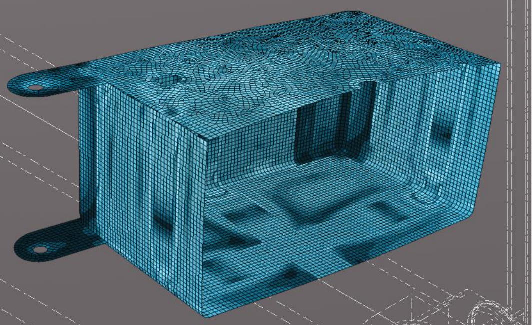
Design and Structural Analysis of the Propellant Tank for a Water Resistojet

I. Granero Moneva



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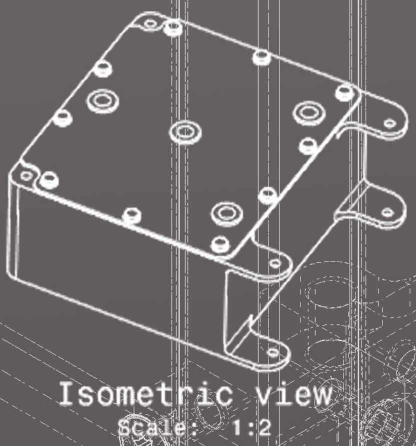

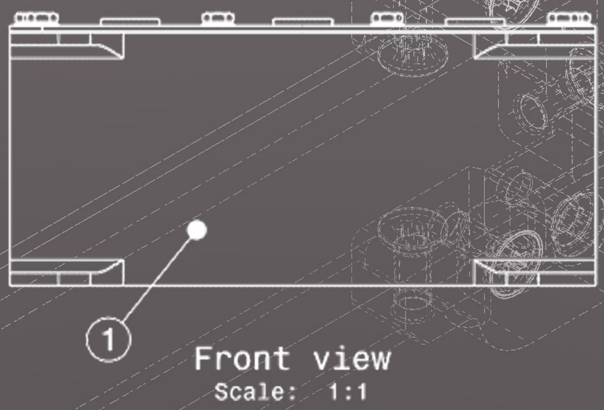

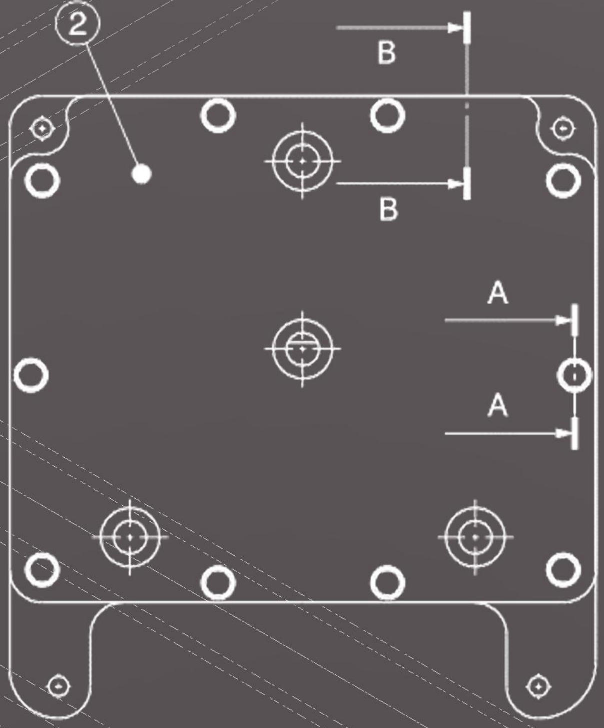

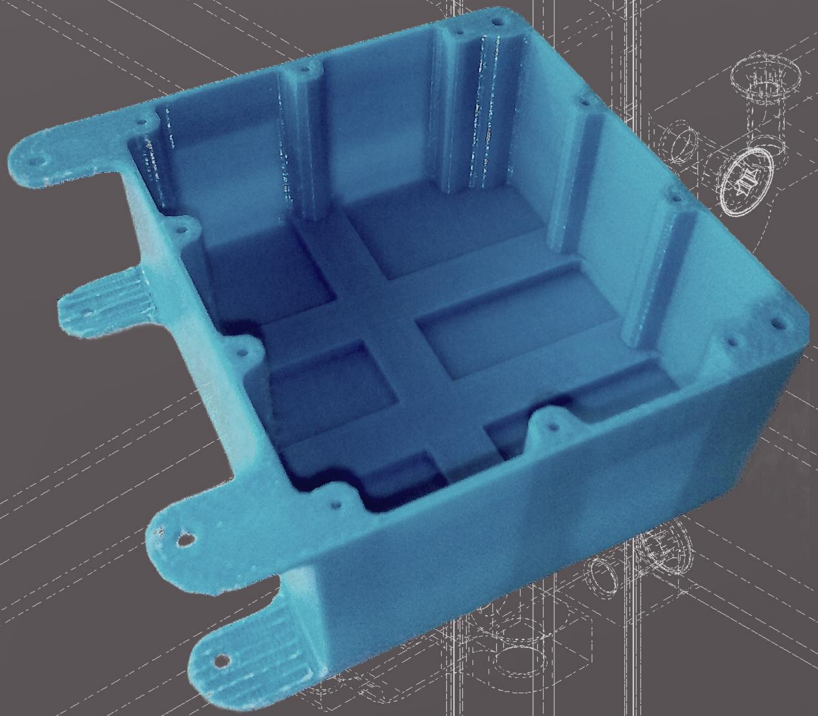

Delft University of Technology

Challenge the future

DESIGN AND STRUCTURAL ANALYSIS OF THE PROPELLANT TANK FOR A WATER RESISTOJET

by

I. Granero Moneva

in partial fulfillment of the requirements for the degree of

Bachelor of Science
in Aerospace Engineering

at the Polytechnic University of Madrid,
to be defended publicly on Thursday July 16, 2015 at 15:30 PM.

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This thesis is confidential and cannot be made public until July 15, 2015.

PREFACE

It all started with Pedro Duque – first Spanish astronaut – and the account of his space trips I was fortunate to listen to at the tender age of 12. The simple questions "how do they do it, how do they travel to space?" came to my mind and triggered a passion and thirst of knowledge of space engineering. The completion of this Bachelor Thesis is just the starting point of a devoted career in the field. It represents the interplay of the different areas learnt during these studies, all applied to a real mission. Developing this work as an exchange student, in different language and environment from the one I am accustomed to has been both a daunting challenge and a tremendous boost of motivation at the same time.

Collaborating on the DelFFi Mission, as well as delivering relevant models and results can be regarded as a successful engineering project, in which theories and knowledge are means to an end. This outcome is useful and serves a need and purpose, from which there is a benefit. Being able to contribute with this project was the ultimate objective, learning from the process and gaining invaluable experience for my future professional career.

I encourage the reader to appreciate the interaction between the different stages of a design project, which are deeply interwoven. Although a step-by-step process is followed, previous and future steps are taken into account, in order to minimise the number of design iterations. Furthermore, the reader should focus on the expected deliverables, which shall ensure the correct functioning of the design. All in all, I hope the reader finds the work presented herein interesting and helpful for future engineering and research projects.

I. Granero Moneva
Delft, July 2015

ABSTRACT

The purpose of this Thesis is to develop the design process of the pressurised propellant tank for a water resistojet, applicable to nanosatellite missions. The motivation of this system is its use on the CubeSat mission DelFFi, from the Technical University of Delft. The need for a small-sized pressure vessel is covered by the Detail Design delivered in this Thesis, which is a result of the application of decision making techniques as well as a structural analysis.

It is possible to distinguish two fields of investigation throughout the work: design and structures. The design of the propellant tank is tackled following the Design Trades: a systems engineering approach which makes use of decision making, a trade-off process and uncertainty analysis. By applying a 10-step methodology, a set of conceptual designs is developed and further refined into a preliminary design. As far as the structural analysis is concerned, both an analytical study and a Finite Element Analysis are completed. The former is mainly used for verification and validation of the latter. The result is a Detail Design, ready for manufacture and testing.

As a result, a design compliant with the requirements is delivered, together with CAD and Finite Element models. This design involves a rectangular section pressurised tank, compatible with CubeSat structures, manufactured from aluminium via CNC milling. The conclusion is a successful application of the methodologies, a complex design and guidelines with expected correct performance and a know how on pressurised propellant tank design and analysis.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

CAD	Computer Aided Design
CNC	Computer Numerical Control
CTE	Coefficient of Thermal Expansion
DOT	Design Option Tree
FEA	Finite Element Analysis
LV	Launch Vehicle
PCB	Printed Circuit Board
PMD	Propellant Management Device
TRL	Technology Readiness Level

1

INTRODUCTION

1.1. MOTIVATION AND STRUCTURE OF THE DIPLOMA PROJECT

The DelFFi Mission is the third satellite project within the Delfi Program of TU Delft. Its design will make use of an active propulsion system on board, which is being developed entirely by TU Delft. The baseline option, already under development at the start of this thesis or Diploma Project, is a water-based micro resistojet. The DelFFi Propulsion System relies on a Propellant Storage System that maintains the water in a pressurised state in a Propellant Tank.

At the start of this thesis, the status of the DelFFi Propulsion System called for a complete design iteration of the Propellant Tank [1], for which only a concept design had been developed. This status report created a need for the design and structural analysis of the Propellant Tank. Even though there are companies with commercially available pressure tanks, they do not fit the needs and requirements of the system, so it was decided to carry out the development of the propellant tank internally, enabling further student participation in the project.

The purpose of this Thesis is to develop the design process of the Propellant Tank until manufacturing and testing stage, delivering a Detail Design. The process will consist in generating a Preliminary Design and perform a structural analysis via Finite Element Methods so as to define a Detail Design. This satisfies the need for a Propellant Tank redesign, and leaves space for further student work regarding the manufacturing and testing campaign.

In this way, the objectives of the Thesis are listed as follows:

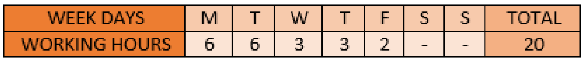
- Create a Detail Design in compliance with the requirements of the Propulsion System.
- Contribute to the DelFFi Mission by generating a CAD (Computer Aided Design) Model of the Propellant Tank at the Detail Design stage.
- Perform a structural analysis of the Propellant Tank.
- Contribute to the DelFFi Mission by generating a Finite Element Model of the Propellant Tank at the Detail Design stage.

The process followed to achieve these objectives is the following one:

1. Establish the requirements of the Propellant Tank, taking into account the propulsion system requisites, the interfaces with other subsystems and the environmental conditions.
2. Create a Preliminary Design in compliance with the requirements, making use of the CAD software CATIA V5 (under the licence of TU Delft) and relying on an analytical study of the different load cases.
3. Perform a structural analysis of the Preliminary Design via Finite Element Methods, with the help of Abaqus 6.13 software (under the licence of TU Delft).
4. Generate a Detail Design ready for manufacturing and testing.

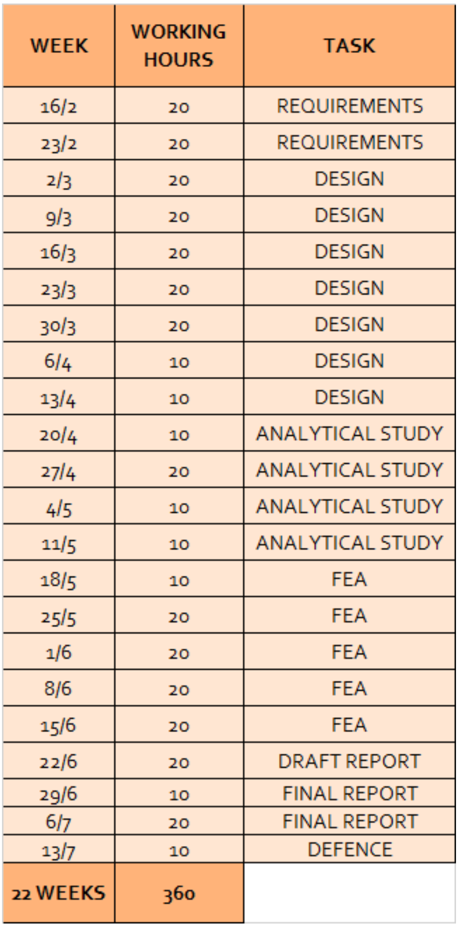
The structure of this Thesis follows the chronological order of the design process. The introduction gives an overview of the mission. Subsequently, the requirements are displayed and explained. The third chapter covers the design process until the Preliminary Design. Subsequently, the analytical study and verification plan are presented. The Finite Element Analysis results in the Detail Design, and lastly the conclusions and recommendations are exposed. This Diploma Project is oriented to the development of a real engineering project within the DelFFi Mission. This is why simplicity and functionality may be a deterrent to research and experimentation. Nevertheless, the work includes the application of systems engineering, decision making processes and theory of structures. The results obtained call for an incisive analysis and understanding, for which all the know how of the engineer is required.

With respect to the work schedule, a Working Hours Breakdown, together with a working schedule including the important milestones, were developed before the start of the Thesis and were adjusted during its development. Figures 1.1 and 1.2 show the distribution of working hours per week and the schedule of work, respectively. In the latter, notice that the weeks which include holidays or exams will result in less hours of dedication to the Thesis. However, the total number of working hours corresponds to the working load of 12 ECTS that the Diploma Project requires. A weekly meeting of the DelFFi Propulsion Team is established to keep track of the progress being made, to take team decisions and to give feedback on the work done.



WEEK DAYS	M	T	W	T	F	S	S	TOTAL
WORKING HOURS	6	6	3	3	2	-	-	20

Figure 1.1: Weekly working hours breakdown



WEEK	WORKING HOURS	TASK
16/2	20	REQUIREMENTS
23/2	20	REQUIREMENTS
2/3	20	DESIGN
9/3	20	DESIGN
16/3	20	DESIGN
23/3	20	DESIGN
30/3	20	DESIGN
6/4	10	DESIGN
13/4	10	DESIGN
20/4	10	ANALYTICAL STUDY
27/4	20	ANALYTICAL STUDY
4/5	10	ANALYTICAL STUDY
11/5	10	ANALYTICAL STUDY
18/5	10	FEA
25/5	20	FEA
1/6	20	FEA
8/6	20	FEA
15/6	20	FEA
22/6	20	DRAFT REPORT
29/6	10	FINAL REPORT
6/7	20	FINAL REPORT
13/7	10	DEFENCE
22 WEEKS	360	

Figure 1.2: Work schedule for the Thesis

1.2. THE DELFFI MISSION

The DelFFi Mission Statement [2] is as follows:

"The DelFFi mission shall demonstrate autonomous formation flying and provide enhanced scientific return within QB50 from 2015 onwards, by utilizing two identical triple-unit Cubesats of TU Delft which further advance the Delfi-n3Xt platform."

The objectives of the DelFFi mission are threefold [2]:

- Demonstrate autonomous formation flying using various Guidance, Navigation and Control (GNC) architectures.
- Facilitate students with hands-on experience and cutting-edge technology.
- Characterize low thermosphere with enhanced scientific return by using distributed observation on various geometric baselines.

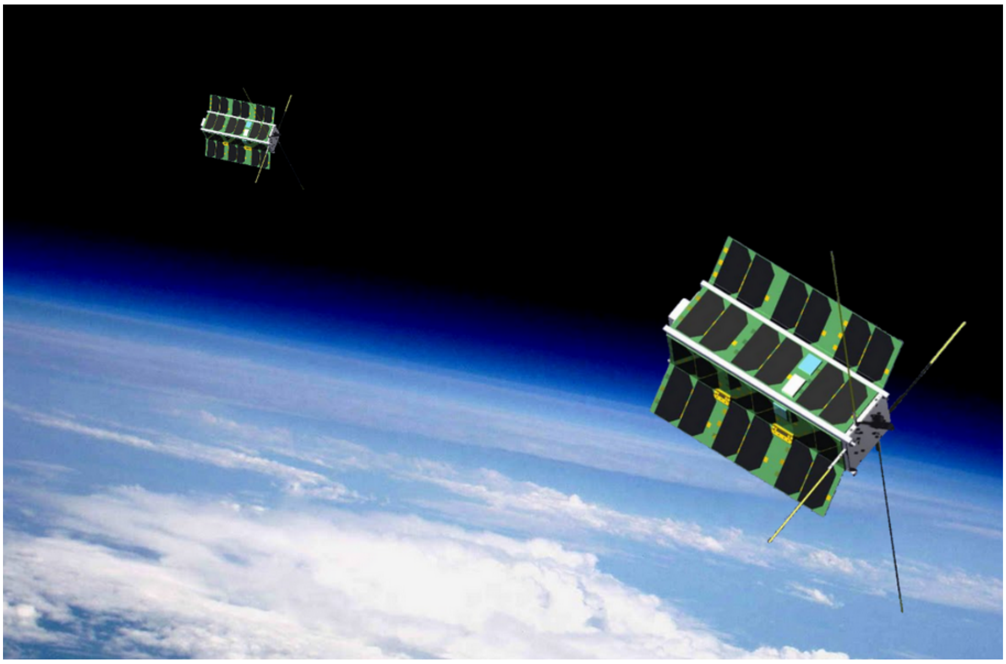


Figure 1.3: Artists image of the DelFFi Satellites (Source [2])

1.2.1. QB50 PROJECT

An increasing interest in nano-satellites for the past years has motivated universities and space agencies to organise educative space programmes based on this technology, such as the QB50. This ambitious project called for 50 nano-satellites fully designed by institutions from all around the globe. TU Delft, already an experimented university in nano-satellite technology, will contribute to this programme with a 2-satellite mission (DelFFi), whose main objective is to demonstrate autonomous formation flying.[1]

The objective of the QB50 mission is to demonstrate the possibility of launching a constellation of 50 CubeSats built by Universities Teams all over the world as a primary payload on a low-cost launch vehicle to perform first-class science in the largely unexplored lower thermosphere.[3]

In order to achieve this, the approach taken by the mission is to take in-situ measurements. Space agencies cannot undertake this approach due to the high cost of a network of 50 satellites built to industrial standards with the limited orbital lifetime (the altitude and type of mission are the main drivers of the lifetime of this mission). As no atmospheric network mission for in-situ measurements has been carried out in the past or is planned for the future [3], there is an opportunity for institutes and universities to actively contribute to space exploration. This gives students a hands-on experience in real missions, as well as it increases the know-how of the institutions and professors, all in benefit of the education level.

The network required for in-situ measurements in the lower thermosphere can only be realised by using very low-cost satellites, and CubeSats are the most feasible option. By collaborating with different universities, the QB50 project provides them with a sustained and affordable access to space. It will be proved that significant scientific and technological research can be achieved by means of low-cost satellites. Standardisation is an important cost-reducing key, but given the multiple stakeholders involved in this early stage of nano-satellite technology, it has not yet been achieved, as each institution has tried to develop their own projects with little interface to the community. The use of 50 CubeSats in coordination with 15 different partners is a challenge that QB50 faces in order to enable the harmonisation and standardisation of the CubeSat platform, increasing its TRL. QB50 will put a great number of the stakeholders together, thus generating an extraordinary situation to develop more cost-effective platform solutions.[3]

1.2.2. CUBESAT MISSION CONCEPT

CubeSats were developed by a collaboration with California Polytechnic State University and Standford University's Space Systems Development Laboratory which started in 1999. The primary mission of the CubeSat Program is to provide access to space for small payloads[4]. The CubeSat Program provides[5]:

- A standard physical layout and design guidelines.
- A standard, flight proven deployment system (P-POD).
- Coordination of required documents and export licences.
- Integration and acceptance testing facilities with formalized schedules.
- Shipment of flight hardware to the launch site and integration on the LV (Launching Vehicle)
- Confirmation of successful deployment and telemetry information.

1.2.3. PROPULSION SYSTEM

In order to achieve the mission statement, it was decided that the DelFFi satellites will count with an active propulsion system. Already under development, it consists in a water-propelled micro resistojet, based on MEMS technology. After applying a Subsystem Breakdown Structure, the propulsion system has been divided into 5 branches, namely Mission (MIS), Thruster System (THR), Propellant Storage System (STOR), Feed System (FEED) and Printed Circuit Board (PCB). Within the STOR branch, the Propellant Tank (STOR-TNK) will be the main focus of this Thesis.

1.2.4. DELFFI PROPULSION TEAM

The current members of the DelFFi Propulsion Team can be found in table 1.1. A meeting of the complete team is carried out on a weekly basis.

Table 1.1: DelFFi Propulsion Team (from February 2015 to July 2015)

Member	**Position**	**Responsibility**
B.T.C. Zandbergen	TU Delft Staff Member	Propulsion Expert
A. Cervone	TU Delft Staff Member	Propulsion Expert
E. Jansen	TU Delft Student	Propulsion AIT Engineer
T. van Wees	TU Delft Student	Propulsion Engineer
I. Granero	TU Delft Student	Stress Analysis Engineer

2

PROPELLANT TANK REQUIREMENTS

2.1. APPROACH: REQUIREMENT DISCOVERY

The design of a system or part of a system in space engineering is driven by the requirements. The requirements represent the characteristics and performance that the product shall have, and must be taken into account during the design process. Thus, in order to start with the design of the Propellant Storage System, the set of specific requirements for the system have to be defined. The Propellant Storage System consists of the Propellant Tank, the Propellant and the Pressurant. The former is the only within the scope of this Thesis. This is why only the requirements on the Propellant Tank are discussed during this chapter, although the Propellant Storage System Requirements are the ones incorporated into the Propulsion Subsystem Requirements [6].

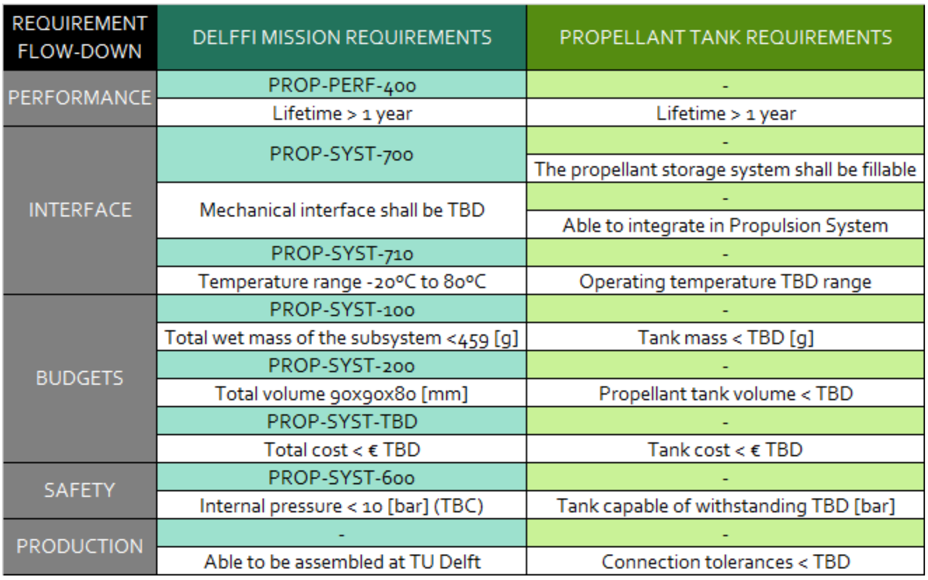
With the aim to obtain a complete set of requirements before starting the design of the Propellant Tank (this will avoid pursuing useless design directions), a structured method will be followed, known as the Requirement Discovery [11]. Even if the method would start by defining the needs of the system, designing a part of a larger system calls for a previous step: gathering what has already been defined about the system to be designed. This may be found in top level requirements, requirements flow-down charts, design indications or other technical documents. The following step is to complete these requirements or guidelines given via the requirement discovery method. Finally, all requirements are analysed to confirm that they are verifiable and consistent with the other documents, systems and subsystems.

The Propellant Tank is a part of the Propulsion Subsystem. In consequence, part of the requirements that concern the Propellant Storage System and the Propellant Tank had already been defined in the document [7], which describes the flow-down of top level requirements of the subsystem into its different components. However, this flow-down does not assign yet a specific numbering or a defined requirement statement, but merely indicates the top level requirements to be taken into consideration in the form of pseudo requirements. After gathering all these pseudo requirements in a set, it is completed with the requirements it may still lack because of them only affecting the Propellant Tank and its children, but not its parents. This generates a complete set of pseudo requirements, which may be discussed with the stakeholders. In the case of the Propellant Storage System, the stakeholder taken into account is the DelFFi Propulsion Team. After this, each requirement is correctly formulated and assigned an identifier. The process of generating requirements has iterations due to feedback given by stakeholders and reviewers.

A common way to generate the complete set of requirements is by using a Requirements Discovery Tree. This type of diagram is an AND tree, widely used in the Requirement Discovery method, and its purpose is not to forget any requirement. To generate the Requirements Discovery Tree, a classification has been followed based on the different dimensions on which requirements should be established.

2.2. REQUIREMENTS ON THE PROPELLANT TANK

From document [7], it is possible to obtain requirements on the Propellant Tank that flow down from the subsystem level requirements. These are summed up on figure 2.1.

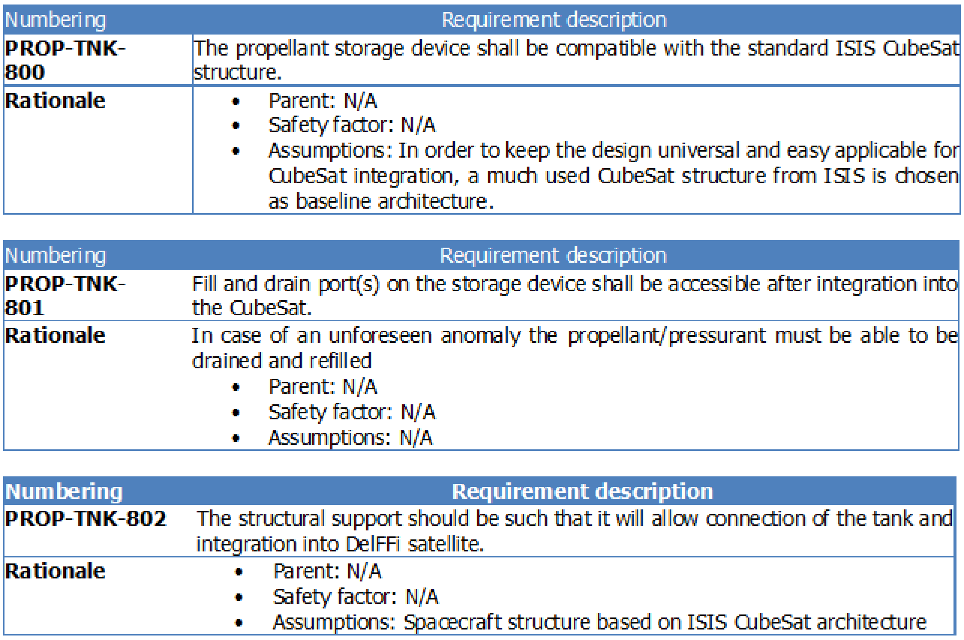


REQUIREMENT FLOW-DOWN	DELFFI MISSION REQUIREMENTS	PROPELLANT TANK REQUIREMENTS
PERFORMANCE	PROP-PERF-400	-
	Lifetime > 1 year	Lifetime > 1 year
INTERFACE	PROP-SYST-700	-
		The propellant storage system shall be fillable
	Mechanical interface shall be TBD	-
		Able to integrate in Propulsion System
	PROP-SYST-710	-
	Temperature range -20°C to 80°C	Operating temperature TBD range
BUDGETS	PROP-SYST-100	-
	Total wet mass of the subsystem <459 [g]	Tank mass < TBD [g]
	PROP-SYST-200	-
	Total volume 90x90x80 [mm]	Propellant tank volume < TBD
	PROP-SYST-TBD	-
	Total cost < € TBD	Tank cost < € TBD
SAFETY	PROP-SYST-600	-
	Internal pressure < 10 [bar] (TBC)	Tank capable of withstanding TBD [bar]
PRODUCTION	-	-
	Able to be assembled at TU Delft	Connection tolerances < TBD

Figure 2.1: Flow down requirements for the Propellant Tank

In order to complete the set of requirements, the Requirements Discovery Tree is shown on figure 2.9 at the end of this section. It was elaborated by E. Jansen and I. Granero, resulting in an internal document which was later used to complete the Propulsion Subsystem Requirements [6], under section Propellant Storage System Requirements. The values stated on the graph are not definitive, and some were changed during their incorporation to document [6]. Notice also that they still do not have an identifier or numbering, which is only assigned in the aforementioned document.

Given that not all the requirements from the Propellant Storage System are taken into account during the design and structural analysis of the Propellant Tank, only the applicable requirements will be presented here (figures 2.2, 2.3, 2.4, 2.5, 2.6, 2.7 and 2.8). When used during the design and structural analysis, they will be cited or referred to by the identifier. Furthermore, a Compliance Matrix for the requirements was elaborated and updated. It can be found in Appendix A.

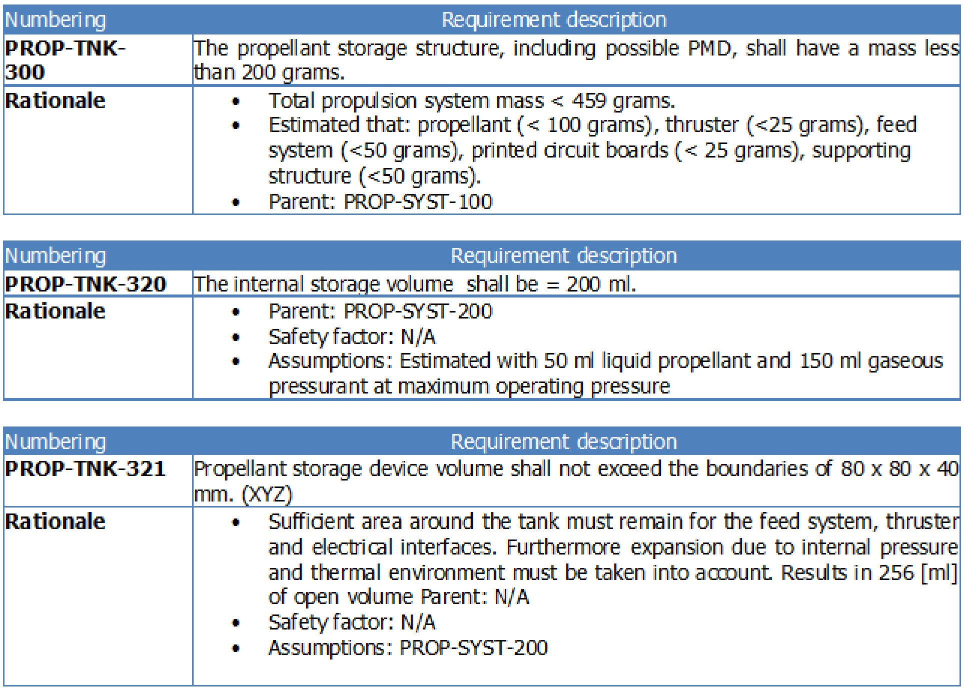


Numbering	Requirement description
PROP-TNK-800	The propellant storage device shall be compatible with the standard ISIS CubeSat structure.
Rationale	• Parent: N/A • Safety factor: N/A • Assumptions: In order to keep the design universal and easy applicable for CubeSat integration, a much used CubeSat structure from ISIS is chosen as baseline architecture.

Numbering	Requirement description
PROP-TNK-801	Fill and drain port(s) on the storage device shall be accessible after integration into the CubeSat.
Rationale	In case of an unforeseen anomaly the propellant/pressurant must be able to be drained and refilled • Parent: N/A • Safety factor: N/A • Assumptions: N/A

Numbering	**Requirement description**
PROP-TNK-802	The structural support should be such that it will allow connection of the tank and integration into DelFFi satellite.
Rationale	• Parent: N/A • Safety factor: N/A • Assumptions: Spacecraft structure based on ISIS CubeSat architecture

Figure 2.2: Propellant Tank Requirements: Assembly and Installation

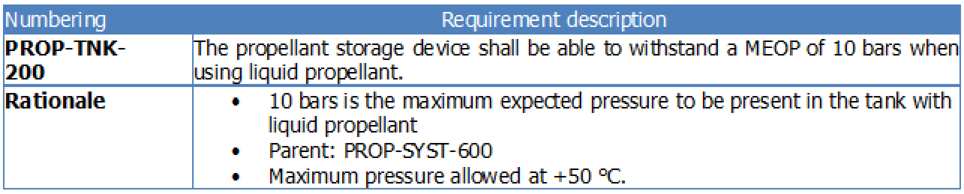


Numbering	Requirement description
PROP-TNK-300	The propellant storage structure, including possible PMD, shall have a mass less than 200 grams.
Rationale	• Total propulsion system mass < 459 grams. • Estimated that: propellant (< 100 grams), thruster (<25 grams), feed system (<50 grams), printed circuit boards (< 25 grams), supporting structure (<50 grams). • Parent: PROP-SYST-100

Numbering	Requirement description
PROP-TNK-320	The internal storage volume shall be = 200 ml.
Rationale	• Parent: PROP-SYST-200 • Safety factor: N/A • Assumptions: Estimated with 50 ml liquid propellant and 150 ml gaseous pressurant at maximum operating pressure

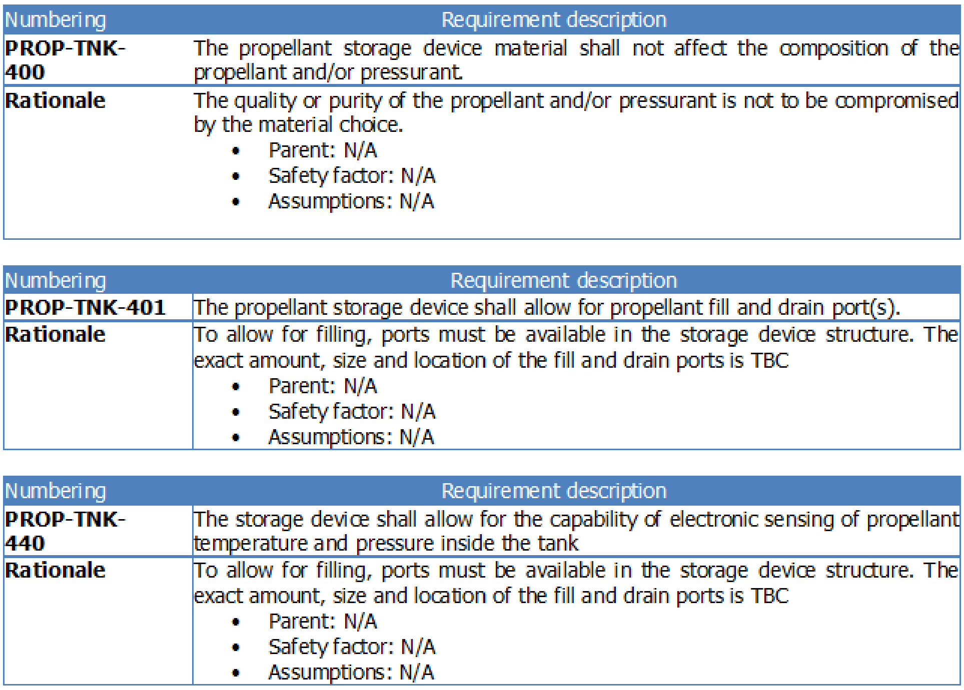
Numbering	Requirement description
PROP-TNK-321	Propellant storage device volume shall not exceed the boundaries of 80 x 80 x 40 mm. (XYZ)
Rationale	• Sufficient area around the tank must remain for the feed system, thruster and electrical interfaces. Furthermore expansion due to internal pressure and thermal environment must be taken into account. Results in 256 [ml] of open volume Parent: N/A • Safety factor: N/A • Assumptions: PROP-SYST-200

Figure 2.3: Propellant Tank Requirements: Budgets



Numbering	Requirement description
PROP-TNK-200	The propellant storage device shall be able to withstand a MEOP of 10 bars when using liquid propellant.
Rationale	• 10 bars is the maximum expected pressure to be present in the tank with liquid propellant • Parent: PROP-SYST-600 • Maximum pressure allowed at +50 °C.

