks:

- WIP - A new task has been started (Work In Progress).

- CheckMe - The task has been finished, but needs checking.

- Checking - The task is being checked by any team member but the quality manager. This prevents teammembers working on same issue on same time.

- Finished - The task has been checked, but needs approval from the quality manager.

- Approved - The task has been approved by the quality manager and is thus in a deliverable state.

3.4 Schedule

Besides the detailed schedule charts, this schedule provides the group with an overview of all the deliverables and the activities directly related to them.

- **Week 1: April 19th - April 23th**
  Activities:
  DSE kick-off
  Getting to know each other
  Determining the goal of the exercise
  Accurate planning of the coming project weeks
  Determining the work involved

  Deliverables:
  Project Plan
  Organogram
  Work Flow Diagram
  Work Breakdown Structure
  DSE Schedule Gantt chart
  Sustainable development approach

- **Week 2: April 26th - April 30th**
  Activities:
  Determining the requirements
  Determining the functions of the system

  Deliverables:
  Baseline report
  Requirements Discovery Tree
  Functional Flow Diagram
  Functional Breakdown Structure

- **Week 3: May 3rd - May 7th**
  Activities:
  Determining all design options
  Development of multiple concepts
  Trade-off preparation

  Deliverables:
  Design Options Tree
  Concepts
  Trade-off criteria

- **Week 4: May 10th - May 14th**
  Activities:
  Developing multiple concepts
  Visualisation of the concepts
  Determining resource usage per concepts
  Trade-off

  Deliverables:
  Mid-Term report
  Concept designs
  Trade-off method
  Configuration definition
  Technical Risk Assessment
  Final concepts

- **Week 5: May 17th - May 21th**
  Activities:
  Breaking up of the chosen concept into different sub-systems
  Detailed design of each sub-system

  Deliverables:
  Sub-system division
  Constraints overview
  Detailed designs

- **Week 6: May 24th - May 28th**
  Activities:
  Detailed design of each sub-system
  Assembly of the sub-systems

  Deliverables:
  CATIA drawings of the system and its components

- **Week 7: May 31th - June 4th**
  Activities:
  Simulating the system in MATLAB
  Adjusting the design
  Constructing the prototype
  Testing the prototype
  Preparing the poster

  Deliverables:
  Simulation results
  Prototype
  Experiment results
  Final design
  Draft report

- **Week 8: June 7th - June 11th**
  Activities:
  Writing the report and executive summary
  Designing and producing the poster
  Preparing a presentation outline

  Deliverables:
  Final report
  Poster
  Executive summary

- **Week 9: June 14th - June 18th**
  Activities:
  Presentation preparation
  Creating visual support for the presentation

  Deliverables:
  Draft presentation

- **Week 10: June 21th - June 25th**
  Activities:
  Presentation preparation

  Deliverables:
  Final presentation

Chapter 4

Design options

When brainstorming about different possible balloon designs, it is clear that many sub-systems need to be worked out. These sub-systems all have alternative possibilities. When arranging all the elements in a list, it quickly becomes unclear to the designer which choices of subsystems are available. The design option tree, often abbreviated as DOT, provides a solution to this problem. The tree is an 'or' tree, meaning that when moving to a sub-level of the tree other design options on the levels above will be discarded. If it is decided for example to use wind energy, it is undesirable to also have a nuclear power source on board of the satellite. The tree is based on the concepts generated, and will change when new design options are added. In this chapter the concepts are discussed first in section 4.2. The deployment of the balloon is discussed next in section 4.3. The design options from section 4.2 are combined into the DOT in figure 4.1. Lastly some choices are made from the DOT, resulting in three concepts ready for the trade off, treated in chapter 6.

4.1 Design option tree

The DOT gives a brief overview of the options. However, it will also help the designer eliminate design options, and combine solutions of different trees for a general concept. The DOT can be found below.

4.2 Subsystem Concepts

Before any detailed designing can take place, concepts need to be defined. This section is dedicated to those concepts. For simplicity and flexibility the concepts are split up into subsystems. The most important subsystem discussed in section 4.2.1: the balloon shape itself. In section 4.2.2 the gasses that could keep the balloon afloat are discussed. Following that, section 4.2.3 discusses the reeling of the cable when the balloon is tethered. The power concepts are treated in section 4.2.4. Finally payload concepts are discussed in section 4.4.

4.2.1 Balloon shape

The shape of the balloon is a very important parameter. It affects the way it is inflated, what stresses it can withstand and the drag coefficient. The most simple shape for a balloon is the near spherical shape of COTS products [27]. The advantages and disadvantages are listed in table 4.1. The drag could be both a positive and negative factor. For a tethered balloon it could be undesirable. A higher drag will increase the wind loading on the cable. However

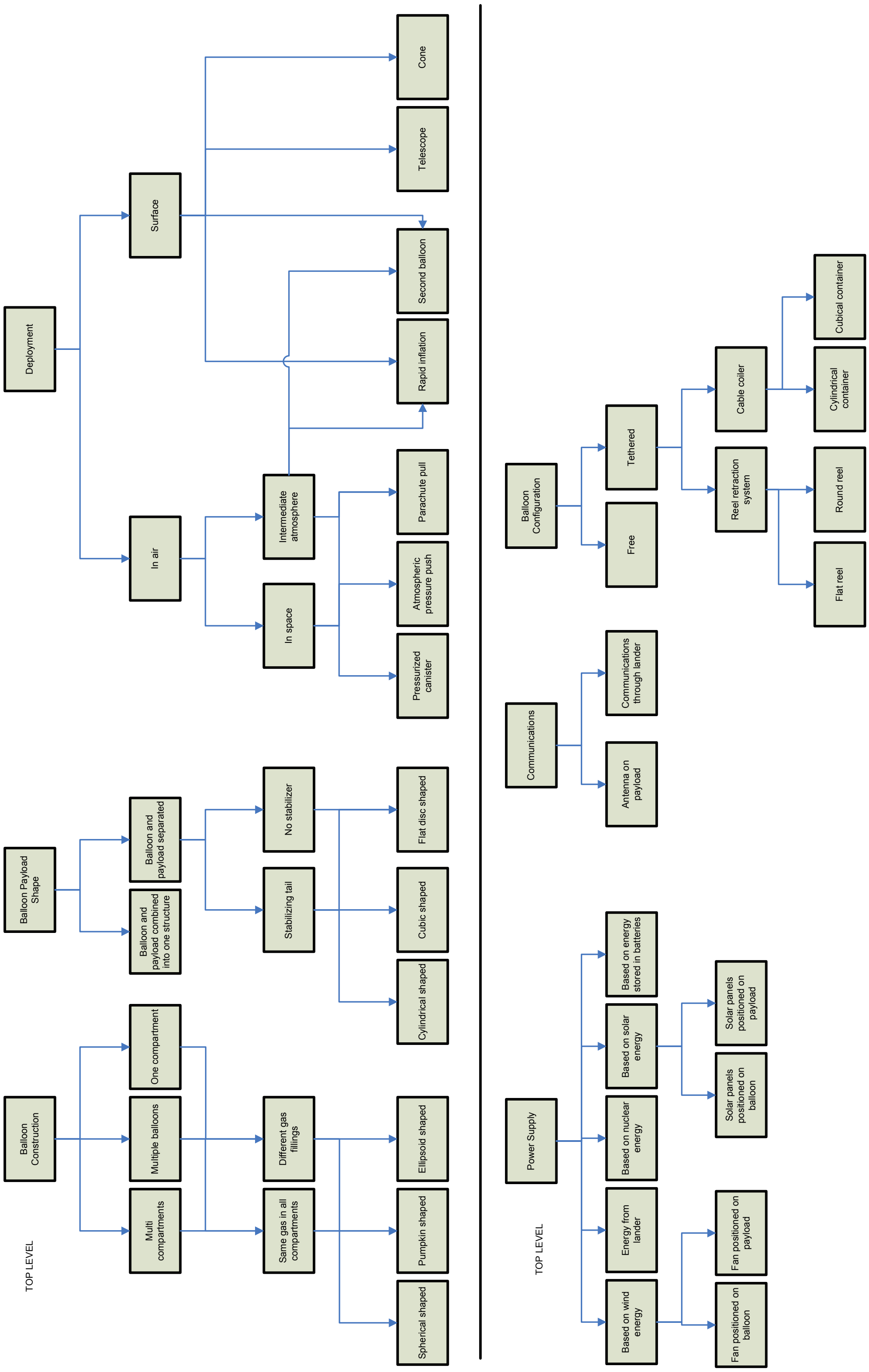


Figure 4.1: Design option tree

for a free balloon it could be advantageous to have a high drag. A higher drag will make it possible to cover more ground using the wind. In order to reduce the drag (if necessary) the balloon could also be made in an ellipse. If the balloon relies on the sun to heat the lifting gas, which generates extra lift, there is more surface area that is heated by the sun. However a balloon shaped like an ellipse might not be commercially available. The additional characteristics are summarized in table 4.1.

Pumpkin balloon

An option designed and built by NASA is the pumpkin balloon. The volume of this type of balloon is proportional to the radius to the third power and the stress is directly related to the radius. Therefore, the stress will be determined by the volume of gas needed for the mission. A design that successfully distributes stresses in the balloon skin is called a "pumpkin" balloon, which is visualised in figure 4.2. It can withstand five times the pressure of a sphere with the same volume. By shortening the seams of a fabric balloon with a sewing machine, excess material in the circumferential direction is introduced. Consequently, the circumferential radius of curvature is reduced and higher pressures can be accommodated. The advantages and disadvantages for the pumpkin balloon design can be found in table 4.1.

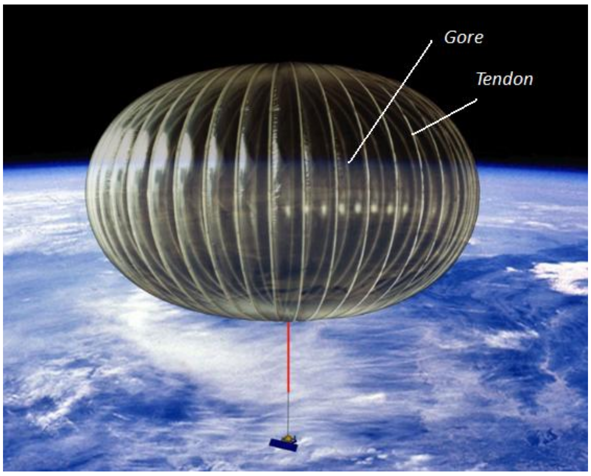


Figure 4.2: A "pumpkin" shaped balloon [24]

Multiple balloons

LLDPE or Mylar balloons are very vulnerable. Generally, they are only 20 μm thick [38]. Keeping that in mind it is wise to create some redundancy. This could be done by using a cluster of multiple balloons. If one of the balloons fails, the mission need not be over. Of course the maximum altitude achievable will decrease, but the mission could proceed. A downside of having multiple balloons connected to the payload is that it will increase the mass for the same amount of lift compared to a regular COTS balloon limiting the amount of payload mass. The advantages and disadvantages for a multiple balloon design are present in table 4.1.

Multiple compartment balloons

An adaptation to the theme of redundancy is a balloon with multiple compartments. This would remove the need for extra cables. Yet it also means that material only 20μm thick

needs to be fused together to make an airtight seal. That could prove to be quite a challenge to overcome. In table 4.1 the advantages and disadvantages can be found.

Montgolfiere - helium hybrid

Blamont [12] suggests a Montgolfiere balloon where two balloons are present. The first is a helium balloon that generates enough lift to keep the second main balloon afloat at night. By keeping the second balloon in the air it is protected from the Martian surface. The payload will rest on the Martian surface at night. The advantages and disadvantages of a Montgolfiere-helium hybrid are described below (table 4.1).

Table 4.1: Advantages and disadvantages of balloon shape

Balloon type	Advantages	Disadvantages
COTS spherical balloon	COTS, so probably cheaper than developing one in-house High drag	High drag
Elliptical balloon	Less drag than a sphere [26] More surface area visible to the sun	Not COTS available
Pumpkin balloon	It can withstand five times more pressure than an ordinary COTS balloon. Mass penalty much smaller for higher pressures.	Not commercially available, but under development by NASA.
Multiple balloons	Redundancy Higher drag COTS	Higher drag More mass The individual balloon cables can get entangled
Multiple compartment balloons	Redundancy Less drag compared to cluster Only one cable so no likelihood of entanglement	Not COTS available Difficult to produce
Montgolfiere - helium hybrid	The helium balloon keeps the Montgolfiere from touching the surface	Not COTS available Complicated Heavier than a single balloon

4.2.2 Balloon gases

A balloon needs to create lift to ascend. This is done by filling the balloon with a substance which has a lower density than the surrounding atmosphere. Six lifting substances are treated in this section: starting with hydrogen, helium, water, ammonia, carbon dioxide and finally methanol are described in the following sections.

Hydrogen

The most obvious choice for a lifting gas would be hydrogen, as it is very light. Hydrogen has a molar mass of only 1 g/mol [21]. This results in a density of 0.39 kg/m^3 (using equation (8.4) with M = 1) in the atmosphere of Mars. However, hydrogen has one major drawback: it is highly flammable [44]. The flammability of hydrogen gas might restrict it from being used in this project, since this project needs to be low-risk. From a sustainability point of view, this would be a possibility. Although hydrogen does not occur in the Martian atmosphere, it can react with the available oxygen to form water vapour. This does occur naturally in the Martian atmosphere [19]. The advantages and disadvantages of hydrogen gas as a lifting gas are presented below table 4.2.

Helium

Just like hydrogen, helium is a very light gas. Though helium is more dense than hydrogen, with a density of 1.54 kg/m^3 (using equation (8.4) with M = 4 g/mol [45]) at Martian temperatures and pressures, yet the density is low enough to ensure the balloon will rise into the atmosphere. An advantage helium has over hydrogen is the fact that helium is inert, whereas hydrogen is highly flammable and thus dangerous. Nevertheless, helium has its own risks: the gas has to be compressed when transported from Earth to Mars, because it would simply take up too much space otherwise. Also helium will leak through polyethylene and rubber materials [33]. Bringing a pressure vessel into space will create an additional risk, as it will have to be very robust to withstand launch loads without failing. Furthermore, there is a chance of damage to the launcher if the canister would fail on the way to Mars. According to E.J.Grayzeck [19] helium does not occur in any significant amounts on Mars. It is not known what influence introducing helium will have on the Martian environment. The advantages and disadvantages are listed in table 4.2.

Water

In an attempt to reduce the complexity of the mission introduced by bringing compressed gas canisters to Mars, Zubrin et al.[48] suggest bringing water as a fluid. When the balloon is heated by the sun, the water (which is present on Mars only in the form of a solid or a gas [14]) will sublimate. Following the increase in temperature the pressure and thus the volume of the balloon will increase. This will cause the density of the water in the balloon to decrease. When the density of the water is lower than that of the Martian atmosphere, the balloon will start to rise, as is shown by equation (8.1). Water occurs in small amounts on Mars [19], thus it is acceptable to leak a small amount of water, needed to lift the balloon, into the atmosphere after completion of the mission. However it does need to be sterilised thoroughly. The pros and cons are summarised in table 4.2.

Carbon dioxide, methanol and ammonia

Other substances not requiring pressure vessels suggested by Zubrin et al. are: carbon dioxide, methanol and ammonia [48]. The achievable payload masses for these substances (and water) are summarised in figure 4.3. However, some of these substances Zubrin et al. suggest could lead to pollution of Mars, as ammonia and methanol do not occur naturally in the Martian atmosphere [19]. Since it is unsure what will happen when ammonia and methanol are released into the Martian atmosphere, no risks should be taken in this respect. Carbon dioxide is a

An alternative approach suggested by Pioneer Astronautics is to place a liquid in the bag that will vaporize at Martian temperatures and pressures, thus filling the bag with a high temperature gas with a molecular weight lower than CO_2. The benefits of using such a positive lift fluid in a solar balloon is seen quite readily in Figures 1 and 2. In Figure 1, we show the payload that can be floated at various altitudes on Mars using an 1529 m^3 commercial off-the-shelf polyethylene balloon manufactured by the Raven company if coated with nickel and inflated variously with CO_2, methanol, ammonia, or water. These balloons are quite lightweight, with an effective surface density of about 6-8 g/m^2, and would reach a temperature of about 340 K on Mars. It can be seen that the water filled balloon can float 12 kg at the surface, or 4 kg at 7 km, which means that such a system could be used to land an 8 kg payload on the surface and then ascend to perform an all-day aerial photographic float at 7 km with a 4 kg gondola. In contrast, the CO_2 balloon could only deliver a 3 kg payload to the surface, and can float no gondola at 7 km altitude.

Table 4.2: Advantages and disadvantages of balloon gases

Balloon gases	Advantages	Disadvantages
Hydrogen	Lightest gas (lowest density)	Highly flammable A pressure vessel is required for transport to Mars
Helium	Very light Inert gas	A pressure vessel is required for transport to Mars
Water	Requires no pressure vessel Mass generally much smaller for higher pressures	Needs sterilization
Multiple balloons	Redundancy	Higher drag
Carbon dioxide, methanol and ammonia	No pressure vessel needed	Ammonia and methanol could pollute Mars

If, on the other hand, we choose to use gold coatings to maximize balloon temperatures, we can no longer employ lightweight polyethylene balloons (they would become non functional at gold's 380 K) and instead must employ Mylar or Kapton systems, requiring netting reinforcement at greater cost. A comparison of the performance of water against CO_2 as a float gas using this balloon technology is shown in Figure 2.

naturally occurring gas on Mars (95% of the atmosphere [19]), so using carbon dioxide would not influence the environment on Mars.

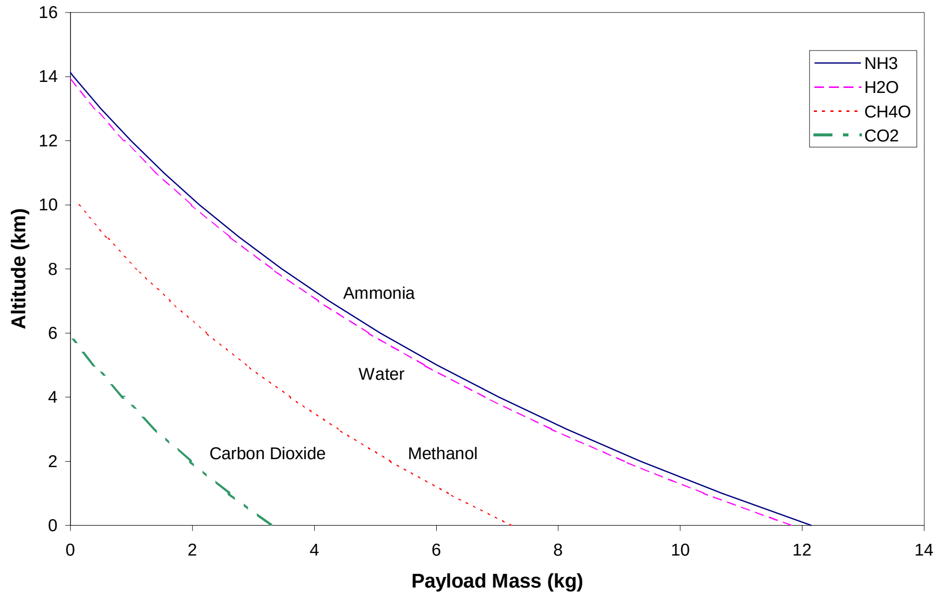


Figure 1. Steady-State Altitude vs. Payload Mass for 1529 m^3 COTS Balloon (Coated with Nickel: $\alpha_s = 0.4$, $\varepsilon = 0.1$)

Figure 4.3: Steady-State Altitude vs. Payload Mass for 1529 m^3 COTS Balloon (Coated with Nickel: albedo $\alpha_s = 0.4$, emissivity $\epsilon = 0.1$)

It can be seen that the performance improvement offered by the use of water in this system is even more dramatic. Finally, since water can perform well in the 340 K environment provided by metallized polyethylene technology, we could compare the performance of water in an metallized polyethylene balloon with CO_2 in a gold-coated mylar balloon of areal density 13 g/m^2. In this case the payload advantage of the water system was found to exceed an order of magnitude over what a CO_2 system could carry with a balloon of equivalent volume.

4.2.3 Cable reeling

When a tethered balloon is considered, cable storage and reeling need to be taken in account. This section discusses three different cable reeling concepts. A conventional reel will be reviewed first. Next a flat reel is treated. Three variations on cylindrical reels are discussed last.

Conventional reel

The option that immediately springs to mind is a conventional reel. Figure 4.4 shows a typical reel. An electric motor will be needed to reel in the cable or give the cable some slack. A spring type of system could also be an option provided the spring has enough travel. The advantages and disadvantages are given in table 4.3.

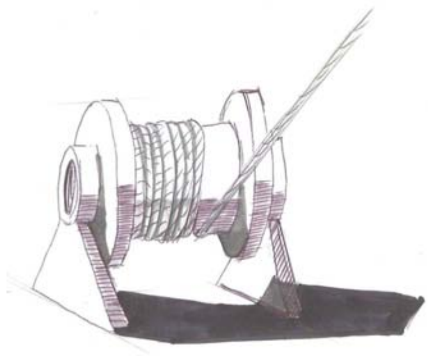


Figure 4.4: A typical reel

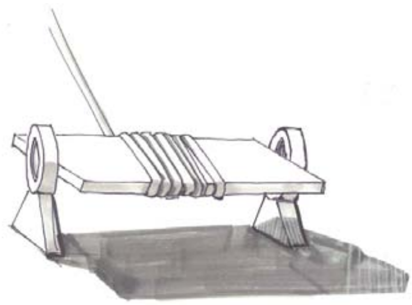


Figure 4.5: A flat reel

In order to save space the barrel of the reel could also be flat. In principle the pros and cons from the regular reel apply. The following additional advantages and disadvantages apply to a flat reel:

+ Takes up less space than the conventional reel.

− The local radius of curvature at the ends could be too small resulting in failure of the cable.

Cylindrical reels

Another option is to have the cable pre-wound on a tube. The system will consist of a cylindrical container. A tube in the centre should keep the cable from entangling. Figure 4.6 shows the cylindrical reel. A list of advantages and disadvantages is given in table 4.3.

Figure 4.6: A cylindrical reel

Figure 4.7: A cylindrical reel with a rotating lid

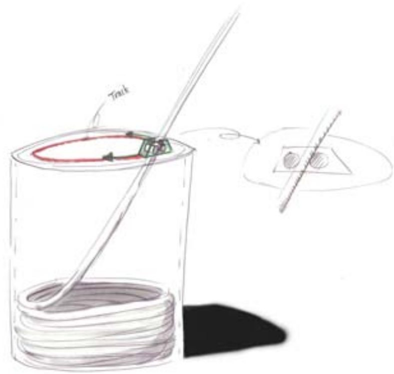


Figure 4.8: Cable coiler.

A variation to the cylindrical reel is a cylindrical reel with a rotating lid (figure 4.7). The lid has a hole that helps the cable coil. The advantages and disadvantages for the cylindrical reel with lid are similar to the cylindrical reel, but now possible to rewind the cable into

the container. Advantages and disadvantages in addition to those of the cylindrical reel are found in table 4.3.

In order to prevent the cable from tearing a mechanism shown in figure 4.8 could be used. The two wheels seen in figure 4.8 pull in the cable when the balloon descends and release the cable when it slackens. The cable coiler also provides an active way of reeling the cable as opposed to the passive way of coiling applied by the cylindrical reel with the rotating lid. It has two advantages over the cylindrical reel with rotating lid as shown in table 4.3.

Table 4.3: Advantages and disadvantages of cable reeling

Reel type	Advantages	Disadvantages
Conventional	Relatively easy to design Protects the cable from damage caused by touching the surface Simple Inert gas	In the case of an electric motor, the system uses energy to spin the reel Does not protect the cable from debris carried by the wind
Flat	Requires less space	
Cylindrical	No moving parts The cable is protected from the environment when stored The container could also act as transport container for the complete system	The cable could become entangled Rewinding is not possible
Cylindrical	The cable can be recoiled	Power is needed to rewind the cable The friction on the hole could damage the cable
Rotating lid with two wheels	Less risk of cable damage due to pulling mechanism Active coiling instead of passive coiling	Dust can easily damage the cable when it gets trapped between the wheels The wheels have to exert much force which could damage the cable.

4.2.4 Basic power concepts

Power supply is one of the most important factors in the Delft2Mars balloon mission. Without power the instruments and communications will not work. Different power sources can be used for the power supply of the balloon. A form of energy often used in space missions around planets near the Sun is solar energy, as the solar flux is strong enough to generate sufficient power. In case of the Delft2Mars balloon, the solar panels could be placed on top of the balloon, see figure 4.9. Another solution is to place the panels on the payload box, as shown in figure 4.10. Both configurations have their advantages and disadvantages, which are obtained from Sabbadini et al.[40], and are stated below each figure. Less conventional alternative solutions are discussed further on in this section.

Solar panels on top of the balloon

Solar panels are widely used in satellite applications. Due to extensive research in the recent decades the photovoltaic panels have become lighter and more efficient.

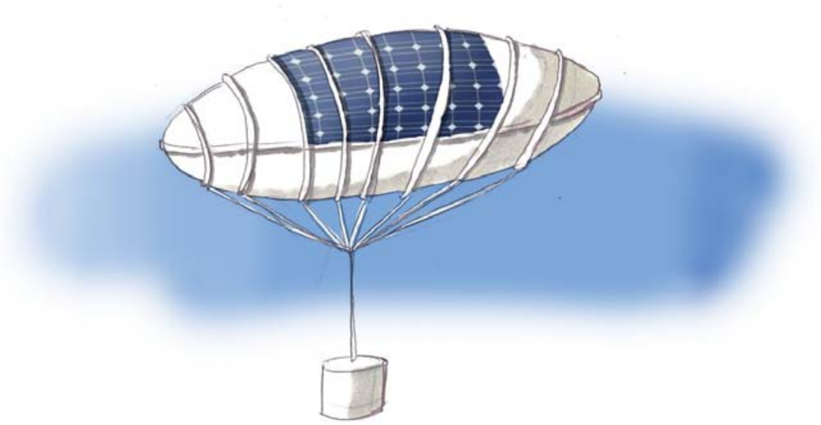


Figure 4.9: Solar panels on top of the balloon

Solar panels on the payload

Figure 4.10: Solar panels on the payload

Mirrors could be placed to concentrate the light, in order to create a higher efficiency of the solar panels. The mirrors will increase the weight. Therefore it will have to be investigated if the increase in efficiency of the panels will be greater than the penalty of increasing weight by using the mirrors.

The advantages and disadvantages can be found in table 4.4.

Wind energy

The wind on Mars is an important force one has to keep in mind when designing a balloon [19]. This force does not only pose danger to the mission, but could also be used to its advantage. Where a fan could be placed on the balloon this concept will generate power only when the balloon is kept at a constant place with wind, which only is the case with a tethered design. The mass/power ratio of a solar panel configuration can be larger than a configuration consisting of a small fan, figure 4.11. The advantages, disadvantages and (as yet) unknowns are stated below in table 4.4, and are partially derived from Bluck [13].

Figure 4.11: Fan configuration based on wind energy

Nuclear energy

Another option is to consider using nuclear energy. Nuclear energy is used often for missions on planets further away from the Sun, where the solar intensity becomes too small to generate sufficient energy [47] by solar panels. Furthermore nuclear energy is able to generate more power and thrust than solar energy and fossil fuel, but will increase the mass significantly. When considering nuclear energy, the payload could contain a small power plant which generates energy for the balloon. Again the advantages and disadvantages are stated below, and are partially derived from Zaitsev [47].

Batteries

Instead of obtaining the energy from the environment, one could install batteries as only power supply. The advantages and disadvantages:

Obtain power from EDL vehicle

When one selects the tethered balloon, an extra option appears: implementing a conducting cable into the structural cable so power can be obtained from the lander. The advantages and disadvantages are listed in table .

Table 4.4: Advantages and disadvantages of cable reeling

Power concepts	Advantages	Disadvantages
Solar panels (balloon)	Efficient due to angle of incidence	Does not work at night Heavy load on balloon material, as the material is very thin and fragile Difficulties during inflation Manufacturing difficulties (double curved solar panels)
Solar panels (payload)	No load on balloon material Could be combined with use of a stabilising fin	Does not work at night Could be overshadowed by balloon
Wind energy	No load on balloon material	Too heavy (section 6.3) Reliability depends on wind
Nuclear Energy	Constant power supply Heat supply for thermal control Lower mass/power ratio	Could influence Martian environment (radiation) high impact in case of failure Experimental technology Experimental technology Very expensive Shielding required
Batteries	Constant power supply Heat supply for thermal control Mass reduction due to the absence of power generating instruments	Mass increase due to battery mass, which is much larger than the reduction When using a battery of reasonable size, it is only possible to supply the balloon for few sols not 90 sols [31]
Power from EDL	Constant power supply Mass reduction of the balloon: the power generating instruments are installed on the lander	Mass of the cable increases When the conducting cable breaks, the mission will fail. The chance of fractures occurring in the conducting cable is rather high, because the tensile and thermal properties differ from the structural cable

4.2.5 Thermal control subsystem

The payload must be engineered to withstand strong fluctuations of temperatures in the Martian environment. This is made possible by using a Thermal Control System (TCS). The function of the TCS is keeping the temperature of the payload within a prescribed range, this in turn requires monitoring that temperature.

After a conversation with engineers of the Concurrent Design Facility at European Space Research and Technology Centre (ESTEC) in Noordwijk, it can be concluded that two major thermal related problems can arise.

First of all, during the night temperatures on Mars attain very low values. The instruments need a minimum temperature to operate properly, meaning that they will fail when not heated at that moment. Heating requires a large amount of power for an extended period of time, and this heating energy can not be stored in batteries due to weight constraints. The problem is that it is not possible to use enough power from the lander at night for heating, since the lander will then need most of the available power to keep its own systems warm.

Secondly, during the voyage to Mars certain thermal factors need to be considered. Three factors that can cause problems during this phase of the mission are known so far. The first problem could arise when using helium or another substance as balloon gas: a high pressure tank containing the gas will have to be kept at a low temperature during transport to Mars due to structural requirements. Furthermore, during the voyage to Mars some parts of the payload will have to be kept above a certain temperature by heating them. This could easily be accomplished by using the power subsystem of the launcher, which in turn could obtain its power from solar panels. Finally, if a nuclear heating unit is used, it will have to be cooled since this unit already produces a lot of heat during the trip to Mars. This nuclear heating unit will also be discussed in this paragraph.
For thermal control of the payload two techniques can be used:

Passive thermal control

The first option [17] is to use passive thermal control such as applying surface finishes, regulating conductive heat paths and selective placement of power dissipating components.

1) Surface finishes [18]:
Wavelength-dependent thermal control coatings such as solar reflectors can be used to minimise the absorbed solar energy, but emit energy almost like a black body.

2) Insulation [18]:
The payload will also need to be insulated. Multilayer insulation (MLI) can be used either to prevent excessive heat loss from a component or excessive heating from environmental fluxes. Providing cut-outs for radiators could solve the problem of internally generated waste heat.

An idea could be to use the ambient carbon dioxide on Mars as an insulation medium, with a multilayer insulation enclosure separated by Mylar stand-offs [28]. This way of insulating is lighter, cheaper and faster to manufacture than insulations used in previous Mars missions. The reason why carbon dioxide is suitable for insulation is that the thermal conductivity of the gas is close to that of aerogel and battery material. However, no enclosure of the gas will be needed to provide structural support as opposed to using aerogel. This means that the weight penalty accompanied with needing more fibreglass battery material will be circumvented by using carbon dioxide.

Another light-weight insulation option could be to inject aerogel into a light-weight fibreglass structure. Unlike the previous 'gas gap' option, this insulation provides a rigid structure to support installation of equipment such as sensors mounted on the outside of the insulation.

Instead of MLI, single-layer radiation barriers can be used when a lesser degree of thermal insulation is required. Since these barriers are lighter and cheaper to manufacture, they are preferred.

3) Radiators [18]:

During the Martian day radiators can reject the produced waste heat by IR radiation from their surfaces. They can be mounted on the side of the payload module and also require surface finishes. The infra-red radiation only becomes significant during the Martian day since it is proportional to the fourth power of the internal temperature.

It is important to mention that these three passive control options are characterized by low absorbency and high emissivity with relation to the environment. Also degradation due to environmental effects (solar absorbency and dust impact) over 90 sols needs to be considered, since this will lower the emissivity of the material used.

Active thermal control

Unfortunately, thermal control of the payload can probably not be achieved using only passive techniques such as surface finishes [?]. Instead, active thermal control techniques will have to be used. However, this is generally more complex and expensive and stabilises the temperature by active means such as using heaters or thermo-electric coolers. This is especially needed for components with narrow allowable temperature envelopes. There are several possibilities for the balloon payload module:

1) Heaters :

According to the ESTEC engineers the use of a nuclear cell is not uncommon to heat the system. A radioisotope heater unit (RHU) can be used. The RHU produces a constant heat output through the decay of radioactive isotopes without requiring electrical power [17]. A RHU weighing 1 kg could provide continuous power of 17.2 W. On of the basic power concepts is to use nuclear energy from a radioisotope thermoelectric generator (RTG). The RTG works in the same way as the RHU, only now the heat is converted into electricity. With efficiencies lower than 10% a large amount of heat will be produced, which can also be used for thermal control.

There are two drawbacks related to the RHU and RTG. They will also produce an excess of heat during the day, meaning that this heat will need to be rejected by using low α/ε ratio material and coatings. A solution could be coupling the RHU/RTG to a radiator through thermal switches to allow heat dissipation. The second drawback is that this heater is radioactive. As already mentioned this could influence the Martian environment in a negative way and shielding will be required.

2) Louvers :

Louvers are thermally actuated shutters that control the thermal environment of the structural and electrical equipment [1]. They sense the temperature of the baseplate or radiator and then react at a critical temperature by rotating a set of highly polished aluminium blades. This new position of the blades allows the heat from the baseplate/radiator to be reflected.

3) Heat pipes :

Heat pipes can be used to transport large quantities of heat from one location to another without requiring electrical power [18]. This is especially handy to separate the heat source (RHU/RTG) and sink (surface/radiator) and to reduce large temperature gradients.

It will be necessary to perform calculations and iterations during the detailed design phase to see which of the thermal control systems listed above will be required in the payload module. Louvers are very complex and radiators result in a lower weight than when only surface finishes are used. Therefore, omitting these systems when feasible would be favourable.

4.3 Balloon deployment concepts

The balloon deployment is a critical phase in the balloon system mission, hence it is important to pay attention to it when making concepts. Different ways of deployment are possible, such as deployment from space and deployment on the ground. Each deployment method has its (dis)advantages and determines to some extend what mission can be performed. This section treats three different types of balloon deployment, first deployment from space will be treated in section 4.3.1. Section 4.3.2 describes deployment after entry in the Martian atmosphere. The last section 4.3.3 treats balloon deployment from the Martian surface.

4.3.1 Balloon deployment from space

The first type of deployment concepts treated are based on deployment from space. When in orbit around Mars the balloon mission module will decouple from the EDL and independently enter the atmosphere of Mars. Once the balloon module has been sufficiently decelerated by atmospheric drag a parachute can be deployed to decelerate the balloon module even more. At the same time the heat shield of the balloon module will be dropped so that the balloon module itself will be exposed to the Martian atmosphere. From this point on different balloon deployment methods can be used to eventually get a fully inflated balloon. Advantages and drawbacks of the deployment from space compared to atmospheric and ground deployment are listed below:

+ The balloon system does not have to brought to the Martian surface with the EDL. This reduces the costs of piggy-backing and makes the system less dependant of the EDL.

– Separate atmosphere entry system for the balloon module is needed, this will be more expensive and risky

– Performing a tethered balloon mission is not impossible, but it means that the balloon will have to go to the surface of Mars, then drop the reel and after that go up again

The first concept describes a system where the braking parachute is used to pull the balloon out of its container, after which the balloon is inflated. The next concept, described in balloon deployment using atmospheric gas pressure, involves a balloon module with vents so that the atmospheric flow can exert a pressure force on the balloon such that it is pushed out of the container. Next a deployment method is discussed where the balloon can easily be deployed from its canister using liquid gas which will expand under the influence of solar radiation, this is described in the section pressurised balloon deployment out of a canister. The fourth concept explained about rapid balloon inflation uses no such system, the balloon

module is simply opened after parachute release and then the balloon will be inflated while it is still in the balloon canister. Fifth and last a concept which uses two balloons is describes, a small secondary balloon here deploys the main balloon.

Balloon deployment using a parachute

Deployment using a parachute to pull the balloon out of its canister is a standard method of balloon deployment [16]. An impression of this deployment method is given in figure 4.12.

This concept has been selected because it is less probable that the balloon will get entangled during deployment than compared to the other concepts. After the balloon is deployed the parachute is released, this will unload the balloon. Next inflation follows,using the inflation module attached under the balloon payload module, when the balloon module is falling towards the Martian surface. After inflation is completed the inflation module is dropped and the balloon is ready to operate. The (dis)advantages of this deployment concept are listed below and shortly in table 4.5.