Figure 2.4: Propellant Tank Requirements: Performance

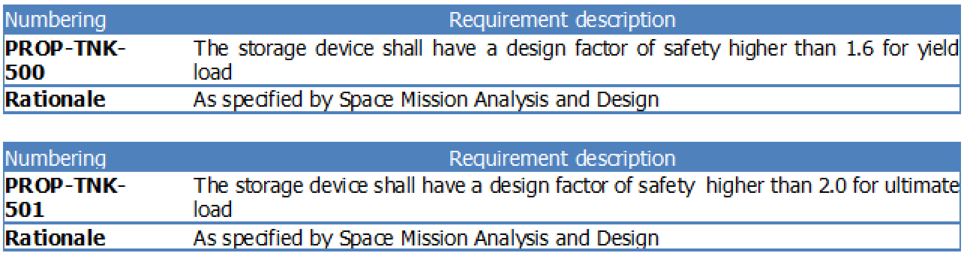


Numbering	Requirement description
PROP-TNK-400	The propellant storage device material shall not affect the composition of the propellant and/or pressurant.
Rationale	The quality or purity of the propellant and/or pressurant is not to be compromised by the material choice. • Parent: N/A • Safety factor: N/A • Assumptions: N/A

Numbering	Requirement description
PROP-TNK-401	The propellant storage device shall allow for propellant fill and drain port(s).
Rationale	To allow for filling, ports must be available in the storage device structure. The exact amount, size and location of the fill and drain ports is TBC • Parent: N/A • Safety factor: N/A • Assumptions: N/A

Numbering	Requirement description
PROP-TNK-440	The storage device shall allow for the capability of electronic sensing of propellant temperature and pressure inside the tank
Rationale	To allow for filling, ports must be available in the storage device structure. The exact amount, size and location of the fill and drain ports is TBC • Parent: N/A • Safety factor: N/A • Assumptions: N/A

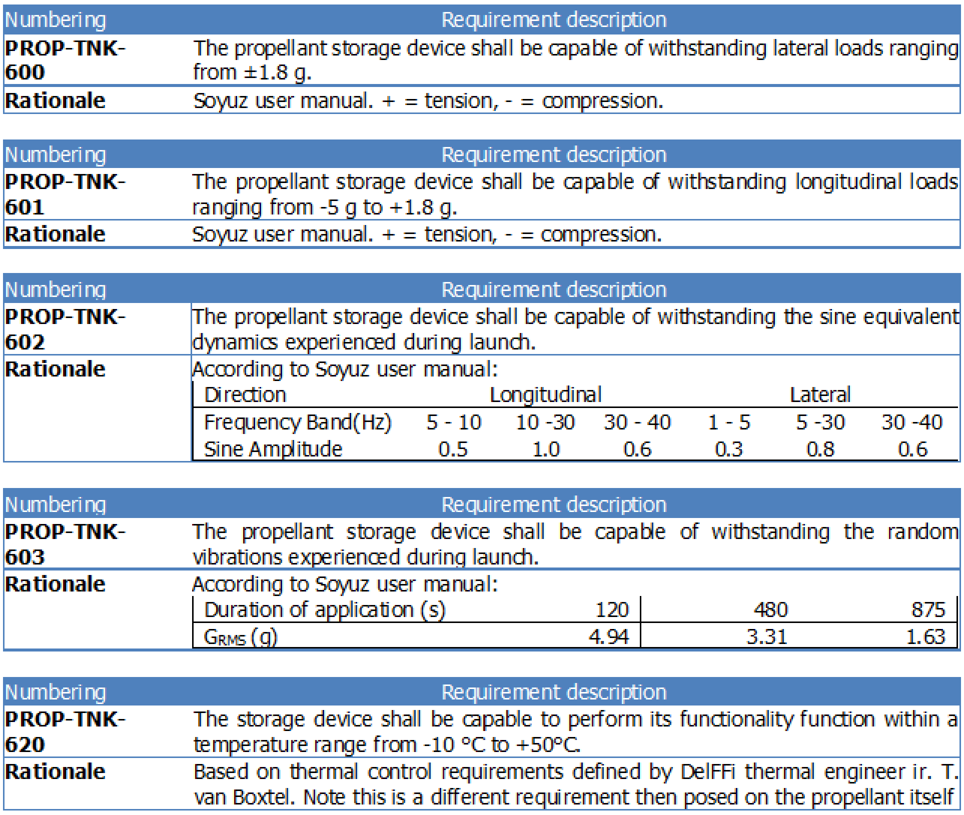
Figure 2.5: Propellant Tank Requirements: Interface



Numbering	Requirement description
PROP-TNK-500	The storage device shall have a design factor of safety higher than 1.6 for yield load
Rationale	As specified by Space Mission Analysis and Design

Numbering	Requirement description
PROP-TNK-501	The storage device shall have a design factor of safety higher than 2.0 for ultimate load
Rationale	As specified by Space Mission Analysis and Design

Figure 2.6: Propellant Tank Requirements: Safety



Numbering	Requirement description
PROP-TNK-600	The propellant storage device shall be capable of withstanding lateral loads ranging from ±1.8 g.
Rationale	Soyuz user manual. + = tension, - = compression.

Numbering	Requirement description
PROP-TNK-601	The propellant storage device shall be capable of withstanding longitudinal loads ranging from -5 g to +1.8 g.
Rationale	Soyuz user manual. + = tension, - = compression.

Numbering	Requirement description
PROP-TNK-602	The propellant storage device shall be capable of withstanding the sine equivalent dynamics experienced during launch.
Rationale	According to Soyuz user manual:

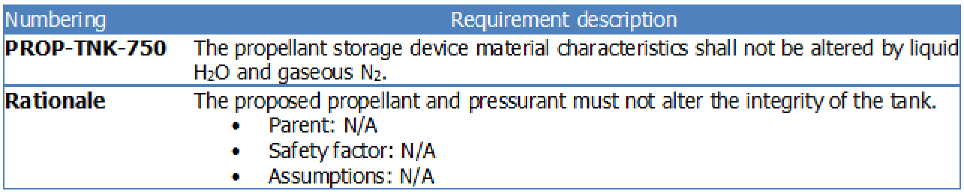
Direction	Longitudinal			Lateral		
Frequency Band(Hz)	5 - 10	10 -30	30 - 40	1 - 5	5 -30	30 -40
Sine Amplitude	0.5	1.0	0.6	0.3	0.8	0.6

Numbering	Requirement description
PROP-TNK-603	The propellant storage device shall be capable of withstanding the random vibrations experienced during launch.
Rationale	According to Soyuz user manual:

Duration of application (s)	120	480	875
G_{RMS} (g)	4.94	3.31	1.63

Numbering	Requirement description
PROP-TNK-620	The storage device shall be capable to perform its functionality function within a temperature range from -10 °C to +50°C.
Rationale	Based on thermal control requirements defined by DelFFi thermal engineer ir. T. van Boxtel. Note this is a different requirement then posed on the propellant itself

Figure 2.7: Propellant Tank Requirements: Environment



Numbering	Requirement description
PROP-TNK-750	The propellant storage device material characteristics shall not be altered by liquid H_2O and gaseous N_2.
Rationale	The proposed propellant and pressurant must not alter the integrity of the tank. • Parent: N/A • Safety factor: N/A • Assumptions: N/A

Figure 2.8: Propellant Tank Requirements: Production and Materials

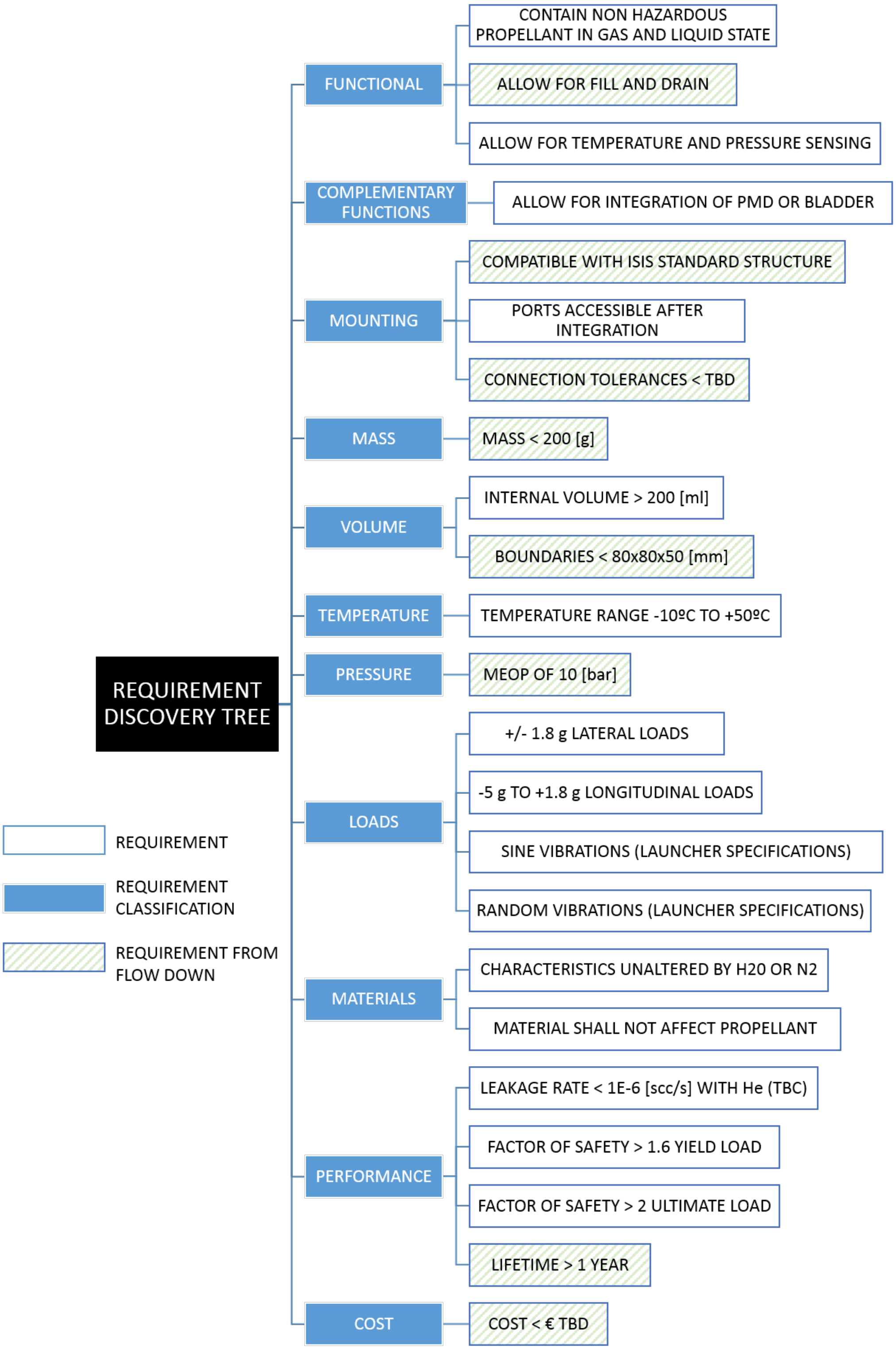


Figure 2.9: Propellant Tank Requirements Discovery

3

FROM CONCEPTUAL DESIGNS TO A PRELIMINARY DESIGN

3.1. APPROACH: DESIGN TRADES

Once the requirements of the Propellant Tank have been defined, it is possible to proceed with the next step of the design process: the design trades, within the framework of Systems Engineering. The idea behind this phase is to obtain design concepts that could comply with the requirements without the need to explore each possibility in depth. The broad range of solutions to the requirements has to be narrowed down to a small set of feasible options, using general criteria based on the key requirements. The output of the initial trades will be a reduced set of conceptual designs, to which a further trade-off study will be applied, in order to generate a single preliminary design.[11]

The design trades lead to decisions on implementation. Following a complete and well-defined step-by-step process helps on this decision making. This is called a Trade-off Process. In the beginning of a design project, few but crucial trades are made. As the project continues, more decisions have to be taken, but they have a smaller impact on the project as a whole. This is why the initial phase has to be thoroughly completed, without missing any step.[11] This first section will explain the applied theory behind decision making, whilst the following sections will explain the details of the design trades of the Propellant Tank project.

A consistent and well-rounded Trade-off process, which will be taken as baseline, is discussed in the reference [12]. Herein, it is argued that decision analysis process can be decomposed into ten process steps (see also figure 3.1):

1. frame decision and tailor process,
2. develop objectives and measures,
3. generate creative alternatives,
4. assess alternatives via deterministic analysis,
5. synthesise results,
6. identify uncertainty and conduct probabilistic analysis,
7. assess impact of uncertainty,
8. improve alternatives,
9. communicate trade-off studies,
10. present recommendation and implementation plan.

Figure 3.1: Decision Management Process Map (Source [12])

The first step of the decision making is to frame the decision. The traceability of the choices made has to be documented and accessible, in case a design iteration is needed. With respect to the frame of the decisions, a schedule and a list of available resources should be developed, and the decision makers and stakeholders should be identified. It is important to define the decisions to be made throughout the whole project, making a distinction between the ones to be addressed at the moment and the ones to be addressed at later stages. In this Thesis, the working schedule (figure 1.2) presents the different stages of the project. Furthermore, the DelFFi Propulsion Team was identified as the decision maker (see table 1.1).

Once the decision has been fully framed, the decision process has to be tailored. It will vary from one decision to another, as the available information, the amount of parameters to be optimised and the number of options considered determine which method to follow. Option trees, for example, are only used when the options are few and limited because as the number of decision nodes increases, the size of the tree quickly grows and loses communicative power. The different processes that can be followed include optimisation models, table trade-offs or MODA (Multi Objective Decision Analysis) approach. All major decisions taken during the design iterations of the Propellant Tank involved few choices, so decisions trees were used effectively, combined with table trade-offs.

The following step is to define the objectives and measures. The requirements define the boundaries of the decision, and all the choices considered shall comply with them. But some of the requirements may still be in a TBD phase. It is important, thus, to take into account the stakeholder requirements, key requirements and the killer requirements (these were already defined in the previous chapter). The output of this step should be a Fundamental Objectives Hierarchy. This is a diagram which shows the objectives of the decision (optimise, maximise or minimise different features) together with the measure or parameter that fully represents each feature. It is a clear way to identify the criteria to take into account during the trade-off study. How important one feature is with respect to another one has a strong subjective component, and relies on the experience of the decision makers. It is always advisable to seek for different views regarding this matter in order to have a less subjective hierarchy of the features to optimise. This results in a set of criteria with their weights, fully defined and measurable. As for the Propellant Tank trade-off process, the importance of the different features on each decision was discussed within the DelFFi Propulsion Team.

At this point, the actual decision making process begins. It is time to generate creative alternatives. The ability to quickly communicate the differentiating design features of given alternatives is a core element of the decision making exercise. A clear and simple approach is to develop a DOT (Design Option Tree)[11]. This is an "OR" tree in which all the different solutions to a problem are presented. It is crucial to make a complete tree so that all options are considered. The construction of this tree begins with the "tried and true" solutions, and it is further expanded with all the concepts that could reach a solution, even if their TRL (Technology Readiness Level) will discard them at a very initial stage of the decision making. This is done and documented for two main reasons: (i) the TRL or feasibility of a concept may evolve during the development of the project, and if another iteration is required, the concept could then be considered, (ii) the performance of "tried and true" solutions to some problems is not successful enough, so listing the full set of options can lead to an improvement in the solution to the problem.

The concepts presented in the DOT are called Strawman concepts, and they shall be broad enough to represent major branches of the tree, as well as specific enough to give a proper idea of the solution it represents. Directly on the DOT, some options will be eliminated. These will not be removed, just crossed and ruled out, adding an explanation of the decision. The options that should be eliminated directly on the DOT are the obviously non-feasible, the ones that do not represent a concept or lack implementation, and concepts that cannot be analysed or developed yet. With respect to the project of this Thesis, DOT have been developed to present all the options in each decision concerning the Propellant Tank, and they will be further explained on the following sections.

Subsequently, the different options have to be assessed via deterministic analysis. With objectives and measures established and alternatives identified and defined, the decision team should engage subject matter experts, ideally equipped with operational data, test data, models, simulation and expert knowledge. Scoring sheets for the evaluation of the different options shall be provided to the decision makers. Each scoring sheet contains a summary description of the alternative under examination and a summary of the scoring criteria to which it is being measured. This scoring sheet can directly be the trade-off table if the number criteria and options allows it. If not, the results should then be summarised before including them on the trade-off table. On this table, each column represents a criterion with its assigned weight and each row represents a particular alternative. Trade-off tables have been developed for the Propellant Tank design choices, filled in by three members of the DelFFi Propulsion Team and revised by the whole team.

After the trade-off table is defined, the results may have to be synthesised in order to facilitate understanding. Adding colour with heat map conventions, or computing total values as the weighted sum of the scores on each criteria will help summarise the information, as well as make it suitable for presentation. Some additional graphs of aggregated visualisation may be used to convey the information in a more efficient way. An example of this is the value component graph. It consists in a bar diagram where each bar represents the total score of the option, and it is subdivided into the score of each criterion. An ideal case bar is included as a reference of the perfect solution, so as to give an indication of the overall effectiveness of the options considered. These guidelines have been taken into account for the results presentation of the trade-off study for the project, and different colour schemes have been used.

The next step is to identify uncertainty and conduct a probabilistic analysis, as well as assessing the impact of uncertainties. Given that the scores are not based on in-depth analysis of the options, nor the selection criteria is thoroughly assessed, it is necessary to discuss the potential uncertainty surrounding the scores and criteria. One source of uncertainty that is easily computed is the TRL of each option. Further Monte Carlo simulations can be executed to identify which uncertainties are relevant and which are not. To compute the impact of uncertainties, another possibility is to perform sensitivity analyses.

An example of such analysis could be to sweep the weight of a criterion and compute the different outcomes of the trade-off. If small variations of the weight provoke different outcomes, the solution of the trade-off is greatly dependent on that weight, and a greater effort has to be done in order to accurately estimate the correct weight. On the contrary, if changing the weight of a criterion does not vary the outcome of the trade-off, then that criteria is of less importance than the others, or the solutions score similarly on that criterion. Should the latter be the case, the criterion has to be re-evaluated, as the main purpose of the criterion is to create distinction points between the different options. During the trade-off of the Propellant Tank, uncertainty was assessed, and sweeps of criterion weights were carried out only in the cases where the results would be of interest, leading to possible changes on the trade-off criteria or the outcome.

It would seem reasonable to end the process here, with a clear winner, and claim success. However, and recalling figure 3.1, the feedback loop is an important feature of the design trades. Now that an evaluation of each option has been completed, it is possible to redefine weak points in order to achieve a higher score, improving each alternative. Another point to bear in mind is the possibility of adding new options, either from previously discarded ones due to changes in the expected performance after completing initial analyses, or from the options that could not be developed yet. In the case of the Propellant Tank design, a major point of feedback was given by the Workshop in the Aerospace Faculty. Winning alternatives were discussed with them, analysing the possibilities of improvement.

Finally, communicating the trade-off results as well as presenting the recommendations and implementation plan is the last step to be taken. It is crucial to highlight the competing objectives, which drive the trade, and how they influence the design. The process of documenting each step with every decision taken and its rationale is culminated on this point. Although these resulting documents should be the only ones presented, it was interesting for this Thesis to justify the process followed to generate each decision. This is the reason why the approach taken has been extensively discussed hereby.

3.2. FIRST DESIGN CHOICES

This section will give an insight into the trade-off process which resulted in the generation of Conceptual Propellant Tank Designs, by applying the already explained approach taken for design trades and decision making. The section will follow a chronological order, from the starting point to the results.

3.2.1. INITIAL DESIGN

Despite the fact that an initial concept design had already been proposed (see figure 3.2), recommendations were made in the Status Report of the DelFFi Propulsion System [1], calling for a complete design iteration. As it is stated on the document, several critical points were identified in the concept of the Propellant Tank. These included, among others, extremely small wall thickness, insufficient connectors and poor definition of the overall design. The objective of this design was to create an initial model in order to test the thruster, but was never manufactured. The scope of this Thesis is the redesign the Propellant Tank and the development of a structural analysis in order to deliver a Detail Design, which will be manufactured and used on the testing campaign of the propulsion system.

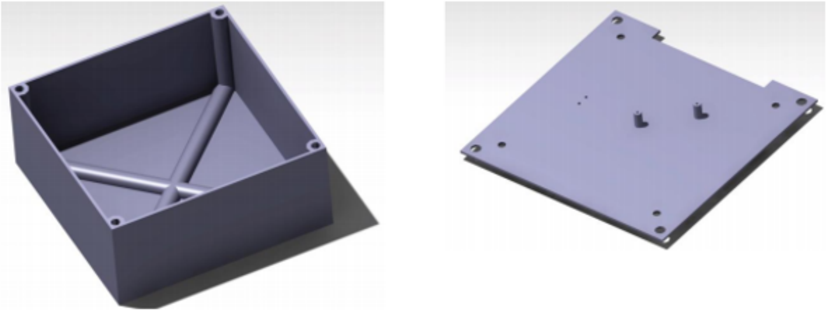


Figure 3.2: Conceptual design of the Propellant Tank before the start of this Thesis (Source [1])

The design process of this initial concept design was not sufficiently documented. This is why a fresh start was required for the Propellant Tank design, following a consistent approach and documenting all decision and design choices.

3.2.2. DESIGN TRADES AND FUNDAMENTAL OBJECTIVES HIERARCHY

The starting point of the design of the Propellant Tank is a well-defined set of requirements, an N2 chart with the interfaces of the Propulsion System (Appendix D), the available literature on the topic and the experience of the DelFFi Propulsion Team. The set of requirements are general enough to allow multiple design alternatives, which is why a narrow-down process was applied, following the Design Trades approach. As it was mentioned before in the previous section, the DelFFi Propulsion Team (see table 1.1) is identified as the decision maker. The time allocated to complete the first design trades and deliver conceptual designs is stated in the working schedule (figure 1.2.

Firstly, the general characteristics of the tank have to be defined. It is decided that the main points to define on an initial stage are Shape, Configuration, Material and Manufacturing Process (further explained in table 3.1. These four characteristics drive completely the design, and would determine radically different solutions. Due to the correlation between some of the characteristics, it is possible to assess them in pairs: (Shape + Configuration) and (Material + Manufacturing Process).

Table 3.1: Characteristics to be defined in the initial design trades

Characteristic	**Description**
Shape	General features that define the structural performance, fuel capacity and assembly to the bus
Configuration	Number of components and their distribution, considering their interactions, and is dependent on the shape chosen
Material	Affects the structural performance and mass, as well as the shape and manufacturing processes to be used
Manufacturing Process	Limited by the choice of material, it has an impact on the achievable shape and mass

Secondly, and having selected the characteristics to be determined, the Fundamental Objectives Hierarchy must be created. This graph can be found in figure 3.3. It divides the objectives into primary and secondary, and creates a relationship between the objective and the parameter or measure to control in order to achieve the objective.

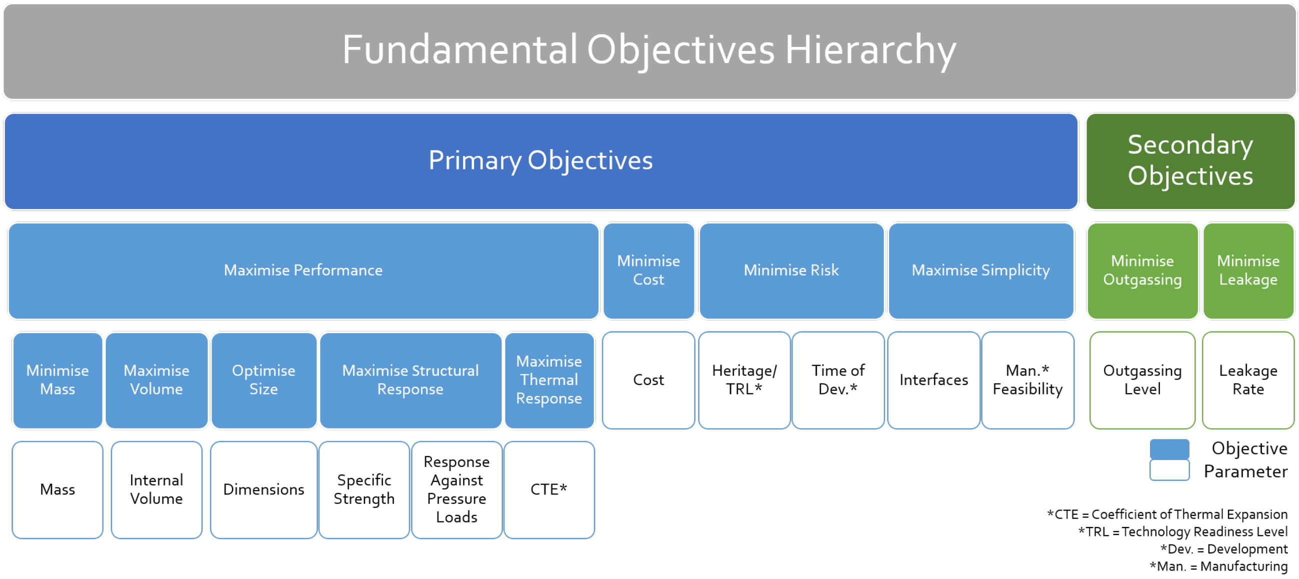


Figure 3.3: Fundamental Objectives Hierarchy

In order to create the Fundamental Objectives Hierarchy, the requirements were taken into account. Requirements on performance, cost and risk generate the primary objectives whilst requirements on outgassing and leakage generate secondary objectives. The reason behind this is that an increase in the optimisation of the primary objectives results in an added value to the mission (i.e. reducing mass can allow for mass increments in other subsystems, increasing the internal volume directly increases the amount of fuel that the Propulsion System can use, etc.). On the contrary, secondary objectives should just be fulfilled, but an increase in their minimisation or maximisation does not result in a benefit for the mission (i.e. as long as the tank meets the bare minimum requirement on leakage rate, this will not pose a threat). Simplicity is added to the primary objectives due to the nanosatellite mission philosophy, with an impact on cost, risk and time.

3.2.3. Design Option Tree

After having a clear overview of the objectives, it is possible to develop DOT for the 4 characteristics of the Propellant Tank that have to be defined (recall table 3.1). These diagrams (figure 3.4) show a complete overview of the design alternatives for each characteristic. The characteristics, due to the correlations between them, are assessed in pairs: (Shape + Configuration) and (Material + Manufacturing Process).

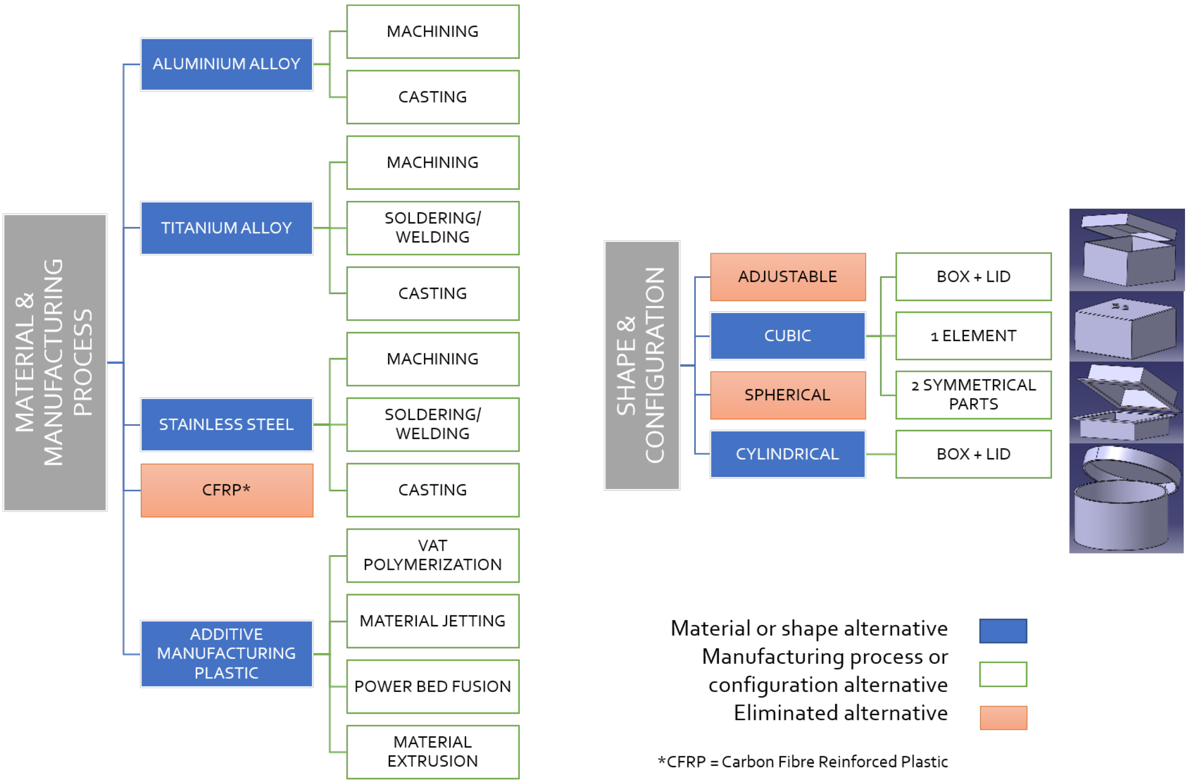


Figure 3.4: Design Option Tree for Shape, Configuration, Material and Manufacturing Process

DOTs need to be concise and identify each alternative with few words. In consequence, some alternatives may be difficult to understand without a brief explanation. With the aim to facilitate the understanding of the diagrams, tables 3.2 and 3.3 shall be consulted. Reference [13] was consulted to include the metals, and the available Additive Manufacturing techniques in TU Delft are the ones taken into consideration.

The alternatives will be compared and contrasted with in a trade-off table in the following subsection. As a final comment, the DOT was presented to part of the DelFFi Propulsion Team, and feedback only included a more detailed explanation of the alternatives and the reasons for elimination.

Table 3.2: Description of the alternatives for the first DOTs

Alternative	**Description**
Aluminium Alloy	The alloy taken into consideration for the trade-off study and whose characteristics will be used as model is the 6061 T6 (common and with enhanced performance)[14]. Given the difficulty inherent to welding aluminium, it was not considered in the DOT.
Titanium Alloy	The alloy taken into consideration for the trade-off study and whose characteristics will be used as model is the 6Al-4V(common and with enhanced performance), both for casting and machining[15].
Stainless Steel	The alloy taken into consideration for the trade-off study and whose characteristics will be used as model is the A743 for casting [16] and A316 for machining and welding [17].
Carbon Fibre Reinforced Plastic	Laying plies in different orientations to achieve optimal structural performance per mass. However, it is discarded due to the complexity of manufacturing and fragility for such a small component. All reasons for elimination are further explained on table 3.3.
Additive Manufacturing Plastic	Depending on the process of manufacturing, different plastics are used as reference, namely Prototherm 12120 (Thermal Postcure) for VAT Polymerization[18], FullCure 720 for Material Jetting [19], Windform XT 2.0 for Power Bed Fusion [20] [21] and ABS for Material Extrusion [22]. These have been selected from the materials and processes available in TU Delft [23]
Machining	Numerical Control (CNC) milling to achieve the small thickness on the Propellant Tank[24].
Casting	Only alternative for the 1 Element configuration, requires a high precision technique.
Welding/ Soldering	Not considered in aluminium because of the difficulties it implies, it is a simple alternative to bolted joints and sealing, but the stress produced on the material is difficult to analyse without testing.
VAT Polymerization	Stereolithography technique that makes use of photopolymerization.
Material Jetting	Makes use of an inject head to selectively deposit product material.
Power Bed Fusion	The Selective Laser Sintering technique has been chosen among the different Power Bed Fusion processes. It uses therman energy to create layers of the product from a powder of the material.
Material Extrusion	The Fused Deposition Modeling has been selected among the different Material Extrusion processes. The material is extruded into filaments which are deposited as layers to create the product.
Adjustable	Includes the possibility to modify the shape of the tank in order to make it suitable for different propulsion systems. However, the complexity of the design discarded this option, given that the same result can be achieved with standardisation or modularity.
Cubic	A rectangular cross section which results in a box-shaped tank. It benefits from fitting the shape of the bus structure, but its performance under pressure loads is worse than cylindrical or spherical.
Spherical	Although optimal for internal pressure, its integration on the bus structure resulted in an immediate no-go.
Cylindrical	A cylinder allows small thickness on the walls by using sheet of metal and only allows the box + lid configuration.
Box + Lid	The main tank is a hollow open component, closed by one or 2 lids, either bolted or welded.
1 Element	The tank is a single hollow closed component, with only small openings for sensors and fill/empty processes. It has to be manufactured by casting or additive manufacturing.
2 Symmetrical Parts	Greatly used in casting, it increases modularity. Two symmetrical parts are joined together by bolts or welding, and becomes a variation of box + lid configuration.

Table 3.3: Alternatives eliminated before the trade-off process

Alternative	**Reasons for elimination**
Carbon Fibre Reinforced Plastic	With high specific properties, it is used in pressure vessels as a sole component and as reinforcement together with metal structures. Even though, the only fabrication processes allowed are bag-molding, centrifugal casting and filament-winding and contact molding [24]. These have a high cost and a complex manufacturing, which is not justified with the mass reduction achieved.
Adjustable	The complexity of mechanisms it entails does not align with the philosophy of a nanosatellite mission, in which simplicity and functionality are key. Taking into account modularity and standardisation will result in a Propellant Tank suitable for multiple platforms.
Spherical	Given its optimal performance against internal pressure loads, it is widely used in space propulsion to reduce mass. However, the difficulties it creates for integration on the bus structure outweigh the mass reduction for this small-sized Propellant Tank.

3.2.4. TRADE-OFF TABLE AND ANALYSIS OF THE RESULTS

Once all the possible alternatives have been described, they are assessed with the help of a trade-off table. This decision making graph displays the alternatives in rows with the criteria in columns, each one with its corresponding weight. The trade-off table is filled in by different decision makers and the results are a merge of all the tables.

So far, the criteria used to evaluate each alternative has still to be introduced. The Fundamental Objectives Hierarchy (figure 3.3), already introduced in a previous section, is the baseline to define the decision criteria. Analysing how the different alternatives affect each measurable parameter and determining which one is closer to the objective should be the nominal procedure. However, the criteria sets are different for the trade-off of Shape + Configuration and for the trade-off of Material + Manufacturing Process. The explanation to this is that not all the characteristics affect the objectives in the same way. As an example, and recalling the Fundamental Objectives Hierarchy, the thermal response of the Propellant Tank is highly influenced by the Material choice, but it is almost independent of the Configuration choice. In this way, it is possible to create a clearer trade-off table by leaving out the irrelevant influences.

The criteria selected for the trade-off of Shape + Configuration is described in table 3.4 and for the trade-off of Material + Manufacturing Process is described in 3.5. In the former, the objectives taken into account are Minimise Cost, Minimise Risk, Maximise Simplicity, Maximise Volume, Optimise Size, Minimise Mass and Maximise Structural Response. These do not include the secondary objectives (it was already mentioned that an optimisation of these objectives does not result in an improvement of the design), nor the objective of Maximise Thermal Response. The reason why the thermal response is not considered is because the tank is a cold component, without active sources of heat. The closest heat source is the resistojet thruster. Due to the characteristics of this particular propulsion system, heat radiated from the thruster into the tank will result in an increase of the performance. This is why the tank does not have to be insulated. The thermal response considered in the Fundamental Objectives Hierarchy is related to the size variations of the material and the variation of the structural properties of the material with the temperature.

On the Material + Manufacturing Process trade-off, the objectives taken into account are all the primary ones. The secondary ones are not considered, the reasons being the same as for the other trade-off. This trade-off has some criteria which are measurable parameters, such as Specific Strength and the CTE. It is always advisable to use this kind of criteria, as it increases the objectivity of the trade-off study.

Table 3.4: Criteria for the Shape + Configuration trade-off

Criterion	Weight	Description
Manufacturing Feasibility	2	Measures the complexity of the design from the manufacturing point of view and accounts for imperfections during the process. It also takes into account the heritage of the configurations. The objectives it considers are Minimise Cost, Minimise Risk and Maximise Simplicity.
Max. Capacity	3	Maximum achievable internal volume of the Propellant Tank within the maximum dimensions specified on the requirements. The objective taken into account is Maximise Volume.
Min. Mass	3	Minimum structural mass necessary to meet the requirements on loads and maximum mass. It considers the thickness difference between the various shape alternatives as well as the needed structure for interfaces with the rest of the satellite. The objectives it considers are Optimise Size, Maximise Structural Response, Minimise Mass and Maximise Simplicity.

Table 3.5: Criteria for the Material + Manufacturing Process trade-off

Criterion	Weight	Description
Feasibility	2	Gives an idea of the time to manufacture and the cost of the process and the material. Notice that the cost of Additive Manufacturing is low due to the available 3D printers in TU Delft. The objectives it considers are Minimise Risk, Minimise Cost and Maximise Simplicity.
Heritage	2	Takes into account previous use of the technology/material in space conditions and its expected performance. The objective taken into account is Minimise Risk and Maximise Simplicity.
Specific Strength	3	Maximum yield strength of the material divided by its density. As the values are available, it is an objective criteria. The objectives it considers are Minimise Mass and Maximise Structural Response.
CTE	1	Coefficient of Thermal Expansion. As the values are available, it is an objective criteria. The objective it considers is Maximise Thermal Response. A value inferior to 50 m/m-ºC should be valid.
Tolerances	2	Ability to reproduce details with narrow tolerances. The objectives it considers are Minimise Mass, Maximise Volume and Optimise Size.

Tables 3.4 and 3.5 already include the weights of each criterion. These were the result of an iteration with the members of the DelFFi Propulsion Team that completed the trade-off table. From the Shape + Configuration trade-off, there were doubts about the weights of Max. Capacity and Min. Mass. From a performance point of view, an increase of the mass of propellant has a greater impact on the delta-V produced by the Propulsion System than a dry mass reduction. This is better understood with the following example by using equation 3.1 (Tsiolkovsky Rocket Equation [25]), which compares a 20 grams reduction of initial mass to a 20 grams increase of propellant:

$$\Delta V = I_{sp} \cdot g_0 \cdot ln\frac{M_0}{M_0 - M_P} \tag{3.1}$$

$$M_p = 0.2 \quad kg \quad ; \quad \Delta M_P = 0.02 \quad kg \quad ; \quad M_0 = 4 \quad kg \quad ; \quad \Delta M_0 = -0.02 \quad kg$$

$$\left(\frac{\Delta V}{I_{sp} \cdot g_0}\right)_0 = ln\frac{M_0}{M_0 - M_P} = 51.29e-3$$

$$\left(\frac{\Delta V}{I_{sp} \cdot g_0}\right)_1 = ln\frac{M_0}{M_0 - M_P - \Delta M_P} = 56.57e-3 \qquad \left(\frac{\Delta V}{I_{sp} \cdot g_0}\right)_2 = ln\frac{M_0 + \Delta M_0}{M_0 + \Delta M_0 - M_P} = 51.56e-3$$

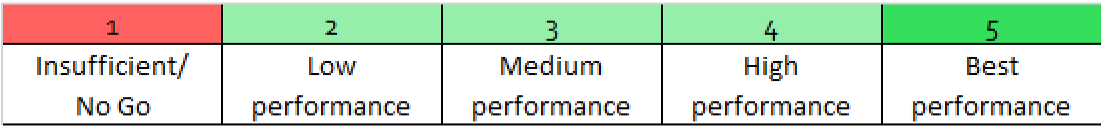
Given that the propellant represents only a very small fraction of the total mass of the satellite, it is more convenient for the performance to increase this fraction than to reduce the dry mass, as it can be deduced from the example above. This would lead to conclude that the criterion Max. Capacity should weigh more than Min. Mass. However, given that the latter takes into account more objectives than the former, it was decided to leave the weights equal, both greater than the manufacturing feasibility, which is left on a second level of importance. Note that during the uncertainty analysis both weight distributions will be analysed in order to assure that the result does not vary.

As far as the Material + Manufacturing Process is concerned, the weight distribution is intuitive. The CTE is the less important, as there are ways to account for the size changes associated with changes of temperature (e.g. leaving enough space on the interfaces; removing the interfaces with components that require a precise positioning etc.). Heritage, Manufacturing Feasibility and Tolerances are of medium importance, and can be compared to the Manufacturing Feasibility from the other trade-off. Finally, Specific Strength is the most critical criterion. The Specific Strength is the best indicator possible for structural applications where mass is a scarce resource. Once again, during the uncertainty analysis the weights will be altered on a sensitivity analysis to assure that the choice is the correct one.

Having discussed the criteria and their weights, the trade-off tables can be explained. Each trade-off table shows one alternative per row and one criteria per column, plus two final columns with the sum of the scores (equation 3.2) and the square sum of the scores (equation 3.3). The square sum is computed to benefit the alternatives that score high in the most important criteria. It is only used to decide between two scores with a similar sum. Each alternative is assigned a score from 1 (lowest) to 5 (highest) (see figure 3.5). The minimum requirements for an alternative to be considered in the choice is: (i) score ≥ 2 for all alternatives; (ii) have a at least an equal score to the one obtained by with a 3 in every option (that is ≥ 24 for the Shape + Configuration trade-off and ≥ 30 for the Material + Manufacturing Process trade-off).

$$(Sum)_i = \sum (Score_i \cdot Weight_i) \tag{3.2}$$

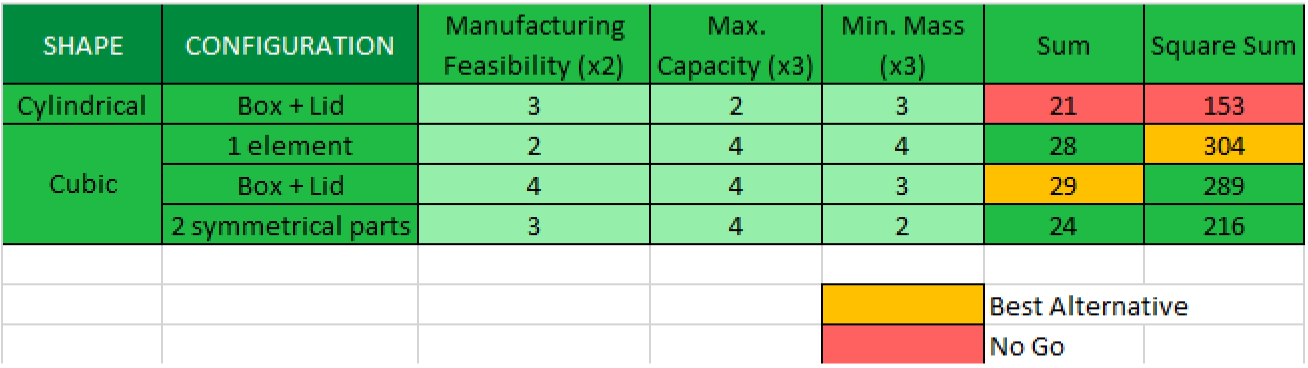
$$(Square \quad Sum)_i = \sum (Score_i \cdot Weight_i)^2 \tag{3.3}$$



1	2	3	4	5
Insufficient/ No Go	Low performance	Medium performance	High performance	Best performance

Figure 3.5: Explanation of the scores used on the trade-off tables

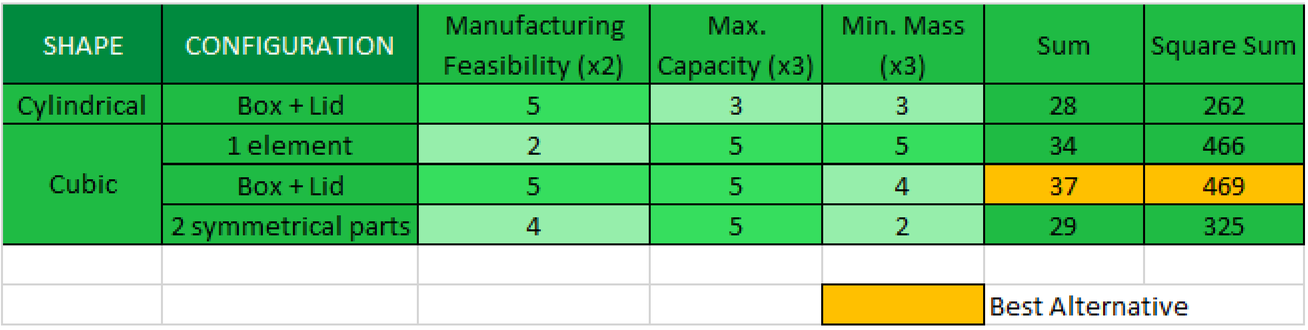
Figures 3.8, 3.6 and 3.7 represent the trade-off tables for the Shape and Configuration characteristics, filled in by 3 different members of the DelFFi Propulsion Team, and figure 3.9 shows the combination of all the results.



SHAPE	CONFIGURATION	Manufacturing Feasibility (x2)	Max. Capacity (x3)	Min. Mass (x3)	Sum	Square Sum
Cylindrical	Box + Lid	3	2	3	21	153
Cubic	1 element	2	4	4	28	304
	Box + Lid	4	4	3	29	289
	2 symmetrical parts	3	4	2	24	216

🟧 Best Alternative
🟥 No Go

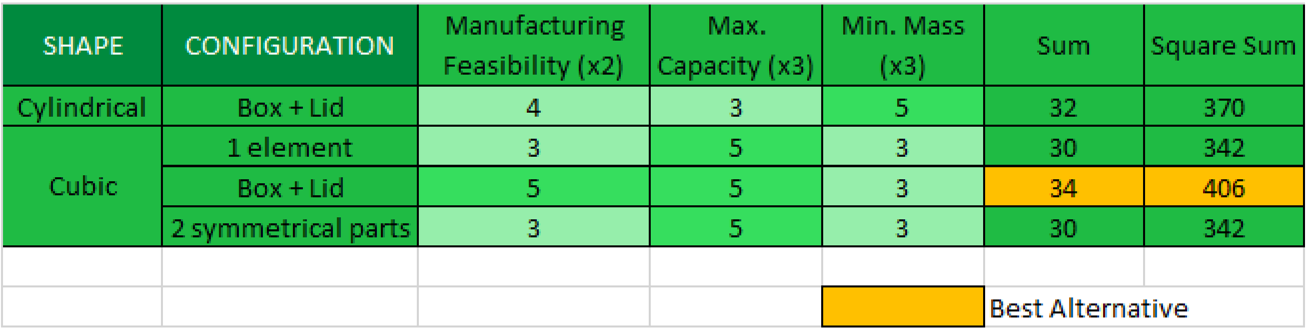
Figure 3.6: Shape + Configuration trade-off table (E. Jansen)



SHAPE	CONFIGURATION	Manufacturing Feasibility (x2)	Max. Capacity (x3)	Min. Mass (x3)	Sum	Square Sum
Cylindrical	Box + Lid	5	3	3	28	262
Cubic	1 element	2	5	5	34	466
	Box + Lid	5	5	4	37	469
	2 symmetrical parts	4	5	2	29	325

🟧 Best Alternative

Figure 3.7: Shape + Configuration trade-off table (T. van Wees)

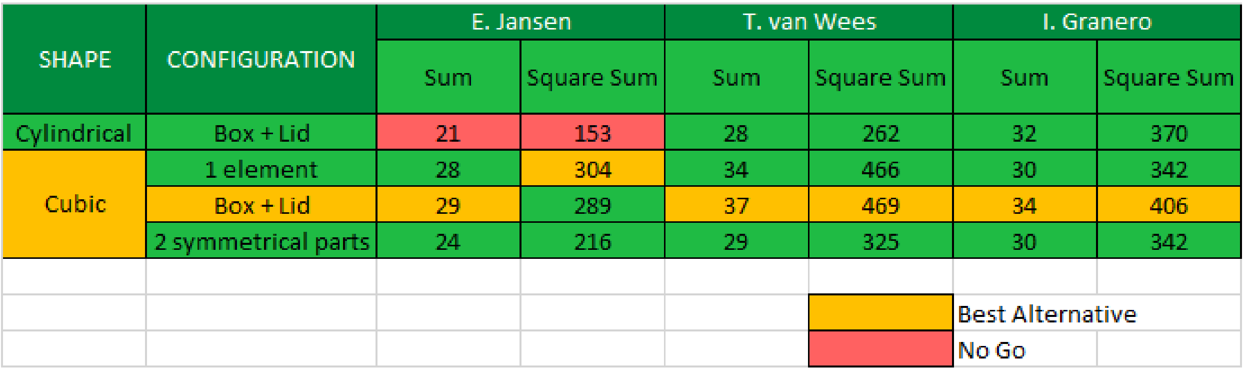


SHAPE	CONFIGURATION	Manufacturing Feasibility (x2)	Max. Capacity (x3)	Min. Mass (x3)	Sum	Square Sum
Cylindrical	Box + Lid	4	3	5	32	370
Cubic	1 element	3	5	3	30	342
	Box + Lid	5	5	3	34	406
	2 symmetrical parts	3	5	3	30	342

🟧 Best Alternative

Figure 3.8: Shape + Configuration trade-off table (I. Granero)

In order to better understand the scores assigned to each alternative, a justification of the ones in figure 3.8 (trade-off table completed by I. Granero) is given. To begin with, the simplest configurations are the cubic and cylindrical box + lid in terms of Manufacturing Feasibility (cubic scores higher because of the simple interfaces when compared to the cylindrical). Cast parts and 3D printing (only options for 1 element) have higher manufacturing errors. Heritage is on the side of cylindrical tanks, which gives this alternative a better score than 1 element and 2 symmetrical parts configurations. For the Max. Capacity criteria, it is clear that cubic shapes will adapt better to the available space on the bus satellite, whilst cylindrical shapes will leave the corners unused. However, the cylindrical shape has the best score on Min. Mass. This is because the wall thickness required to withstand the internal pressure is considerably smaller on cylindrical shapes than on rectangular cross-sections, which will have stress concentration on the corners.



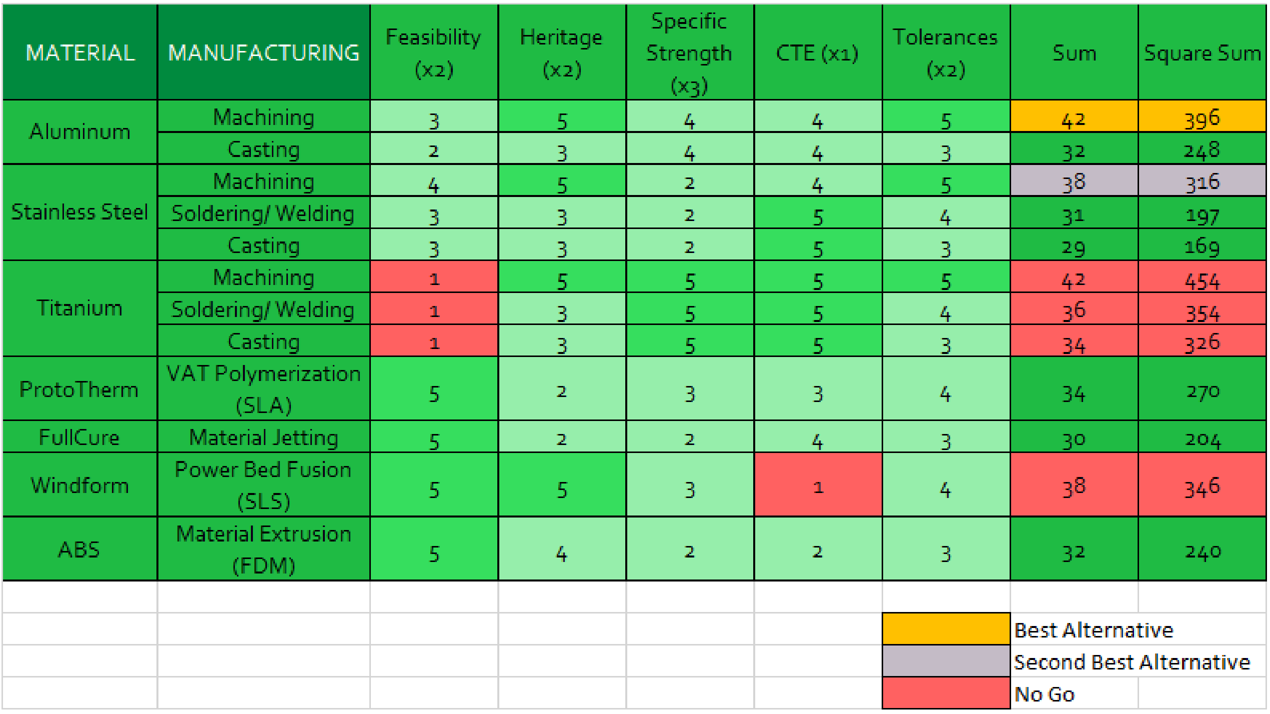
SHAPE	CONFIGURATION	E. Jansen		T. van Wees		I. Granero	
		Sum	Square Sum	Sum	Square Sum	Sum	Square Sum
Cylindrical	Box + Lid	21	153	28	262	32	370
Cubic	1 element	28	304	34	466	30	342
	Box + Lid	29	289	37	469	34	406
	2 symmetrical parts	24	216	29	325	30	342

🟧 Best Alternative
🟥 No Go

Figure 3.9: Shape + Configuration trade-off combined results

Figure 3.9 shows that the clear winner alternative is a Cubic Shape with a Box + Lid Configuration. This combination achieves the highest score in both Sum and Square Sum for every evaluation done (except for E. Jansen in Square Sum). This combination has the advantage of being simple and easy to manufacture. It suits perfectly the rectangular section of the satellite's structure, using the maximum space available to fit as much propellant as possible, and will have a straight forward interface with the bus. Its disadvantage is a worse structural performance when compared to the Cylindrical Shape. This calls for an in depth structural analysis, which will be addressed throughout this Thesis. As a small remark, the cylindrical configuration is a No Go for E. Jansen because it does not reach the minimum of 24 in the Sum score.

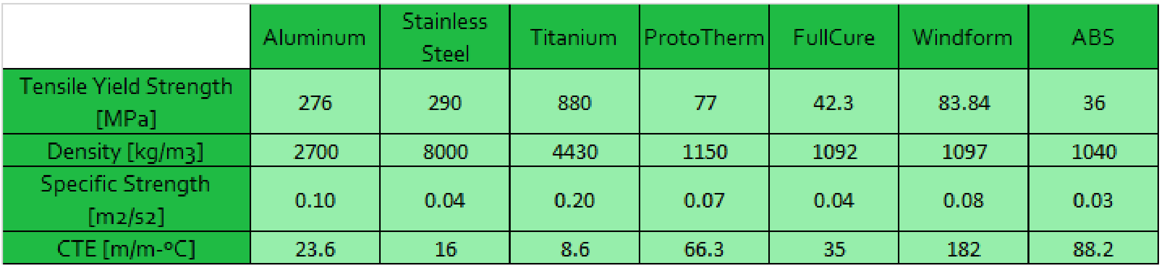
Figures 3.10, 3.14 and 3.15 represent the trade-off tables for the Shape and Configuration characteristics, filled in by 3 different members of the DelFFi Propulsion Team, and figure 3.16 shows the combination of all the results.



MATERIAL	MANUFACTURING	Feasibility (x2)	Heritage (x2)	Specific Strength (x3)	CTE (x1)	Tolerances (x2)	Sum	Square Sum
Aluminum	Machining	3	5	4	4	5	42	396
	Casting	2	3	4	4	3	32	248
Stainless Steel	Machining	4	5	2	4	5	38	316
	Soldering/ Welding	3	3	2	5	4	31	197
	Casting	3	3	2	5	3	29	169
Titanium	Machining	1	5	5	5	5	42	454
	Soldering/ Welding	1	3	5	5	4	36	354
	Casting	1	3	5	5	3	34	326
ProtoTherm	VAT Polymerization (SLA)	5	2	3	3	4	34	270
FullCure	Material Jetting	5	2	2	4	3	30	204
Windform	Power Bed Fusion (SLS)	5	5	3	1	4	38	346
ABS	Material Extrusion (FDM)	5	4	2	2	3	32	240

🟧 Best Alternative
▨ Second Best Alternative
🟥 No Go

Figure 3.10: Material + Manufacturing Process trade-off table (I. Granero)



	Aluminum	Stainless Steel	Titanium	ProtoTherm	FullCure	Windform	ABS
Tensile Yield Strength [MPa]	276	290	880	77	42.3	83.84	36
Density [kg/m3]	2700	8000	4430	1150	1092	1097	1040
Specific Strength [m2/s2]	0.10	0.04	0.20	0.07	0.04	0.08	0.03
CTE [m/m-ºC]	23.6	16	8.6	66.3	35	182	88.2

Figure 3.11: Material properties from references [14], [15], [17], [18], [19], [20], [21] and [22]

Once again, a justification is given for the results of figure 3.10 (trade-off table completed by I. Granero). First of all, the winners in Feasibility are the Additive Manufacturing choices. The scores on this criterion are deeply influenced by the characteristics of the application: a propulsion system developed by TU Delft. This benefits the Additive Manufacturing processes because the university already counts with the machines proposed (one of the main reasons to include them in the trade-offs), so the cost of production will not include the amortisation of the machines, but just the material and time operation, resulting in a competitive price. Stainless steel is cheaper than Aluminium, and this one is considerably cheaper than Titanium (see Appendix B). The latter is also difficult to machine, and the processes of cast are only justified for at least a small set of components, not just a single one.

Heritage of pressurized Propellant Tanks is high for machined Aluminium, Stanless Steel and Titanium, and Power Bed Fusion has already been used successfully [36]. VAT Polymerisation and Material Jetting have a low TRL, while Material Extrusion and Power Bed Fusion are close to being able to compete with CNC [26]. The Specific Strength and CTE of each material are objective parameters, which can be seen in figures 3.11, 3.13 and 3.12. The excessive CTE of Windform makes it a No Go alternative. Finally, the Tolerances achieved with CNC machining are the best of all options (considering the 3D printers available in TU Delft). The tolerances of welding and some additive manufacturing techniques also score high.

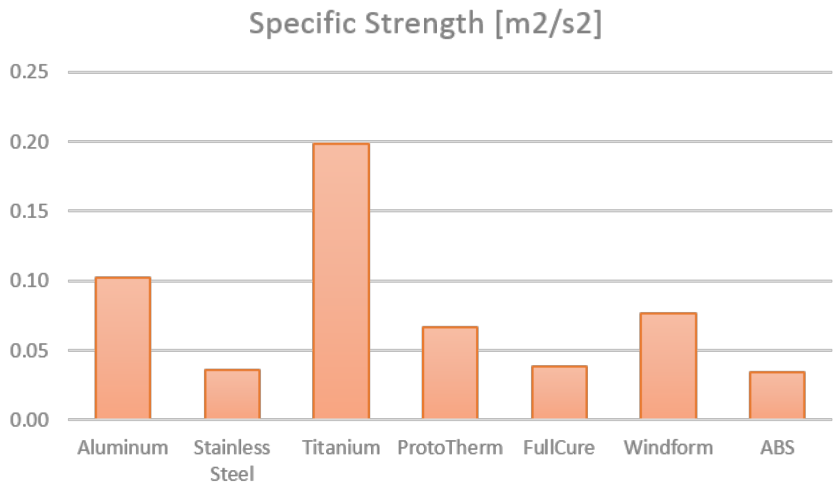


Figure 3.12: Specific Strength of the Material alternatives

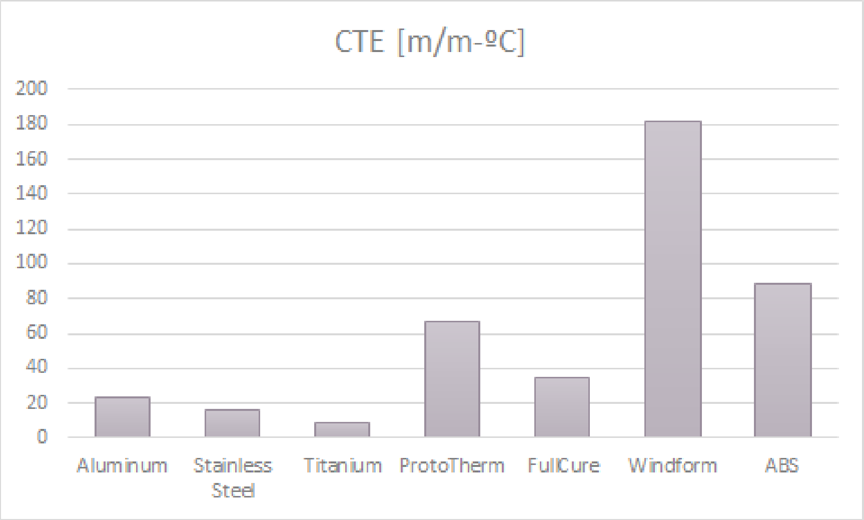
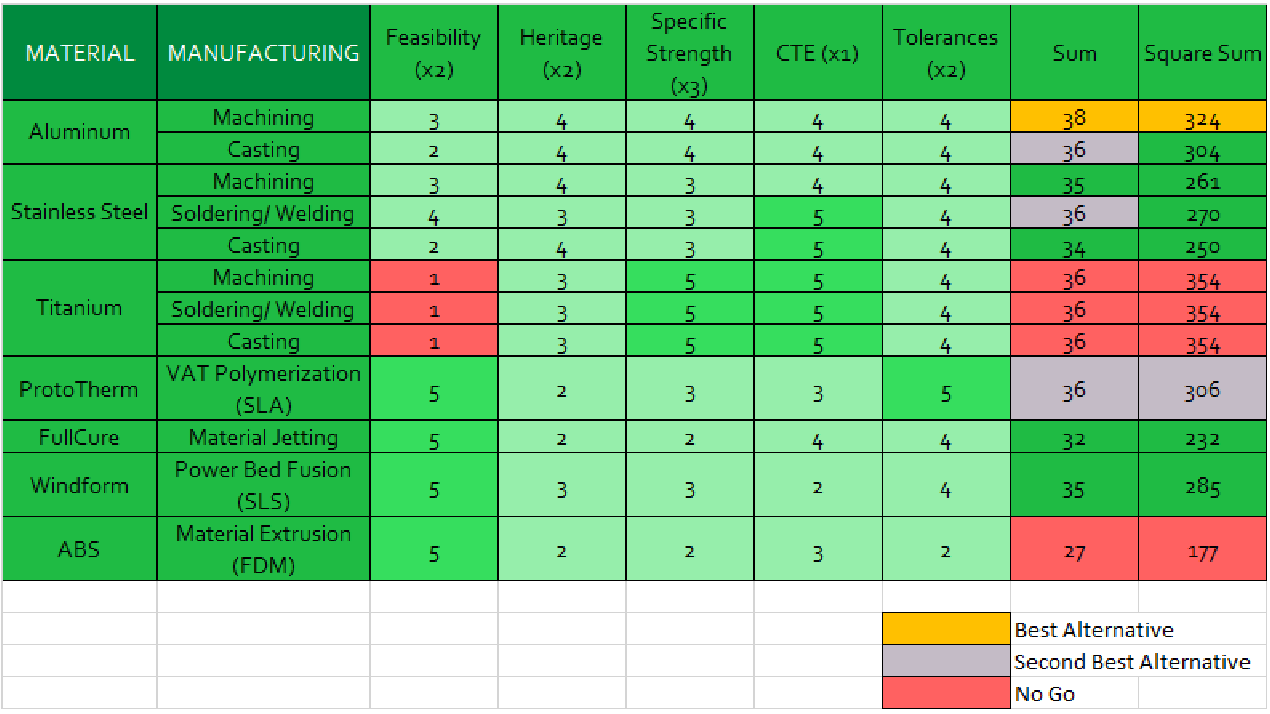


Figure 3.13: Coefficient of Thermal Expansion of the Material alternatives



MATERIAL	MANUFACTURING	Feasibility (x2)	Heritage (x2)	Specific Strength (x3)	CTE (x1)	Tolerances (x2)	Sum	Square Sum
Aluminum	Machining	3	4	4	4	4	38	324
	Casting	2	4	4	4	4	36	304
Stainless Steel	Machining	3	4	3	4	4	35	261
	Soldering/ Welding	4	3	3	5	4	36	270
	Casting	2	4	3	5	4	34	250
Titanium	Machining	1	3	5	5	4	36	354
	Soldering/ Welding	1	3	5	5	4	36	354
	Casting	1	3	5	5	4	36	354
ProtoTherm	VAT Polymerization (SLA)	5	2	3	3	5	36	306
FullCure	Material Jetting	5	2	2	4	4	32	232
Windform	Power Bed Fusion (SLS)	5	3	3	2	4	35	285
ABS	Material Extrusion (FDM)	5	2	2	3	2	27	177

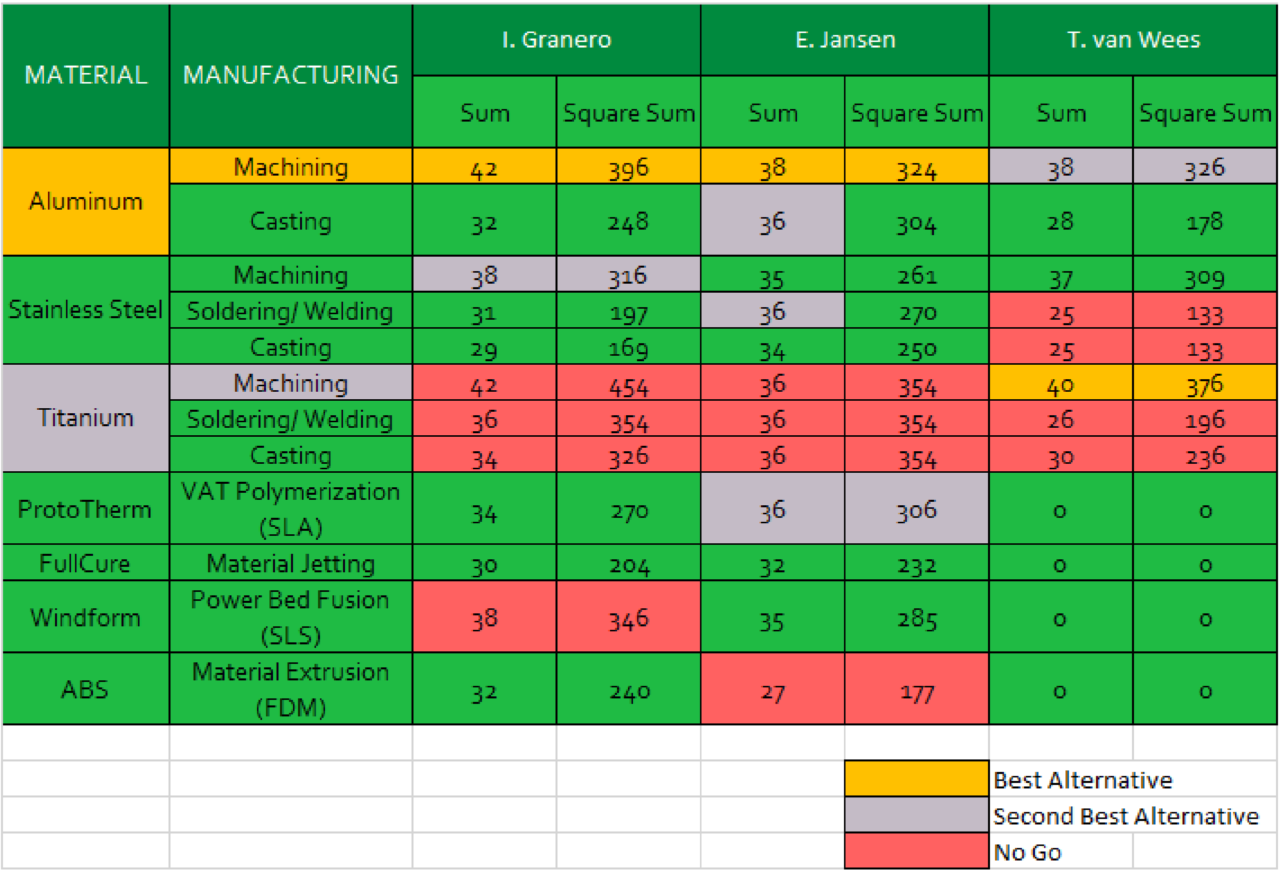
🟧 Best Alternative
🟪 Second Best Alternative
🟥 No Go

Figure 3.14: Material + Manufacturing Process trade-off table (E. Jansen)

MATERIAL	MANUFACTURING	Feasibility (x2)	Heritage (x2)	Specific Strength (x3)	CTE (x1)	Tolerances (x2)	Sum	Square Sum
Aluminum	Machining	3	5	3	3	5	38	326
	Casting	2	3	3	3	3	28	178
Stainless Steel	Machining	4	5	2	3	5	37	309
	Soldering/ Welding	3	2	2	3	3	25	133
	Casting	2	3	2	3	3	25	133
Titanium	Machining	2	5	4	4	5	40	376
	Soldering/ Welding	1	2	4	4	2	26	196
	Casting	1	3	4	4	3	30	236
ProtoTherm	VAT Polymerization (SLA)						0	0
FullCure	Material Jetting						0	0
Windform	Power Bed Fusion (SLS)						0	0
ABS	Material Extrusion (FDM)						0	0

🟧 Best Alternative
🟪 Second Best Alternative
🟥 No Go

Figure 3.15: Material + Manufacturing Process trade-off table (T. van Wees)



MATERIAL	MANUFACTURING	I. Granero		E. Jansen		T. van Wees	
		Sum	Square Sum	Sum	Square Sum	Sum	Square Sum
Aluminum	Machining	42	396	38	324	38	326
	Casting	32	248	36	304	28	178
Stainless Steel	Machining	38	316	35	261	37	309
	Soldering/ Welding	31	197	36	270	25	133
	Casting	29	169	34	250	25	133
Titanium	Machining	42	454	36	354	40	376
	Soldering/ Welding	36	354	36	354	26	196
	Casting	34	326	36	354	30	236
ProtoTherm	VAT Polymerization (SLA)	34	270	36	306	0	0
FullCure	Material Jetting	30	204	32	232	0	0
Windform	Power Bed Fusion (SLS)	38	346	35	285	0	0
ABS	Material Extrusion (FDM)	32	240	27	177	0	0

🟨 Best Alternative
▨ Second Best Alternative
🟥 No Go

Figure 3.16: Material + Manufacturing Process trade-off combined results

From figure 3.16 it is possible to conclude that the winner is Aluminium as Material and Machining as the Manufacturing Process. This alternative is relatively cheap (if the fabrication process is optimised and the number of operations is minimised). It counts with an important heritage, and the tolerances achievable are very high. The CTE of Aluminium is not the best, but for the application considered it is more than sufficient (as an example, materials such as INVAR would have scored much higher in this criterion, but the benefit for the performance would not have justified its price and mass). Finally, the specific strength of Aluminium makes it suitable for a space mission.

The second best alternative represented in figure 3.16 is Machined Titanium. The reason why it is rated as the second best option despite being assigned a No Go by two of the three decision makers is that the single cause of elimination comes from the Feasibility criterion. The extremely high price together with the difficulty of manufacturing make it unsuitable for a University mission, such as the one that concerns this Thesis. Nevertheless, it scores higher than Machined Aluminium for the three decision makers. Taking this into consideration, other types of mission (developed by companies or agencies) should choose the Machined Titanium option, as long as the budget allows it, because the performance would outweigh the one of Machined Aluminium.