+ Standard method, has been tested before, [16]
– Impact loading on balloon during pull-out by parachute; pumpkin balloon with tendons carrying tension loads may be be required
– Buckling loads when inflation module is released can damage balloon, [36]

Balloon deployment using atmospheric gas pressure

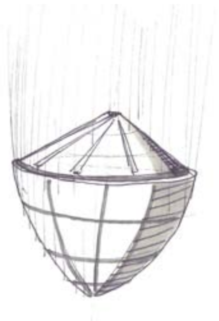
Since balloon deployment using a parachute imposes considerable impact loads on the balloon another option is here is considered. When the balloon module is falling in the atmosphere after the parachute has been released vents will be opened in the aero shell of the module. The atmospheric pressure exerted via these vents on the balloon will push the balloon out of its canister. The balloon will then be inflated and the inflation module will be released afterwards. This sequence of events is depicted in figure 4.13. The first three phases of the balloon entry are depicted in sub figures (a), (b) and (c) of figure 4.12.

The (dis)advantages of this deployment concept are listed below and shortly in table 4.5.

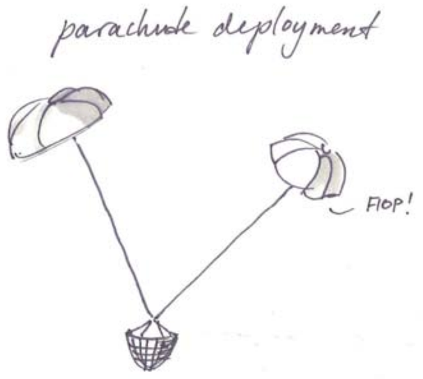
+ Lower loading of balloon compared to balloon deployment using a parachute
– The Martian atmosphere is very thin, hence the balloon module must have sufficient velocity for balloon deployment or be low in the atmosphere. This requires rapid deflation, otherwise the balloon module will crash on the Martian surface
– Buckling loads when inflation module is released can damage balloon, [36]
– Stability of the balloon module when the parachute is released, the air vents must be directed downward to be able to deploy the balloon

Pressurised balloon deployment out of a canister

To reduce the complexity of the balloon system the next concept does not make use of an external inflation system. Instead, this concept of Pioneer Astronautics [48] uses a liquid gas stored in the balloon under pressure which in turn is inside a canister. Part of this liquid inside the balloon will vaporize at Martian temperatures and pressures once the lid of the

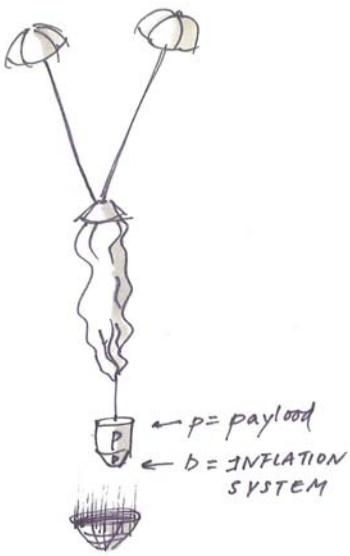


(a) Entry

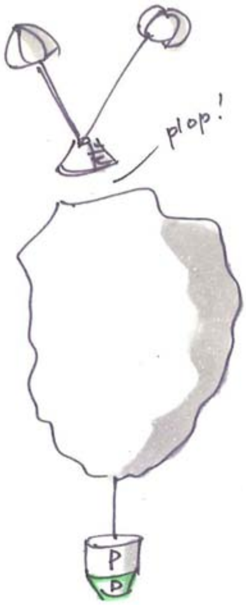


(b) Parachute deployment

(c) Heat shield release



(d) Balloon deployment



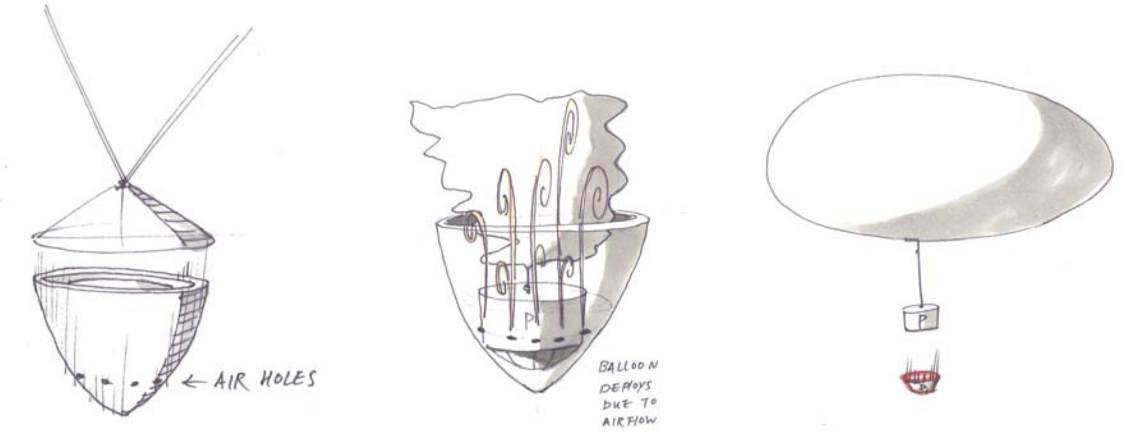
(e) Balloon inflation

(f) Mission success

Figure 4.12: Entry of the balloon module in the Martian atmosphere

canister is released. Under influence of the solar radiation the rest of the liquid will evaporate so that the balloon is fully inflated. This concept is depicted in figure 4.14. Advantages and drawbacks of this deployment concept are listed below and shortly table 4.5.

+ No external inflation system needed, hence lower weight
+ No external inflation system needed, hence no shock loading due to inflation system release
+ Deployment system has been flight tested [48]
+ Loads on the balloon due to absent parachute deployment are lower



(a) Release of payload

(b) Parachute deployment

(c) Inflation success and inflation module release

Figure 4.13: Balloon deployment concept using atmospheric pressure

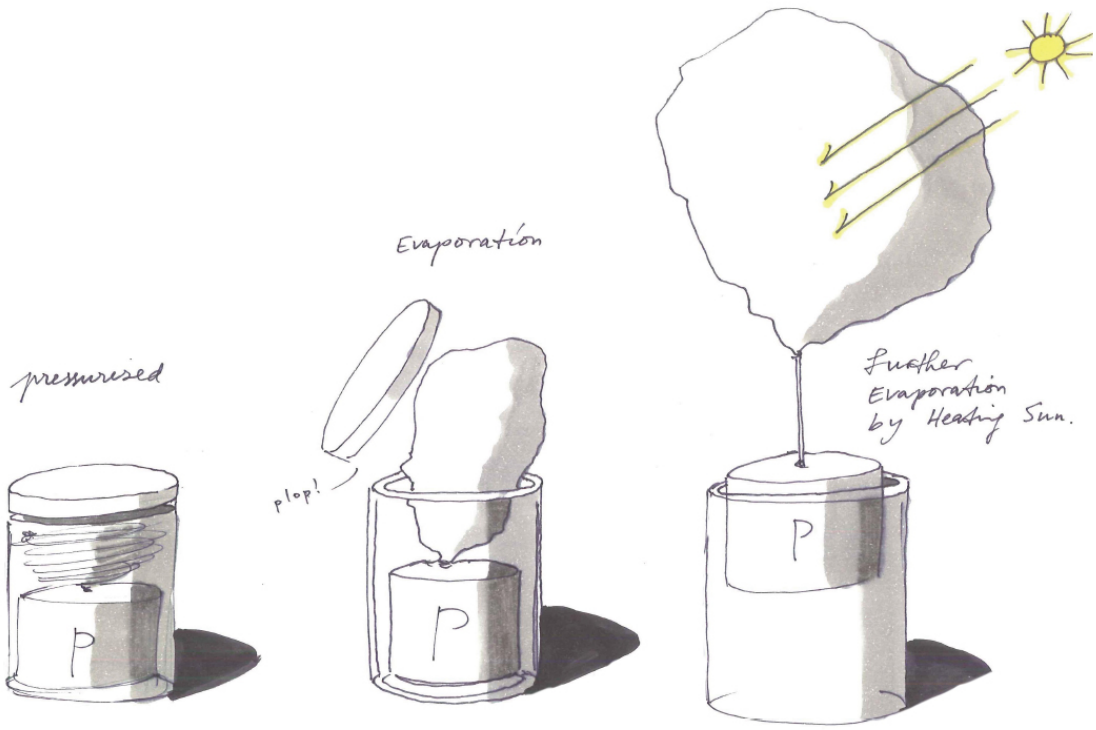


Figure 4.14: Pioneer Astronautics balloon inflation concept in flight or on the ground [48]

– The pressurized balloon canister has to be taken all the way to Mars, this is an extra risk for the EDL

– The pressurized canister with balloon and liquid will be heavier than compressed gas cans with gas only

Rapid balloon deployment out of a canister

This concept from space deployment features a rapid inflation system without the balloon being deployed by atmospheric pressure or a parachute. This concept can be used for all three deployment options: in space, atmospheric and ground deployment. Figure 4.15 shows how this could work, the balloon material is folded in such a way that rapid inflation is possible. After the balloon has been inflated the inflation module is released and the balloon is ready to perform its mission. To compare this concept to other concepts advantages and drawbacks

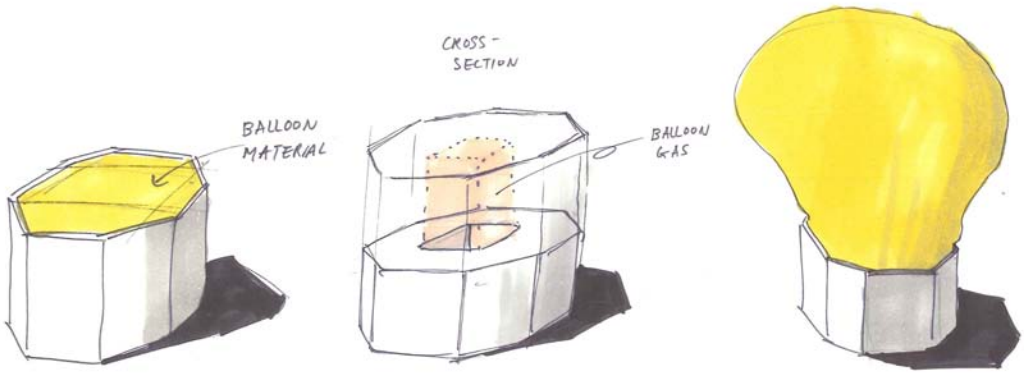


Figure 4.15: Rapid balloon inflation concept

are listed below and shortly in table 4.5.

+ No deployment system needed, this reduces weight and complexity
– Unloading when inflation module is released may damage balloon, [36]
– Deployment of the balloon is not really done, hence the balloon may get stuck during inflation or be damaged
– The orientation of the balloon module must be vertical, otherwise the balloon will be inflated sideways and due to drag be drawn along the edges

Balloon deployment using a secondary deployment balloon

Deployment of the balloon is a critical phase in the mission life of the balloon system. A big balloon may fall to one side during the deployment and can then be damaged by being drawn along sharp edges of, for instance, the payload module. The following concept is to prevent this from happening using a small secondary balloon which pulls out the main balloon in a correct way, see figure 4.16. This concept has its advantages, but of-course also its drawbacks, as listed next and shortly in table 4.5.

+ Little additional weight, as secondary balloon can stay attached
– Initial cost of second balloon may be high
– Attachment at fragile top part of the balloon
– Additional complexity of inflation system

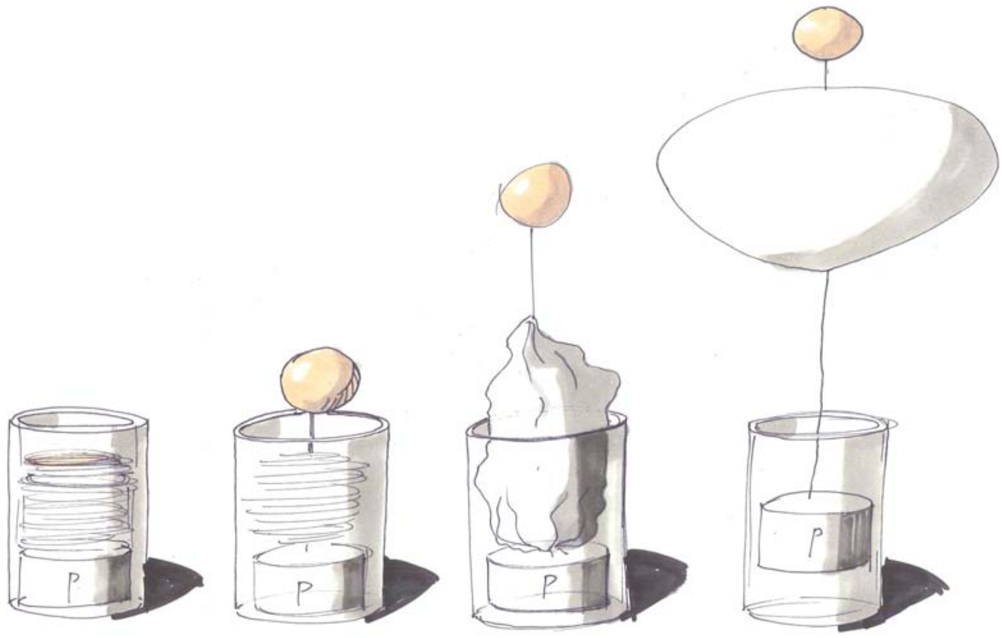
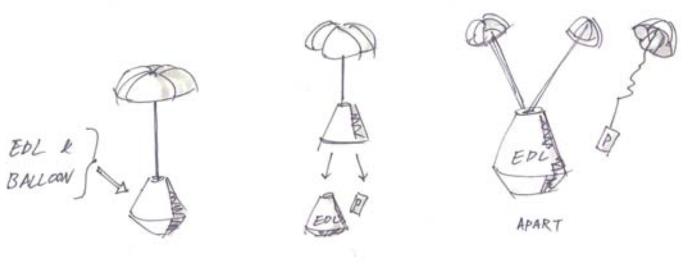


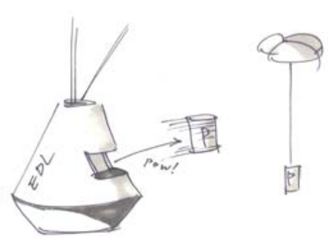
Figure 4.16: Main balloon deployment using a secondary balloon

4.3.2 Atmospheric deployment

The second main deployment option is atmospheric deployment. The first part of the entry into the Martian atmosphere will be performed along with the EDL. After the velocity of the combined EDL and balloon module has been sufficiently reduced by the braking parachute the main parachute will be released. The EDL and balloon module will then continue their mission individually, this is depicted in figure 4.17, so the balloon module at this stage is lower in the Martian atmosphere than compared to deployment from space. This means that bthe balloon deployment and inflation have to be performed more rapidly than with deployment from space. Two options are shown here, one with the EDL and balloon system apart from each other integrated in the entry capsule and the other one where the balloon module is integrated in the aero-shell of the EDL. The last concept makes the design of the entry capsule less complicated but requires a higher integration level of the EDL and balloon module.



(a) EDL and balloon separation



(b) Deployment

Figure 4.17: EDL and balloon module separation options

The concept of atmospheric deployment has been generated because it offers benefits

Table 4.5: Advantages and disadvantages of balloon deployment from space

Space deployment concepts	Advantages	Disadvantages
Parachute deployment	Standard method, has been tested before, [16]	Impact loading on balloon during pull-out by parachute; pumpkin balloon with tendons carrying tension loads may be be required
Atmospheric pressure	Lower loading of balloon	Thin Martian atmosphere, hence rapid deflation required Buckling loads can damage balloon, [36] Stability of balloon module when the parachute is released
Pressurised deployment canister	No inflation system, hence lower weight No inflation system, so no shock loading Deployment is flight tested [48] No parachute deployment, so lower loads	Pressurized canister is an extra risk for the EDL Heavy pressurized canister
Rapid deployment	No deployment system, less weight and complexity	Buckling may damage balloon, [36] Balloon may get stuck during deployment Orientation balloon module must be controlled
Secondary balloon	Little additional weight	High initial cost Attachment at fragile top balloon Complex inflation

over deployment from space and ground deployment. However, the atmospheric deployment option also has some drawbacks. Together these are listed below:

+ The balloon system does not have to brought to the Martian surface with the EDL. This reduces the costs of hitch-hiking

+ The balloon module control system can be less autonomous since the first phase of entry is performed in conjunction with the EDL

+ A separate atmosphere entry system for the balloon module is not needed, this reduces risk and cost

– An extra parachute is needed to perform the decelerating manoeuvres, this increases weight and complexity

– Performing a tethered balloon mission is not impossible, but it means that the balloon will have to go to the surface of Mars, then drop the reel and go up again

– Multiple parachutes deployment and later separation of the EDL and balloon module means that the balloon deployment and inflation will take place lower in the atmosphere. Hence the deployment and inflation have to be performed rapidly to prevent the balloon module from crashing on the Martian surface

A number of deployment and inflation options are possible for the atmospheric deployment option, however all of these options have already been discussed in the deployment from space option. Therefore this section is limited to a discussion about the suitability of the concepts described in the previous section 4.3.1 with deployment from space.

Balloon deployment using a parachute With the balloon module already lower in the atmosphere the parachute used for deployment and deceleration of the balloon (module) must be large enough to accomplish this, hence it will likely be big and heavy due to the thin Martian atmosphere. Furthermore the balloon inflation must be done rapidly due to the low altitude.

Balloon deployment using atmospheric gas pressure The concept using atmospheric pressure to push out the balloon is also influenced by the lower altitude of the balloon module in the atmosphere. The atmospheric pressure at this lower altitude is higher and so the force exerted on the balloon is also higher. Now, the balloon deployment and inflation should be done faster than with deployment from space to prevent the balloon from crashing into the Martian surface. The larger pressure force is thus beneficial, but the lower altitude is a constraint. It is questionable whether the balloon will be deployed in time, hence this concept is less suitable for atmospheric deployment.

Pressurised balloon deployment out of a canister Third, the pressurised balloon deployment out of a canister can be used. The deployment will be influenced by the higher pressures prevailing in the lower regions of the Martian atmosphere, hence the balloon deployment rate may be slowed down. From testing done on earth, [48], the deployment time was found to be 1 minute. A reference altitude for balloon deployment on Mars is 7 km, [36], hence it seems plausible that deployment is completed in time.