As a final comment on the trade-off tables for Material and Machining, ABS for Material Extrusion (FDM) is discarded by E. Jansen because it does not reach the minimum score of 30 in Sum. The same happens to Stainless Steel with Soldering/Welding and Casting on the trade-off from T. van Wees. He did not complete the part of Additive Manufacturing due to lack of expertise on the field. Windform for Power Bed Fusion (SLS) is discarded in the trade-off of I. Granero due to a No Go in its CTE, which is excessive. Finally, machined metals score higher than Additive Manufacturing plastics.

3.2.5. UNCERTAINTY ANALYSIS: LINE DIAGRAMS

In order to assess the uncertainty on the decisions taken, a sensitivity analysis has been carried out on the trade-off tables completed by I. Granero. Decision analysis uses many forms of sensitivity analysis including line diagrams, tornado diagrams, waterfall diagrams and several uncertainty analyses including Monte Carlo Simulations. Following the reference [12], line diagrams will be used to represent the sensitivity to weighting. This analysis is made to understand how sensitive a particular recommendation is to the weights, and see if the best alternatives change when changing the weights.

The line diagrams are generated as follows: considering the sum of the weights of the criteria as a constant value, the weight of one criterion is swept from zero to the total value. When doing this, the relative relationship between the other weights is maintained. This means that the maximum total score remains unchanged. However, it is possible to see how the total score of each alternative varies while modifying the weights. By representing the total score on the y axis and the weight of the criterion being swept on the x axis, the alternatives will be different lines with different slopes. There may be, thus, values of the weight for which the winning alternative changes. In order to obtain an unbiased trade-off study, these points should be far from the selected weights, or even non existing.

Although this sensitivity analysis (by means of line diagrams) gives an insight into the uncertainty of the analysis, it does not represent a complete uncertainty analysis. This is because some factors are not included in the scope of this analysis, such as the possibility of changing various relative relationships between weights at the same time, or the possibility of errors being made in the actual scores given to the alternatives by the decision makers. The latter uncertainty source is addressed by having at least 3 decision makers, so that the average results are taken into account, and the impact of outliers is reduced. Nevertheless, in order to have a complete uncertainty analysis, more methods such as the named in the beginning of this subsection should be used together with the line diagrams. The time available, as well as the amount of detail of the decisions considered made it unnecessary to complete further uncertainty analyses.

Figures 3.17 and 3.18 show the line diagrams computed for, respectively, the Shape + Configuration trade-off and the Material + Manufacturing trade-off (the original weights are marked with a vertical red line).

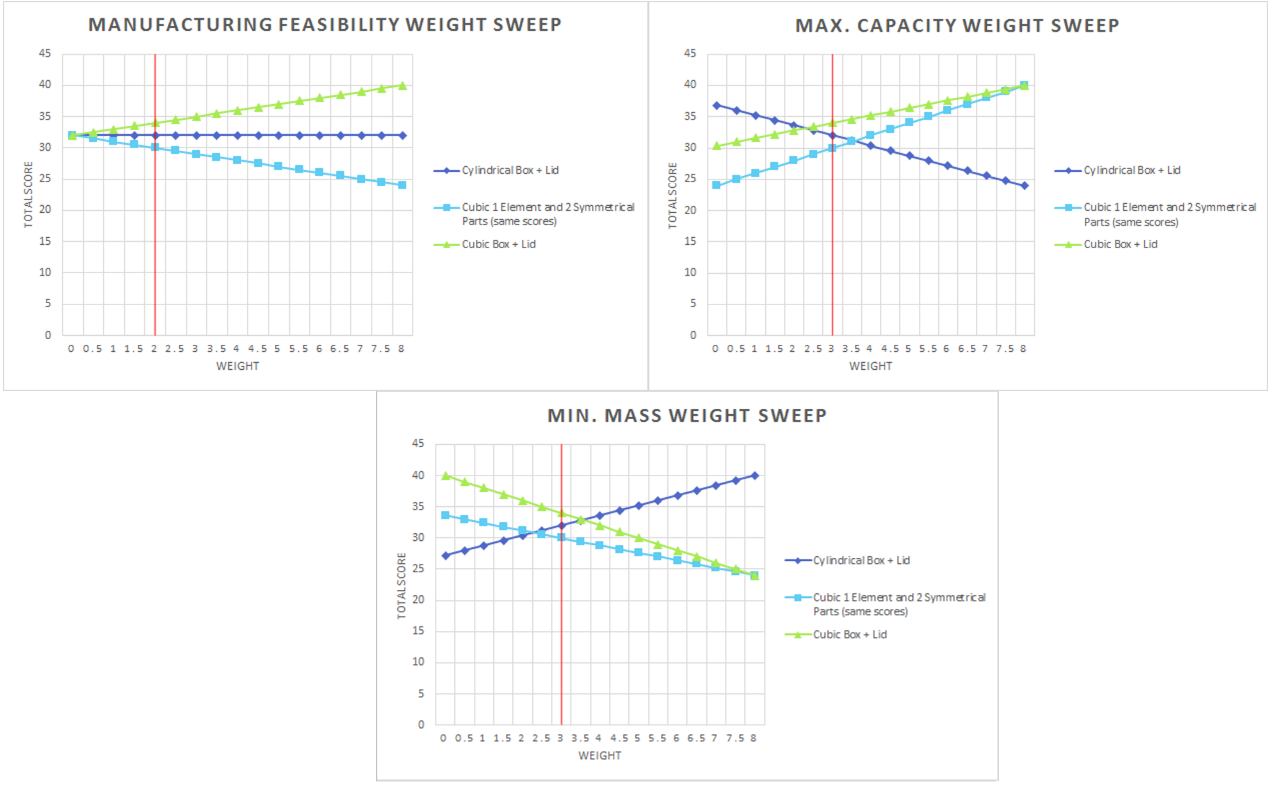


Figure 3.17: Weight Sweep for Shape + Configuration trade-off

To comment on the graphs, from the first line diagrams (figure 3.17), it is interesting to notice how the Cylindrical Box + Lid configuration would have won if slightly less importance had been given to the Max. Capacity criterion or slightly more importance had been given to the Min. Mass criterion. It was clearly explained (and demonstrated by an example earlier in the chapter) that increasing the internal volume is more beneficial than reducing the dry mass. If the characteristics of the system had been others, then the Cylindrical shape may have won. The Cubic 1 Element and Cubic 2 Symmetrical Parts, however, would have never won varying the weights, and are thus objectively eliminated.

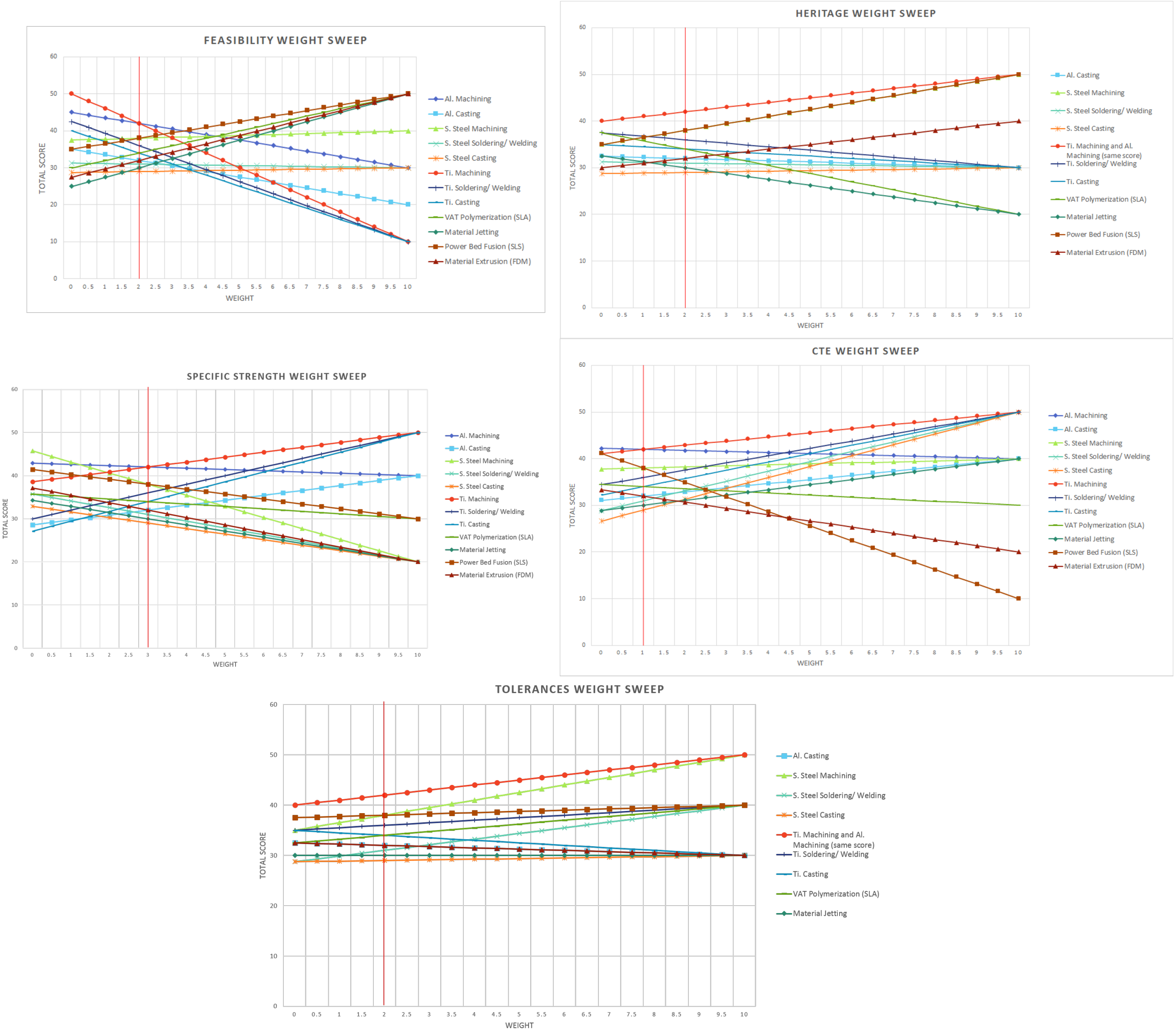


Figure 3.18: Weight Sweep for Material + Manufacturing Process trade-off

From the second line diagrams (figure 3.18), the only alternatives that achieve a winning position during the sweeps are the Machined Aluminium, Machined Titanium and Machined Stainless Steel. Titanium is the clear winner in most of the criteria around the original weight, and Aluminium is either close or equal to Titanium. This reinforces the conclusions drawn, were Aluminium and Titanium were the winner alternatives, as it is clear that varying the weights would not have changed this decision.

3.2.6. OUTCOME OF THE DECISION PROCESS

In the end, and after following the procedure described in the approach section, a decision has been made. The shape will be Cubic, the Configuration will be Box + Lid, the material will be Aluminium Alloy and the Manufacturing Procedure will be CNC Machining. These can be seen in the DOT of figure 3.19. The second best alternatives are also indicated in the DOT so that it is possible to know which design options to choose if the selected ones fail to generate a successful design during the following steps. Should this happen, the designers will come back to this chapter and start from here with the second best alternative. These are Machined Titanium Alloy and Cylindrical Box + Lid.

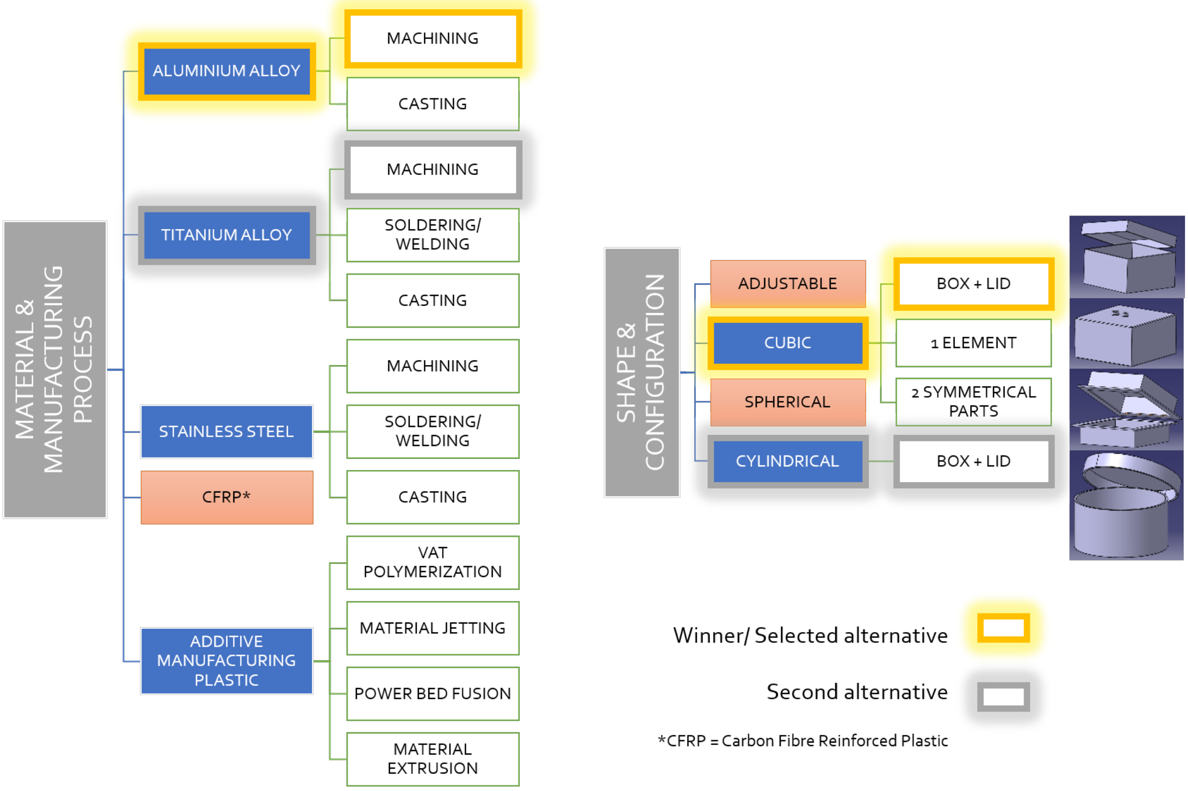


Figure 3.19: Material + Manufacturing Process trade-off combined results

At this point, it is possible to create the Conceptual Designs. The design choices made reduce the set of possible solutions to the problem, but as the design progresses, new trades have to be made. Once again, a top down approach has to be followed in the decision making, defining the general characteristics before the details, but with a procedure that bears in mind the final objectives (Fundamental Objective Hierarchy). In this case, a set of Conceptual Designs is developed, all complying with the decisions already made, and each one proposing a different solution. These Conceptual Designs will be then analysed in the following section, in order to generate a Preliminary Design.

3.3. CONCEPTUAL DESIGNS AND PRELIMINARY DESIGN

This section will explain the steps of the design process between the first design choices and the Preliminary Design, which is submitted to an in-depth structural analysis on following chapters. A midpoint is represented by the Conceptual Designs, elaborated to help with the decision making towards the Preliminary Design.

3.3.1. FURTHER DESIGN CHOICES

Given that the design options are still too many to consider them all at the same time, a new set of characteristics is evaluated: the interface between the Lid and the Box, and the interface between the Propellant Tank Assembly and the rest of the satellite. Although the interfaces between the Propellant Tank and the rest of the Propulsion System had already been established (see N2 chart in reference [1]), there is still no clear structural interface definition between the Propulsion System and the bus structure. As the Propellant Tank is the largest component of the subsystem, and considering its structural capabilities to withstand the loads in the requirements (such as PROP-TNK-200), it was decided by the Propulsion Team that the Propellant tank will have to be attached to the bus structure.

Table 3.6: Characteristics to be defined in these design trades

Characteristic	**Description**
Interface Lid-Tank	General features that define the structural joints between the lid(s) and the main tank, securing the propellant and meeting the leakage rate requirement. It is closely related to the objectives of Optimise Size, Minimise Mass, Maximise Volume, Maximise Simplicity and Minimise Leakage.
Interface Tank-Bus	General features that define the structural joints between the Propellant Tank assembly and the bus structure of the satellite. It addresses the objectives of Maximise Structural Response, Optimise Size, Maximise Volume, Minimise Mass and Maximise Simplicity.

In order to define the decision environment, table 3.6 is provided, defining the characteristics, and the DelFFi Propulsion Team is again identified as the decision maker. The Fundamental Objectives Hierarchy defined in figure 3.3 in the previous section will be taken into account for this decision process as well. Once the scope of the decision is defined, a DOT is generated with the different alternatives considered for each characteristic. However, the broad set of possible solutions for the interfaces resulted in an initially unclear DOT, with too many options to convey the information efficiently. In this way, a variation of the approach is required. The two initial characteristics are subdivided into subcategories, allowing a greater level of detail, and arranging the parent subcategories and children subcategories in an optimal way to avoid unnecessary repetition. Furthermore, a set of 5 Conceptual Designs are modelled in 3D, allowing a better understanding of the subcategories and the alternatives. In the initial design choices, 3D models were not as relevant (although a small rendering was provided to illustrate the different Shape + Configuration alternatives). The reason why is because the alternatives considered are general were straight-forward. In the trades considered in this section, per contra, the alternatives become deeply related to the case considered, and are not general anymore. This makes them harder to understand for a reader who has not been directly involved in the design process. The Conceptual Designs aim to tackle this problem.

The subcategories in which each characteristic is divided are explained in tables 3.7 and 3.8. Each subcategory, thus, will have its corresponding alternatives. Once again, given that the subcategories are related to each other, only some alternatives from different subcategories are compatible with each other. It is possible to understand this idea by looking at the DOTs in figures 3.21 and 3.20, which also introduce the alternatives. Tables 3.9 and 3.10 describe the alternatives considered for each subcategory in order of appearance in tables 3.7 and 3.8.

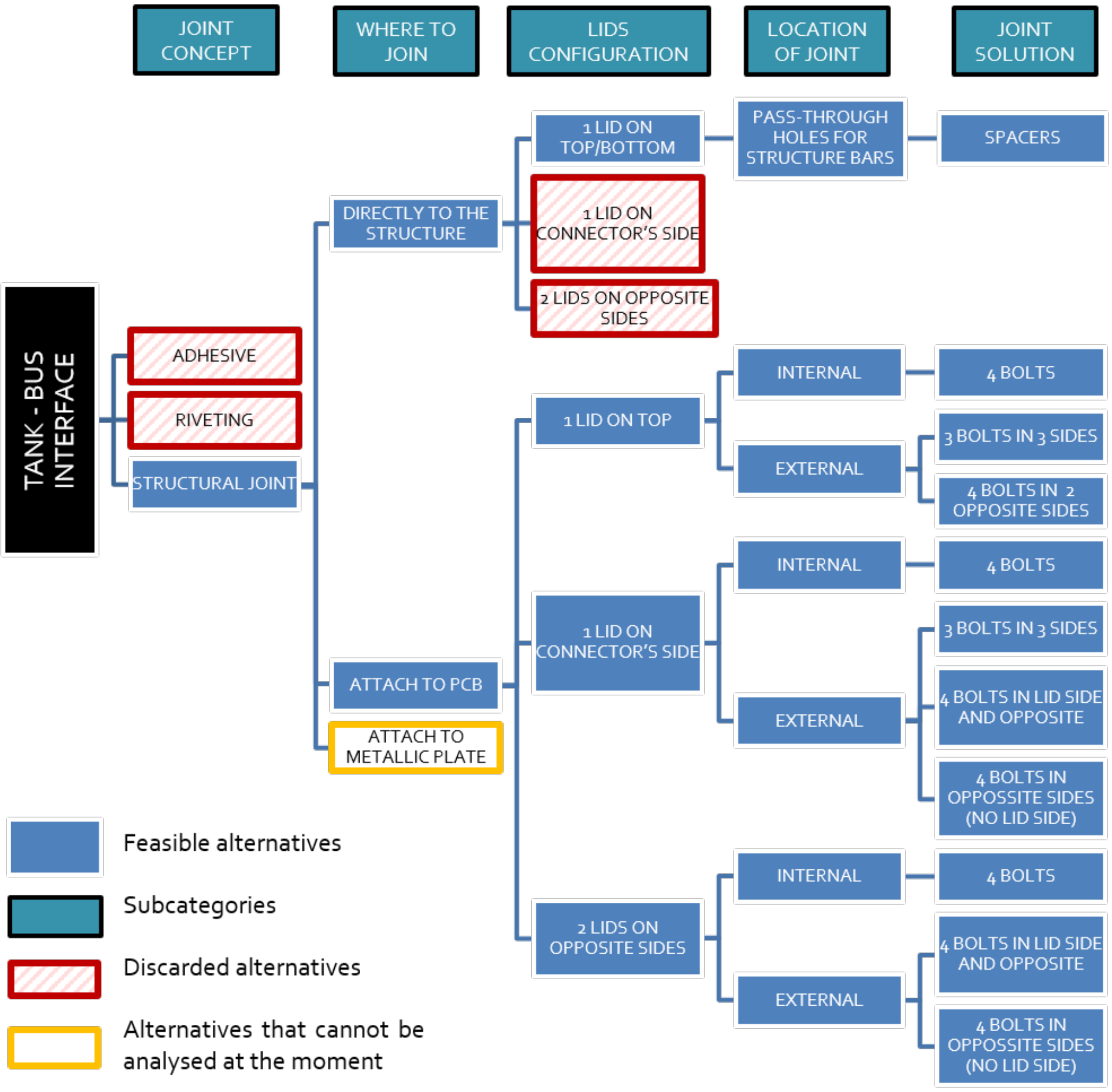


Figure 3.20: Material + Manufacturing Process trade-off combined results

Table 3.7: Subcategories from the Tank-Bus Interface characteristic

Subcategory	**Description**
Joint Concept	Defines the theory or systems that will held the Tank Assembly and the Bus structure together, assuring a correct transmission of the loads through the interface.
Where to Join	Considered the part of the bus to which the tank should be attached, as well as the possibility of adding intermediate components.
Lids Configuration	Defines the number and location of the lids.
Location of Joint	It analyses the position of the joints in the Tank Assembly and its impact on the size: either the joints can be located inside the Tank box or features have to be added to the box.
Joint Solution	Defines the actual configuration of the joint. It is the last level of detail (that is why its alternatives are the last children on the DOT).

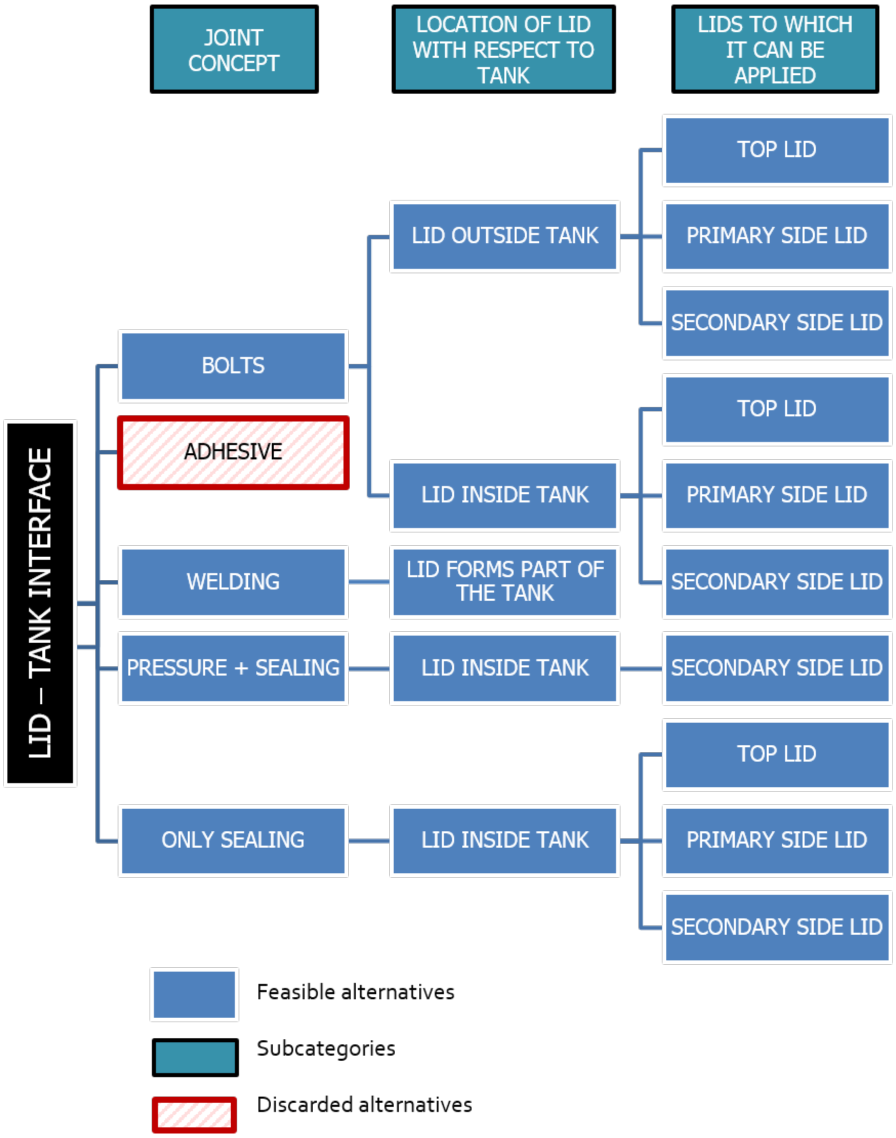


Figure 3.21: Material + Manufacturing Process trade-off combined results

Table 3.8: Subcategories from the Lid-Tank Interface characteristic

Subcategory	**Description**
Joint Concept	Defines the theory or systems that will held the Lid and the Tank together, meeting the leakage requirement.
Location of the Lid with respect to the Tank	The Lid can be placed inside the tank (the size of the assembly is given by the size of the tank) or outside the tank (the size of the assembly is given by the sum of the Lid and the Tank.
Lids to which it can be applied	With respect to the number of lids and the side of the tank they will be attached to, there are different alternatives. This subcategory considers the ones that are compatible with the parent subcategory alternatives. It is depends on the subcategory Lids Configuration from the Tank-Bus Interface characteristic, which determines the space left for attaching the lid once the interface with the bus is solved.

Table 3.9: Description of the alternatives for the Tank-Bus Interface, divided into Joint Concept, Where to Join, Lids Configuration, Location of Joint and Joint Solution

Alternative	**Description**	**Concept. Design**
Adhesive	An adhesive joint is considered. Table 3.11 will explain why it is discarded.	
Riveting	A riveted joint is considered. Table 3.11 will explain why it is discarded.	
Structural Joint	It refers to bolted joints or mechanical clamps.	1,2,3,4,5
Attach Directly to the Structure	The Bus structure counts with four vertical bars along its Z axis [38] to facilitate the assembly of PCBs. It would be possible to attach the Tank directly to these bars.	5
Attach to PCB	Following the approach taken in Delfi n3Xt [37], the Tank can be mounted on a PCB, and the PCB is then attached to the Bus structure. This is convenient because a PCB is needed for the thruster, and there has to be space for cabling between the connectors and the thruster, which has to be allowed by the Tank.	1,2,3,4
Attach to Metalic Plate	Given the poor structural performance of the PCB's, a possibility is to use a metallic plate instead. The reason why this alternative is not analysed at the moment is given in table 3.11.	
1 Lid on Top/Bottom	The top and bottom of the Tank are the faces with the normal along the Z axis of the Bus structure. Top is the side closest to the thruster, and Bottom is the side closest to the PCBs and the rest of the satellite subsystems.	3,5
1 Lid on Connector's Side	Having all the cabling pass from the connectors on the PCB to the thruster (Z direction) through the side of the bus on which the connectors are gives.	1,2
2 Lids on Opposite Sides	It is a variation of the previous alternative which consists in adding a second lid.	4
Pass-through Holes for Structure Bars	Self-explanatory, it only applies to joining directly to the structure.	5
Internal	It refers to having the joints inside the original size of the tank, limiting the internal volume.	
External	It refers to having the joints outside the original size of the tank, complicating the design to include these features.	1,2,3,4
Spacers	Only applies to the directly to structure joint. The Tank Assembly is clamped to the bars of the Bus via spacers on the bars.	
4 Bolts	Only applies to attaching to PCB internally. It consists in at least one bolt per corner/side of the tank (4 or more).	5
3 Bolts in 3 Sides	Only applies to attaching to PCB externally. It avoids introducing a joint on the side of the connectors.	3
4 Bolts in 2 Opposite Sides	Only applies to attaching to PCB externally. The sides considered may include or not the side of the connectors. However, it never includes a side with lid.	2
4 Bolts in the Lid's Side and its Opposite Side	Only applies to attaching to PCB externally. The sides considered may include or not the side of the connectors.	1,4

Table 3.10: Description of the alternatives for the Lid-Tank Interface, divided into Joint Concept, Location of the Lid with respect to the Tank and Lids to which it can be Applied

Alternative	Description	Concept. Design
Bolts	A bolted joint is considered, including washers and nuts if necessary.	1,2,3,5
Adhesive	An adhesive joint is considered. Table 3.11 will explain why it is discarded.	
Welding	A welded joint is considered. It was the process followed in the Delfi N3XT mission [37].	
Pressure + Sealing	Only possible with a secondary lid, it uses the internal pressure and the sealing to secure the lid. In a tank with two openings, the lid is introduced through one hole and is adjusted to the other hole, which has a physical barrier. The the internal pressure presses the lid against this barrier.	4
Only Sealing	It relies on the friction between the sealing and the aluminium, which is sufficient to place the lid in is position if it is tightly inserted.	4
Lid Outside Tank	The size of the tank is increased by attaching the lid. Only possible with bolted joints. Against internal pressure, the lid reinforces the tank structurally.	1,2,3,5
Lid Inside Tank	The size of the tank remains the same after attaching the lid. Against internal pressure, the tank reinforces the lid structurally.	4
Top Lid	Lid is placed on one of the faces whose normal is the Z axis of the bus structure, top being the closest to the thruster and bottom being the opposite one.	3,5
Primary Side Lid	Either the single Lid on the side or one of the 2 Lids.	1,2,4
Secondary Side Lid	One of the 2 lids on the sides. This distinction is done because the Pressure + Sealing alternative is only feasible when there are two lids.	4

Table 3.11: Alternatives eliminated before the trade-off process

Alternative	Reasons for elimination
Adhesive (Tank-Bus)	It requires a verification process to certify that the joint is done correctly. Although it would entail a weight reduction if compared to bolted joints, it does not compensate the added complexity to the fabrication process.
Riveting	Although useful with sheets of metal, it would cause stress on the PCB, which is an already weak structural component.
1 Lid on Connector's Side	The Directly to Structure alternative requires additional structure on the corners of the tank. This limits the space available on the sides. Moreover, given that the bars of the bus are along the Z axis, it is suitable to create the holes for these bars in the same direction as the tank's interior, which would result in a top/bottom lid.
2 Lids on Opposite Sides	Same reasons as the previous alternative.
Adhesive (Lid-Tank)	Same reasons as the ones given for discarding adhesive on the Tank-Bus Interface. Moreover, once the Lid is adhered, it cannot be removed, limiting the accessibility.

3.3.2. CONCEPTUAL DESIGNS

After having introduced the DOT's and the different alternatives, the Conceptual Designs are presented in figures 3.22, 3.23, 3.24, 3.25 and 3.26. These were developed at the same time as the DOT's, and by doing this, more alternatives were imagined, as the 3D representation gave a better view of the problem. The Conceptual Designs do not aim to optimise objectives, just show different alternatives in a visual way and how they would be implemented.

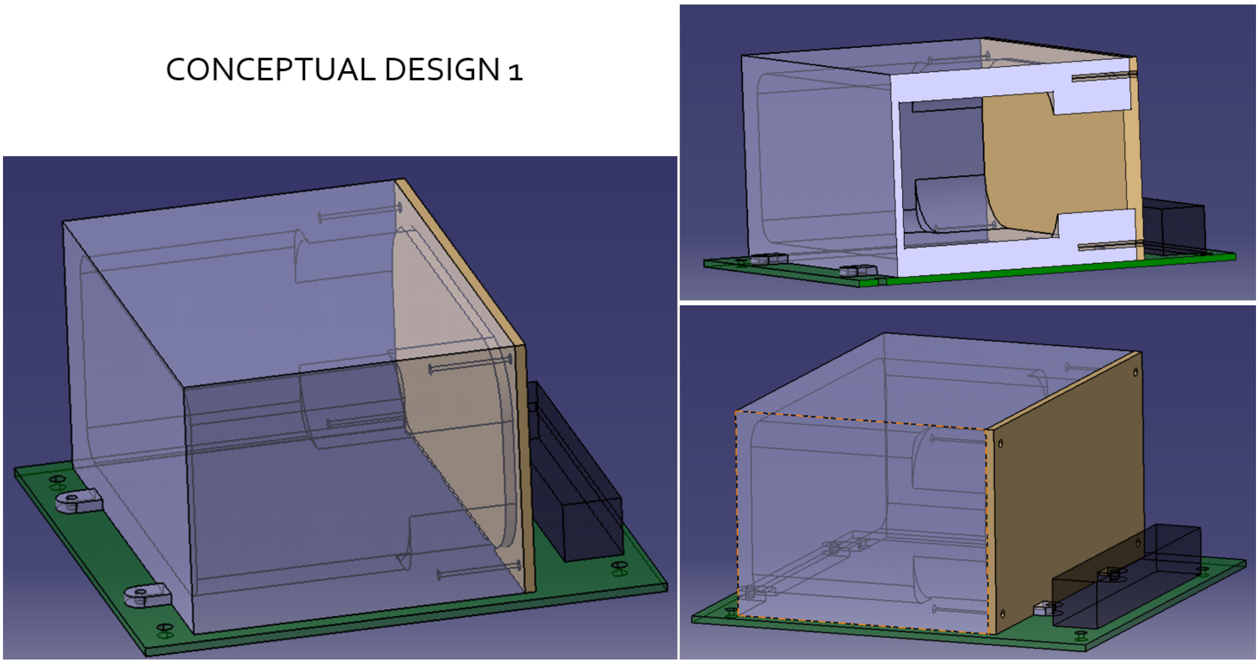


Figure 3.22: Conceptual Design 1

The Conceptual Design 1 represents the Propellant Tank attached to the PCB by 4 external bolts on the side of the Lid and the opposite side, the Lid on the side of the connectors and joined by 4 internal bolts, leaving the Lid outside the Tank. Thanks to putting all the interfaces with the PCb on two opposite sides (normal to the Y axis), the other direction can be extended to fit the maximum volume possible. Having the lid on the side of the connectors, however, limits the accessibility to the lid once it is mounted. The lips used for the bolted joints between the Tank and the PCB are hard to manufacture, need additional operations and may have structural problems.

Making some small modifications, the Conceptual Design 2 is generated. The lips that had to be incorporated to the tank for the interface with the PCB are extended along the Z axis. On the one hand, this reduces the number of operations and acts as a reinforcement of the walls of the tank. On the other hand, it increases the mass of the assembly. These joints are also changed to the sides normal to the X so that they do not interfere with the lid. Another modification is to locate the bolts of the Lid to the Tank outside. This increases the internal volume, but the Lid needs to be thicker, as the Tank no longer reinforces it against internal pressure.

For the Conceptual Design 3, the Lid is located in the Top instead of the side. The interface with the PCB is done by 3 bolts on 3 different sides. Although the number of bolts required is reduced, having the X and Y directions with bolts reduces the size of the Tank noticeably. The option of using the lips from the Tank-PCB interface as also the way to join the Lid to the Tank results in an efficient use of space.

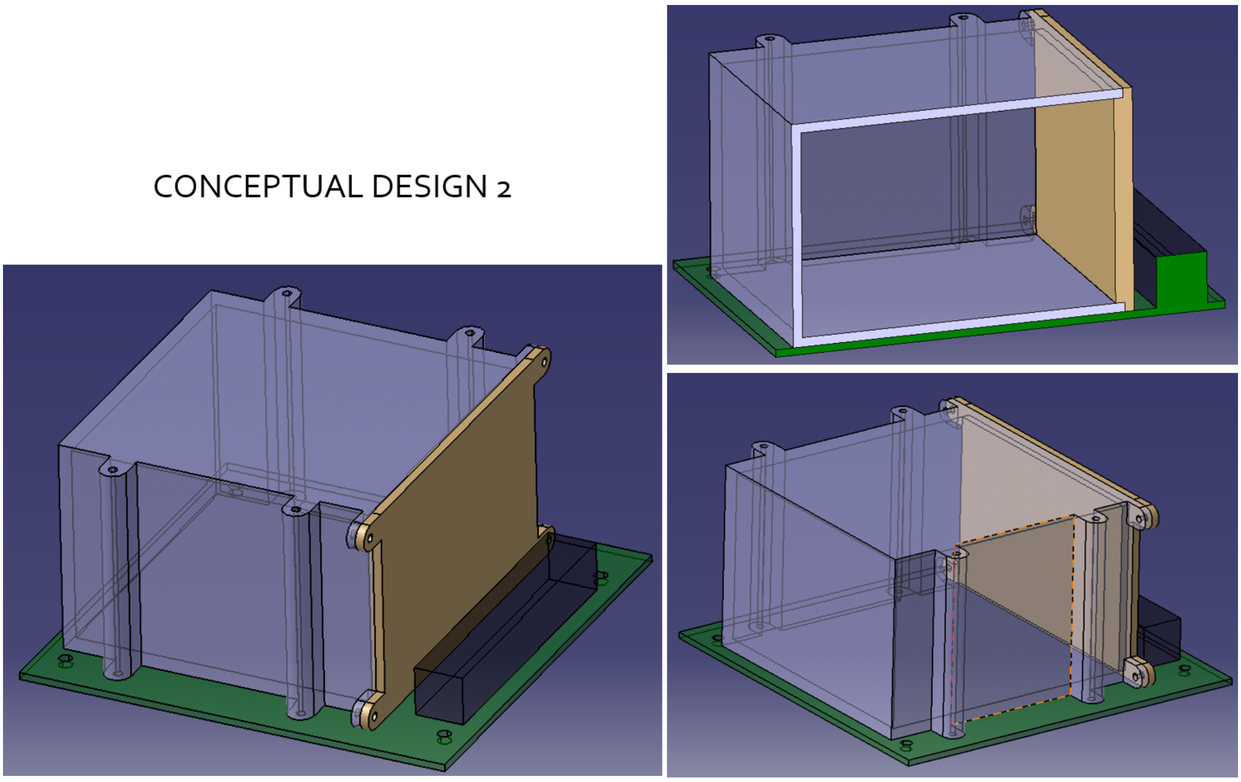


Figure 3.23: Conceptual Design 2

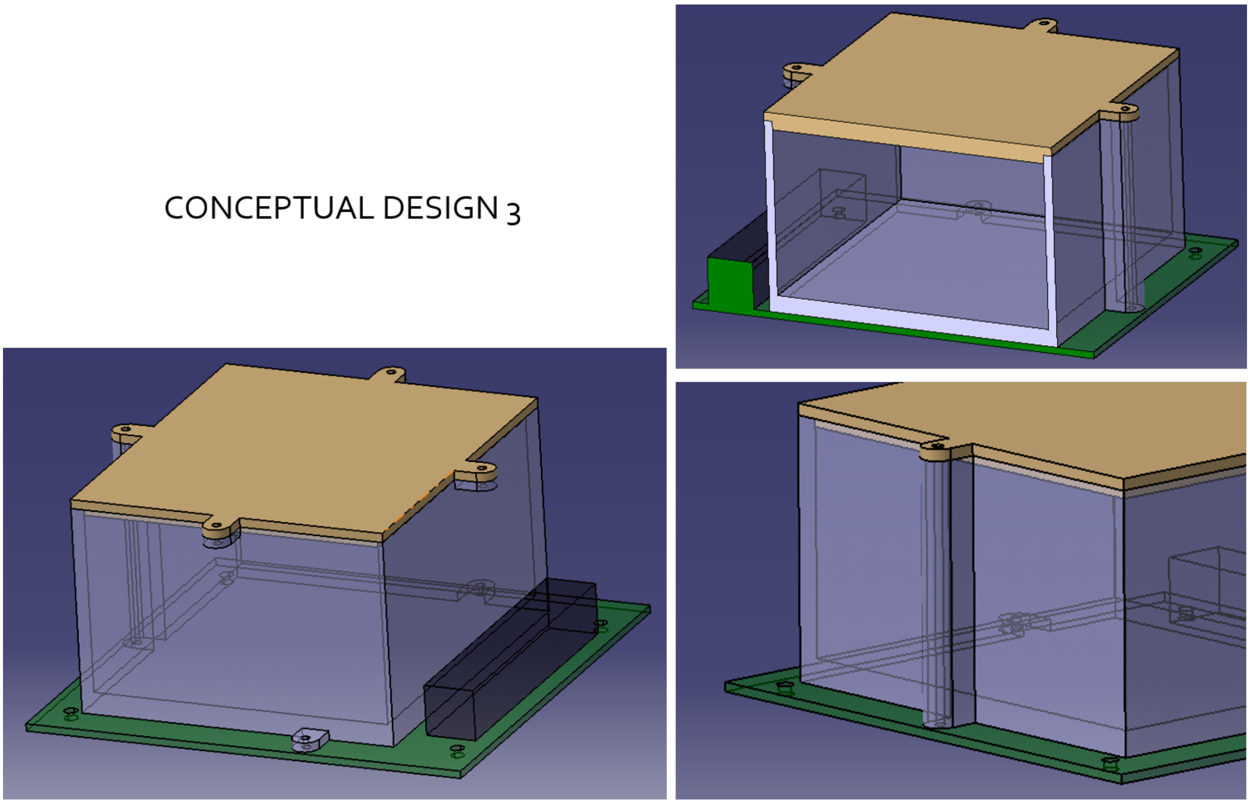


Figure 3.24: Conceptual Design 3

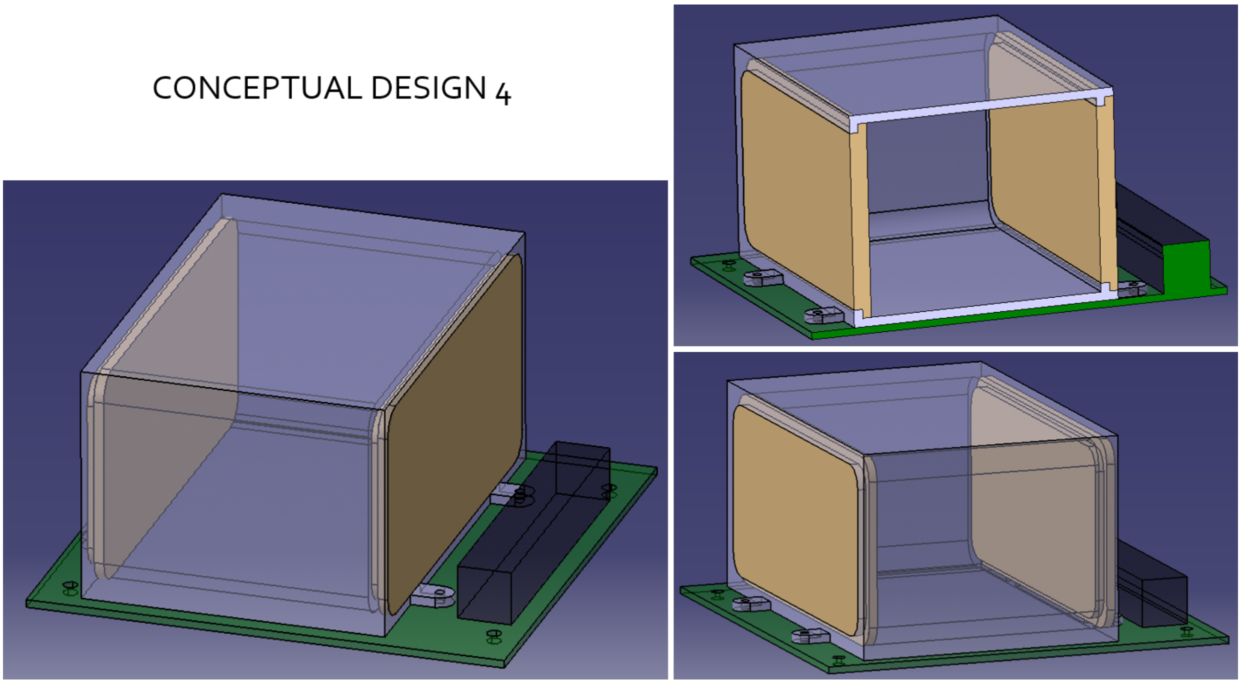


Figure 3.25: Conceptual Design 4

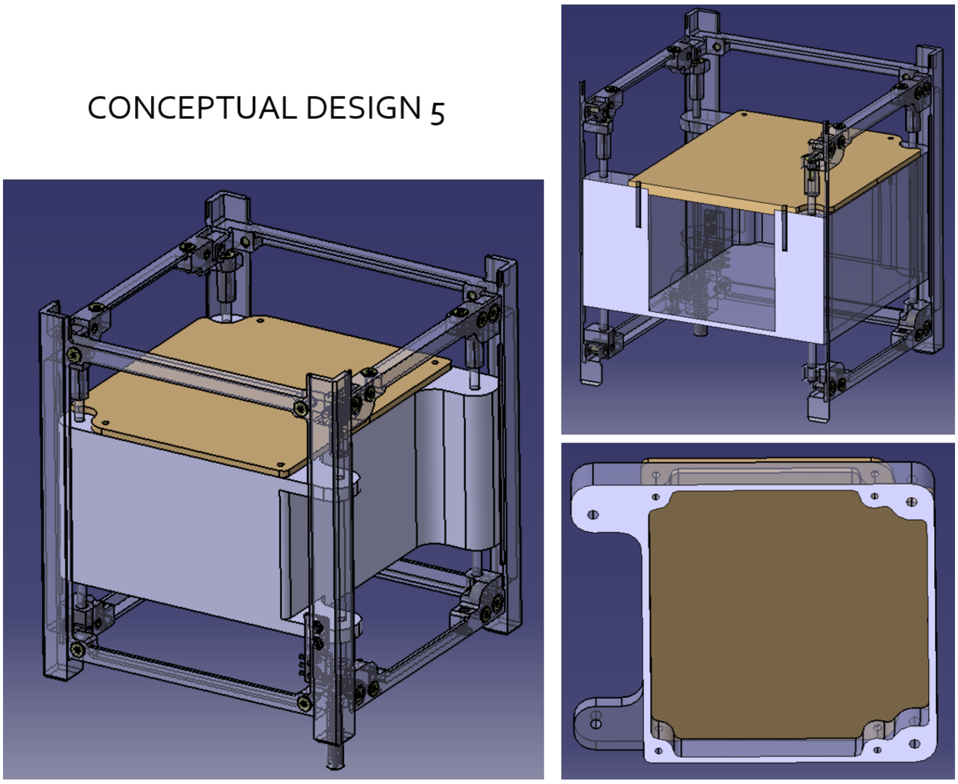
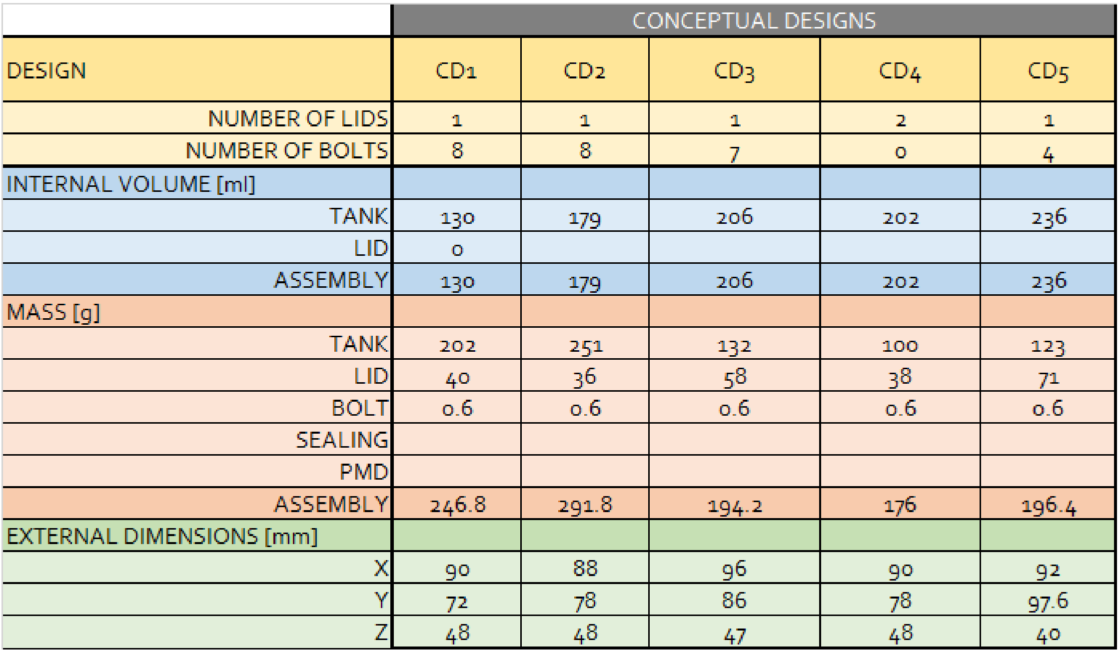


Figure 3.26: Conceptual Design 5

Conceptual Design 4 is a small variation of Conceptual Design 1. Instead of one Lid, it incorporates 2 on opposite sides. In the section view it can be noticed that the Lid on the connector's side uses the Only Sealing Joint Concept, while the opposite Lid uses the Pressure + Sealing Joint Concept (the Lid will be pushed against the tank, providing an efficient closure. Even though, this concept will not work as effectively when the pressure inside is low. The risk of having leakage is also incremented when having 2 lids.

Finally, the Conceptual Design 5 represents the Tank joint directly to the Bus structure (part of this structure is also shown). There is a space on one of the sides to leave room for the connectors and cabling. This design allows an irregular interior shape, maximising the internal volume. This design is stiffer and more modular.

To keep track of the important budgets established by the requirements, a dynamic document is created together with the Conceptual Designs. This document contains the Mass, Size and Volume Budgets of the Propellant Tank Assembly, and is updated with each redesign. Figure 3.27 shows the status of the document at the time of the Conceptual Designs. Notice that most of the requirements are not met in these designs. This is because a conservative approach was taken, considering a minimum thickness of 2 mm, whereas the estimations on the requirements considered thicknesses of 1.5 mm. In addition, the mass of some components has not been estimated yet (i.e. PMD, Sealing, etc.)



	CONCEPTUAL DESIGNS				
DESIGN	CD1	CD2	CD3	CD4	CD5
NUMBER OF LIDS	1	1	1	2	1
NUMBER OF BOLTS	8	8	7	0	4
INTERNAL VOLUME [ml]					
TANK	130	179	206	202	236
LID	0				
ASSEMBLY	130	179	206	202	236
MASS [g]					
TANK	202	251	132	100	123
LID	40	36	58	38	71
BOLT	0.6	0.6	0.6	0.6	0.6
SEALING					
PMD					
ASSEMBLY	246.8	291.8	194.2	176	196.4
EXTERNAL DIMENSIONS [mm]					
X	90	88	96	90	92
Y	72	78	86	78	97.6
Z	48	48	47	48	40

Figure 3.27: Budgets during the Conceptual Designs

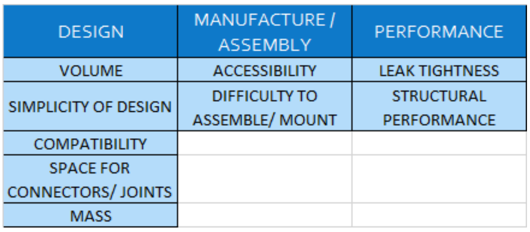
3.3.3. ADVANTAGES AND DISADVANTAGES

For the initial trades, the trade-off study was carried out by means of trade-off tables. These assessed the different alternatives based on criteria that could be traced back to the objectives from the Fundamental Objectives Hierarchy. This was possible due to the fact that the decisions were general enough to be done by members of the DelFFi Propulsion Team without the need of a deep understanding of the case, but only the general knowledge of the system, the requirements and the aspects of each alternative. However, the design choices at this point require an deeper immersion of the decision maker on the subject. It would not be efficient to have the whole Propulsion Team looking into this matter, as all parts of the system need attention. This is why the approach taken for these decisions is altered. I. Granero, responsible for the design of the Propellant Tank and author of this thesis, dives into the matter and produces a set of advantages and disadvantages for all the options considered, including his conclusions. This document is then presented to the Team, which takes a decision based on the advantages and disadvantages, as well as the conclusion already drawn.

Presenting the performance of each alternative with respect to the objectives in the form of advantages and disadvantages results in a clearer way to convey the noticeable amount of information considered in the decision. Whilst a trade-off is more objective, it takes longer to understand it, as all the numbers and criteria require an additional explanation (as it was done for the first decisions). A simple table with the pros and cons sums up the decision effectively.

Figure 3.29 shows the Advantages and Disadvantages tables (one for each characteristic). The alternatives are represented in rows and the general categories of criteria are represented in columns, plus a final column with the outcome of the decision. As it can be seen, not all the subcategories of each characteristic are represented. In order to make the table more compact and reduce the unnecessary information, some subcategories are joined together. For the Tank-Bus Interface, the subcategory Joint Concept is removed because after the DOT it only counted with one alternative: Structural Joint, and the subcategory Location of Joint is merged with Joint Solution, as the only difference it generates is Internal or External bolt connections to the PCB. For the Lid-Tank Interface, the subcategory Location of Lid with respect to the Tank is merged with the Joint Concept, as it only makes distinction between Lid Outside or Inside the Tank. Furthermore, the subcategory Lids to which it can be applied is removed from the table. As the decision on the Lid Location is done for the Tank-Bus Interface, this choice already determines the feasibility of some Joint Concepts of the Lid-Tank Interface (e.g. the Pressure + Sealing alternative).

With respect to the criteria, three general categories were created based on the Fundamental Objectives Hierarchy: Design, Manufacture/Assembly and Performance. Inside these general categories, specific criteria were evaluated. Figure 3.28 shows the corresponding criteria (although they are all self explanatory, it should be noticed that Compatibility is meant towards other alternatives, and Accessibility is referred to the connections on the Lid as well as the interior of the Tank). The advantage/ disadvantage scheme used does not require to show on the table how the alternative performs with reference to each and every criterion, but only the criteria in which the alternative either generates an advantage or a disadvantage with respect to the other options. If the disadvantage cannot be coped up with, then it is classified as "no go".



DESIGN	MANUFACTURE / ASSEMBLY	PERFORMANCE
VOLUME	ACCESSIBILITY	LEAK TIGHTNESS
SIMPLICITY OF DESIGN	DIFFICULTY TO ASSEMBLE/ MOUNT	STRUCTURAL PERFORMANCE
COMPATIBILITY		
SPACE FOR CONNECTORS/ JOINTS		
MASS		

Figure 3.28: Advantages and Disadvantages table

As not all the evaluations of each alternative for each criteria is shown on the table, it is not possible to generate the results by adding the advantages and disadvantages. Rather than that, the conclusions are drawn during a meeting with the DelFFi Propulsion Team. Here, the table is presented and explained to the team, with the advantages, disadvantages and "no go"s made by I. Granero (before this, the Conceptual Designs and the DOTs are introduced). After agreeing on the classification, the alternatives with at least one "no go" are assigned a No Go in the result category. Subsequently, a Go or a No Go is given to each alternative, based on the advantages and disadvantages they produce.

Some alternatives, however, required a further in depth study of feasibility. The alternative of mounting on PCB was decided to require a Structural Analysis on its own before developing it. As the Structural Analysis was not performed, the result is neither a Go or a No Go yet, as it fell outside of the scope of this Thesis. Choosing between having the Lid on Top or on the Side (given the No Go of having 2 Lids) required a greater detail of the Connectors and Accessibility Needs. Once it was provided by E. Jansen, responsible for this part, it was decided that having the Lid on Top was the best alternative. Additionally, the feasibility of having internal bolts on the Tank meant introducing inserts such as helicoils (as the thread in Aluminium is quickly deteriorated due to its low Hardness). In order to make a decision on this, a meeting took place with E. Roessen, from the Workshop of the Aerospace Faculty, who confirmed the feasibility of using helicoils with the metrics cosidered (for instance, M2). He also recommended to discard the alternative of Welding the Lid to the Tank, due to the stress generated on the material, as well as the precision required for a correct joint with the size considered.

TANK-BUS INTERFACE		DESIGN		MANUFACTURE / ASSEMBLY		PERFORMANCE		RESULT
WHERE TO JOIN	DIRECTLY TO THE STRUCTURE	VOLUME	BETTER USE DUE TO CUSTOM SHAPE	DIFFICULTY TO ASSEMBLE/ MOUNT	LOW	STRUCTURAL PERFORMANCE	HIGH	GO
		COMPATIBILITY	INCOMPATIBLE WITH SIDE LID/S					
		SIMPLICITY OF DESIGN	IRREGULAR SHAPE					
	MOUNT ON PCB	COMPATIBILITY	SYMMETRIES	DIFFICULTY TO ASSEMBLE/ MOUNT	LOW	STRUCTURAL PERFORMANCE	PCB MAY NOT RESIST	STRUCTURAL ANALYSIS
		SIMPLICITY OF DESIGN	COMPATIBILITY WITH OTHER OPTIONS					
LIDS CONFIGURATION	LID ON TOP	SPACE FOR CONNECTORS/ JOINTS	TOP SURFACE GREATER THAN SIDE SURFACE	ACCESSIBILITY	ONCE IT IS MOUNTED (WHEN THRUSTER PLACE ON TOP)			GO (CONNECTORS AND ACCESSIBILITY NEEDS)
	LID ON SIDE	SPACE FOR CONNECTORS/ JOINTS	SPACE FOR CONNECTORS/JOINTS	ACCESSIBILITY	HIGH			NO GO (CONNECTORS AND ACCESSIBILITY NEEDS)
		COMPATIBILITY	INCOMPATIBLE WITH DIRECTLY TO STRUCTURE					
	2 LIDS	SPACE FOR CONNECTORS/ JOINTS	TWO LIDS FOR CONNECTORS	ACCESSIBILITY	HIGH	LEAK TIGHTNESS	RIKS INCREASES WITH MORE THAN ONE LID	NO GO
		COMPATIBILITY	INCOMPATIBLE WITH DIRECTLY TO STRUCTURE					
JOINT SOLUTION	SPACERS	SIMPLICITY OF DESIGN	PRE-DEFINED AND SUCCESSFUL					GO
	4 BOLTS INTERNAL	VOLUME	MORE INTERNAL VOLUME	DIFFICULTY TO ASSEMBLE/ MOUNT	NEED FOR HELICOILS			GO (WORKSHOP FEEDBACK)
	3 BOLTS IN 3 SIDES	VOLUME	BOTH SIDES ARE LIMITED			STRUCTURAL PERFORMANCE	NO BACKUP FOR FAILURE OF ONE BOLT	NO GO
	4 BOLTS IN 2 OPPOSITE SIDES	VOLUME	ONE SIDE CAN BE EXTENDED					GO
	4 BOLTS IN LID SIDE AND OPPOSITE SIDE	VOLUME	ONE SIDE CAN BE EXTENDED	ACCESSIBILITY	LIMITED BY THE BOLTS			NO GO
		SIMPLICITY OF DESIGN	LID PLACEMENT INTERFERES					

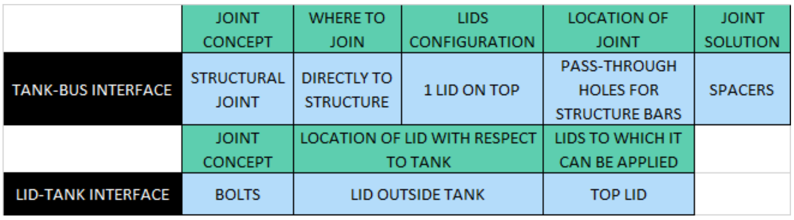
LID-TANK INTERFACE		DESIGN		MANUFACTURE / ASSEMBLY		PERFORMANCE		RESULT
JOINT CONCEPT	BOLTS (INTERNAL)	VOLUME	LESS INTERNAL VOLUME SO AS TO PLACE HOLES FOR THE BOLTS	DIFFICULTY TO ASSEMBLE/ MOUNT	NEED FOR HELICOILS			GO (WORKSHOP FEEDBACK)
		MASS	HEAVY (NEEDS MORE THAN 4 BOLTS FOR LEAK TIGHTNESS)					
	BOLTS (EXTERNAL)	VOLUME	LESS EXTERNAL VOLUME SO AS TO PLACE HOLES FOR THE BOLTS					GO
		MASS	HEAVY (NEEDS MORE THAN 4 BOLTS FOR LEAK TIGHTNESS)					
	WELDING	SIMPLICITY OF DESIGN	NO NEED FOR SEALING	ACCESSIBILITY	CANNOT OPEN THE LID AGAIN	LEAK TIGHTNESS	EXCELENT	NO GO (WORKSHOP FEEDBACK)
						STRUCTURAL PERFORMANCE	STRESS ON THE MATERIAL	
	PRESSURE + SEALING	MASS	NO ADDINIONAL COMPONENTS			LEAK TIGHTNESS	RISK WHEN INTERNAL PRESSURE IS LOW	FATHER IS NO GO
	ONLY SEALING	MASS	NO ADDINIONAL COMPONENTS			LEAK TIGHTNESS	RISK AS IT RELIES TOO MUCH ON SEALING	NO GO

🟩 ADVANTAGE
🟨 DISADVANTAGE
🟥 NO GO

Figure 3.29: Advantages and Disadvantages table

As it can be seen on figure 3.29, the design choices result in 2 options: either joining the Tank directly to the structure with passing-through holes for the bars and clamped with spacers and the lip on top or perform a structural analysis of the PCB in order to know its structural capabilities and decide between joining the Tank to the PCB via 4 internal bolts or 2 external bolts on opposite sides. With respect to joining the Lid to the Tank, the choice is still between having the bolts inside the tank or outside the tank.

Given that the structural analysis of the PCB is out of the scope of this Thesis, and having another feasible alternative within reach, it was decided to leave the structural analysis for future research and choose the Directly to structure joint. With respect to the bolted joints of the Lid and the Tank being internal or external, the internal volume is considered more important than the external one, thus the alternative of internal bolts is the one undertaken. Figure 3.30 shows the decision on a more graphic and summed up way.



	JOINT CONCEPT	WHERE TO JOIN	LIDS CONFIGURATION	LOCATION OF JOINT	JOINT SOLUTION
TANK-BUS INTERFACE	STRUCTURAL JOINT	DIRECTLY TO STRUCTURE	1 LID ON TOP	PASS-THROUGH HOLES FOR STRUCTURE BARS	SPACERS
	JOINT CONCEPT	LOCATION OF LID WITH RESPECT TO TANK		LIDS TO WHICH IT CAN BE APPLIED	
LID-TANK INTERFACE	BOLTS	LID OUTSIDE TANK		TOP LID	

Figure 3.30: Decision made on the Tank-Bus Interface and the Lid-Tank Interface

3.3.4. PRELIMINARY DESIGN

Having decided on the interfaces of the Propellant Tank, it is possible to generate a Preliminary Design. The idea of this design is to set the baseline for the next step: structural analysis via Finite Element Modelling. A Preliminary Design should have enough detail and the main characteristics should already be defined and unaltered (frozen configuration). Some details, measures and configurations still have to be defined, so they are subject to change during the structural analysis. Once the desired structural performance is achieved, the Detail Design will be delivered. If the desired performance is not achieved, a complete design iteration should be done, either starting from the Conceptual Designs or redesigning from the initial trades.

Table 3.12: Minor design choices made for the Preliminary Design

Characteristic	**Decision**
Sealing	A polymer sealing material will provide the leak tightness of the Tank. On the meeting with the Workshop, it was decided to place the sealing on a groove made on the Lid because the walls of the Tank do not have enough thickness to create a groove. The sealing can adapt to the irregular shape of the Lid.
PMD	E. Jansen is responsible for this component (if needed). The design of the tank should not be altered by it, thus the only impact of the component so far is on the mass budget.
Connectors	E. Jansen is responsible for this part of the Propulsion System. Although the components have not yet been chosen, the Propellant Tank shall allow for propellant fill and drain, as well as temperature and pressure sensing (requirements). A burst disk will be included as well as the failure point if the pressure exceeds a certain maximum, avoiding explosion and controlling the possible damage. For the Preliminary Design, 4 holes on the lid will represent the connection points. Their location will be assessed during the structural analysis.
Number of Bolts	Although the leak tightness is assured with 4 bolts theoretically, the irregular shape of the Tank as well as the need for risk reduction, it is decided to incorporate 10 bolted joints M2 throughout the Lid-Tank interface. The distance between bolts is maintained similar so that no weak points are created.

The meeting with E. Roessen from the Aerospace Workshop shed light upon some details of the design which had not yet been considered. In order to sum up the minor design choices made for generating the Preliminary design, table 3.12 is provided.

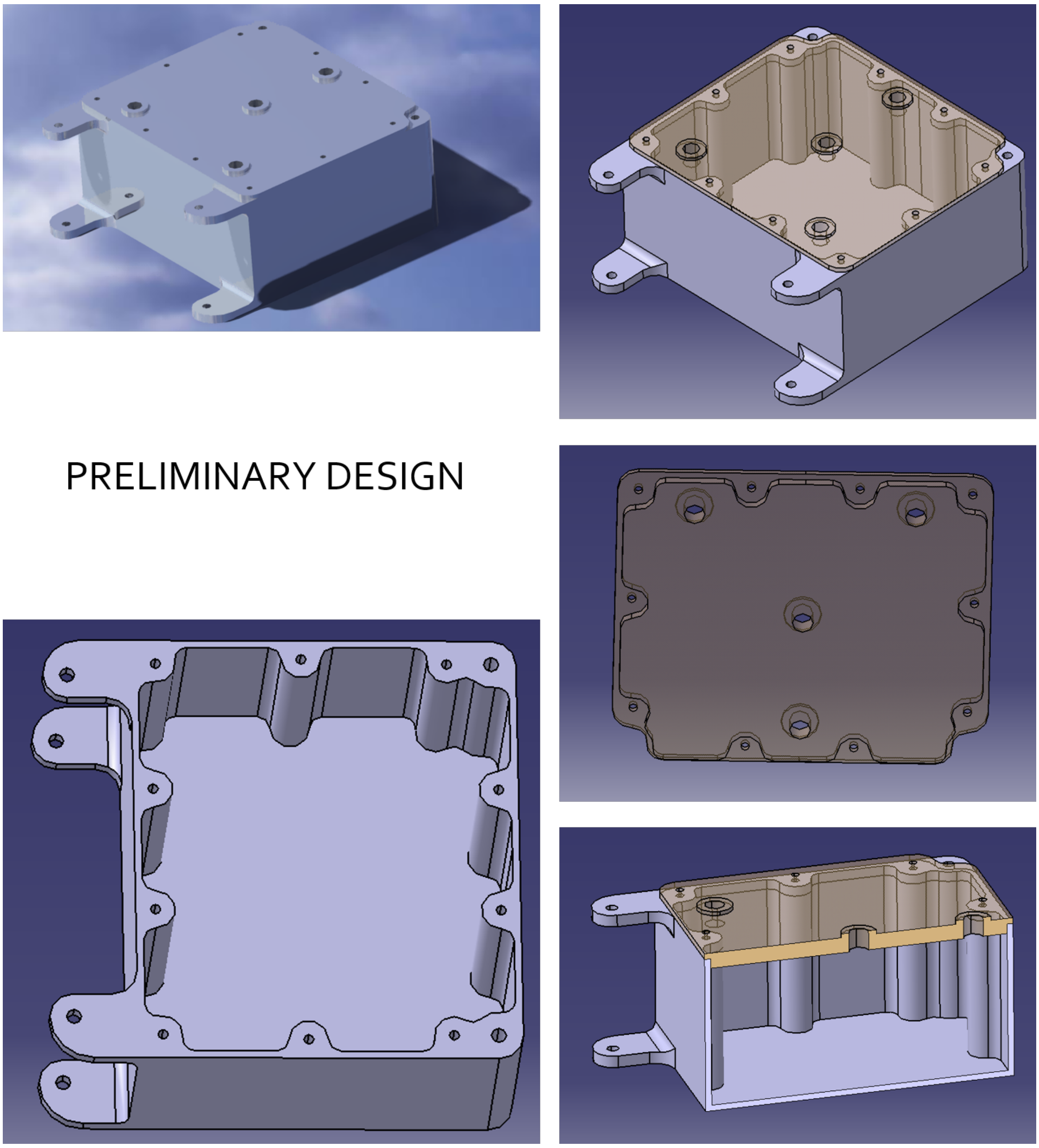


Figure 3.31: Decision made on the Tank-Bus Interface and the Lid-Tank Interface

Figure 3.31 shows a render of the Preliminary Design, as well as cut sections and the Tank and Lid as separate components. The budgets at the time of the Preliminary Design are shown on the Appendix C under the name of PD1.

4

ANALYTICAL STUDY

4.1. MOTIVATION FOR THE ANALYTICAL STUDY

The aim of this chapter is to estimate the effects of the load cases on the Preliminary Design already developed. In order to do this, an analytical study of each load case is performed. Although the complexity of the problem calls for a Finite Element analysis, it is always advisable to carry out an analytical study of a simplification of the problem so as to perceive the order of magnitude of the results to be obtained with the in-depth analysis.

Not all the load cases can be solved analytically (which is why the Finite Element Analysis is used). However, with the appropriate simplifications, it is possible to obtain relevant results. These simplifications shall be based on assumptions or refer to the literature. The results obtained have, thus, limitations which should be taken into account at the time of drawing conclusions.

As it was seen in the Propellant Tank Requirements Chapter, specific load cases have already been defined (PROP-TNK-200, PROP-TNK-600, PROP-TNK-601, PROP-TNK-602 and PROP-TNK-603) as well as the Factors of Safety (PROP-TNK-500 and PROP-TNK-501) that the Propellant Tank must provide in all cases. The load cases stated on the requirements include internal pressure, g-accelerations and vibrations. Each one of them will be described during the following sections of this chapter, together with an analytical study. Moreover, the decisions made on the design result in an additional load case, not stated on the requirements. This is the loads on the bolted joints in the Lid-Tank interface. In conclusion, the following load cases will be studied:

1. Internal pressure
2. G-accelerations
3. Loads on bolted joints
4. Vibrations and natural frequency

A simplified tank will be used for the analytical study, whose dimensions can be seen in figure 4.1. The base is considered a square of side L and the thickness, t, is constant throughout the whole tank (this thickness is derived from an estimation, but it is subject to change, as its value fully depends on the stresses generated by the loads). The assumptions made in order to swift from the Preliminary Design, with a complex shape and only one symmetry axis, to this simplified tank, which is symmetric in three axis, are explained here:

- The Propellant Tank is considered clamped in all 4 corners on which it interfaces with the bus structure.
- The space allowed for passing cabling is removed, as well as the lips that join the tank to the bus structure. These lips will be sized during the Finite Element Analysis.
- Instead of a Lid joined with bolts, the Propellant Tank is considered a closed box without holes for interfaces. This simplification will result in lower stress level. However, the assumption of a uniform wall thickness, leaving out the parts were the bolts are joined to the tank, is a conservative assumption and will result in a higher level of stress, as these will act as stiffeners.