Rapid balloon deployment out of a canister This concept is not influenced that much by the lower deployment altitude, because the inflation system is not dependant on the surrounding atmosphere. Hence the only issue one has to take care of is timely inflation.

Balloon deployment using a secondary deployment balloon The last concept is the use of a secondary balloon to deploy the main balloon. Inflation is done using the inflation system, the small balloon will then lift the main balloon, slow or fast depending on the buoyancy gas used. In this case rapid deployment is desirable, so a light buoyancy gas must be used.

4.3.3 Ground deployment

The third option is to deploy the balloon from the ground. The whole system travels with the EDL to the Martian surface after which deployment can be started. Since the EDLS mission of ESA in 2016, [8], will land on Mars this option is considered. The advantages and disadvantages of this option compared to space and atmospheric deployment are listed shortly in table 4.6 and below.

+ No need for aero breaking manoeuvres and control/communication during descent, reducing complexity

+ Balloon does not need to be deployed at high velocities, lowering the strain on the balloon material

+ Tethered balloon missions can more easily be performed since the balloon module has been brought to Mars

+ Communications and power supply can run via the EDL

– Balloon material could tear if balloon material drops on Martian surface, or when drawn over sharp EDL protrusions

– Landing on surface is more expensive

To mitigate the risk of tearing the balloon five concepts were created: 1) Shielded Mars Balloon Launcher, 2) telescopic extraction, 3) the use of a secondary balloon, 4) rapid deployment, 5) an upper inflation concept. Each of these concepts is shortly discussed.

Shielded Mars Balloon Launcher (SMBL)

The company Aurora Flight Sciences has developed a SMBL concept for deploying balloons safely from the ground [15], as depicted in figure 4.18. It features an inflatable cone which protects the balloon from falling on the surface or EDL, and tearing. Advantages and drawbacks of this concept are listed in table 4.6 and below:

+ Development already started by commercial party

– Considerable weight increase due to rigidity requirements of cone

– Secondary inflation system required

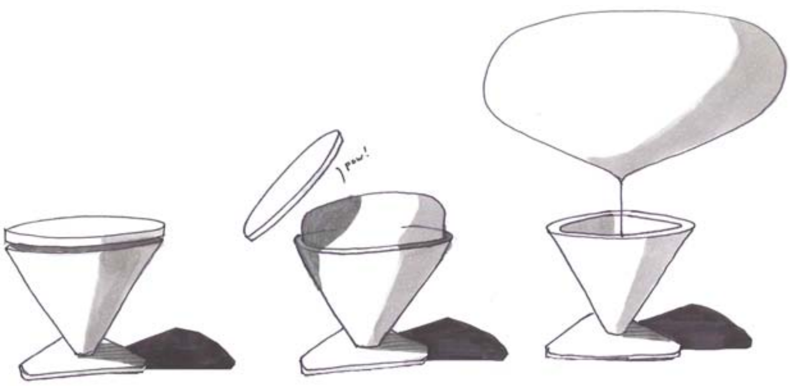
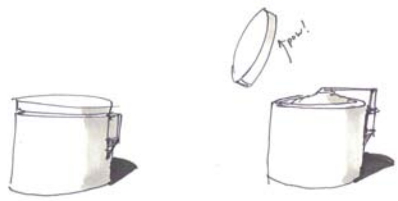


Figure 4.18: Example of the SMBL concept

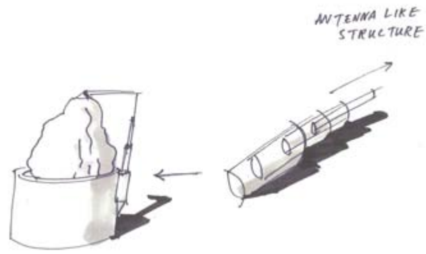
Telescopic extraction

To ensure that the balloon doesn't fall on the ground during inflation, the balloon could be held up by a telescopic arm (see picture 4.19). The telescope would need to stand far enough from the centre of the balloon as not to accidentally touch the balloon material. The (dis)advantages are listed in table 4.6 and below:

+ Possibly reusable as antenna
– Difficult to design within mass and volume constraints
– Attachment at fragile top part of the balloon



(a) Release



(b) Deployment

(c) Release

Figure 4.19: Telescopic extraction of balloon

Secondary balloon

To ensure that the balloon stays up-right, a smaller secondary balloon could be inflated first, which pulls the balloon out of the EDLS (see figure 4.16). The secondary balloon could stay attached after the primary balloon is fully inflated to reduce the loss of useful weight. This has already been described in section 4.3.1, the (dis)advantages are listed in table 4.6 and below:

+ Little additional weight, as secondary balloon can stay attached
– Initial cost of second balloon may be high

– Attachment at fragile top part of the balloon

– Additional complexity of inflation system

Rapid inflation

By rapidly inflating the balloon the balloon material will have little chance of falling on the ground. It is one of the most simple deployment and inflation system, that is why it has been selected. Table 4.6 shows the advantages and drawbacks of this concept, this is also done below:

+ No additional systems required

– High stresses in balloon material

– Topple over risk of balloon may still be too high

Upper inflation

In case of a pumpkin balloon the tendons could incorporate an inflation tube to the top of the balloon. This way the balloon start inflating from the top, lifting the remaining balloon material from the EDL. This concept is shown in figure 4.20. The pros and cons of this concept may be found in table 4.6.

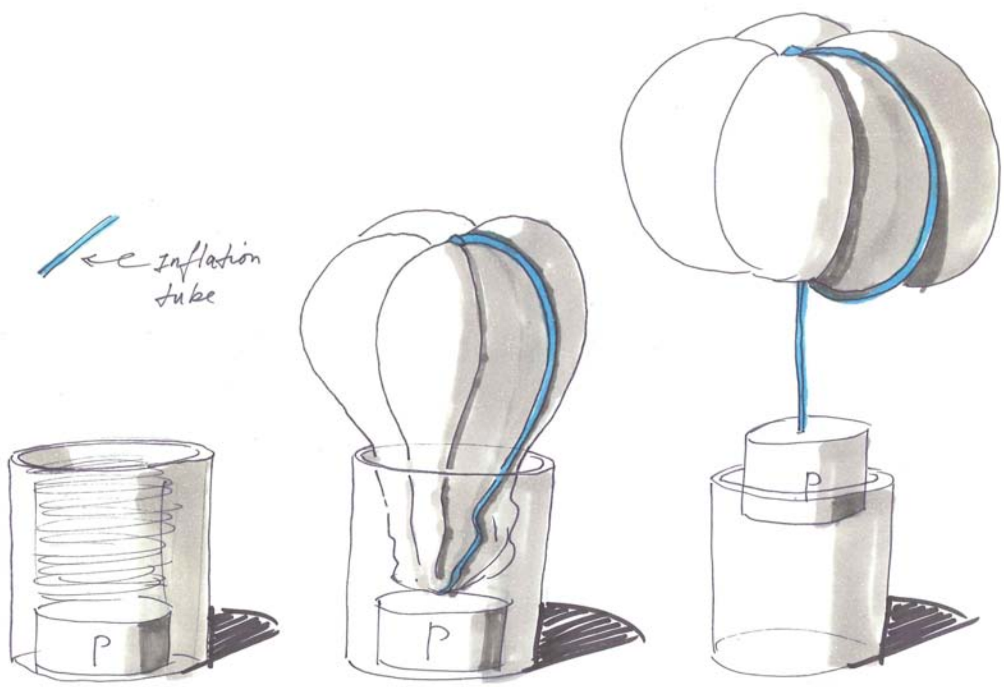


Figure 4.20: Top-down inflation of a pumpkin balloon on the ground via a tendon

+ Little to no additional weight

– Difficult to fabricate

Table 4.6: Advantages and disadvantages of balloon deployment from the ground

Ground deployment concepts	Advantages	Disadvantages
SMBL	Development started	Weight due to rigidity requirements Secondary inflation system
Telescopic extraction	Use as antenna	Mass and volume of antenna Attached at fragile top balloon
Secondary balloon	Little additional weight	High initial cost Attached at fragile top balloon Complex inflation system
Rapid inflation	No additional systems	High stresses High topple over risk
Upper inflation	Little to no additional weight	Difficult to fabricate

4.4 Payload module concepts

This section is the result of a brainstorm session about various payload module shapes. In section 4.4.1 the shape of the payload module is discussed, several shapes and their (dis)advantages are treated. To keep the payload module from spinning payload module stability is discussed next in section 4.4.2. Lastly, in section 4.4.3, the antenna placement is discussed. The results of this section will in the end be used in the design option tree.

4.4.1 Payload module layout concepts

In this section different shapes for payload module concepts are discussed. First a rectangular concept is presented, then a cylindrical shape which is followed by a disc shaped concept. The last concept that will be presented is a combination of balloon and payload module shape, this is the blimp. Along with these design options the advantages and disadvantages of the different options are listed.

Rectangular payload module

The first concept is that of a plain rectangular box. This concept is depicted in figure 4.21. A rectangular shape has been selected since it is a very basic shape and easy to use in combination with standard sized COTS components.
The advantages and disadvantages of the rectangular concept follow below(figure 4.21):

+ This layout enables easy manufacturing.
+ This layout ensures optimal use of internal space.
+ External components (like solar panels) can be attached to all sides of the module.
– The exposed, outside surface area is relatively large compared to a cylindrical shape, leading to increased heat loss.
– The frontal drag area is relatively large compared to other shapes, see the disc shape section, increasing the effect of wind on the payload.

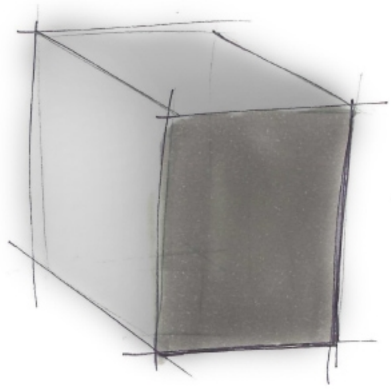


Figure 4.21: Basic rectangular payload module layout

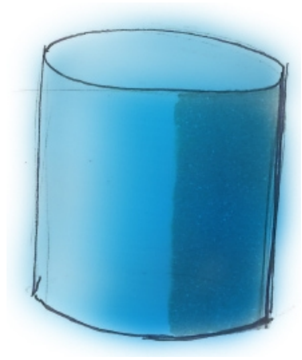


Figure 4.22: Basic cylindrical payload module layout

Cylindrical payload module

The next concept is a cylindrical shaped payload module, as depicted in figure 4.22. A cylindrical shape has the advantage that, for a fixed volume, the outer surface area with respect to other shapes like the rectangular box is smaller. This will minimise the heat loss of the payload module, which benefits the thermal control of the payload module. The shape also generates less drag than the cubic shape discussed before. According to Hoerner, [26], the C_D value of a cylinder in a lateral flow equals 1.17, and that of a rectangular box equals 2.05. The advantages and disadvantages of this concept are:

+ The exposed outside surface area is minimised, this is beneficial for thermal control during the cold Martian nights.

− This shape is more complicated to manufacture than the rectangular shape.

− COTS components might not fit in easily due to the circular shape.

Disc shaped payload module

The third concept presented here is a disc-shaped payload module. This layout is depicted in figure 4.23. Because the wind velocity on Mars typically has values of about 10 m s^{-1} [32], the balloon payload may be affected by this. In order to minimise the frontal drag area exposed to this wind a disc-shaped payload module has been proposed.

Figure 4.23: Disk shaped payload module layout

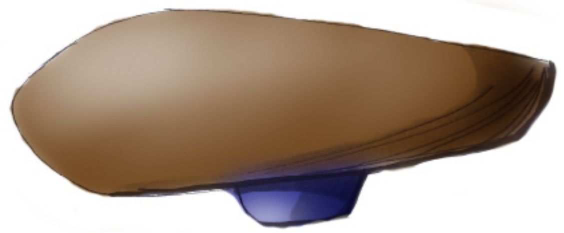


Figure 4.24: Blimp with attached payload module

The advantages and disadvantages of the disc-shaped payload module are:

+ The frontal drag area of this layout is small, hence the drag force acting on the payload module will be small.

– The exposed outside surface area is large compared to cylindrical and rectangular shapes, hence thermal control will be more difficult.

– It may be more difficult to make efficient use of the internal space available when standard sized COTS components are used because of the small height and round shape.

– External components cannot easily be attached to the sides of the payload module due its round shape.

– This shape may be complicated to manufacture.

Blimp with attached payload module

The last concept is more like a blimp than a balloon. In this concept the cable between the balloon and payload module is omitted: the payload module is directly attached to the balloon. This concept has been proposed because removing the need for this attachment cable reduces the weight of the system. This also simplifies the dynamics of the design: now the payload and balloon cannot move independently any more with respect to each other. An example of this concept can be seen in figure 4.24. Below follows a list of advantages and disadvantages:

+ The payload attachment cable is absent, this saves weight.

+ The frontal drag area is minimised, hence the influence of the wind is reduced.

– The exposed outside surface area is relatively large compared to cylindrical and rectangular shapes.

– Attaching the payload module to the balloon is more difficult than with the other configurations that use a cable.

– It may be more difficult to make efficient use of the internal space available when standard sized COTS components are used.

– The balloon temperature and composition may influence the measurements done by the payload (for example, the payload is in the shadow of the balloon).

4.4.2 Payload module stability

Something to consider for the payload module layout is the stability of the payload configuration. In order to increase the spin stability of the payload module a fin may be fitted to the module to help keep the payload aligned in the direction of the wind. This is illustrated in figure 4.25 for a rectangular configuration and in figure 4.26 for a cylindrical configuration. The rectangular fin creates a larger surface area, which means that the moment due to the fin counteracting the spin will be larger, hence the payload will be more stable. However the mass of this rectangular fin will be larger than that of a triangular fin with the same side lengths. This means that in case the mass of the fin is too large one can opt for the triangular fin instead of the rectangular one. The fin may further be used as a surface to mount the solar panels to.

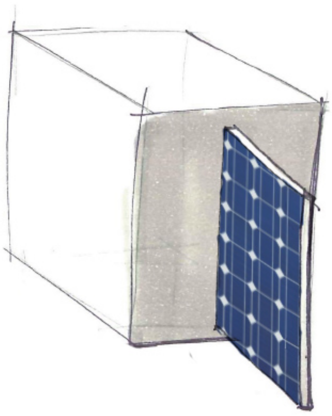


Figure 4.25: Rectangular payload module with rectangular fin

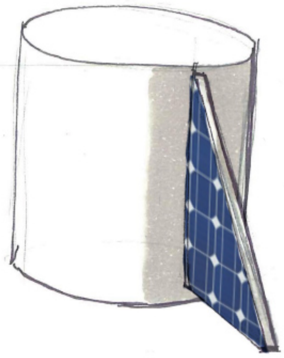


Figure 4.26: Cylindrical payload module with triangular fin

4.4.3 Payload module antenna placement

Another issue to be considered during the payload module design is the antenna placement. The antenna could be placed on the fin should a stabilising fin be used. However it can also be positioned at the lower side of the payload module or be incorporated in the cable attaching the payload module to the balloon.

4.5 Technical risks

In this chapter the risks the mission faces will be analysed. The first section describes the risks and lists ways of preventing the associated failures from materialising, as well as remedies in case they do materialise. The second section contains a risk map.

4.5.1 Risk assessment

In this section an assessment will be made of the technical risks the mission faces. All conceivable risks (as detailed as the progress of the project allows) will be listed along with the associated failure. For each failure the impact on the mission, ways to prevent the failure from happening, and possible remedies are listed.

1.	**Risk**	Deployment failure.
	Description	Failure to deploy the balloon system.
	Impact	Mission lost.
	Prevention	Redundant deploying systems.
	Remedy	Design the system such that some measurements can also be taken from the ground, preventing the system from becoming completely useless if deployment fails.

2.	**Risk**	Fabric failure.
	Description	Failure of the balloon fabric due to loading and/or degradation (due to radiation etc.).
	Impact	Mission lost.
	Prevention	Use fabrics that are strong enough to handle all conceivable loads, or possibly make use of self-healing materials. Coatings should be applied for thermal and radiation protection. Another option is to use a redundant balloon concept where the balloon is made up of several compartments.
	Remedy	Use of self-healing materials and/or coatings.
3.	**Risk**	Dust storm damage.
	Description	Damage due to dust particles entering the system, and wear and tear of fabrics.
	Impact	Either loss of function or mission lost.
	Prevention	Avoid landing during the dust storm season, insulation of the system from dust particles, using redundant systems, corrosive resistant materials or self-healing fabrics.
	Remedy	None.
4.	**Risk**	Cable failure.
	Description	Breaking of the cable (in case of a tethered balloon) due to wear and tear or high loads.
	Impact	Mission lost.
	Prevention	Selecting a wear-resistant material capable of handling all conceivable loads. Landing during storm season should be avoided.
	Remedy	None.
5.	**Risk**	Electrical failure.
	Description	Failure of the electronic systems.
	Impact	Either loss of function or mission lost.
	Prevention	Use redundant electrical systems (double wiring, multiple power sources).
	Remedy	None.
6.	**Risk**	Computer failure.
	Description	Failure of computer systems, such as memory.
	Impact	Either loss of function or mission lost.
	Prevention	Shielding of computer systems, using redundant systems, using simple systems (no unnecessary complexity).
	Remedy	Ability to remotely reboot system, possibly reprogram the system from Earth.
7.	**Risk**	Communications failure.
	Description	Failure of the communications system.
	Impact	Either loss of function or mission lost.
	Prevention	Use of redundant systems.
	Remedy	None.

8.	**Risk**	Launch failure.
	Description	Failure of the launch vehicle.
	Impact	Mission lost.
	Prevention	Select most reliable launcher available (using statistics).
	Remedy	None, loss reduction by insuring the system.
9.	**Risk**	Delivery system failure.
	Description	Failure during transport from Earth to Mars, for example because of debris collision or failing to reach orbit.
	Impact	Mission lost.
	Prevention	Use of protective shielding against debris, use of debris charts.
	Remedy	None, loss reduction by insuring the system.
10.	**Risk**	Lander failure.
	Description	Failure to land the system properly on Mars.
	Impact	Mission lost.
	Prevention	Select most reliable lander system available (using statistics or risk analysis if no track record is available).
	Remedy	None.

4.5.2 Risk map of technical risks

In this section a risk map is presented. This risk map was constructed by identifying the probability that each failure or damage mentioned in section 4.5.1 occurs, and the impact that failure would have on the mission (figure 4.27). Where possible these figures are obtained from literature or derived statistically, but where this is not possible general categories are used to indicate probability. A complete calculation of reliability is outside the scope of this report.

Probability

This subsection lists the probability of each risk materialising. For some risks a definite percentage can be calculated or found in literature, in this case the percentage will be mentioned. If this is not possible the risk will be categorised in one of the more general risk groups: low (0-33 %), medium (33-67 %) and high (67-100 %).

1. **Deployment failure**
   At this stage of the project the deployment system has not yet been designed. Further more the concept of launching a balloon from the surface of another planet is new and has not been tested. The only successful balloon missions on another planet (Venus) were deployed during the descent [41]. Recent tests on Earth using this method have been moderately successful [29], but translating these results to the Martian environment is still experimental. Because of the experimental nature of both types of deployment systems the probability of failure is deemed to fall in the high risk category.

2. **Fabric failure**
   A final selection of the fabric has not yet been made, but currently the best candidate is a polyethylene film. This material has been used before in tests with balloons in

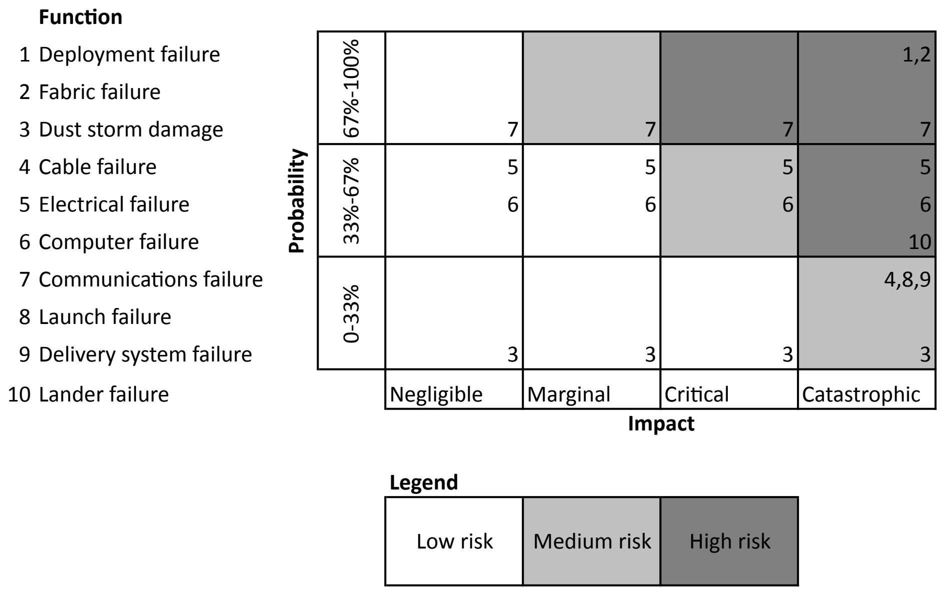


Figure 4.27: Risk map in which probability is plotted against impact. Bottom left having the lowest risk and top right having highest risk as shown in the legend. The numbers in the list on the left correspond to those in the risk map. 3,4,5 and 10 have different impacts on the mission depending what part of the mission is affected.

the Earth's stratosphere [38]. The thickness of this material is about 20 microns. This thickness means the balloon is very sensitive to tearing. The most critical moments with respect to tearing of the balloon fabric are during the deployment on Mars and in the production stage, when the balloon is folded in its container (inspection for any tears may not be possible after packing the balloon). Previous experiences with the polyethylene fabric have shown that structural failure is indeed likely to occur [29]. These considerations result in a classification of this type of failure as a high probability risk.

3. **Dust storm damage**
   Dust storms on Mars pose a significant risk to any mission, but occur mainly in the dust storm seasons (3 out of the 12 seasons of Mars) [10]. For this mission it will be assumed the balloon does not deploy or operate during the dust storm seasons. This means the risk of damage due to dust storms falls in the low risk category.

4. **Cable failure**
   The cable system is one of the most vital systems for the tethered balloon concept. Failure of the cable would mean loss of the mission. One of the reasons for this is that the cable is essential to the communications and power subsystems of the tethered balloon concept as it is currently being considered.Furthermore, breaking of the cable could make it impossible to carry out certain missions because the balloon will start to drift. The risk of cable failure is reduced by modelling the possible forces on the cable and applying a safety factor to minimise the risk of failure due to high loads. The risk of wear and tear is reduced by selecting a wear-resistant material, and is further reduced by the short duration of the mission (90 sols). Because of this, failure will only occur due to exceptionally high loads or possibly dragging of the cable along the surface. The former is unlikely to occur, and as a solution to the latter the use of a reel to keep the cable from sagging is being considered. Because of all this, the overall probability of

cable failure is deemed to fall in the low risk category.

5. **Electrical failure**
The balloon system will be subject to radiation, extreme temperatures and possibly dust storms. These environmental factors combined with the standard probability of malfunction create a high risk of electrical failure. This risk is mitigated by providing insulation from radiation and particles, and making sure al systems are redundant. Using these methods to lower the risk, the probability of electrical failure falls within the medium risk category.

6. **Computer failure**
For the computer, the argument is very similar to the one presented for electrical failure. To prevent failure due to radiation, extreme temperatures or dust, the system needs to be well-insulated and redundant parts need to be installed. An extra safety mechanism that is possible with computers is the option to reprogram or reset the computer if anything goes wrong. These mitigating factors, combined with the short duration of the mission, combine to produce a medium risk of computer failure for this mission.

7. **Communications failure**
The communications subsystem is also subject to radiation, extreme temperatures and possibly dust particles. Next to this the antenna can be damaged or misaligned during transport or deployment. Depending on the way the communications subsystem is implemented (directly to Earth, via the lander or via a relay satellite) it could also fail when one of these systems it depends on fails. Finally, a cable, computer, or electrical failure could also cause a failure of the communications system. These factors combined create a high probability of failure of the communications system.

8. **Launch failure**
For this risk the assumption is made that an Atlas V rocket is used to launch the mission, the launcher used for the ESA Exomars mission [8]. The probability this launcher will fail is about 12.5 % [5].

9. **Delivery system failure**
Of all missions to Mars that were launched successfully and left the Earth atmosphere, 6 out of 34 failed to reach Mars orbit [6]. Improvements in technology and understanding in the past 5 decades since Mars exploration first started might have lowered the risk. The probability of a failure of the spacecraft between Earth and Mars is thus deemed to fall in the low risk category.

10. **Lander failure**
A landing on Mars has been attempted 12 times in history, of which 7 attempts succeeded. This would correspond to a probability of failure of about 40 %. Since the beginning of Mars exploration, technology has improved however: in the last 20 years, 2 out of 6 landers failed to land, corresponding to a failure probability of 33 % [6]. This means the probability falls in between the low and medium risk groups.

Impact

This subsection lists the impact of each risk materialising. Most failures mentioned in the risk assessment (section 4.5.1) either always or sometimes result in the loss of the mission, corresponding to an impact of 100 %. Only 4 types of failures or damage do not necessarily

result in complete loss of the mission. These failures are: electrical failure, dust storm damage, computer failure and communications failure. Each of these could possibly result in a loss of the mission, but the impact could also be less catastrophic. The impact of the materialising of each of these risks could range between almost none to catastrophic. A definite number for the impact cannot be derived, because all different possible kinds of failure belonging to the different categories result in broadly different impacts.

Chapter 5

Interface identification

By identifying interfaces between functions, their interactions can be analysed. The interface analysis is performed using an N^2 chart (table 5.1). The functions used in this chart are the top-level functions from the function break down diagram found in appendix A.1.

The functions in an N^2 chart are listed on the diagonal. The arrows in the chart define interfaces. They give an indication of how the functions interact with each other in terms of input and output. Above the diagonal the output comes from the left and the input is used by the function below that arrow. Below the diagonal the output comes from the right of the arrow and the input is used by the function directly above the arrow. Functions are numbered 1 through 11 and interfaces are labelled [a] through [δ] for easy reference. All main functions and their interfaces are discussed next. After all functions are explained, critical system functions are discussed in section 5.1.

Start-up and system check (1)

Once the Entry Descent and Landing (EDL) vehicle has landed, the system has to start up. As a result of this function, monitoring of all subsystems [a] and calibration of the instruments [b] is started.

Determine position and attitude (2)

First of all, power [h] is required for the position and attitude determination subsystem. Next, the system could make use of the structural state (e.g., the cable tension and angle) [s] or measurement results (e.g., through image tracking) [y] to support calculations on position and attitude.

The output of this function is input for the monitoring [c] to verify that an ascent or descent command is executed correctly. Also, the position and attitude [d] influence the lift. Finally, the position is required to provide a tag for the measurement data [e].

Provide communication (3)

The communications subsystem requires power [i] to perform its task. Monitoring requires information from the communication system [f] to check the link health.

The communication system transfers received data to the data handling system (e.g., commands) [g], and sends data from the data handling system (e.g., measurement data) [r]. Both go through the data handling as data may first need to be encrypted, decrypted or compressed.

Table 5.1: *N^2 chart for the top-level functions of the balloon system. Functions are listed in the first column and numbered on the diagonal; interfaces are indicated by arrows and labeled [a] through [δ].*

Start-up and system check	1				a				b		
Determine position and attitude		2			c			d		e	
Provide communication			3		f	g					
Provide electrical power		h	i	4	j	k	l			m	
Monitoring				n	5	o				p	q
Data handling			r			6					
Provide suitable structure		s			t		7			u	
Lift payload							v	8			
Calibrate instruments						w			9	x	
Perform measurements		y			z	α			β	10	
Provide disposal			γ	δ							11

Provide electrical power (4)

The power subsystem can be informed by the monitoring system to cut power to failing subsystems [n], thereby saving valuable energy. Also, the other way around, monitoring should be informed about battery health or low power levels for example [j]. Note that this is the only interface of the power function which is not concerned with the transfer of actual power.

Most subsystems need power to operate. Output is therefore delivered to the positioning and altitude control [h], communication system [i], data handling [k], the structure (e.g., for rolling up the cable or inflating the balloon) [l], and for performing the measurements [m]. The lifting of the balloon does not necessarily require power since this system only gives the command to increase or decrease lift. The calibration of the system also does not require extra power because the calibration simply consists of the first measurements. The system start-up and check doesn't require extra power either as this is performed by the various subsystems.

Monitoring (5)

The data produced by the monitoring system is communicated with the data handling system in order to send reports about the health of the overall structure back to Earth [o]. The instrument package is informed about the status of several subsystems [p] so that instruments can be switched on or off to prevent damage due to low temperatures for example. If the monitoring system recognises that all systems have degraded past a predefined point, it can send a signal to start disposing the system [q]. All information on subsystem health is also sent to the power system [n], so malfunctioning subsystems can be shut down to save energy.

Most systems feed information to the monitoring system about their health [a] [c] [f] [j] [t] [z]. The systems that do not feed information to the monitoring system are systems that simply give commands to other systems. These systems are the data handling, lift, calibration, and disposal systems.

Data handling (6)

Data handling is the function executed before sending [r] or after receiving [g] data. It facilitates in, for example, encrypting, decrypting or decompressing data. Data handling is also responsible for saving measurement data [α] and calibration values [w], as well as monitoring data [o]. Finally, the subsystem needs power to operate [k].

Provide suitable structure (7)

To provide a suitable structure, power for the subsystems (e.g., a cable reel) is required [l], as well as the required configuration of the balloon which follows from the lift requirements [v].

The structure should provide the required operating conditions for the instruments (think of thermal conditions) [u]. When a tethered concept is used the tension in the cable and angle of the cable can be used for computing the position [s]. Finally, the monitoring system needs information of the current state of the structure [t].

Lift payload (8)

To control the ascent of the balloon, feedback is needed to provide the position [d]. This allows the control system to change the balloon configuration (and thus lift force) to control the rate of ascent, as far as this would be possible. The change in configuration is passed

on to the structural system [v], which is in control of cable roll-up in the case of a tethered balloon.

Calibrate instruments (9)

Calibration is performed by taking a measurement [x] after the system is started [b]. The resulting measurement is then used as the zero measurement [β]. This measurement is also transferred to the data handling system [w], so it can be saved and sent to Earth for verification.

Perform measurements (10)

Before measurements can be performed, the instruments need to be calibrated [x]. The first measurement is then saved as the zero measurement [β]. Measurements which need to be transferred to Earth are first passed to the data handling system for intermediate processing [α]. The health of the instruments is transferred to the monitoring system [z]. Finally, measurements could serve as a basis for position and attitude determination [y].

The attitude and position are important for the measurement data, so they can be labelled [e]. Also, the instruments require power [m]. If operating conditions are unfavourable, the instrument package could be notified by the monitoring service [p] so it can shut down the instruments if required. Finally, the instruments have certain structural requirements such as thermal requirements.

Provide disposal (11)

The disposal only needs to be carried out if the monitoring system has determined that the system has degraded to such a point that it could not operate any further [q].

When the disposal is initiated communication has to be provided to Earth [γ] and the power subsystem has to be shut down [δ].

5.1 Critical systems of interface diagram

From an analysis of the N^2 chart some critical systems can be identified. The power, monitoring, and measurement subsystems all provide output to other systems. For the power subsystem this output is mainly in the form of electrical power but also information on power and the health of the system are outputs of this system. The monitoring subsystem communicates the health of the system to subsystems for which the health is important.

The measurements are required by four other subsystems. The system can operate without the monitoring system, provided that all other subsystems remain functioning. However, the power and measurement subsystems are vital to the mission and their failure would be catastrophic.

Input is a main issue for monitoring, data handling, and measurements. If one of the other systems would fail the monitoring, data handling or measurement systems are not necessarily compromised. Data handling and measurements are important for the communication of the obtained data and therefore they are also a critical system.

Chapter 6

Design concepts

The design option tree (figure 4.1) shows all possible combination of subsystems. In this chapter three final design concepts will be chosen. These concepts will be traded off in chapter 7.

First, it has to be noted that some solutions in the design option tree are not compatible with the requirements and constraints. These are discarded and discussed in section 6.1. As a result a limited number of design options will remain, such that three designs can be assembled (sections 6.2, 6.3, and 6.4).

6.1 Discarded design options

The infeasible concepts from each top level item in the design option tree are shortly discussed. From the remaining elements, three optimal design concepts are formed.

6.1.1 Power supply

The power supply option of solely relying on batteries would be too heavy when the mission needs to last for 90 sols [31]. Another power supply option, relying on nuclear energy, is complicated and costly. Moreover the technology is difficult to obtain and too much safety issues influence the risk in a negative sense, as discussed in the baseline report.

The remaining options are solar and wind energy. Both solar panels or a fan can be positioned on the balloon or on the payload. The balloon material is extremely thin, and from earlier research the conclusion was drawn that it is vulnerable [37]. Keeping this in mind the solar panels or fan will have to be placed on the payload.

6.1.2 Balloon construction

For the balloon construction a design implementing one balloon or several balloons can be used. The multiple balloons idea is converted into one balloon with multiple compartments as this saves material resulting in mass reduction compared to multiple balloons. The balloon and payload are separated because the combination of balloon and payload into one structure could severely influence measurements due to the balloon gas and temperature. Furthermore, attaching the payload to the balloon is difficult because of the fragile balloon material.

6.1.3 Balloon configuration

For tethered balloons a reel retraction system is used to retract the balloon, as the cable coiler produces friction to pull the cable. This high friction is created by high pressure on

the cable, which could damage the cable. Moreover pieces of dust and sand could choke up the opening and further damage the cable. The shape of the cable container is irrelevant at this stage of the design process.

6.1.4 Communications

An antenna on the payload can be used for communications. The cable itself can also be used when the balloon is tethered. Both options are left open.

6.2 Design 1: tethered elliptical balloon

The elements of the first balloon design are shown in table 6.2.

Table 6.1: Components of the first design

Balloon	Tethered elliptical balloon with one compartment filled with one type of gas
Energy	Energy from lander via cable
Payload vessel	Flat disc-shaped to reduce drag
Communications	Antenna connected to lander and directed to relay satellite
Deployment	Secondary balloon on the surface

As one can see from table 6.2 the balloon is tethered, as originally stated in the project guide. Since the balloon is tethered both the communication and power supply from the lander can be transmitted through a conducting cable. The advantage of this is a mass reduction of the balloon payload, because batteries and energy generators are not needed. The disadvantage of this configuration is that the cable could be a lot heavier, because a conducting cable must be weaved in the original cable. Moreover the whole mission will fail if the conducting cable fails. Failure of the conducting cable is not unlikely due to continuous stress and strain applied by the wind.

A short study shows that an electricity wire which connects the lander with the balloon is not feasible [22].

In this design power is only needed for the thermal sub-system, the operation of the instruments, and the on-board computer. A rough estimation of the power requirements is made using a comparable mission [10], and using information provided by ESA [30]. The thermal system needs 21 W and the instruments approximately 20 W. Since part of the instruments demanding a lot of energy (e.g., the camera, which uses 10 W) are not continuously active, those will be ignored for these rough calculations. This leaves a continuous power requirement of 31 W.

It is assumed that all instruments require 12 V. To accomplish the energy transport of 31 W a current of 2.6 A is needed. When accepting a 2 % energy loss, a cable with a diameter of 11.6 mm can transport a 12 V current up to 323 m [22].

Such a cable is too heavy for this mission. When the voltage is increased the maximum distance can be increased. To increase the voltage an electric transformer is needed which is too heavy for a Mars mission. It can be concluded that a conducting cable, either made of copper or aluminium, is not feasible. This means that data transport needs to be wireless even for a tethered concept. Other solutions should be thought of to enable the use of the lander energy supply.

The balloon configuration will exist of one compartment filled with one type of gas. The reason for this choice is to keep calculations as simple as possible while keeping the costs as low as possible. Drag due to the wind is undesirable for the tethered balloon, because the dynamical loads created by the wind could stress the cable too much. This is why the balloon is chosen to have an elliptical shape, reducing the drag due to wind [7].

For the same reason the payload vessel is shaped like a flat disc. One disadvantage of the flat disc is that it could cause thermal control problems, because there is a large area through which heat can be lost. In this stage it is still unknown what the thermal effects are.

The deployment of the balloon is a crucial point in the mission. Because this concept incorporates a tethered balloon, deploying in space is not a viable option. Therefore, the balloon will be deployed when the lander has landed on the Martian surface.

A small secondary balloon is a good option for this design because the cable, which has a small weight, needs to be pulled out. The secondary balloon would pull out the main elliptic balloon with a small part of the cable. Now the main balloon can inflate and pull the rest of the cable out.

To summarise the advantages and disadvantages of the concepts, a table is made. See table 6.2.