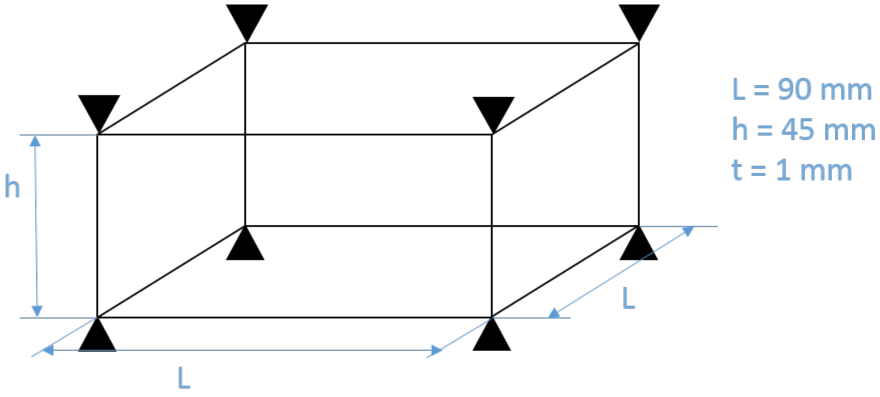
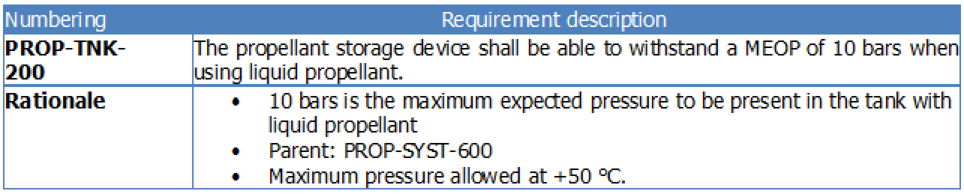


Figure 4.1: Simplification of the propellant tank with dimensions

4.2. INTERNAL PRESSURE

As far as the Propellant Tank is concerned, the most critical load it shall withstand is the internal pressure, as stated in the requirement PROP-TNK-200. It has been included again in figure 4.2.



Numbering	Requirement description
PROP-TNK-200	The propellant storage device shall be able to withstand a MEOP of 10 bars when using liquid propellant.
Rationale	• 10 bars is the maximum expected pressure to be present in the tank with liquid propellant • Parent: PROP-SYST-600 • Maximum pressure allowed at +50 ºC.

Figure 4.2: Propellant Tank Requirements: Performance

The approach taken to analyse this load case is based on reference [10]. In this way, the propellant tank is considered an enclosure of 6 plates. The cross section can be seen in figure 4.3.

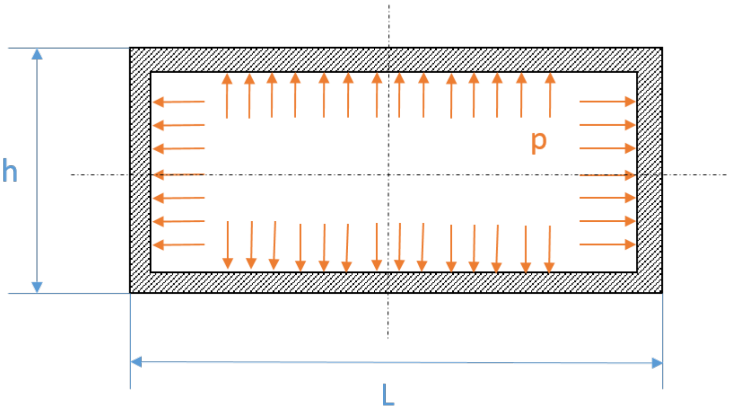


Figure 4.3: Cross section of the simplified propellant tank

Taking advantage of the symmetries of the section, the analysis can be done for one fourth of it, as represented in figure 4.4. Notice that, in order to maintain the symmetries, the joints in points A and C do not constrain the symmetrical displacement. The reaction forces and moments T_A, T_C, M_A M_C (notice that these are forces and moments per unit of depth of the tank) that appear when applying the symmetry are unknown, and have to be computed so as to obtain the stress along each plate.

Applying the equilibrium of forces on both axes (y and z), the forces T_A and T_C can be calculated:

$$\Sigma F_H = 0 \quad \rightarrow \quad T_A = p \cdot \left(\frac{h}{2} - t\right) \simeq p \cdot \frac{h}{2} \tag{4.1}$$

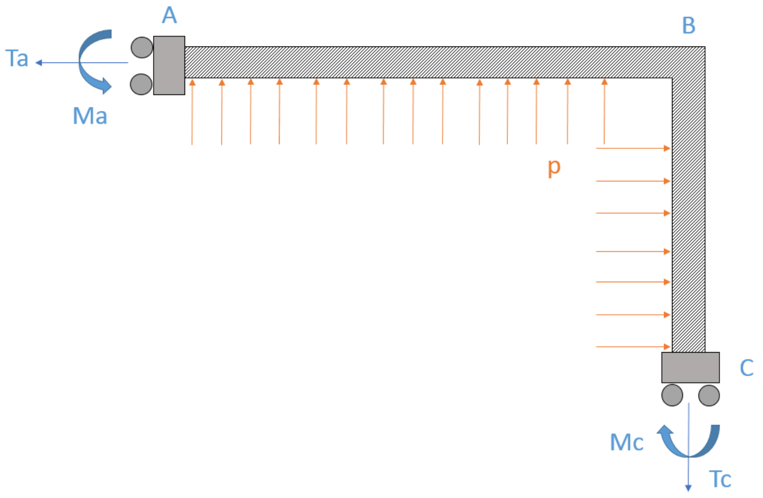


Figure 4.4: Application of symmetrical properties to the tank section

$$\Sigma F_V = 0 \quad \rightarrow \quad T_C = p \cdot \left(\frac{L}{2} - t \right) \simeq p \cdot \frac{L}{2} \tag{4.2}$$

In the same way, it is possible to apply the equilibrium of moments around, for example, point A:

$$\Sigma M = 0 \quad \rightarrow \quad M_A - M_C + p \cdot \frac{h^2}{8} - p \cdot \frac{L^2}{4} + p \cdot \frac{L^2}{8} = 0 \tag{4.3}$$

As the structure is hyperstatic of order 1, an additional equation is needed in order to determine all the reactions (M_A and M_C). This equation can be obtained via Castigliano's Theorem. The slope (rotational deflection in elastic beam theory), ϕ, at any point is given by:

$$\phi = \frac{\partial U}{\partial M} \tag{4.4}$$

where U is the total elastic strain energy of the system, which is defined for bending as:

$$U = \int \frac{M^2 \cdot dx}{2 \cdot E \cdot I} \tag{4.5}$$

where E is Young's Modulus and I is the moment of inertia. In the case considered, the slope at point C is equal to zero (in order to satisfy the symmetry boundary condition), thus providing the additional equation needed:

$$\phi_C = \frac{\partial U}{\partial M_C} = 0 \quad \rightarrow \quad \int_0^{L/2} \frac{M_1 \cdot \partial M_1}{\partial M_C} \frac{dx_1}{I_1} + \int_0^{h/2} \frac{M_2 \partial M_2}{\partial M_C} \frac{dx_2}{I_2} = 0 \tag{4.6}$$

where M_1 and M_2 are the bending moments along AB and BC, respectively. Table 4.1 shows the force and moment distributions along sides AB and BC.

Table 4.1: Force and moment distributions along sides AB and BC

AB	$S_{z1} = p \cdot \frac{L}{2}$ $S_{y1} = p \cdot x_1$ $M_1 = M_C - p \cdot \frac{x_1^2}{2}$
BC	$S_{z2} = p \cdot \frac{h}{2}$ $S_{y2} = -p \cdot \frac{L}{2} + p \cdot x_2$ $M_2 = M_C - p \cdot \frac{x_2^2}{2} + p \cdot \frac{L}{2} - p \cdot \frac{h^2}{8}$

By introducing these distributions in equation 4.6, and solving the system with equation 4.3 we obtain:

$$M_A = \frac{p}{12}\left[1.5 \cdot L^2 - h^2 \cdot \left(\frac{1+\alpha^2 \cdot k}{1+k}\right)\right] \tag{4.7}$$

$$M_C = \frac{p \cdot h^2}{12}\left[1.5 - \left(\frac{1+\alpha^2 \cdot k}{1+k}\right)\right] \tag{4.8}$$

$$\text{where} \quad \alpha = \frac{L}{h} \quad ; \quad k = \frac{I_2 \cdot L}{I_1 \cdot h}$$

With the values described in figure 4.1, and bearing in mind that $I_1 = I_2 = t^3/12$, it is possible to compute the values of all the reactions (see table 4.2).

Table 4.2: Reactions in points A and C (notice that all reactions are per unit of depth)

Magnitude	**Value**
T_A [N/m]	22500
T_C [N/m]	45000
M_A [N]	506.25
M_C [N]	-253.125

Once all the reactions have been computed, it is possible to calculate the stress that they generate on the plates. On the one hand, the forces generate a membrane stress, constant throughout the thickness. On the other hand, the moments generate a bending stress which varies linearly throughout the thickness, being zero in the neutral line (see figure 4.5). The membrane and bending stresses are the following:

$$\text{Membrane stress in side A-B:} \quad S_m = p \cdot \frac{h}{2 \cdot t}$$

$$\text{Membrane stress in side B-C:} \quad S_m = p \cdot \frac{L}{2 \cdot t}$$

$$\text{Bending stress in A:} \quad (S_b)_A = \pm M_A \cdot \frac{c}{I_1}$$

$$\text{Bending stress in C:} \quad (S_b)_C = \pm M_C \cdot \frac{c}{I_2}$$

$$\text{where} \quad c = \frac{t}{2} \quad ; \quad I_1 = I_2 = \frac{1}{12} \cdot t^3$$

The values of the reacting forces did not depend on the thickness, but the stresses do. Given that the internal pressure is the most demanding load case, it will drive the thickness value.

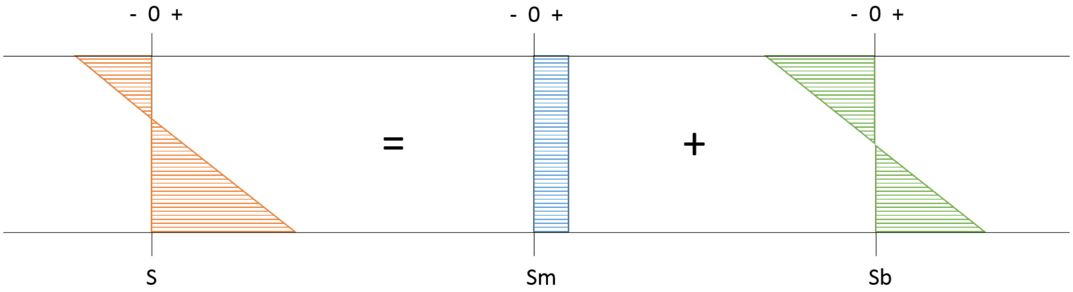


Figure 4.5: Membrane stress plus bending stress equals to total stress along the thickness of a plate

In order to know which thickness will be adequate for the Propellant Tank, figure 4.6 represents the stress versus the thickness of the walls. Two horizontal lines are drawn in the yield stress of Aluminium and the stress limit according to the requirements (that is the yield stress divided by the factor of safety).

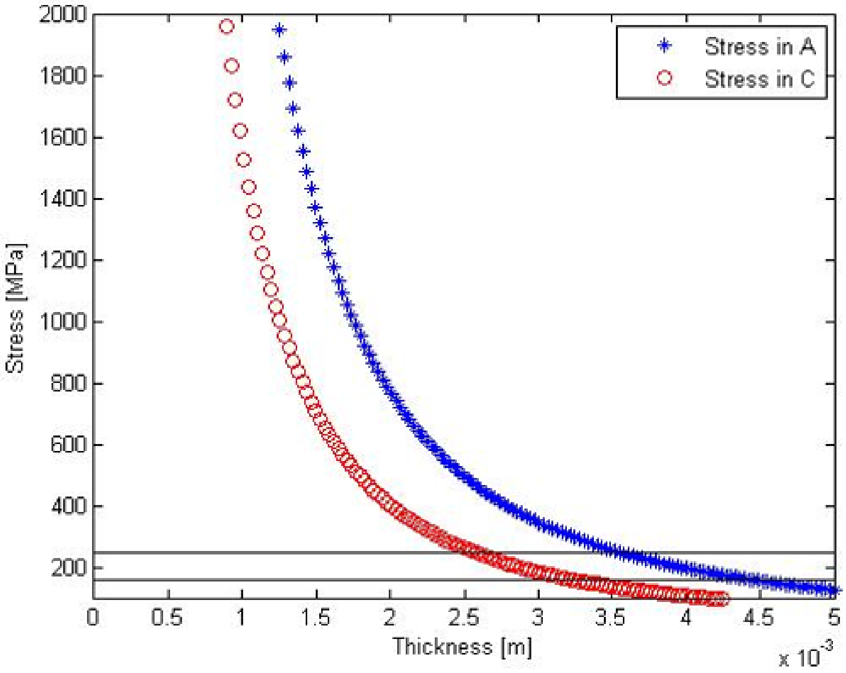
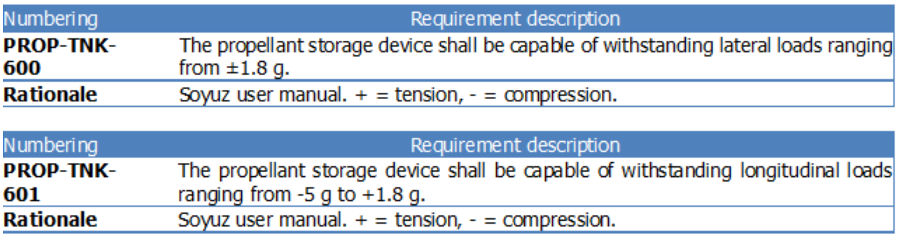


Figure 4.6: Stress versus thickness of the walls

The result is that only a thickness of around 4 mm will be able to stand the stress generated by the 10 bar internal pressure. This value is bigger than expected intuitively when looking at the design. The explanation of this is related with the simplifications of the model. The reinforcements/ stands for the bolts have not been considered, and they will act as stiffeners for the side walls, as their thickness is higher. This is why a higher thickness will be required in the bottom and lid than in the side walls. As a result of this analytical study, it is decided that the Preliminary Design will count with a 4 mm thickness on the lid, 1 mm thickness on the side walls and 2 mm thickness on the bottom of the tank. The expected results are to have stress under the limit or near to the limit on the lid and stress highly over the limit on the bottom. The Finite Element Analysis will verify these assumptions. Given that this is a Preliminary Design and the Finite Element Model still has to be validated, it is possible to use an initial configuration which is expected to fail and see if the Model works correctly.

4.3. G-ACCELERATIONS

The g-accelerations that the tank must be able to stand are stated in the requirements PROP-TNK-600 and PROP-TNK-601, which have been included again in figure 4.7:



Numbering	Requirement description
PROP-TNK-600	The propellant storage device shall be capable of withstanding lateral loads ranging from ±1.8 g.
Rationale	Soyuz user manual. + = tension, - = compression.

Numbering	Requirement description
PROP-TNK-601	The propellant storage device shall be capable of withstanding longitudinal loads ranging from -5 g to +1.8 g.
Rationale	Soyuz user manual. + = tension, - = compression.

Figure 4.7: Requirements on the g-accelerations

The simplest way to analyse a g-acceleration of X g on a structure is to consider that the structure weighs X times its normal weight, which is equivalent to considering a mass X times larger. As the Propulsion System will most likely be attached to the bus via the Propellant Tank, it is coherent to consider the mass of the whole assembly for the g-forces, rather than only the Propellant Tank's mass. This value is extracted from the requirements document [6], and can be seen in table 4.3. Table 4.3 also displays the computed forces.

Table 4.3: Maximum g-accelerations

Mass [kg]	**G-acceleration [m/s^2]**	**Force [N]**
0.459	1.8×g	8.11
	5×g	22.52

The weakest parts of the Propellant Tank are the thin side walls, the bottom and the lid. In order to calculate the stress generated by the forces in those areas, each side is considered a plate with the force applied on the surface of the plate. The formulas from [33] allow to compute the stress generated on a simply supported plate. Figure 4.8 gives an overview of the problem.

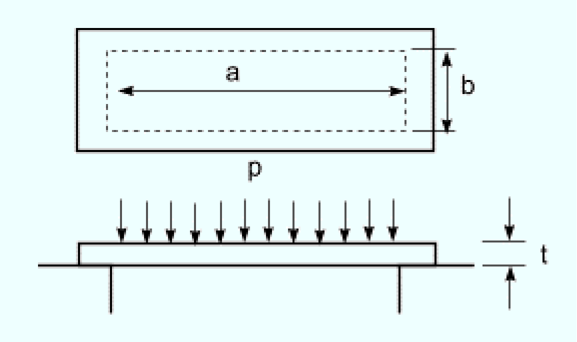


Figure 4.8: Representation of the simplified problem (Source [33])

$$\sigma_m = \frac{0.75 \cdot p \cdot b^2}{t^2 \cdot [1.61 \cdot (b/a)^3 + 1]} \tag{4.9}$$

where p is the force per unit of area (the area is b*a). The stress is represented against the thickness in figure 4.9 for the 0.09x0.09 plates (bottom and lid), as they have no reinforcements. Notice that for both the bottom (2 mm thickness) and the lid (4 mm thickness), the stress is below the megapascal.

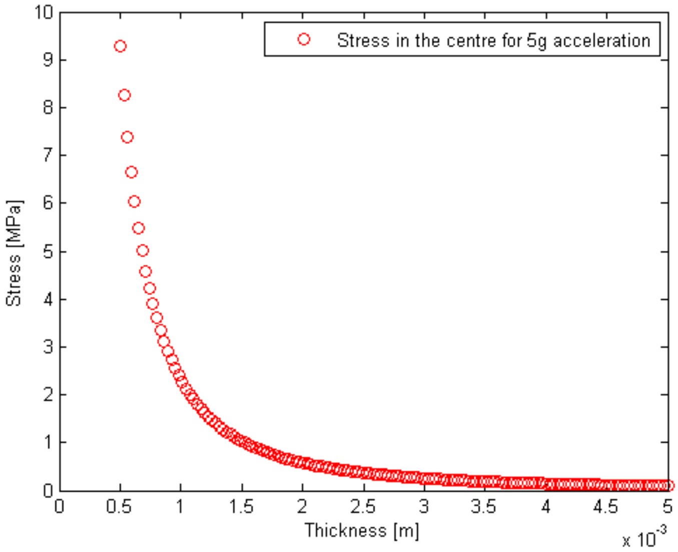


Figure 4.9: Stress versus thickness for g-acceleration forces

Subsequently, the buckling mode of failure is analysed. In order to simplify the problem for the analytical solution, the sides of the tank are considered as thin-walled plates under an in-plane compressive force (resultant of the g-accelerations). The plate is considered to be simply supported (and not clamped) so that the calculations are more conservative, as it was done in the first calculations of this section.

Reference [9] is followed in order to calculate the critical stress for plate buckling. Figure 4.10 illustrates the problem. The critical load, N_{cr} is the minimum compressive load under which the plate buckles (it is per unit of length). In this way, the critical stress, σ_{cr}, is the critical load divided by the thickness. The parameters k and m are obtained based on the ratio a/b, and can be obtained from figure 4.11. The value m is an integer which represents the mode of buckling which is more energetically favourable for the a/b ratio. In the case of the plates of the tank, the mode is sometimes the first and sometimes the second. The second mode of failure results in a higher critical load.

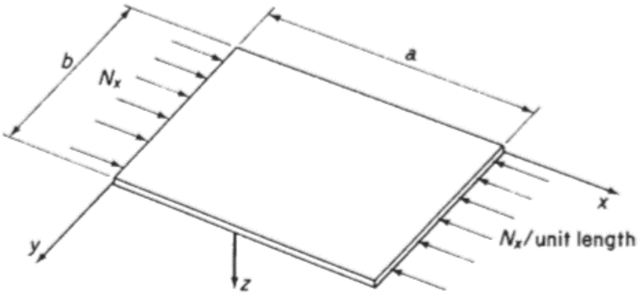


Figure 4.10: Illustration of the plate buckling problem (Source [9]

$$N_{cr} = \frac{k \cdot \pi^2 \cdot D}{b^2} \tag{4.10}$$

$$\sigma_{cr} = \frac{N_{cr}}{t} = \frac{k \cdot \pi^2 \cdot E}{12 \cdot (1 - \upsilon^2)} \cdot \left(\frac{t}{b}\right)^2 \tag{4.11}$$

$$k = \left(\frac{m}{a/b} + n^2 \cdot \frac{a/b}{m}\right)^2 \tag{4.12}$$

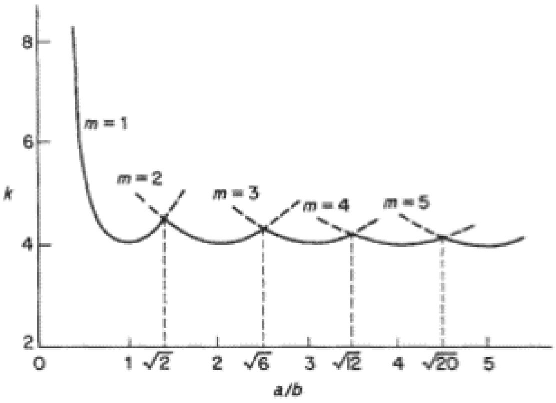


Figure 4.11: Values of m and k for each a/b ratio for the plate buckling under compressive force (Source [9])

Table 4.4: Buckling coefficient and critical stress

	Side Plate	**Lid/bottom Plate**	**Side Plate**
Maximum g-acceleration a [m/s^2]	-5×g	-5×g	-5×g
G-force [N]	-32.33	-32.33	-32.33
a	L	L	h
b	h	L	L
a/b	2	1	0.5
k	4	4	6
σ_{cr} [MPa]	127.6	31.9	47.85

Given that the stresses calculated in the beginning of this section did not surpass the megapascal, it is unlikely that the buckling will be achieved as a cause of g-accelerations, as the critical stress is always over 30 megapascals. Although this load case seems of little interest, it will be analysed via Finite Element Methods in order to verify these calculations as well as analyse the stress on the lips that connect the tank to the bus structure, which are not considered in the simplified modelled analysed here.

4.4. LOADS ON BOLTED JOINTS

In the Internal Pressure load case, the Propellant Tank was considered a hollow box. In reality, it is made up of a box and a lid, which are joined by bolts. In order to know the size and quantity of bolts required to secure the lid to the tank, a brief study can be done.

Considering only the longitudinal loads on the bolts (the loads that are normal to the circular cross section), the resultant force of the pressure on the lid, $p \cdot A_{lid}$, shall be equal to the stress on each bolt times the area of its cross section, $\sigma_b \times A_b \times n_b$. Operating with this equivalence of forces, the results in table 4.5 are computed.

$$\begin{cases} A_b = \pi \cdot R_b^2 \\ A_{lid} = L^2 \\ \sigma_b \cdot A_b \cdot n_b = p \cdot A_{lid} \end{cases} \quad \rightarrow \quad \sigma_b = \frac{2578.31}{R_b^2 \cdot n_b}$$

Table 4.6 shows different options of bolts and the load they can withstand. From this table and the results on the previous one, it is possible to conclude that 10 bolts M2 of grade 8.8 would be sufficient to withstand the stress generated by the internal pressure (412.5 MPa would be the limit stress and 258 MPa would be the maximum stress encountered).

Another point to take into account for the design is that the 10 bolts are considered to be equally separated from the center of the plate, in which the resultant of the pressure is applied. The bolts that are closer to this point or the bolts that have a longer distance between them are expected to suffer higher stress. Notice

Table 4.5: Stress per bolt with different total number and metric

Number of bolts	M2	M3	M4
1 bolt	σ_b= 2580 [MPa]	1150 [MPa]	645 [MPa]
5 bolts	516 [MPa]	229 [MPa]	129 [MPa]
10 bolts	258 [MPa]	115 [MPa]	65 [MPa]

Table 4.6: Tensile strength of different stainless steel bolts

Steel [34]	Grade	Yield Strength [MPa]	With 1.6 FoS [MPa]	Ultimate Strength[MPa]	With 2 FoS [MPa]
A307A	4.6	240	150	400	200
A449	8.8	660	412.5	830	415
A574	12.9	1100	687.5	1220	610

also that placing the bolts is equal to placing the stiffeners on the walls of the tank. This is why the bolt distribution in the Preliminary Design focused on having the bolts as equally separated from the center of the lid as possible, and maintaining the distance between bolts constant. However, the irregular interior shape calls for bolts on the corners, in order to secure the leakage. With these requirements in mind, the intention was to create a balance. Figure 4.12 shows the ideal distribution for combining similar distance to the center with bolts on the corners (image on the left), but the span or distance between some of the bolts is too large. It also shows the configuration chosen for the Preliminary Design (image on the right).

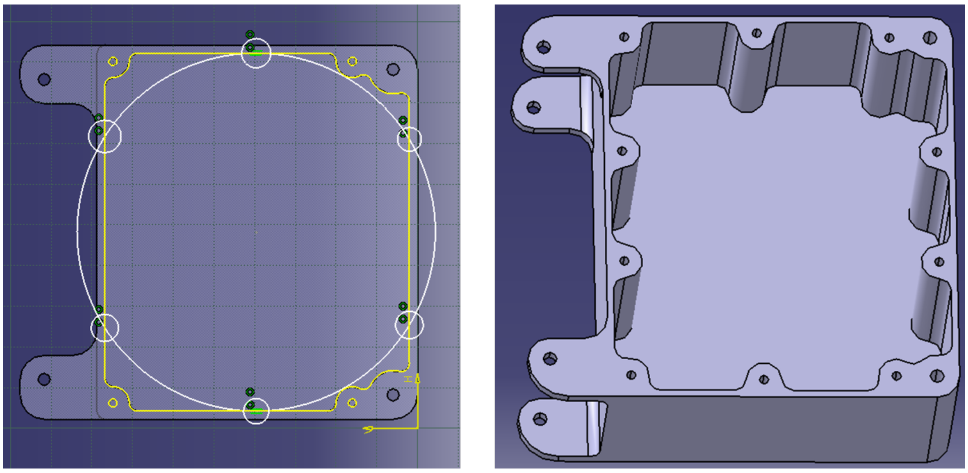


Figure 4.12: Concept Design for bolt distribution on the left and Preliminary Design on the right

4.5. VIBRATIONS AND NATURAL FREQUENCIES

Even though this load case in of high interest to the design of the propellant tank, it will not be addressed in this Thesis, as it falls out of the scope. However, a small analysis of the Natural Frequencies will be carried out with the help of Finite Element Methods in the following chapter.

The vibrations load case is to be considered during the testing campaign of the Propulsion System, where the complete assembly can be analysed together.

5

FINITE ELEMENT ANALYSIS OF THE PROPELLANT TANK

5.1. APPROACH

The objective of this analysis is to understand the influence of different parameters of the design (thickness of walls, configuration of stiffeners etc.) in order to transform the Preliminary Design into a Detail Design to which the load cases will not pose a threat. This analysis will be carried out with the commercial software Abaqus, under the license of TU Delft.

Finite Element Analysis (FEA) is a numerical technique originally developed for solving solid mechanics problems, and it can be applied to boundary conditions problems. It reaches an approximate solution applying integration via numerical methods to solve the systems of partial differential equations that appear in different areas of physics [27]. In order to do so, the method is based on discretizing the solid, dividing it into elements and nodes. Using a simple function to approximate the displacement in each element, it is possible to formulate a set of linear equations with displacements at each node as unknowns. Solving this linear equations gives an approximation of the result, always on the rigid side (if the convergence of the mesh is guaranteed). A conceptual understanding of the Finite Element Analysis is taken for granted, and its explanation is out of the scope of this thesis. However, some important concepts will be explained as they appear on the chapter.

This approach section will focus on describing the practical process followed in order to obtain a Detail Design, rather than on the theory behind it. The starting point is a Preliminary Design, with some dimensions chosen as the result of simple calculations or mere estimations. The parametrisation of these dimensions (i.e. being able to change the design by modifying parameters) is key to the success of this process, as an iterative method is to be followed. The iterations consist in varying the parameters until a convenient set is obtained. Given the small number of parameters, as well as the straight forward relationship between them and the structural performance, there is no need for a numerical optimisation process. It is decided to understand the exact influence of each parameter on the structural response and then modify them until the performance is the desired.

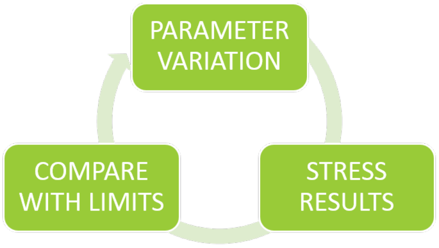


Figure 5.1: Iterative Process

The desired performance is fulfilling the requirements on the structural response of the Propellant Tank to the load cases it shall encounter during its lifetime. Requirements PROP-TNK-500 and PROP-TNK-501 state that the factors of safety on yield load and ultimate load shall be 1.6 and 2 respectively. The interpretation of this is that the stress on the Propellant Tank shall be below both the ultimate strength and the yield strength, divided by their respective factors of safety. Table 5.1 shows a summary of the values to take into account (it is obvious that the most restrictive value will be taken as baseline).

Table 5.1: Maximum allowable stress on the Propellant Tank

Stress	**[MPa]**
Yield Tensile Strength [14]	276
Ultimate Tensile Strength [14]	310
Maximum Allowable Stress (as of req. PROP-TNK-500)	$\sigma_y/1.6 = 172.5$
Maximum Allowable Stress (as of req. PROP-TNK-501)	$\sigma_u/2 = 155$

This stress level is defined as a general value, but there are several ways of computing it. Abaqus provides various of the most used ones. Although they do not differ much from one another, it has been decided to use the Von Mises stress as the baseline, in order to assure consistency. This stress is computed as follows [28]:

$$\sigma_{VM} = \sqrt{\frac{1}{2}\cdot[(\sigma_{xx}-\sigma_{yy})^2+(\sigma_{yy}-\sigma_{zz})^2+(\sigma_{zz}-\sigma_{xx})^2]+3\cdot(\tau_{xy}^2+\tau_{yz}^2+\tau_{zx}^2)} \tag{5.1}$$

The parameters yet to be set are the following ones:

- Thickness of the walls, bottom and lid (tt, tb and tl are the abbreviations)
- Size of the reinforcements/ stands for the bolts (to be called stiffeners from here onwards) (thickness is tst and width is wst)
- Location of the connection ports of the Lid
- Thickness of the lips that connect to the bus bars ($tlip$)
- Metric of the bolts

As a small comment on the above, the location of the connection ports of the lid, which are basically holes to allow sensing, fill and drain, have not yet been fully defined at the date of the analysis. This is why the Detail Design will only include guidelines on how to locate the connections without damaging the structural response of the Propellant Tank.

5.2. MODELLING THE PROPELLANT TANK

Given the iterative approach used to find the correct design of the Propellant Tank, it is crucial to perform the simulations effectively. When it comes to modelling the assembly, simplifications should be made. These will enable the parametrisation of the model (being able to change the design by modifying numerical parameters instead of rebuilding the assembly), which has a great impact on the time it takes to alter the design. More configurations can be tried, and the iterative approach is achieved. However, the parametrisation of a complex assembly such as the Propellant Tank is not an easy task. This is why simplifications have to be done on the model.

Simplification is the basis of FEA modelling, and as long as the assumptions are the correct ones, the results will be representative of the real problem. In our case, the obvious simplification to be done is using Shell elements for the thin-walled parts of the assembly (namely the sides, lid and bottom of the Propellant Tank). These elements allow to represent thin 3 dimensional elements as surfaces with an assigned thickness. This thickness is entered as a value, and is not computed as a thickness per se, but as change in the stiffness of the Shell elements. This approach is straight-forward and widely used in thin-walled problems, characteristic of the aerospace domain.

Once that the walls, lid an bottom have been simplified, the stiffeners can be modelled. These are not thin-walled elements (such elements have two dimensions at least one order of magnitude larger than the other dimension, which is normally the thickness). In order to model them correctly, three possible solutions were considered:

- Leave them as 3-dimensional elements (which increases the use of nodes and the complexity of the model, but gives a better result on the stress distributions)
- Model them as beams with Beam elements (simplification)
- Consider them as changes in the thickness of the Shell walls (simplification)

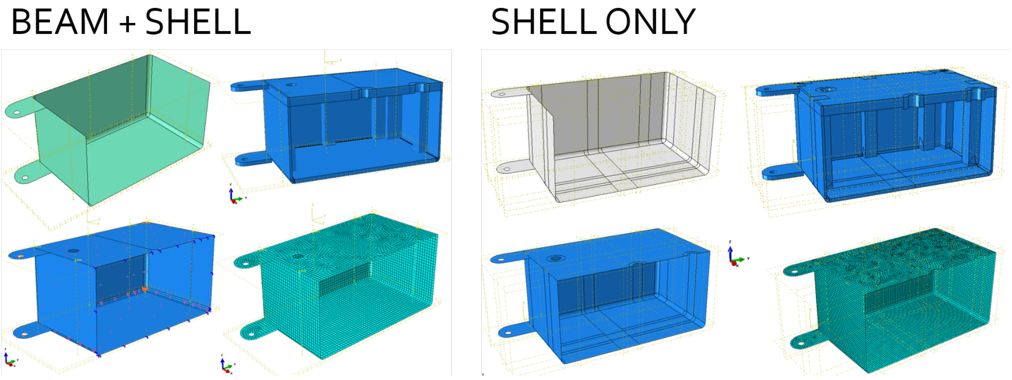


Figure 5.2: Beam + Shell Model and Shell Only Model

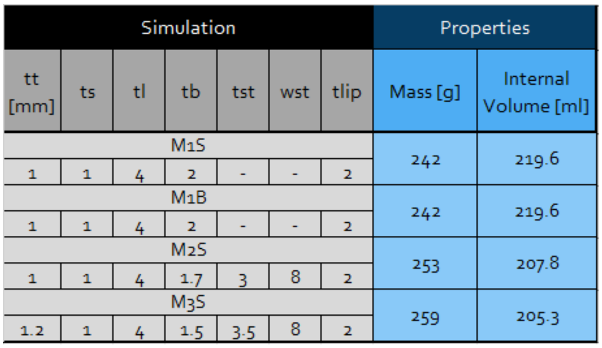
The first option would be necessary if the exact response of the stiffeners to the loads was required. However, the stress levels are the only concern, and they can be accurately computed with the other two methods, which turn out to be easier to modify as well as requiring less nodes. In consequence, the two last methods are used to model the stiffeners in the Propellant Tank. Figure 5.2 shows the two different resulting models (called Shell Only Model and Beam + Shell Model from here onwards). The Beam elements consist in a 3-dimensional curve with an assigned cross-section. Similarly to the Shell elements, this section is used to compute the stiffness, but not considered as a cross-section per se. Both the Shell and Beam elements are easy to mesh.

After defining the elements that will make up each model, the interactions have to be defined. Given the complexity of bolt analysis with Finite Element Models (which could be a thesis topic by itself), the bolted joints also have to be simplified. This is achieved by modelling each bolt as a Tie Constraint. A Tie Constraint (in Abaqus) is to join certain nodal areas together, so that they will not separate one from the other during the application of the loads. These constraints may generate stress concentration problems on the corners, but each case should be interpreted separately. In the case of the Propellant Tank, each bolt is replaced by a Tie Constraint along the edges of the lid and the tank, with a length equivalent to the diameter of the bolt. The Beams are also joined to the tank walls with Tie Constraints. Finally, to join the tank to the bus structure, the points on which the tank interfaces with the bars are considered clamped (this is applied as a boundary condition). Notice also that the boundary condition of symmetry along the X axis has to be applied in the section of the plane of symmetry.

Even though the simplifications are realistic and will make the iterative design process easier, the results will only be valid to a certain extent. The limitations of each model will be analysed together with the results, although the anticipated errors are unrealistic displacements/ deformations and stress concentrations. The latter error is a limitation inherent to the FEA resolution methods. The location of sharp edges and 90º corners generate a singularity in the stress, which grows to infinite. As infinite cannot be represented by the computer, the stress becomes as high as the mesh allows it. This means that refining the mesh will result in an increase of stress in that point without ever approximating an asymptote. This does not occur in the real world, as infinite stress cannot be reached. Identifying this error is key to the interpretation of the results, as well as the validity of the model.

5.3. ANALYSIS OF THE PRELIMINARY DESIGN

The starting point is analysing the Preliminary Design. Based on it structural response, the parameters will be modified to improve it. Figure 5.3 shows the general parameters of the Preliminary Design. These are called by their abbreviations (already named in the Approach section). However, an additional parameter is included. The thickness of the wall with one stiffener is tt, whilst the thickness of the wall with two stiffeners (only one models due to the symmetry) is ts. Moreover, the Shell Only Model is abbreviated as MxS, and the Beam + Shell Model, MxB, where x is the number of the model generated.



Simulation							Properties	
tt [mm]	ts	tl	tb	tst	wst	tlip	Mass [g]	Internal Volume [ml]
M1S							242	219.6
1	1	4	2	-	-	2		
M1B							242	219.6
1	1	4	2	-	-	2		
M2S							253	207.8
1	1	4	1.7	3	8	2		
M3S							259	205.3
1.2	1	4	1.5	3.5	8	2		

Figure 5.3: Parameters, mass and internal volume of the 2 models for the Preliminary Design

The size of the mesh used for these first analyses is 1.5 mm. It is sufficient to obtain convergence and refining the mesh does not alter the results (without taking into account the singularities, which will be explained throughout the different subsections).

5.3.1. INTERNAL PRESSURE

Once the two models have been generated, they load cases are applied. As a result of the analytical study, the Internal Pressure load case is known to be the most demanding for the Propellant Tank. This will be the first analysed one, being applied to both models. The load case consists in a 10 bar internal pressure, which is easily modelled in Abaqus as a Pressure Load.

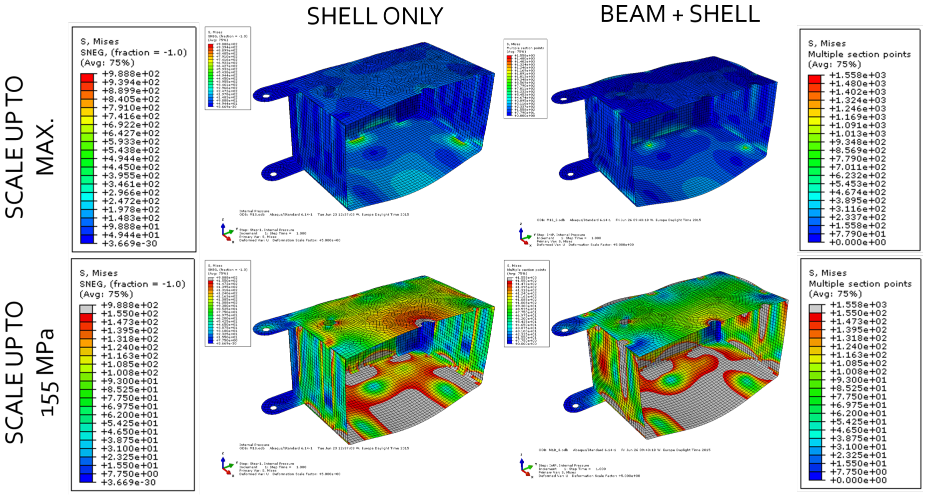


Figure 5.4: 3D View of the Propellant Tank Assembly under Internal Pressure

Figures 5.4, 5.5 and 5.6 show the complete assembly, the tank and the lid results for the internal pressure load case, respectively. All figures represent the Von Mises Stress (see equation 5.1) in the color scheme and the Displacement (multiplied by a factor of 5) as the deformed contour of the model. The figures show the stress until the maximum reached on the top images and the stress until the maximum load that the Propellant Tank should stand on the bottom images. In these latter images, the areas in grey have higher stress than the requirements state, and have thus to be redesigned.

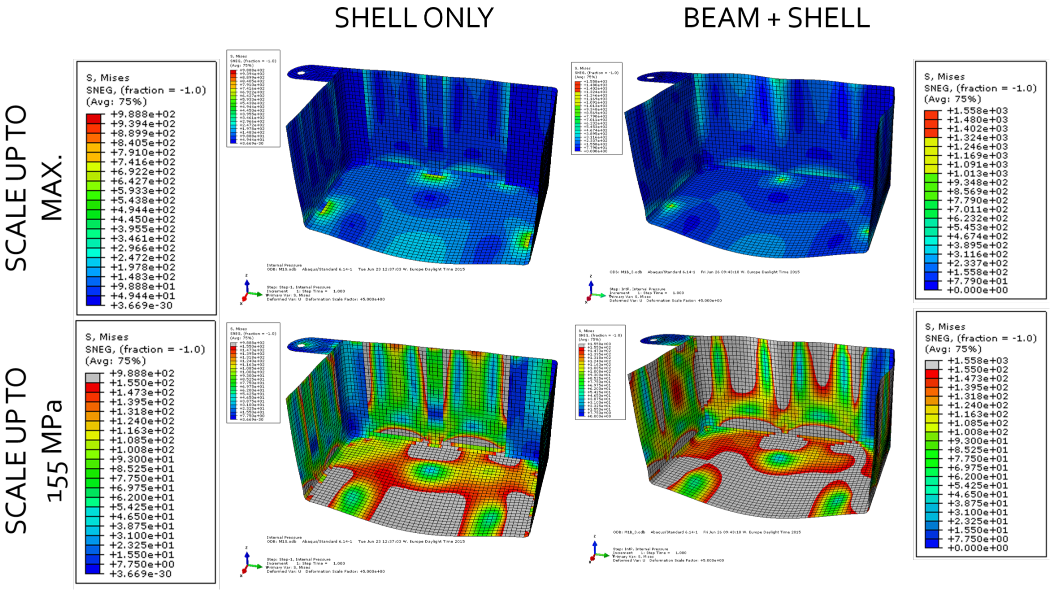


Figure 5.5: 3D View of the Tank under Internal Pressure

Already in the first figures it is possible to notice differences between the results of each model. These differences are: the maximum stress on the overall assembly, the stress distribution on the lid, the stress distribution on the bottom of the tank, the stress distribution on the sides of the tank and the deformed contour of the tank (notice the bottom an walls).

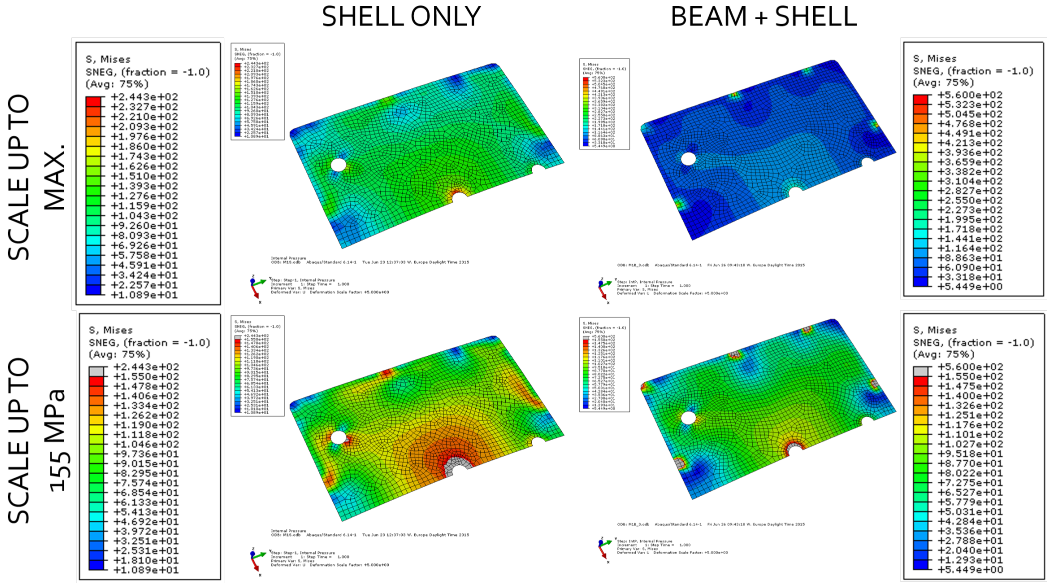
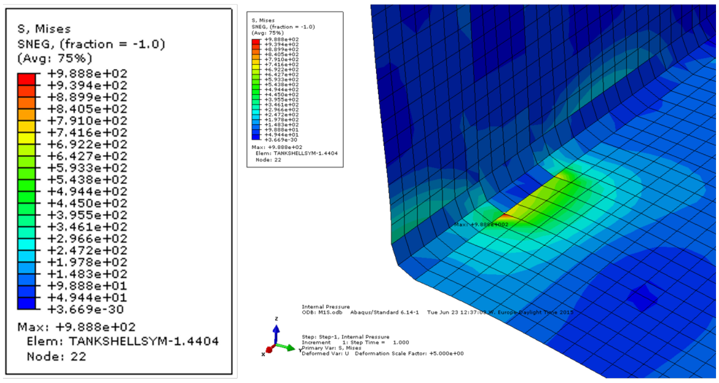


Figure 5.6: 3D View of the Lid under Internal Pressure

On the one hand, the Beam elements are simply lines attached to the tank's wall. Although their cross section is equivalent to the real stiffeners, Abaqus uses this information only to compute the stiffness, and does not take into account the actual cross section. This means that the stiffeners are reduced to a single line with the equivalent stiffness. In this way, the length of thin wall is increased, and suffers a larger deformation. On the other hand, the other model considers the actual width of the stiffener, as the area with an increased thickness is similar to the area occupied by the stiffener in the real case. This results in a more realistic deformation as well as stress level, explaining the stress difference in the walls, lid and bottom (the Beam + Shell model has lower stiffness and results in higher stress level over the assembly).

Even if the analytical study estimated that the thickness required for the walls would be around 4 mm, the stiffeners manage to reduce this value significantly. However, the results obtained are consistent with the analytical study, as the lid appears to be sufficiently stiff with 4 mm (as anticipated by the study), whilst the bottom of the tank has an unacceptably high stress level (over 155 MPa) with the 2 mm thickness (as expected after the study results).

SHELL ONLY



BEAM + SHELL

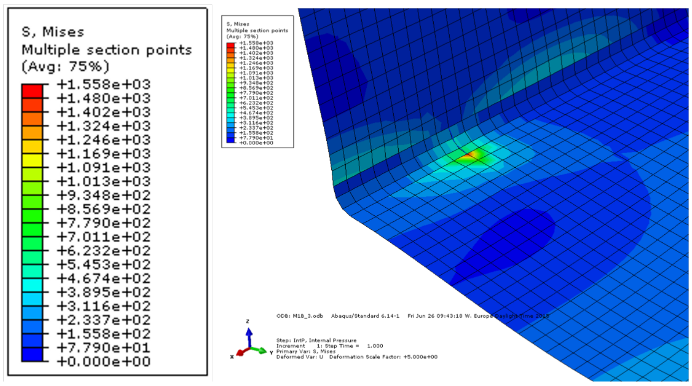


Figure 5.7: Detail View of the Propellant Tank Assembly under Internal Pressure

The different maximum stress on both models is not a problem, due to the fact that this stress level is caused by a stress concentration. Stress concentrations appear in both models. The Shell Only Model has stress concentration on each change of thickness (this is why it is possible to tell where the stiffeners are). Looking at the design, it is obvious that this stress concentration will not appear in the real case, as the change of thickness is made progressively via a radius on the corner. Stress concentrations along lines are less influential than stress concentrations on single points. The Beam elements, for example, do not generate stress concentrations along their length, but they may cause stress concentrations on their starting and ending points. Figure 5.7 gives a detailed view of the stress concentrations generated on each model.

5.3.2. G-accelerations

It was anticipated to be an undemanding load case, although the thickness of the lips to join the tank to the structure could suffer bending loads. These were not considered in the analytical study, so performing the simulation helps to verify the lack of danger that this load case poses to the Propellant Tank. Figures 5.8, 5.9 and 5.10 represent the Von Mises stress caused by the maximum possible acceleration (5 g) along the X, Y and Z axes, respectively. These simulations were only performed on the Shell Only Model because of its more realistic response.

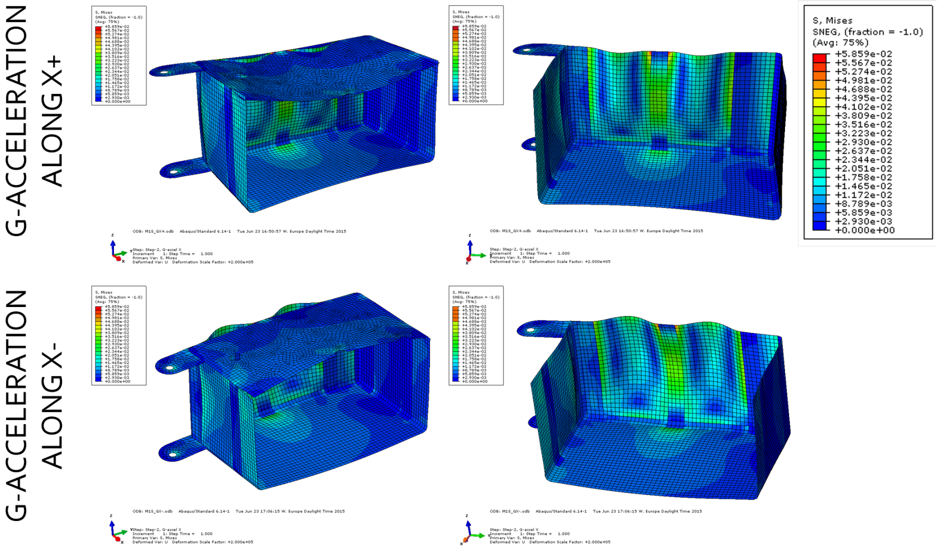


Figure 5.8: G-acceleration along X axis

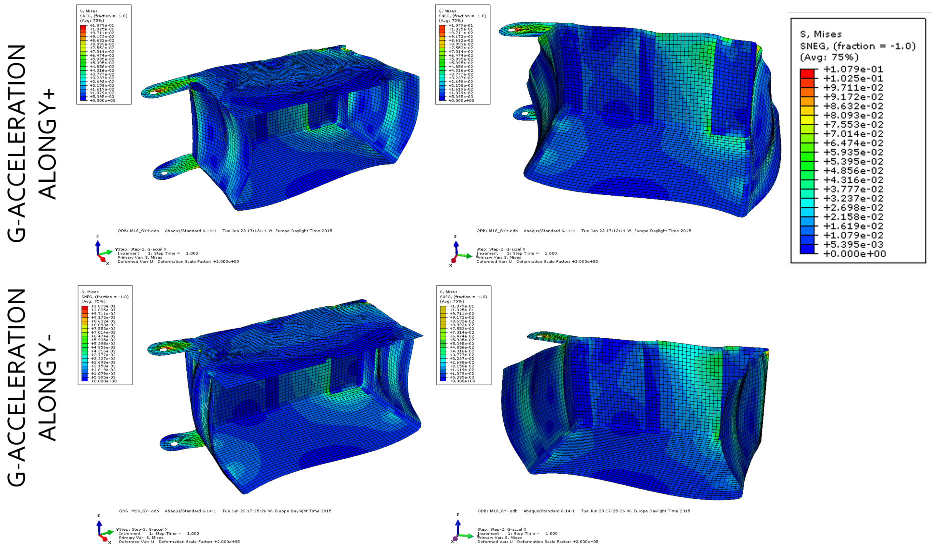


Figure 5.9: G-acceleration along Y axis

The load is simulated with the Gravity Load option in Abaqus. This function allows to enter the value of the acceleration and its direction. Abaqus then multiplies it by the density and the volume of the assembly (it also accounts for the symmetrical side). Given the fact that the mass considered for these accelerations is the mass of the whole Propulsion System, the load introduced is not 5 g, but the necessary load to account for the mass difference.

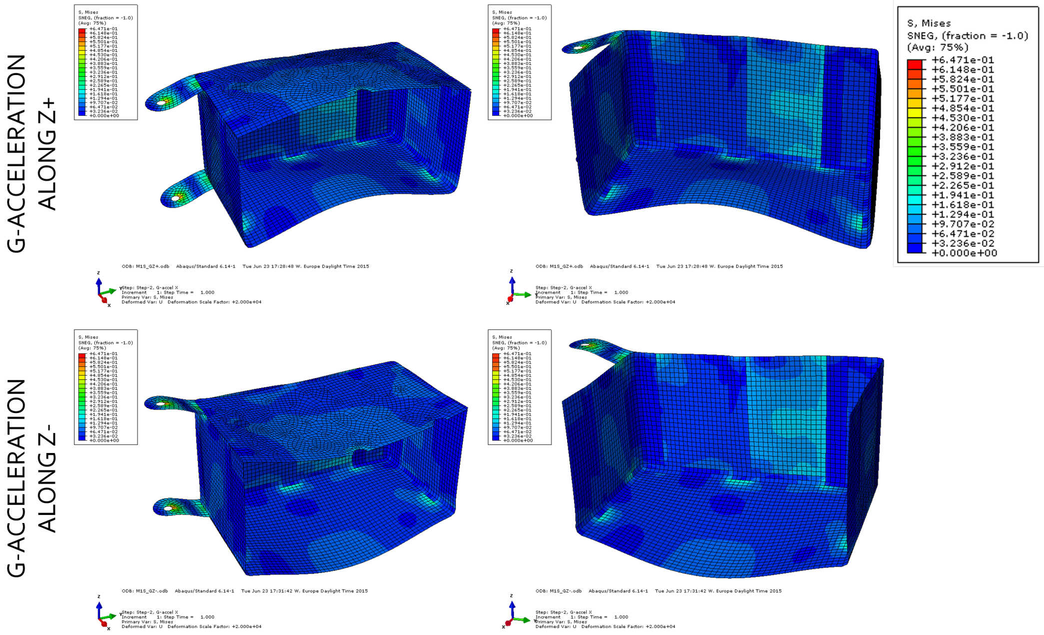
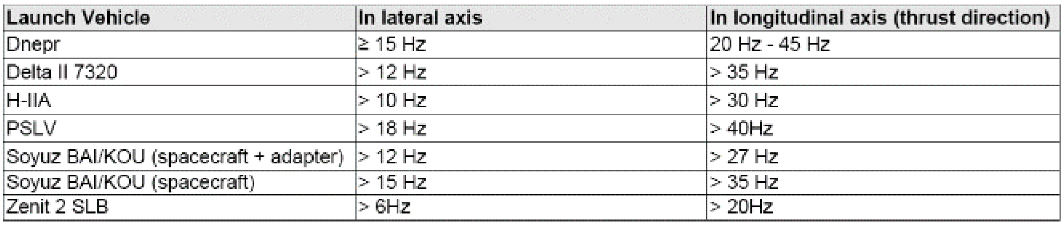


Figure 5.10: G-acceleration along Z axis

As it can be seen in the figures, the stress levels are always below the megapascal, which is in line with the analyses performed on the previous chapter. It was also well anticipated that stress could appear in the lips. Comparing with the analytical study, the loads that appear are in the same order of magnitude.

5.3.3. VIBRATION MODES

It has already been explained that the vibration analysis is out of the scope of this Thesis, and will be assessed via testing. Even though, the vibration modes and natural frequencies of the model can be easily obtained with Abaqus, making use of its eigenvalue solver. Although there is no requirement on the natural frequency of the assembly, it is always analysed that its value is below the nominal range of frequencies of the rocket launcher. These values are presented in figure 5.11.



Launch Vehicle	In lateral axis	In longitudinal axis (thrust direction)
Dnepr	≥ 15 Hz	20 Hz - 45 Hz
Delta II 7320	> 12 Hz	> 35 Hz
H-IIA	> 10 Hz	> 30 Hz
PSLV	> 18 Hz	> 40Hz
Soyuz BAI/KOU (spacecraft + adapter)	> 12 Hz	> 27 Hz
Soyuz BAI/KOU (spacecraft)	> 15 Hz	> 35 Hz
Zenit 2 SLB	> 6Hz	> 20Hz

Figure 5.11: Requirements on natural frequencies for the payload on different launcher vehicles (Source [29])

Figures 5.12 and 5.13 represent the vibration modes and the natural frequencies of the assembly.

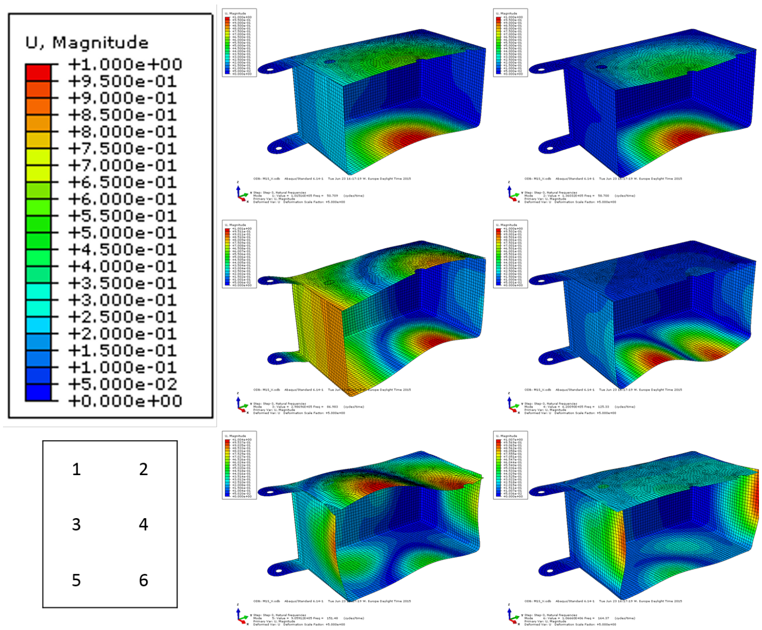
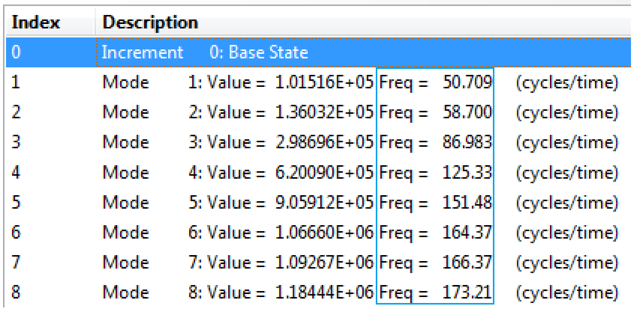


Figure 5.12: Vibration Modes 1 to 6

Notice that in this figure both the color scheme and the deformed contour represent the displacement. The lowest natural frequency is over 50 Hz, while the greatest frequency excited by the launchers is 40 Hz (see figure 5.11). This means that, as a first estimate, the design will not enter resonance with the launcher. However, attaching the thruster or the propellant sloshing can alter the natural frequencies of the assembly. In this way, it is advisable to carry out a vibrations test with the whole assembly.



Index	Description
0	Increment 0: Base State
1	Mode 1: Value = 1.01516E+05 Freq = 50.709 (cycles/time)
2	Mode 2: Value = 1.36032E+05 Freq = 58.700 (cycles/time)
3	Mode 3: Value = 2.98696E+05 Freq = 86.983 (cycles/time)
4	Mode 4: Value = 6.20090E+05 Freq = 125.33 (cycles/time)
5	Mode 5: Value = 9.05912E+05 Freq = 151.48 (cycles/time)
6	Mode 6: Value = 1.06660E+06 Freq = 164.37 (cycles/time)
7	Mode 7: Value = 1.09267E+06 Freq = 166.37 (cycles/time)
8	Mode 8: Value = 1.18444E+06 Freq = 173.21 (cycles/time)

Figure 5.13: Natural Frequencies 1 to 8

5.4. VARIATION OF THE PARAMETERS

The high stress levels obtained in the bottom of the tank call for more than an increase of the thickness. The use of stiffeners is undeniably a strong and reliable solution, as proved in the sides of the tank. The straight forward solution is then to extend the stiffeners through the bottom of the tank. The stiffeners in the corners will not be extended, as the stress close to those points is relatively low (as we will see in this section). Figure 5.14 shows the addition of these stiffeners both to the CAD design and to the Abaqus models.

The changes in the parameters are summed up in figure 5.3, which appeared before in the chapter (the model considered in this section is *M2S*). The initial stiffeners have a thickness (Z direction) of 3 mm and a width of 8 mm. There is a mass increase as well as a reduction of the internal volume. This is why the thickness of the bottom is reduced from 2 mm to 1.7 mm (having the stiffeners, the thin-walled bottom of the tank will be less loaded, requiring a smaller thickness). These changes can be seen in the Appendix C.

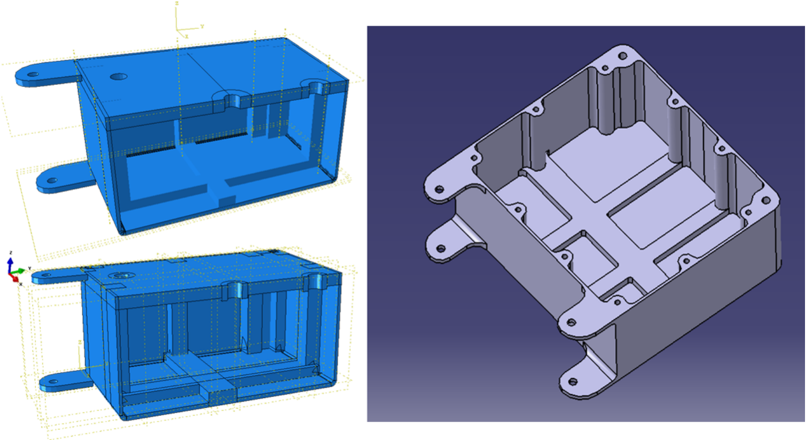


Figure 5.14: Tank with bottom stiffeners (Right), Beam + Shell Model (Left Up) and Shell Only Model (Left Down)

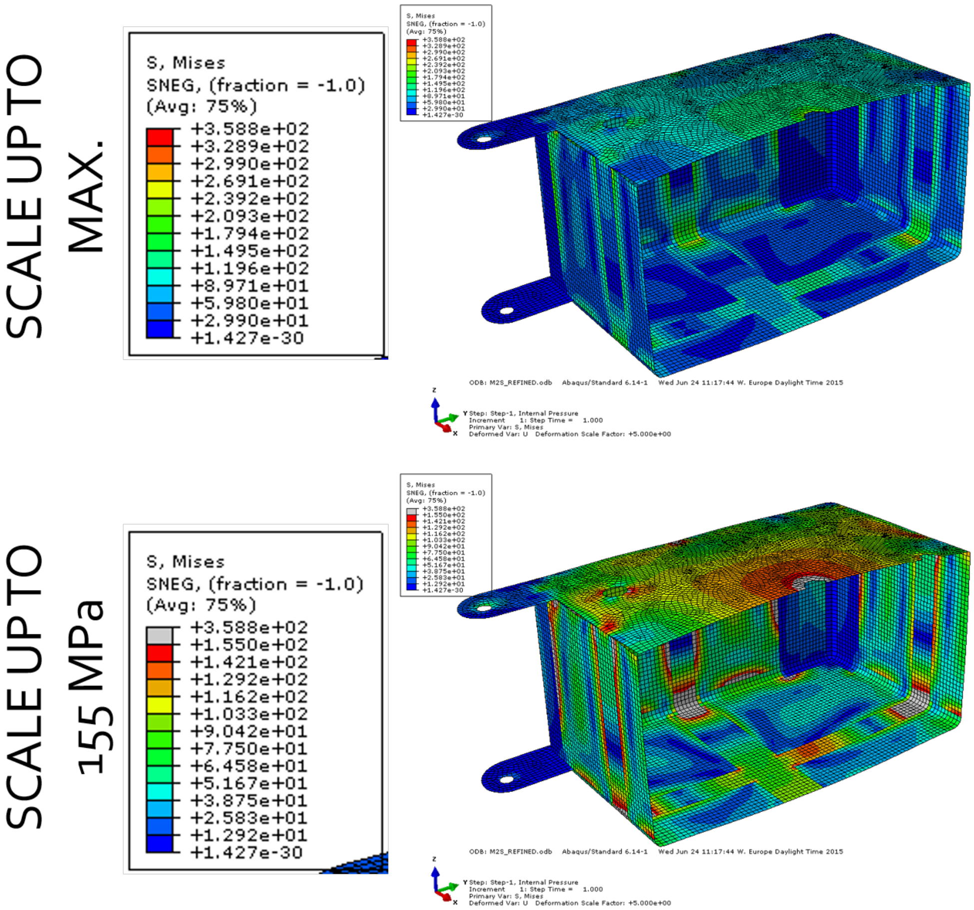


Figure 5.15: 3D View of the Propellant Tank Assembly under Internal Pressure

As it was explained previously in this chapter, the Shell and Beam elements do not compute the thickness and cross-section as it is seen on figure 5.14, but only as a change in the stiffness. Figures 5.15, 5.16 and 5.17 show the results of the addition of stiffeners to the Shell Only Model (the Beam + Shell Model will only be used again when the final values of the parameters are determined, as the accuracy of this model is worse than the Shell Only one).

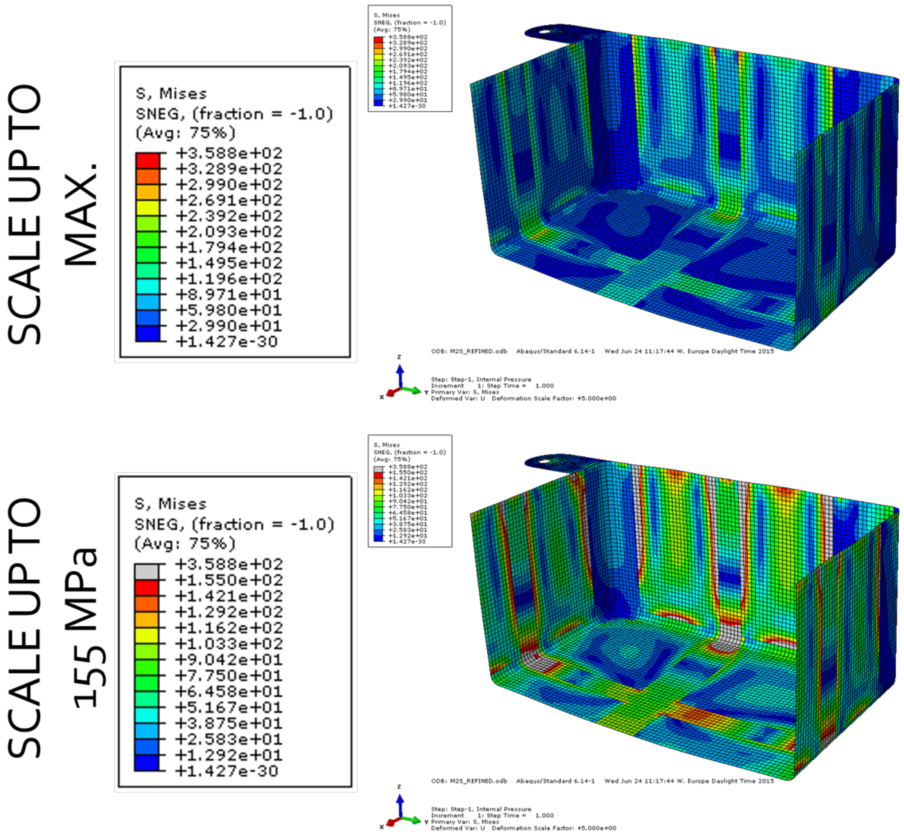


Figure 5.16: 3D View of the Tank under Internal Pressure

Now the stress in the vast majority of the bottom of the Tank is below the limit of 155 MPa. The stress on the walls and lid does not change excessively. On the one hand, the thin-walled bottom of the tank is certainly unloaded now, which means that the thickness can still be reduced. The stiffeners, on the other hand, are severely loaded in the point of coincidence with the lateral stiffeners. This point could be a stress concentration point caused by the change of thickness from the horizontal stiffener to the vertical stiffener. In order to fully understand the behaviour of the structure in this points, figure 5.18 is included.

The colour scale of the models in figure 5.18 is not enlarged because it is not necessary for understanding the concept of stress concentration due to a change in the thickness. The figure shows images on the right, which correspond to detail views of M2S, which includes abrupt changes in the thickness of the shells. The images on the left are generated by making the thickness equivalent, causing the stress concentration to disappear. The top images focus on the line of interface of the stiffeners. This line is visible in the left image, due to the change in thickness and the stress concentration it entails. However, it is not visible in the image on the right, where the thickness was modified so that there is no abrupt change. On the images on the bottom, the focus in on the interface of the side walls and the bottom wall. It is the same situation as with the stiffeners.

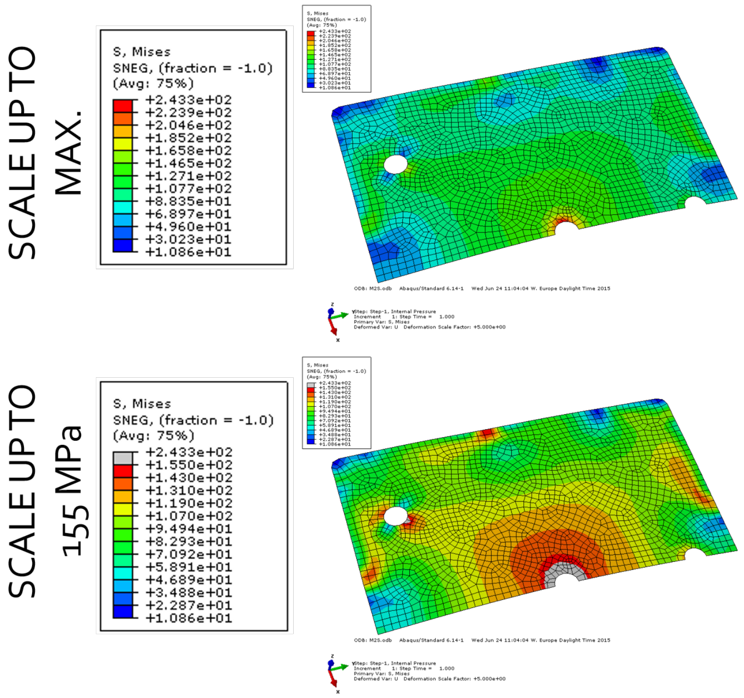


Figure 5.17: 3D View of the Lid under Internal Pressure

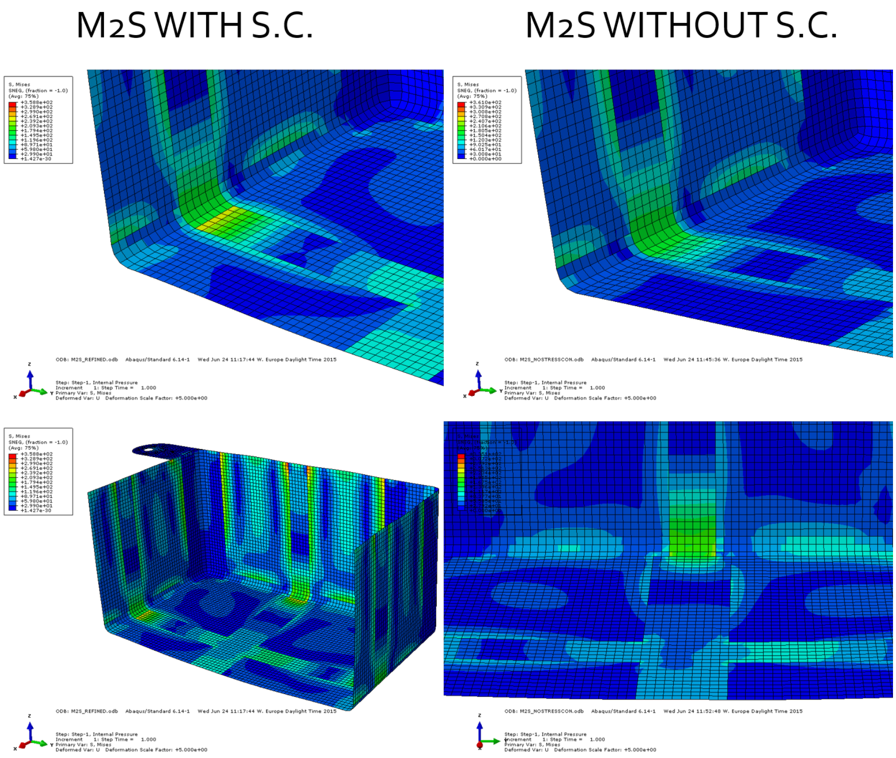
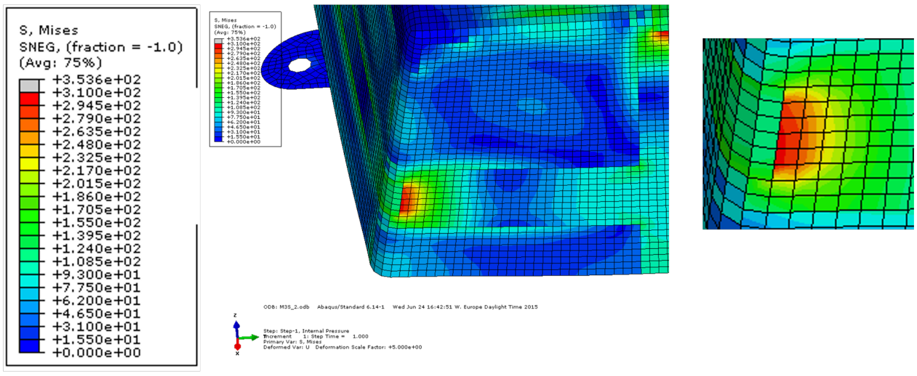


Figure 5.18: Detail View of the Stress Concentration

The stress concentration that appears in the model will not appear in reality, as the changes of thickness are always done with a radius and not abruptly. Understanding this is crucial for the interpretation of results, as the design should not take into account the stress generated on these situations. However, although the stress is not as high as the program indicates, it may still higher than the limit. This is why it is necessary to determine the exact points in which the stress concentration appears. In order to do so, the best approach is to make the mesh thinner and see the points in which the stress grows. Figures 5.19 and 5.20 are used to determine the area affected by stress concentration in the interfaces of vertical stiffener - horizontal stiffener and side wall - stiffener, respectively.