Table 6.2: Benefits and drawbacks of design 1

Benefit	Use of an elliptical balloon results in low drag and low costs (Commercial off the shelf product)
Benefit	Constant energy supply
Drawback	Heavy dependence on the lander and cable, can only scout an area nearby lander
Drawback	Heat loss of payload vessel due to large area

6.3 Design 2: free pumpkin balloon

The components of this design are listed in table 6.3. This design makes use of a pumpkin-shaped balloon because it can handle up to 5 times higher internal pressures than conventional balloons [37]. The downside of such a pumpkin balloon is that it is quite expensive because it is not commercially available off the shelf. The balloon is untethered (free) because this enables the balloon to cover a large area instead of being limited to a certain area. This is an advantage if a general picture of the Martian atmosphere needs to be obtained, but it is very unlikely that a certain point can be sampled twice if needed.

Table 6.3: Components of the second design

Balloon	Free pumpkin-shaped balloon with multiple compartments and a variety of gases
Energy	Wind energy or solar energy
Payload vessel	Cylindrical shape with a fin
Communications	Antenna on payload vessel directed to the relay satellite
Deployment	Mid-air parachute

In this initial design it is assumed that the balloon uses wind energy to power its system. Therefore, it is necessary that the balloon will stay airborne, day and night. To keep the balloon airborne, multiple compartments are introduced in the balloon. These compartments

are filled with different gases. One gas can keep the balloon airborne during the night, the other delivers extra lift when it is heated by the sun to make the balloon climb during daytime.

Because using wind energy with a free balloon requires a high velocity of the relative wind, it is necessary to first determine whether such a design will be feasible using rough calculations. As in design 1 it is assumed that 31 W is required for the system to operate because not all systems are continuously active. The wind turbine formula (6.1) obtained from the website of the American Wind Energy Association is used [9] to check feasibility.

$$P = 0.5\rho A C_p V^3 N_g N_b \tag{6.1}$$

Here P is the power in watt, A is the swept area of the rotor in m^2, C_p is the coefficient of performance which is .59 in an ideal situation, V is the wind velocity in m s^{-1}, and N_g and N_b are both efficiencies with ideal values of .80 and .95 respectively [9].

To determine if using a wind turbine is feasible the swept area of the rotor is determined. If this area would turn out to be unrealistic this would mean that using a wind turbine is impossible in this concept. Equation (6.1) is rewritten to an equation for A (6.2) and filled in with data from the NASA Mars fact sheet [19]. Because this is a free balloon the relative wind velocity is used as the wind velocity in (6.1). It is assumed that the relative wind is very small and does not exceed 1 m s^{-1}. Using these values, the required sweep area becomes

$$\begin{aligned} A &= \frac{P}{0.5\rho C_p V^3 N_g N_b} \\ &= \frac{31}{0.5 \cdot 0.02 \cdot 0.59 \cdot 1^3 \cdot 0.8 \cdot 0.95} \\ &= 65677 \text{ m}^2 \end{aligned} \tag{6.2}$$

Such a rotor sweep area is unrealistic in terms of weight and dimensions, so wind energy is not an option for the free balloon.

An other option would be using solar cells. The newest (experimental) solar cells have an efficiency of 42.8 % [34], but as this is a feasibility study a more realistic efficiency of 32 % is chosen [20]. With a solar flux of 590 W/m^2 [19] this results in an available power of $590 \cdot 0.32 = 188.8$ W/m^2. In this calculation it is assumed that the sun is perpendicular to the solar cells. With the current assumptions 31 W is needed. This means that a solar array area of $\frac{31}{188.8} = 0.164$ m^2 would suffice. This is a more realistic solution than the on-board wind turbine, keeping in mind the very rough assumptions.

To maximise the distance travelled the drag should be maximised which is achieved by maximising the area of the payload vessel. A square vessel would result in a larger frontal area than a cylindrical vessel with the same volume and height. A larger frontal area would also result in more heat radiation. This is very unfavourable because more solar cells would be needed to compensate for the heat loss. Therefore a cylindrical vessel is chosen for this design as it has a smaller radiative area for the same volume.

To stabilise the payload a fin can be added to prevent uncontrolled rotation of the payload. In addition this fin can be used to determine the wind heading. This is a feature that needs more investigation.

For the free balloon there is no other possibility than using an antenna to communicate with Earth. It is assumed that the balloon will move out of the line of sight of the lander at a certain time. This leaves only the relay satellites as a realistic communication option. A

disadvantage of this communication option, in combination with the fact that the balloon is free, is that it is not certain when and how often communication will be possible.

Because this design uses a pumpkin balloon, which is relatively strong, a deployment in space can be done. By using the atmospheric deployment concept the EDL does not need to take the Mars balloon to the surface which saves costs.

For the deployment a parachute is utilised as shown in section 4.3. The two compartments can be filled with gas while in the air. If all goes correct than the balloon will be fully deployed before it reaches the surface. Only because this is a though balloon this deployment method can be used, other balloons would rip during the deployment due to the high loading during the parachute pull-out.

To summarise the concept all the benefits and drawbacks are included in table 6.4

Table 6.4: Benefits and drawbacks of design 2

Benefit	Tough balloon
Benefit	Global area coverage
Benefit	Always floats, so it can sample day and night
Drawback	Heavy because of solar cells and battery
Drawback	Energy supply dependent on the Sunlight direction
Drawback	Uncontrollable
Drawback	Low COTS component usage, so it is expensive

6.4 Design 3: free spherical balloon

The sub-elements of design 3 are described in table 6.5. The first thing that distinguishes

Table 6.5: Components of the third design

Balloon	Free single spherical balloon, filled with one type of gas
Energy	Solar energy
Payload vessel	Cubical shape with fin
Communications	Antenna on stabilizing fin directed to relay satellite
Deployment	Mid-air pressurised canister

design 3 from the other designs is the spherical balloon. The spherical balloon is known to be less efficient than the elliptical and pumpkin balloon, because the latter two configurations can handle five times more pressure than a spherical concept. The advantage of the spherical shape however, is the cost associated with it. Since the balloon is commercially off the shelf available, using this shape would be far cheaper than using the complicated pumpkin balloons used only by NASA. For simplicity, and thus cost reduction, the balloon does not contain multiple compartments and is filled with one type of gas.

The power supply utilises sunlight, which is converted to electricity by photovoltaic cells. The most efficient cells at this moment have an efficiency of 42.8 %, however, as with design 2 an efficiency of 32 % is assumed. When panels with 32 % efficiency are used sufficient energy would be generated for the instruments. However, one has to keep in mind that the incidence angle and dust storms could influence the power generated [34].

The shape of the payload vessel is cubic. Instruments can be fitted more efficiently using this shape, which means the space is optimally used. The cubical shape however can result in payload vessel rotations due to wind excitations. To avoid the payload from spinning in circles, a stabilising fin is placed on the cube. The fin can also be covered by solar panels in order to use the area efficiently. The fin is also used as an antenna.

As this is a very thin and simple spherical balloon, no high loading is allowed during deployment because it could tear the balloon. The safest way would be to deploy the balloon on the surface on Mars, but this is expensive. To keep this mission as low-cost as possible this option employs deploying the balloon in the atmosphere. The pressurised balloon out of a canister deployment system does not include a parachute and therefore the loadings during deployment are lower. To deploy the balloon a pressurised canister is opened. The gas in the canister vaporises once the lid is opened and the gas fills the balloon. Sun heats the gas, which increases the buoyancy. The main advantage of this method is that no sudden motions are present during deployment, which minimises the loading.

The advantages and disadvantages of the third design are summarized in table 6.6:

Table 6.6: Benefits and drawbacks of design 3

Benefit	Cheap balloon
Benefit	Global area coverage
Benefit	Fin offers stability
Drawback	Heavy because of solar cells and battery
Drawback	Energy supply dependent on the Sunlight direction

6.5 Other considerations

When using a free balloon (as in design 2 and 3) there are some additional considerations. A free balloon can be used for missions that do not require a high temporal resolution since the balloon is uncontrollable. This means that changes of the atmosphere and surface in time can not be measured using this design.

What this balloon design can do is create an atmospheric map of Mars. To create such a map the system needs a camera on board to determine its location. This camera can also be used for high resolution images of the surface because the balloon is quite close to the surface at the beginning and the end of a Martian day.

It is clear that it is far more efficient to direct the panels normal to the Sun instead of under an angle. To direct the panels properly one can introduce a sunlight sensor and a rotating fin. The sunlight sensor detects the sun light direction and gives a signal to the rotating tail. In this way the solar panels are always oriented in the Sun direction. Figure 6.1 illustrates this concept. This idea could be worked out further in the next design phase.

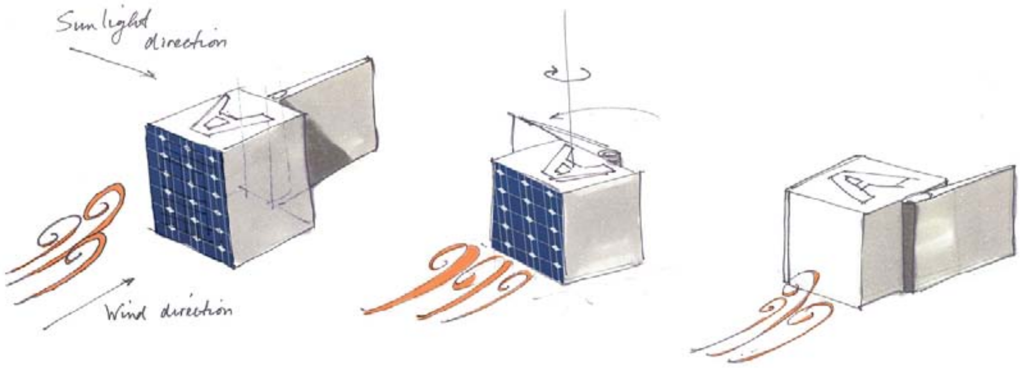


Figure 6.1: Payload with adjustable fin

Chapter 7

Trade-off

Each function can be carried out using different types of subsystem. Several design options for those subsystems have been introduced so far. To find the optimal combination, the different concepts need to be compared with each other. In this section, a trade-off method is described to guide the choice of best concept. These concepts are described in chapter 6.

7.1 Method

Different trade-off methods exist which can roughly be divided into two groups [23]: ordinal (or qualitative), and cardinal (or quantitative).

The ordinal method ranks the different concepts on a relative scale, where the cardinal method does this on an absolute scale using ratings that immediately show which concept is best suited for the particular situation. The latter method is more precise and also enables the use of weighted criteria. The downside is that accurate information needs to be available about the criteria for all the concepts to enable the use of an absolute scale. In this stage not all quantitative information on the concepts is available, so the cardinal method will not be used.

As a cardinal method is not an option the ordinal method will be used. There are four decision rules that use the ordinal scale [23]:

1. **Majority rule**
   Two alternatives are rated for each criterion. If one concept is better than the other it receives one point, regardless of how much better it is. The alternative that is most favourable for the highest number of criteria is the best concept according to the majority rule.

2. **Copeland rule**
   The Copeland rule is similar to the majority rule, but using this method one concept is compared with all other concepts.

3. **Rank-sum Rule**
   When the Rank-sum rule is used, the ranking of the different concepts for all the criteria is summed over the criteria. The concept with the lowest score, hence with the highest rank on the most concepts, is chosen as the best. This rule should be used with care as some criteria might be more important than others. A situation that possibly could occur is that a concept is ranked very high on criteria with a low priority. Due to this high ranking it will be chosen as the "best" concept, although it may not score as high on the most important criteria.

Table 7.1: An example of a Harris profile

	Concept I				**Concept II**				**Concept III**			
	-2	-1	+1	+2	-2	-1	+1	+2	-2	-1	+1	+2
Criterion A												
Criterion B												
Criterion C												
Criterion D												

4. **Lexicographical rule**
With the Lexicographical method, the criteria are ranked from important to less important relative to each other. The concept that satisfies the most important criterion is chosen as the best concept. Only if another alternative exists that also satisfies the same criterion, the second most important criterion is taken into account and so on.

5. **Datum method**
For this method to work a datum is set. This is a reference concept to which all other concepts are compared. The reference concept should be a comparable product or, if this does not yet exist, a concept that is generally considered as the "best". After the datum is chosen, all concepts are rated with respect to the datum. The rating happens on a ordinal level where the concept can be rated better, worse or the same as the datum. The concept that is mostly rated as better than the datum, is the winner.

Because all rules have their advantages and disadvantages, a combination is made for the upcoming trade-off. As this is a feasibility study, it is important that there is no absolute winner. Therefore the criteria discussed in section 7.2 will be ranked according to importance, as with the lexicographical rule, but when the most important criterion is satisfied there will be no elimination and the trade-off will carry on. Furthermore the alternatives will be compared with each other.

For the ranking process itself a Harris profile [25] will be used as this gives a good visual overview of how the concepts score on different criteria. Table 7.1 shows an example of a Harris profile.

7.2 Trade-off criteria

The trade-off criteria are used for evaluating the relative performance of the balloon concepts in the Harris profile. This section will explain what the criteria will be, how they will be measured, and what their relative importance is.

7.2.1 Criteria description

The trade-off criteria are selected from the list of requirements from the baseline report. Solutions to requirements which do not differ much between concepts (e.g., the communication link bandwidth or position determination) are neglected to keep the trade-off relevant and concise.

Table 7.2 shows the selected trade-off criteria, ordered by importance. The criteria are shortly explained together with their performance classification.

Table 7.2: List with trade-off criteria, ordered by importance.

Criterion
Useful payload
Coverage
Dynamic and static stability
Cost
COTS usage
Deployment risk
Mission life extendibility
Available power

Useful payload

The useful payload is the most important criterion as it is the most limiting factor for the instrument package. The useful payload can be measured with two quantities: the absolute and the relative mass of the possible instrument package. The absolute mass is the maximum payload mass that can be lifted by the balloon. The relative mass is the percentage of mass out of the total mass which is used for lifting the payload.

Using the absolute mass would be deceptive as the total mass required to do so may be unacceptable due to, for example, a heavy balloon construction. At this stage of the design the actual number can't be calculated yet, so the useful payload is estimated.

Coverage

The coverage of the balloon (both spatial and temporal) is important for the instrument selection and depends greatly on the chosen balloon concept (i.e., free or tethered). The spatial coverage can be measured by the maximal distance travelled from the landing site, whereas the temporal coverage can be measured by the chance that a specific position will be measured more than once.

Dynamic and static stability

The dynamic and static stability is important for the performance of an instrument such as a camera. It could be that models of the balloon concepts are not detailed enough to provide numerical proof of the stability, so the stability characteristics will be reasoned from logic instead of a simulation.

Cost

The mission is dependent on funds from external parties. Therefore the cheaper the construction, the better. The balloon should not be over-engineered. Cost figures for the concepts are estimates, as it is too difficult to give exact figures at this stage. The total cost also depends on the usage of Commercial off-the-shelf (COTS) components, because completely new components are far more expensive and cost estimates will be more difficult.

COTS usage

If more COTS components can be used, cost can be reduced and risks can be estimated better. Therefore, more usage of COTS components can be beneficial to the design. COTS usage is defined as the ratio of the number of COTS components to the total number of components.

Deployment risk

Deployment of the balloon is crucial as deployment failure equals a lost mission. If a concept uses a proven and simple technique it is preferable above a new deployment concept which has not been tested before.

Mission life extendibility

Previous rover missions to Mars have proven to operate longer than designed for [4]. If a balloon mission concept has the potential to take measurements for more than the designed 90 sols, the concept is more attractive.

Available power

Although mass is the most important driver for the instrument package, the power is the second most important requirement for the instrument selection. If there is more power available more complicated instruments can be selected.

7.2.2 Criteria order rational

The criteria importance is primarily dictated by the instruments. The number one critical requirement for the instruments is the useful payload mass. If more instruments can be added, the mission becomes more valuable. The next criterion, the coverage, is another important criterion as the instrument selection will be different depending on the coverage. The last criteria which influences measurements is the dynamic and static stability, but this does not influence the choice of measurement devices as much as the previous criteria.

The next criterion is the cost. The mission should be funded with a university budget, hence special attention needs to be paid to the overall cost. Related to the cost, but less important, is the usage of COTS components. Although increasing COTS usage likely decreases the overall costs and risks, an ingenious custom solution may actually save more.

Deployment risk is important to take into account but has not been researched enough to place it higher on the list. If more concrete risk assessments are made, this item can be moved higher in the list. Next, the mission life extendibility is considered. This criterion does not have a severe impact on mission design, but would increase the interest in the mission and therefore is placed in the bottom of the list.

Although most instrument criteria are high on the list, the available power is not. An increase in power will most likely result in a mass increase, which is the number one criterion. Also, the mission life extendibility is more interesting than the available power as it is probably more interesting to let the balloon work longer, than to let it work the required 90 sols with a small additional instrument.

7.3 Rationale and organisation

When carrying out a trade-off of the concepts, a certain fixed procedure should be followed during the trade-off such that all concepts get an equal treatment. Before the trade-off, all concepts should have been documented such that a well founded decision can be made for all the criteria in the trade-off. During the trade-off the different alternatives should be compared with each other such that the alternative that scores the highest on a certain criterion receives the highest ranking, and the alternative scoring the lowest obtains the lowest ranking. Because there are only four rankings (so the difference between the rankings is significant) each concept has to be discussed thoroughly.

It is important to realise that this trade-off can provide several good concepts, which all have their strong and weak points. As this is a feasibility study several options could be delivered which can perform the chosen mission. Time and resources are limited so only one concept will be chosen to be detailed further.

7.4 Trade-off summary

In table 7.3 the trade-off summary table is shown. Per criteria, which are explained in section 7.2, it will be explained why a certain rating is given to the design.

- **Useful payload** This criterion is optimally satisfied when the ratio payload over total mass is as big as possible. For design 1 this ratio is smaller than for the other two designs because it needs to lift the cable which tethers the balloon. This cable also requires a reel-in system which reduces the amount of payload which can be taken. Design 2 has multiple compartments in its balloon which make the balloon heavier than with one compartment. This is why it is lower rated than design 3, which has a more simple construction.

- **Temporal coverage** Design 1 has the highest rating for this criterion as it is tethered and can pass over a certain area multiple times. Both the free balloons are uncontrollable. They can not be directed to pass over a point twice, hence they are rated very low on this criterion.

- **Spatial coverage** Design 2 and design 3 are both free balloons and can, in theory, go around Mars during the mission duration [37]. These two designs can therefore cover a larger area than the tethered balloon in design 1 which is restricted by its cable length.

- **Dynamic & static stability** Little can be said about the stability of the designs as there are little specifications known. The reason that design 1 scores slightly less than the other two concepts is that it does not have a fin on the payload. The fin keeps the payload in one direction and prevents the payload from spinning.

- **Cost** A low score on this criterion means a high price. Design 1 requires a cable which increases the overall price. It also uses an elliptical balloon which is not as common as a spherical balloon, hence more expensive. Design 2 utilises a superpressure pumpkin balloon with multiple compartments. This balloon type is not commercially available and only used by NASA. Design 3 uses simple components which are easy to acquire. Hence the price of this design is low and it scores high for this criterion.

- **COTS** All the general components for design 3 are COTS available, hence this design scores the best on the COTS criterion. Design 2 on the other hand requires a complex balloon which is only used in a scientific setting. The balloon is not COTS and because the balloon itself is a prominent part of the design it scores low on this criterion. Design 1 uses COTS components as well, but they are less common than the components used in design 3, hence it scores lower than design 3.

- **Deployment risk** During deployment of the first design the cable needs to be unrolled. If the secondary balloon deploys the cable will unroll slow and there will be low chance of cable entangling. But if the cable entangles the whole mission would fail. Hence this is the lowest rated design. Because design 2 has several compartments which have to be inflated it is also rated as high risk. The space deployment does include extra risk because the parachute exerts a force on the balloon, but because a strong pumpkin balloon is used this risk is not too high. Failure would not result in total failure but in less performance, hence it is higher rated than design 1. Design 3 has the most simple balloon and hence will deploy with less problems than the other two options. The deployment mechanism is already tested so this design is rated best.

- **Mission life extendibility** Design 2 has the highest life extendibility because it uses a high quality balloon with several compartments. If one compartment fails, the mission could possibly still go on at a lower attitude. Design 1 uses a cable which is crucial for the mission. If it snaps the mission can not go on, so mission extendibility is low. It is not rated the lowest because it is unlikely that the cable will snap because of the good properties of Dyneema, the material used for the cable. Design 3 has a low chance to fail, but if it fails it will slowly descend and end the mission. This end is less abrupt than that of design 1 so it is rated higher than design 1.

- **Available power** During the trade-off it was assumed that design 1 could use the energy from the lander by connecting to it with a cable. As this energy generation method is more mass efficient (there is no need to lift the solar panels with the balloon) it was rated the best option. Both the other concepts use solar power on the payload to acquire energy and are therefore rated low.

Table 7.3: Harris profile of the design concepts

	Design I				Design II				Design III			
	-2	-1	+1	+2	-2	-1	+1	+2	-2	-1	+1	+2
Useful payload	■	■					■	■			■	
Temporal coverage			■	■	■	■			■	■		
Spatial coverage		■					■	■			■	■
Stability			■				■	■			■	■
Cost	■	■			■	■					■	
COTS			■		■	■					■	■
Deployment risk	■	■				■					■	
Mission life extendibility		■					■	■			■	
Available power			■	■		■				■		

Chapter 8

Work in progress

Parts of the project which still require work but are significant at this stage of the development are included in this chapter. In the first section, a simulation of the balloon dynamics is developed in order to give detailed information in the form of graphs displaying the influence of design parameters on the maximum balloon altitude. The second section describes the information gathered from the Royal Netherlands Meteorologic Institute (KNMI) with regard to the prototype which will be built later during the project.

8.1 Balloon Dynamics

The goal of this section on balloon dynamics is to graphically show the effects of factors such as volume, payload weight, and balloon material on the maximum altitude the balloon can reach. This information plays an important role in assessing the feasibility of using a balloon in the Martian atmosphere. Furthermore, it will give insight into the most important factors of the design of the balloon itself and will help size the balloon in a quick and easy way.

A Simulink model is created to simulate the dynamic effects that come in to play and affect the altitude during a balloon flight. Even though it takes a substantial amount of time to create a Simulink model like the one created for this section, this same model can later be used as a basic simulation which can be quickly expanded to incorporate additional dynamic systems, such as a tether or Martian weather conditions. Therefore, it is worth the effort to create a Simulink model.

First, section 8.1.1 explains the background on which the model is based in the form of theory and equations. Secondly, section 8.1.2 contains the method used to integrate these equations into a dynamic Simulink model. Thirdly, section 8.1.3 shows the data resulting from the simulation in a graphical way. Finally, section 8.1.4 will describe how this data should be interpreted and how the model could be improved when doing further analysis.

8.1.1 Background

The equations required to create a model of the balloon dynamics are described in this section. There are only three main forces that act on the balloon [39]; buoyancy, gravity, and drag. Note that the variables in the following equations are in SI units.

Buoyancy

The buoyancy force that works on a balloon filled with gas originates from a difference in density between the gas contained in the balloon and the density of the outside atmosphere.

The following equation describes the buoyancy force in zenith direction.

$$B_z = (\rho_b - \rho_a)V_b g_0 \tag{8.1}$$

where B_z is the buoyancy force, ρ_b is the density of the gas in the balloon, ρ_a is the density of the atmospheric gas, V_b is the volume of the balloon and finally g_0 is the gravitational acceleration

Gravity

The gravity force works in nadir direction and is described by

$$W_z = -m_{tot} g_0 \tag{8.2}$$

where W_z is the weight, m_{tot} is the value of the total mass of the balloon system including payload and g_0 is the gravity constant.

Drag

The general equation to calculate drag force is described below.

$$D = -C_d \cdot \frac{1}{2}\rho_a (V_a - V_b)^2 S_b \tag{8.3}$$

where D is the drag force, C_d is the drag coefficient, ρ_a is the atmospheric density, V_a is the velocity of the wind and V_b is the velocity of the balloon, and S_b is the frontal area of the balloon. At this stage, it is assumed that the effect of the payload on the total drag can be neglected.

Equation of State

It is often required to calculate the density of the gas in the balloon or the density of the atmosphere in order to calculate the forces on the balloon. The density of a gas on Earth is different than the density of this same gas on Mars. Therefore, it is necessary to find a method to calculate the density of any gas on Mars. An easy way to do this is to directly use the equation of state.

$$\rho = \frac{MP}{RT} \tag{8.4}$$

where ρ is the density, M is the molar mass of the gas, P is the local pressure, R is the ideal gas constant, and T is the temperature of the gas.

8.1.2 Methodology

This section will show how the simulation is built and how results are graphed from the simulation results. Simulink is a part of the Matlab software package by The MathWorks, inc. It is a tool used for modelling dynamic systems in a graphical way by the use of blocks that carry out functions and arrows directing the flow of data. Many additional software packages and libraries are available for this product, but only the basic version of Simulink is used for this simulation.

Figure 8.1 shows the top level model of the balloon system in the Simulink environment. The diagram shows the three main steps taken. First of all, the forces that work on the

Table 8.1: Standard balloon data used in the Simulink model

Parameter	Value	Unit
Gravity constant	3.73	m s^{-1}
Volume	1500	m^3
Gas	helium	
Atomic weight	4	g mol^{-1}
Skin material	LLDPE	
Skin thickness	20	micron
Skin density	918	kg m^{-3}
Atm. Pressure	see [11]	
Atm. Temperature	see [11]	
Wind	0	m s^{-1}

balloon are calculated in the blocks on the left side of the diagram. The variables required to calculate these forces are used as input into these function blocks. Note that values such as volume do not enter the the Buoyancy block, even though it is used in it's calculation. This is caused by the fact that the mass of the buoyant gas is constant, and hence only the density of the buoyant gas at a certain altitude is required to calculate the volume of the balloon. The second step in the diagram is the calculation of the acceleration due to the sum of the applied forces. The final step is the integration of this acceleration in order to get the velocity and position of the balloon. The position of the balloon is then sent to the Matlab workspace such that it can be used to calculate the maximum altitude reached during the simulation.

At this initial stage, it appeared necessary to simplify certain aspects of the balloon dynamics. The assumptions used in this model are detailed below:

- The balloon used is a super pressure balloon. Therefore, the density of the buoyant gas and the volume of the balloon is constant.
- The atmosphere is modelled using the (very rough and linear) pressure and temperature formulations found in reference [11].
- A 'standard' balloon is used in the simulation, unless stated otherwise. The standard data used in this model can be found in table 8.1.

The simulation will run and output its data to the array 'data', as shown by the block on the very right side of figure 8.1. Then, the maximum altitude reached during the simulation is extracted from this array and stored. A loop repeats the simulation while the volume of the balloon, the payload weight and the skin thickness are varied. The resulting array, filled with maximum altitudes, is plotted in various ways to create useful graphs shown in section 8.1.3.

8.1.3 Results

The following graphs are the result of the simulation. The first graph, shown in figure 8.2, shows the relation between the type of gas in the balloon and the maximum height reached during flight. It is clear that a heavier gas decreases the maximum altitude, yet the slope of the graph stays the same. Gases with molecular weights higher than that of Neon do not appear feasible for a balloon mission to Mars. The maximum payload at which take-off occurs would not be sufficient to carry even the most elementary sensors and subsystems.

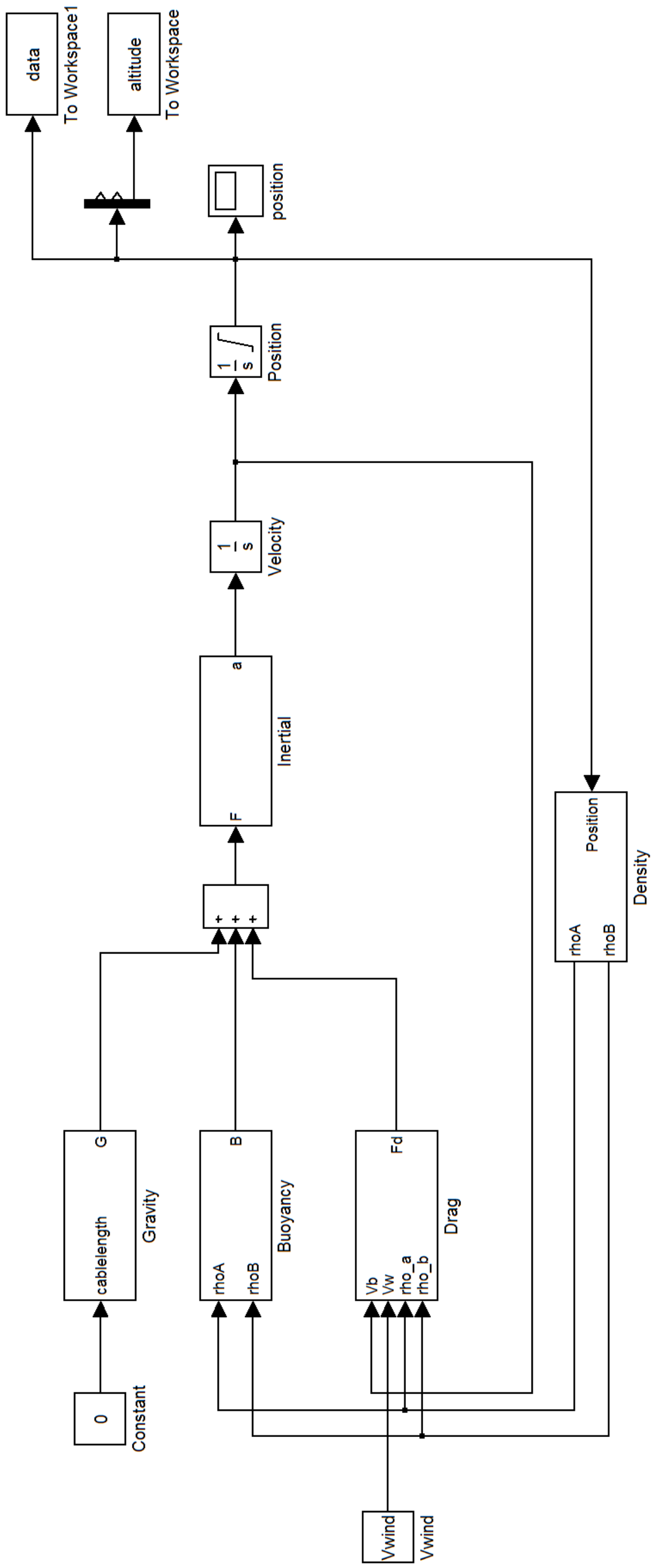


Figure 8.1: Top level Simulink model

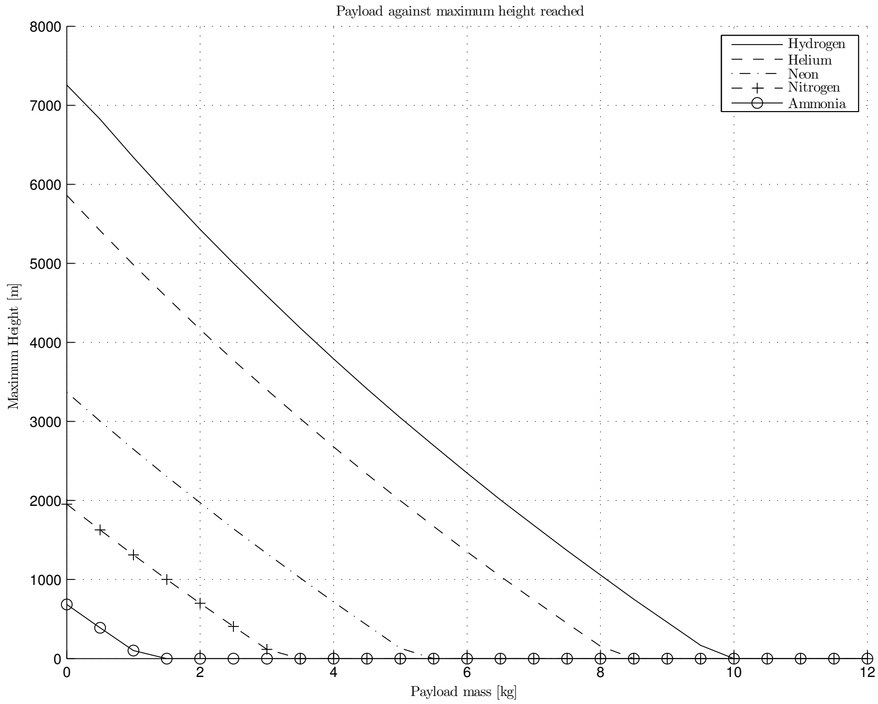


Figure 8.2: The influence of the type of gas on the maximum altitude reached during flight. Standard balloon (table 8.1).

Figure 8.3 shows the relation between the volume of the gas at zero altitude and the maximum flight altitude attained during flight. Note that the slope is not constant between different volumes.

Finally,the relation between maximum height, payload and skin thickness is depicted in Figure 8.4. From these results, it seems like decreasing the skin thickness is the most effective way to increase acceptable payload weight and maximum altitude. Therefore, care should be taken to take a material that has the lowest acceptable skin thickness, while taking reliability into account.

8.1.4 Conclusion and Recommendations

For future use of this basic balloon model, it is recommended to first integrate the pressure and temperature difference of the balloon gas into the simulation. Up to this point, the change of temperature and pressure of the balloon gas has not been taken into account due to time constraints. It is expected that this will influence the lift generated by the balloon in a positive way due to the following reason: the temperature of the gas in a balloon will be higher than the atmospheric temperature. Coatings exist that can increase the temperature of the gas inside the balloon to such extent that it can float even when using plain atmospheric gas [48]. Therefore, the graphs created using the model described in this section will probably give a lower bound for balloon flight altitudes; an actual balloon on Mars will fly higher than the graphs in this section indicate.

A second recommendable improvement to this model is to use a more accurate model of the Martian atmosphere that includes changes in atmosphere density between day and night. The temperature on the Martian atmosphere is known to change greatly between the day and

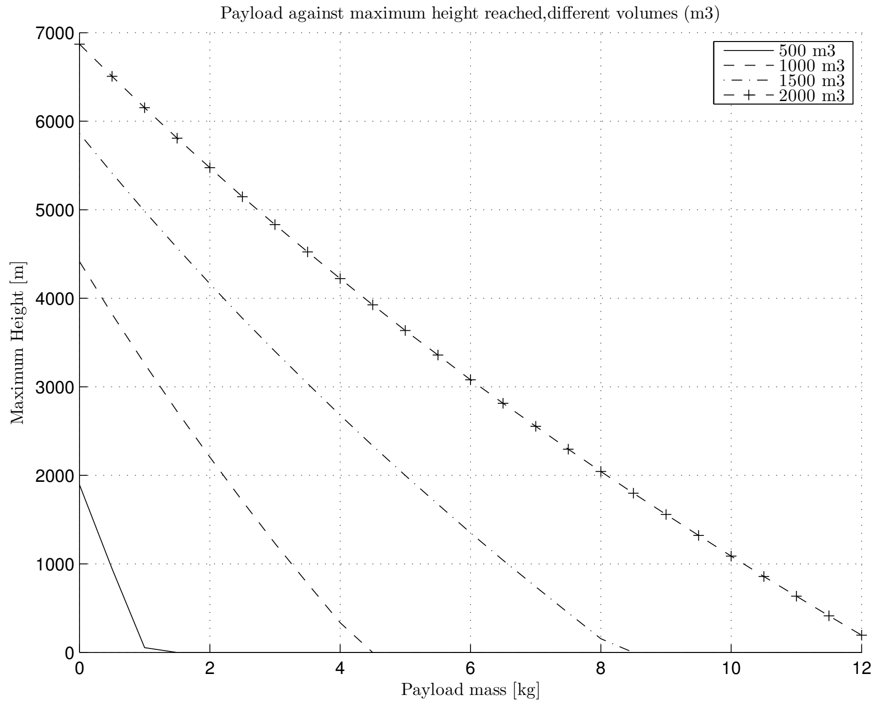


Figure 8.3: The influence of the initial volume of the balloon at zero altitude on the maximum altitude reached during flight. Standard balloon (table 8.1).

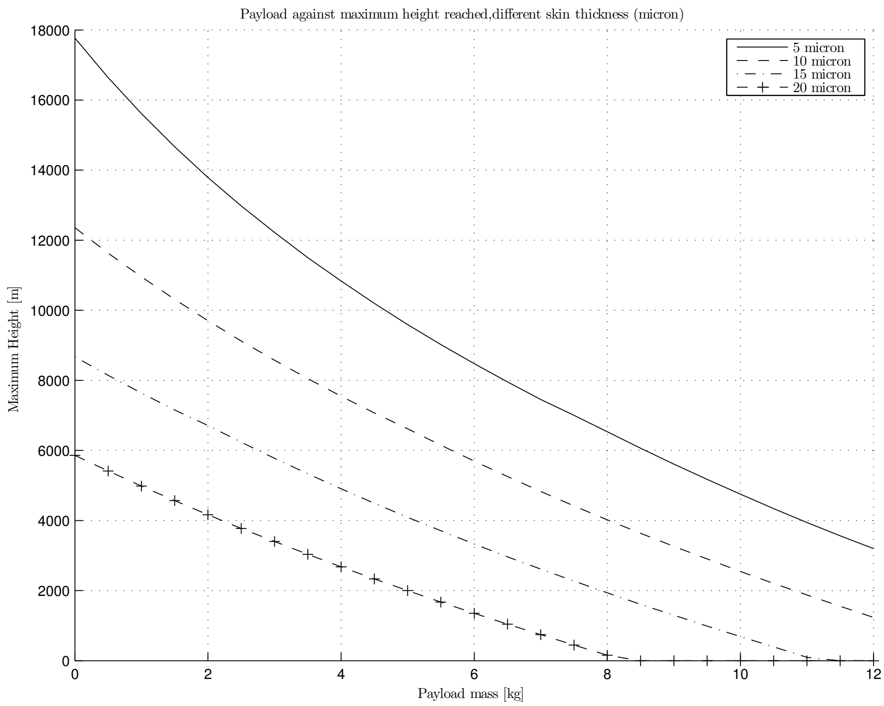


Figure 8.4: The influence of the skin thickness on the maximum altitude reached during flight. Standard balloon (table 8.1).

night [32]. This will have a great impact on the densities of both the atmosphere and the balloon gas, and hence the buoyancy of the balloon. Inclusion of this effect is especially important due to the fact that the mission is likely to be lost should the balloon hit the Martian surface.

A further interesting step in the modeling of this balloon mission is to research the influence of a tether on the balloon. First, the weight of the tether on the balloon should be taken into account. Secondly, an interesting research question would be whether the tether or the balloon will touch the Martian surface during certain extreme Martian weather conditions (such as low temperatures or high wind velocities). As mentioned before in this report, in case this event would occur, it is likely that the mission will be lost.

8.2 Prototype

In order to get insight into prototyping the Royal Netherlands Meteorological Institute (KNMI) was visited. All information in this section without reference to a source was obtained from Richard Rothe at the KNMI. At the KNMI a weather balloon is released at least three times per day. With this balloon temperature, humidity, and pressure is measured while its location is tracked by GPS. Other types measurements are possible as well but these measurements are not carried out on a daily basis. In this section some key elements of the balloon deployed by the KNMI are indicated.

One of the key issues that still has to be investigated is stability. The instruments that are typically used at the KNMI do not need the balloon to be stable because they only measure atmospheric parameters. To prevent excess swaying of the instruments and interference of the balloon with the measurements, the instruments are suspended more than 35 m below the balloon. Furthermore, in the case of a free balloon the relative velocity with respect to the wind is negligible and the instrument package will only be disturbed by gusts.

When a camera is used, which was once done during a solar eclipse, a cardan suspension system is used to prevent the camera from rotating with the balloon. Such a system could be calibrated to be very stable and is a viable option in case a camera is used in the Mars balloon. Figure 8.5 shows a picture of a cardan suspension system.

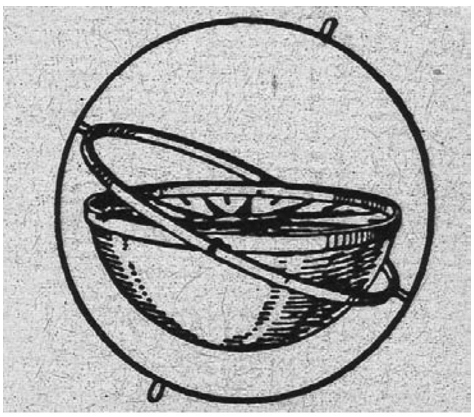


Figure 8.5: Schematic view of a cardan suspension system

The KNMI uses very little insulation for the standard instrument package. It is mainly the batteries and computer chips that are insulated. The lowest temperature measured by this standard package was around 183 K, [2], which is only a few degrees higher than the lowest

temperature during the summer on Mars [32]. When the standard package of the KNMI can operate at such extreme temperatures some easy modifications might be enough to ensure safe operation on Mars. The only obvious concern for a Martian mission is the employment of a camera, which might be more sensitive to extreme temperatures.

The balloon material, a latex compound, is biodegradable and is heavily affected by ultraviolet (uv-)radiation [3]. UV-radiation will make the balloon very brittle and after extended exposure (a few days) the balloon material will be no more than dust. Because the Mars balloon needs to withstand the Martian environment for a longer period of time the use of this specific material is not feasible.

There have been balloons which were used for a longer period of time on the Antarctic. A balloon with solar panels on the payload was released and recorded information for over a month. This shows that weather balloons can be employed in hostile environments for extended periods while utilising solar panels to generate electricity. It should be noted that for a Martian mission a very strict weight limit will be imposed on the system and the viability of such a system may become compromised because of that.

Finally, the data that is recorded by the instruments must be communicated to the ground in some way. The standard package stores data for 10 seconds and than relays this batch to a ground station. This means that some data storage has to be on board together with a communications module.

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Appendix A

Function break down diagram

The functional breakdown structure (figure A.1) displays the functions needed to support the exploration of Mars. The functions are divided in support for the instruments and the operations of the instruments themselves.

The eleven top level functions can be subdivided into smaller, more specific functions. For the N^2 chart only the eleven top level functions are used to maintain oversight.

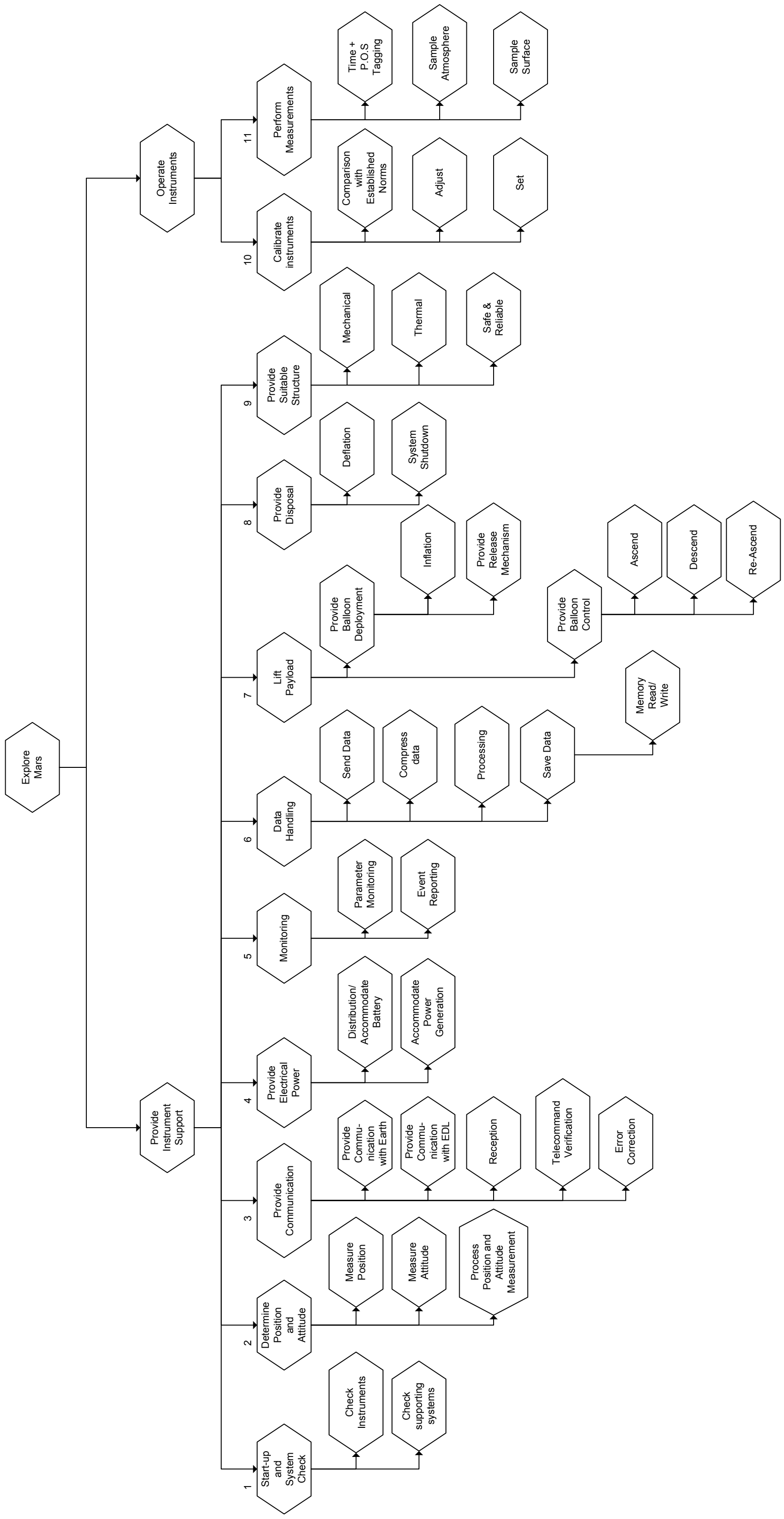


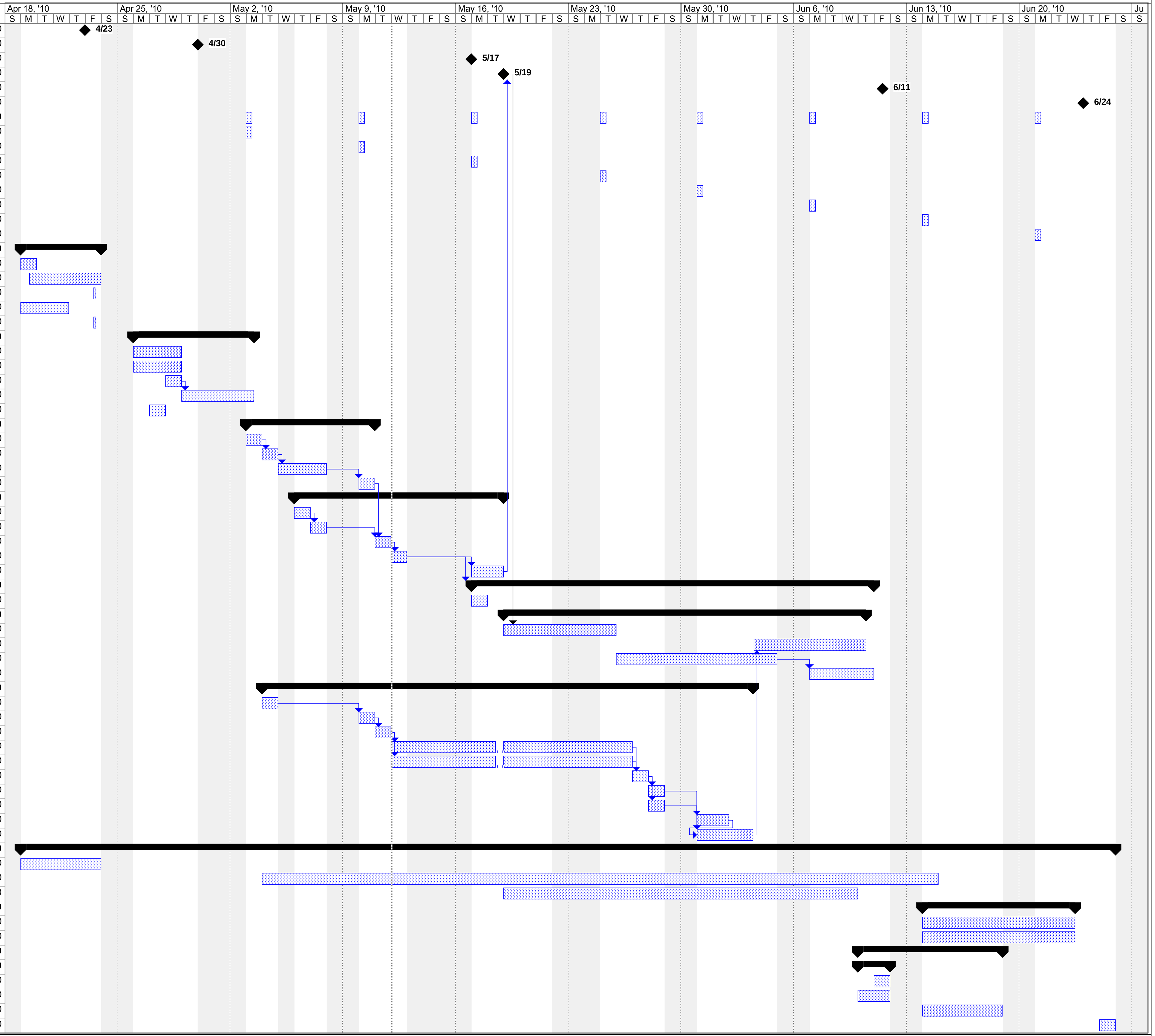
Figure A.1: Function break down

Appendix B

Gantt

Gantt Chart

ID	Task Name	Duration	Start	Finish
1	Project Plan	0 days	Fri 4/23/10	Fri 4/23/10
2	Baseline Report	0 days	Fri 4/30/10	Fri 4/30/10
3	Midterm Report	0 days	Mon 5/17/10	Mon 5/17/10
4	Meeting ESTEC	0 days	Wed 5/19/10	Wed 5/19/10
5	Final Report	0 days	Fri 6/11/10	Fri 6/11/10
6	Presentation	0 days	Thu 6/24/10	Thu 6/24/10
7	**Meeting**	**31.13 days**	**Mon 5/3/10**	**Mon 6/21/10**
8	Meeting 1	1 hr	Mon 5/3/10	Mon 5/3/10
9	Meeting 2	1 hr	Mon 5/10/10	Mon 5/10/10
10	Meeting 3	1 hr	Mon 5/17/10	Mon 5/17/10
11	Meeting 4	1 hr	Tue 5/25/10	Tue 5/25/10
12	Meeting 5	1 hr	Mon 5/31/10	Mon 5/31/10
13	Meeting 6	1 hr	Mon 6/7/10	Mon 6/7/10
14	Meeting 7	1 hr	Mon 6/14/10	Mon 6/14/10
15	Meeting 8	1 hr	Mon 6/21/10	Mon 6/21/10
16	**Project Planning**	**5 days**	**Mon 4/19/10**	**Fri 4/23/10**
17	Objective	1 day	Mon 4/19/10	Mon 4/19/10
18	Framework	4.5 days	Mon 4/19/10	Fri 4/23/10
19	Schedule	0.3 days	Fri 4/23/10	Fri 4/23/10
20	IT Logistics	3 days	Mon 4/19/10	Wed 4/21/10
21	Review/Approve	0.4 days	Fri 4/23/10	Fri 4/23/10
22	**Requirements**	**4.5 days**	**Mon 4/26/10**	**Mon 5/3/10**
23	Obtain data requirements	3 days	Mon 4/26/10	Wed 4/28/10
24	Obtain environmental requirements	3 days	Mon 4/26/10	Wed 4/28/10
25	Obtain structural requirements	1 day	Wed 4/28/10	Wed 4/28/10
26	Derive system requirement	1.5 days	Thu 4/29/10	Mon 5/3/10
27	Functional Flow	1 day	Tue 4/27/10	Tue 4/27/10
28	**Concepts**	**5 days?**	**Mon 5/3/10**	**Mon 5/10/10**
29	Interface definition	1 day?	Mon 5/3/10	Mon 5/3/10
30	Initial concept determination	1 day?	Tue 5/4/10	Tue 5/4/10
31	Detailed concept design	2 days	Wed 5/5/10	Fri 5/7/10
32	Evaluate concepts	1 day	Mon 5/10/10	Mon 5/10/10
33	**Trade-off**	**7 days**	**Thu 5/6/10**	**Tue 5/18/10**
34	Develop trade criteria	1 day	Thu 5/6/10	Thu 5/6/10
35	Develop trade method	1 day	Fri 5/7/10	Fri 5/7/10
36	Set up concept comparison table	1 day	Tue 5/11/10	Tue 5/11/10
37	Select concept and motivate	1 day	Wed 5/12/10	Wed 5/12/10
38	Prepare for meeting ESTEC	2 days	Mon 5/17/10	Tue 5/18/10
39	**Detail design**	**18 days**	**Mon 5/17/10**	**Thu 6/10/10**
40	Determine scaling factors Earth-Mars	1 day	Mon 5/17/10	Mon 5/17/10
41	**Adjust concepts**	**15.5 days**	**Wed 5/19/10**	**Thu 6/10/10**
42	From ESTEC results	4 days	Wed 5/19/10	Tue 5/25/10
43	From prototype results	5 days	Thu 6/3/10	Thu 6/10/10
44	Detail design subsystems	8 days	Wed 5/26/10	Fri 6/4/10
45	Create final designs	4 days	Mon 6/7/10	Thu 6/10/10
46	**Experimental**	**18.5 days**	**Tue 5/4/10**	**Thu 6/3/10**
47	Prepare for contact KNMI	1 day	Tue 5/4/10	Tue 5/4/10
48	Initial visit KNMI	1 day	Mon 5/10/10	Mon 5/10/10
49	Test setup and prototype requirements	1 day	Tue 5/11/10	Tue 5/11/10
50	Produce prototype 2km	7.5 days	Wed 5/12/10	Wed 5/26/10
51	Produce prototype 28km	7.5 days	Wed 5/12/10	Wed 5/26/10
52	Fitcheck	1 day	Thu 5/27/10	Thu 5/27/10
53	Perform experiment 2km	1 day	Fri 5/28/10	Fri 5/28/10
54	Perform experiment 28km	1 day	Fri 5/28/10	Fri 5/28/10
55	Backup balloon days	2 days	Mon 5/31/10	Tue 6/1/10
56	Analyze results	3.5 days	Mon 5/31/10	Thu 6/3/10
57	**Document and Present**	**45 days**	**Mon 4/19/10**	**Fri 6/25/10**
58	Document project plan	5 days	Mon 4/19/10	Fri 4/23/10
59	Document design analysis	26 days	Tue 5/4/10	Mon 6/14/10
60	Document experiment	15 days	Wed 5/19/10	Wed 6/9/10
61	**Delft**	**7.5 days**	**Mon 6/14/10**	**Wed 6/23/10**
62	Poster Delft	7.5 days	Mon 6/14/10	Wed 6/23/10
63	Presentation	7.5 days	Mon 6/14/10	Wed 6/23/10
64	**Barcelona**	**7 days**	**Thu 6/10/10**	**Fri 6/18/10**
65	**Preperation Barcelona**	**2 days**	**Thu 6/10/10**	**Fri 6/11/10**
66	Reading papers of others	1 day	Fri 6/11/10	Fri 6/11/10
67	Poster Barcelona	2 days	Thu 6/10/10	Fri 6/11/10
68	Trip Barcelona	5 days	Mon 6/14/10	Fri 6/18/10
69	Perform lessons-learned session	1 day	Fri 6/25/10	Fri 6/25/10



Project: Planning_(Visio_Gantt_Expor
Date: Wed 5/12/10

Task | Progress | Summary | External Tasks | Deadline
Split | Milestone | Project Summary | External Milestone