NORMAL MESH



REFINED MESH

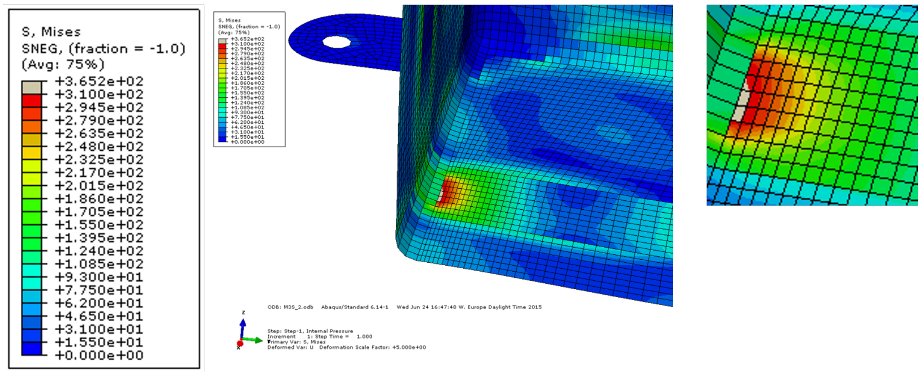
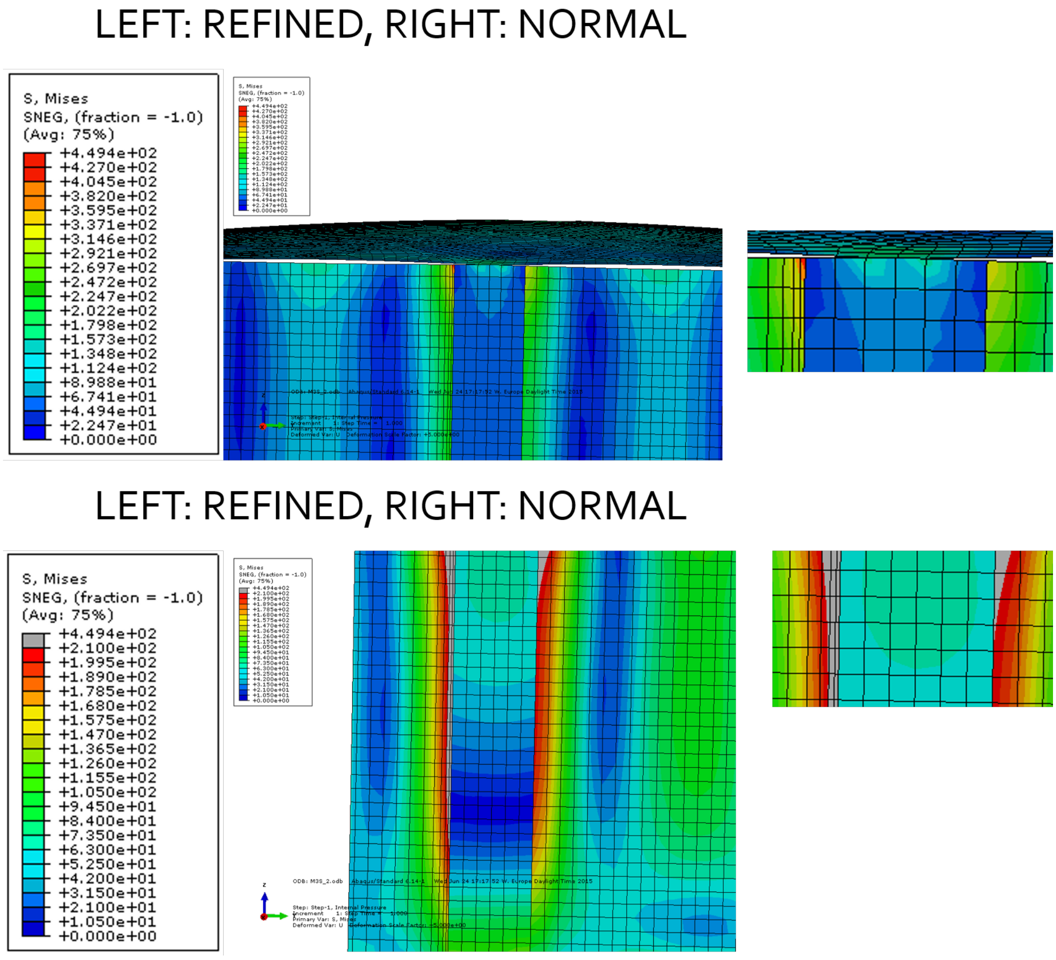


Figure 5.19: Detail View of the Stress Concentration

In figure 5.19 it is possible to see how refining the mesh increases the stress on the stress concentration area. The top image shows the stress for 310 MPa as limit, and it is possible to see that all the stress is below this limit. However, on the bottom image the stress increases, making it surpass the limit. Thus, the area affected by the stress concentration extends until 3 elements from the change of thickness (in the normal mesh). In this way, as long as the stress outside this area is under the threshold value, it can be affirmed that the structure will not reach that level of stress.

For figure 5.20, the mesh was refined on the left side of the stiffener, leaving the right side untouched. In this way, it is possible to analyse the stress concentration due to the change of thickness (bottom image) and the stress concentration due to the corner that appears in the interface of the thin wall, the stiffener and the end of the tank (top image). With the former, varying the mesh only changes the stress in the first element (normal mesh) away from the change of thickness. This means that the stress should remain under the limit at least until the second from last element. The latter affects a larger area, which goes up to 2 elements away from the corner. The conclusion drawn from this is that the stress has to be lower than the threshold until the third from last element.


LEFT: REFINED, RIGHT: NORMAL

LEFT: REFINED, RIGHT: NORMAL

Figure 5.20: Detail View of the Stress Concentration

5.5. DESIGN IN COMPLIANCE WITH REQUIREMENTS

Now that it is clear where should the stress be lower than the threshold (as far as the Tank is concerned), it is possible to modify the parameters until this is accomplished. After the iterations varying the thickness of the walls, of the bottom and of the stiffeners, the design with the lowest mass that had a stress below 155 MPa everywhere (except for the stress concentrations) is the one presented in figures 5.21, 5.22 and 5.23.

The modifications done with respect to the Preliminary Design are the following: (i) the thickness of the side wall parallel to the plane of symmetry is changed from 1 mm to 1.2 mm, (ii) the stiffener in this wall increases its thickness from 6 mm to 6.5 mm, (iii) the bottom wall thickness is reduced from 2 mm to 1.5 mm, (iv) stiffeners are added to the bottom wall with a thickness of 3.5 mm and a width of 8 mm. They are all summed up in figure 5.3.

As it was explained before, the fact that the maximum stress is higher than the threshold does not mean that the design will fail. This maximum value is only found on stress concentrations that were already identified and analysed. It is possible to see that the 2 elements distance is allowed in the stiffener - stiffener interface, the 1 element distance is allowed along the stiffener - side wall interface and the 2 elements distance is allowed in the corner formed by the end of the tank, the stiffener and the side wall. All this points show a stress which will not appear in the real case, and can be thus omitted.

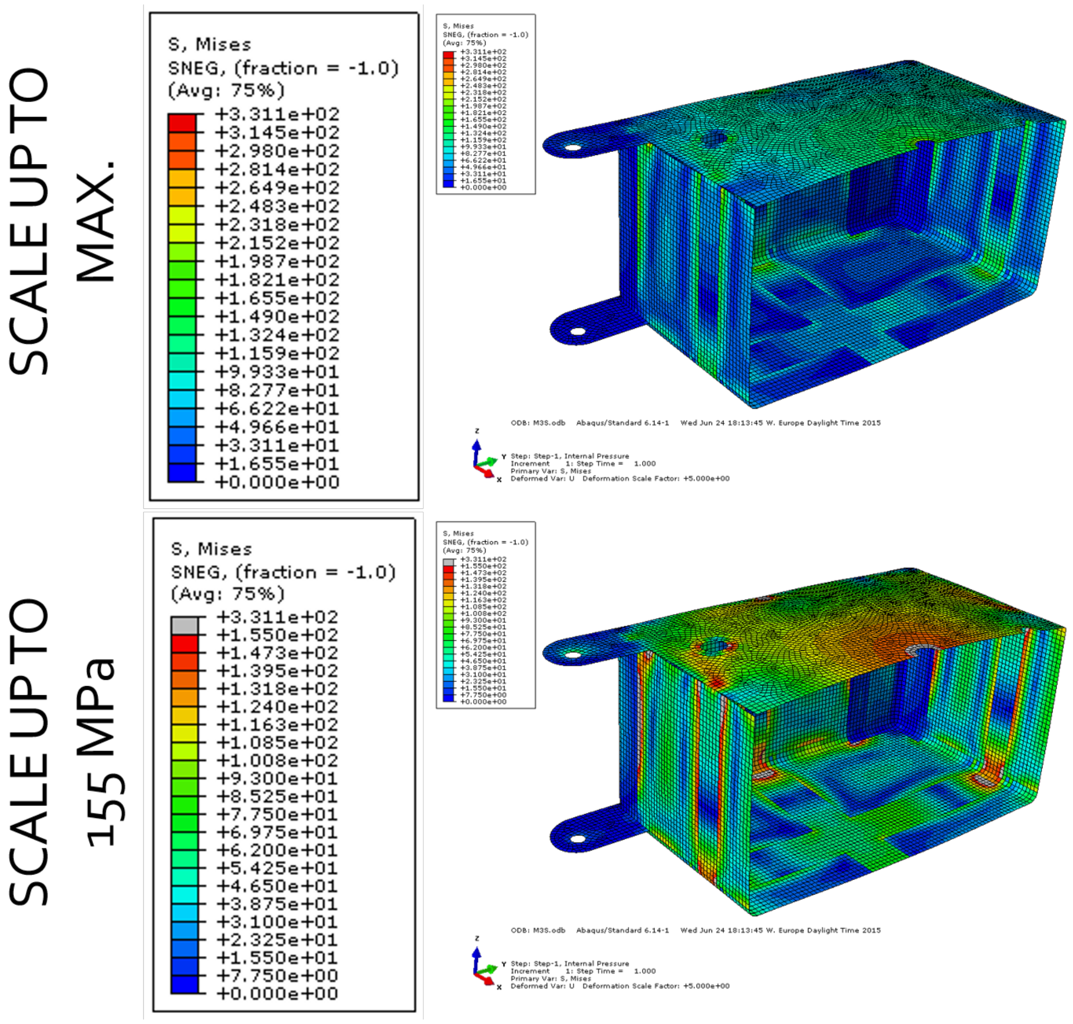


Figure 5.21: 3D View of the Propellant Tank Assembly under Internal Pressure

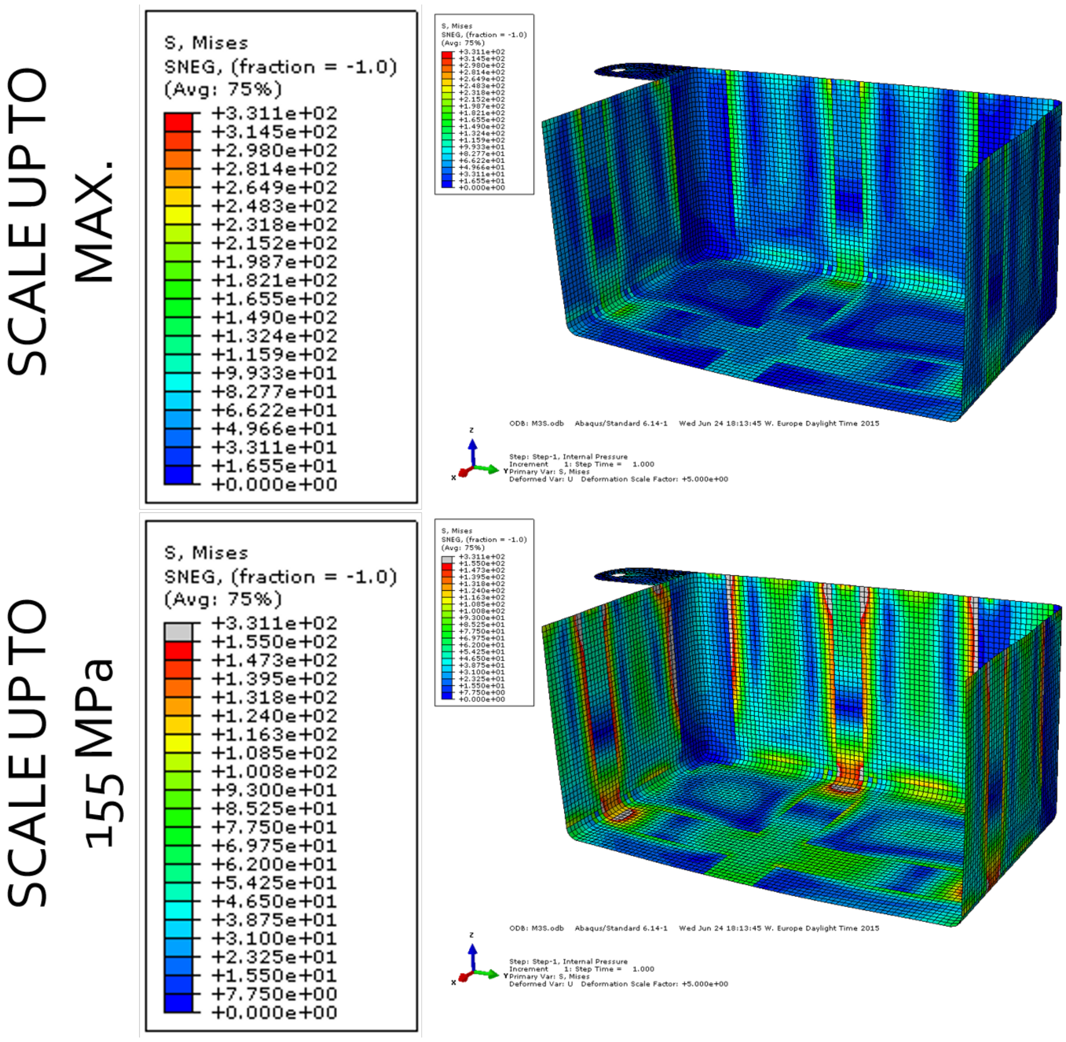


Figure 5.22: 3D View of the Tank under Internal Pressure

Although the stress distribution on the lid has been shown throughout the whole iterative process, no changes have been made to its thickness. This is because the failure points are not in the thin wall, but in special places that should be analysed individually. The first one is the joint with the bolts. The bolted joints are modelled as a Tie Constraint between the tank and the lid. This constraint is applied to a set of nodes with the length equal to the diameter of the bolt. On the real situation, the bolt would deal with all this load, relieving both the lid and the tank. The stress that the bolts can resist is another problem, which will be discussed later. The second point of failure is on the holes for the connectors. Even though the area surrounding the hole has a small increment of thickness, it is not enough to leave the stress below the threshold. However, from the three holes visible in 5.23, one of them does not deal with high stress. This indicates that certain positions of the holes are less damaging than others. In order to know these positions, different holes configurations are tried.

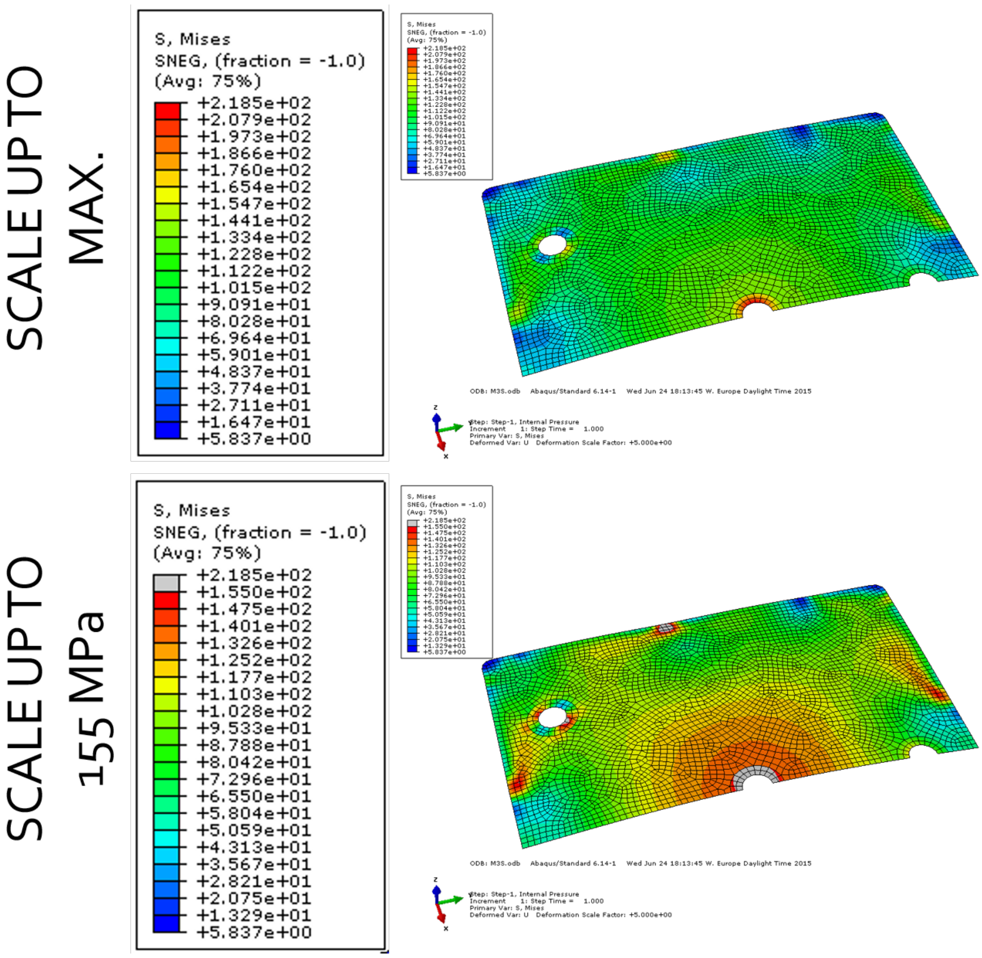


Figure 5.23: 3D View of the Lid under Internal Pressure

A total of 5 different holes configurations were analysed (the 4 included in figure 5.26 plus the Preliminary Design). It is possible to see that all holes fail in two diametrically opposite points, with the exception of the holes on the symmetry axis close to the sides of the tank. The holes which are not placed in the symmetry axis suffer a stress concentration, as seen in the detail figure 5.25. However, this stress concentration is different from the ones seen before. It will appear in real life, a stress concentration proportional to the stress on the rest of the plate [30]. The stress concentration level can be roughly estimated as three times higher than the stress on the surrounding part of the plate. This is why placing the hole in an area with low stress will generate a stress concentration much smaller than placing the hole in an area with high stress level.

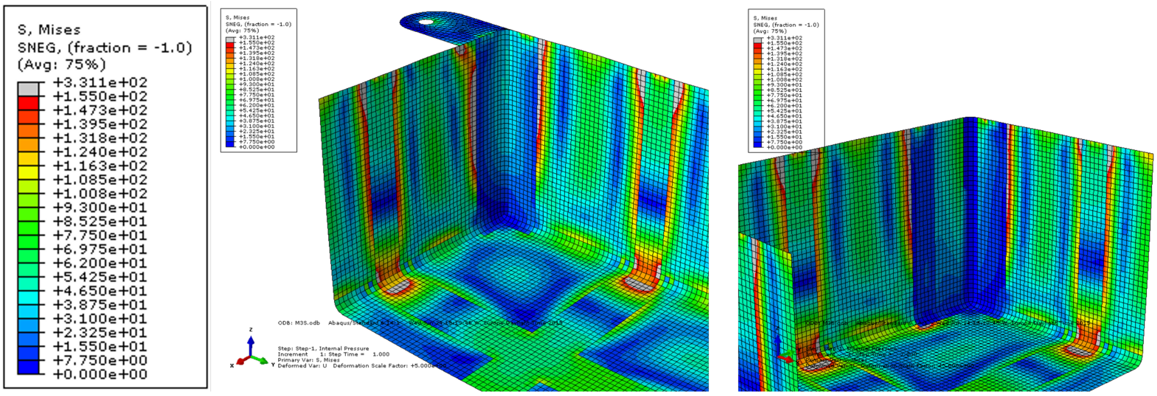


Figure 5.24: Detail View of the Propellant Tank Assembly under Internal Pressure

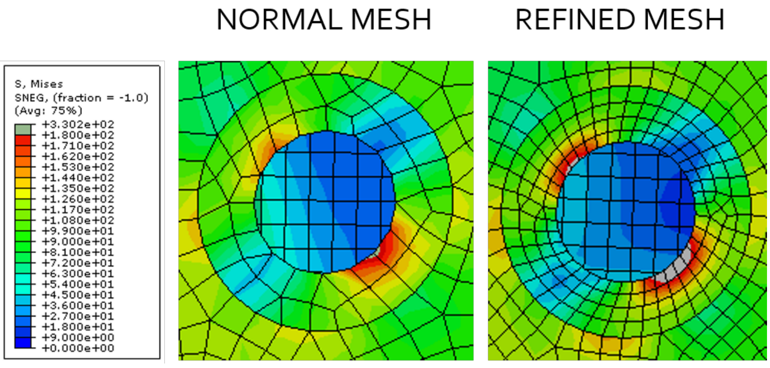


Figure 5.25: Stress concentration in the holes for connectors

By changing the location of the holes, it is concluded that only the bolts placed on the symmetry axis will comply with the load requirements. However, the fact that the holes are not empty then the load is applied (as the connectors will be inside), the results of this study are highly conservative, as the loads will pass also through the connectors, resulting in a less stiff area rather than a hole. The result is a set of guidelines about where to place the holes, rather than where will they fail. In this way, it is advisable to place the holes on the symmetry axis close to the sides and take precaution when placing them near edges of the tank. Never place them on the middle of the lid, and try to keep them relatively close to the sides.

Figure 5.27 shows the Beam + Shell Model with the same characteristics as the last design analysed. It is possible to see that the Lid and the bottom have a similar performance to the Shell Only Model. However, the results are different in the vertical stiffeners and the side walls. This is, once again, caused by the limitation of this model, which allows bigger displacement and deformation of the sides due to the fact that the distance between stiffeners is larger.

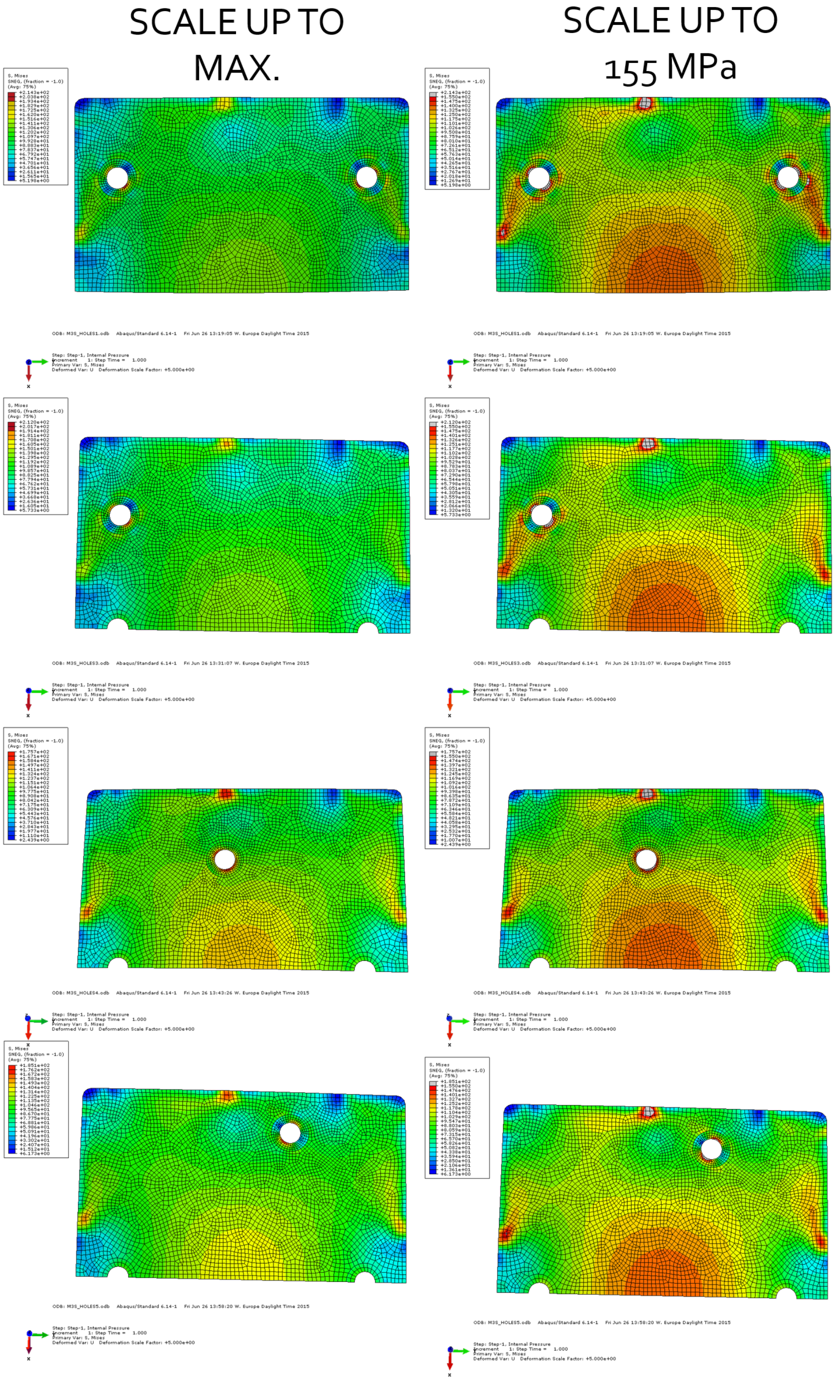


Figure 5.26: Comparison of the different holes configurations in the lid, computing until the maximum stress on the left and until the threshold limit on the right

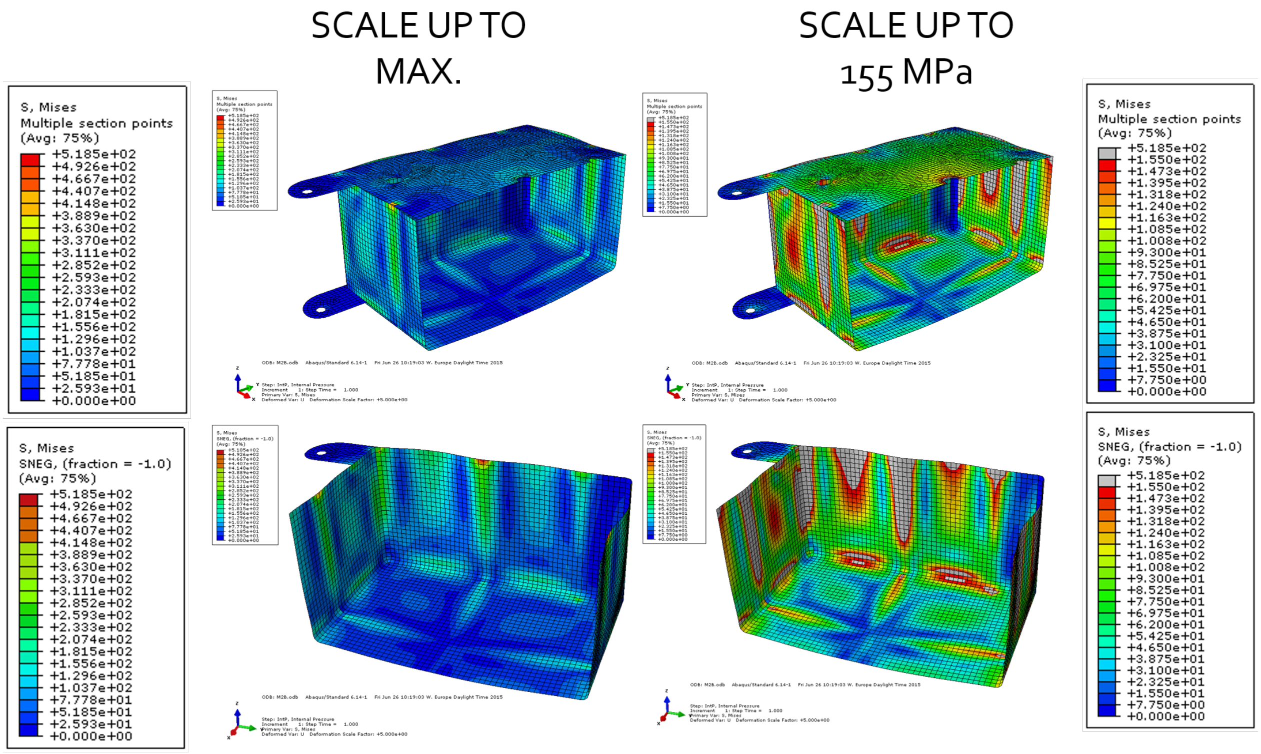


Figure 5.27: Beam + Shell Model with the final parameters

5.6. ANALYSIS OF THE BOLTED JOINTS

As it was explained during the chapter, the bolts are removed for the Finite Element Analysis due to the complexity they add. Given the fact that the objective is to size the bolts, the only information needed is the stress they will stand. This can be obtained by looking at the stress in the Tie Constraints of the model. In the analytical study, this load was estimated, and the yield strength was considered the stress limit. At this point, a deeper analysis can be carried out. This involves calculating the bolt strength according to the ISO standards. Reference [31] is followed in order to do so. The values obtained for different metrics and bolt grades (depends on the strength of the material [32]) can be seen in table 5.2:

Table 5.2: Maximum allowable stress on the Propellant Tank

Steel	**Ultimate Strength [MPa]**	**Bolt Strength (M1.5) [MPa]**	**Bolt Strength (M2) [MPa]**	**Stress from FEA [MPa]**
A449 (grade 8.8)	830 [34]	188.7 [31]	234 [31]	253
A574 (grade 12.9)	1220 [34]	288 [31]	357 [31]	253

Looking at the information presented in table 5.2, it is recommended to use A4-80 (M2) or ASTM F568 (M1.5 or M2) so as to assure that the loads bolt strength (which already includes the factor of safety for ultimate loads) is higher than the stress on the tank. The materials shown are representatives of their grade, but any material of the same grade may be used.

6

DETAIL DESIGN

6.1. CHARACTERISTICS OF THE DETAIL DESIGN

The completion of the Finite Element Analysis results in a Detail Design of the Propellant Tank. This design provides enough detail to allow the manufacturing of the assembly, and is expected to withstand the load cases it will encounter in its lifetime. The parameters, lengths, configurations, thickness, etc. are now fixed (frozen configuration), and should not be subject of change unless the testing campaign does not verify the Finite Element results and a redesign in required. Moreover, due to the state of development of other components of the Propulsion System, some of the features of the Propellant Tank only include guidelines for their design, so they still have to reach a frozen configuration.

Even though the Assembly and Part Drawings are included in the following section, an overview of the characteristics of the Detail Design is given in this section, together with a brief summary of the justifications for each design choice.

To begin with, the initial trade-off studies resulted in a Box + Lid configuration, with a Cubic shape, made of Aluminium 6061-T6 via CNC milling. These characteristics resulted in an optimisation of the objectives, and were not changed during the rest of the design process. However, the material may be changed for another type of Aluminium, as long as the specific strength is not reduced. This may include a swift to a 2000 series or to 7000 series (which can achieve similar and higher specific strengths).

After the Conceptual Designs were proposed, it was decided to join the tank directly to the structure of the bus by mounting the 4 bars on passing-through holes in the structure of the tank, and clamping it with spacers. Furthermore, the lid would be mounted on top of the tank and secured with bolted joints and an o-ring for sealing.

These design choices defined a Preliminary Design, in which the dimensions and parameters were estimated via an analytical study. Ten evenly distributed M2 steel bolts with a grade of at least 8.8 would join the lid to the tank. The lid thickness would be 4 mm, the bottom 2 mm and the side walls 1 mm. A space of nearly 20 mm is allowed for cabling passing from one side of the tank to the other thanks to 2 mm lips that join the tank to the bus structure.

Finally, the Finite Element Analysis conducted modified the parameters estimated by the analytical study. The only major design change was to add reinforcements to the bottom wall of the tank (3 in total). The final parameters and dimensions obtained with this analysis can be seen in the Drawings of the following section.

As it was mentioned before in this section, there are details of the propellant tank that still have to be defined, and which could affect the already fixed dimensions. These include the Propellant Management Device, the Connectors, the Fill and Drain Ports and the interface with the thruster. They are all out of the scope of this thesis, and belong to the thesis of other members of the DelFFi Propulsion Team. These features affect two main features of the design: the mass/ size/ internal volume budgets and the holes in the lid.

Beginning with the former, the Detail Design of the Propellant Tank complies with all requirements except for the size (which will be modified to allow for mounting directly to the bus structure) and the mass. This last requirement is not met because the Propellant Tank exceeds the maximum mass in 9 grams (see Appendix

C). Given that the PMD is not defined yet, and its estimated mass is 50 grams, a PMD of 40 grams or less would mean meeting the mass requirement with this Detail Design. Should the PMD exceed the 40 grams, the size of the tank should be modified. In particular, the Z side which is now 41 mm will be reduced without compromising the structural response. In order to allow for this modification, the CAD model as well as the Abaqus model have been designed in a way that the side Z is a parameter, easy to modify. This means that a Structural Analysis can be rapidly carried out if this dimension is to be changed. The reason why this dimension has not been reduced already is to allow the compliance with the volume requirement. If a redesign is needed, then the volume requirement should also be analysed.

As far as the holes in the lid are concerned, a rough estimate of 5 mm diameter was used in the Finite Element Analysis. However, this size is subject to change, as well as the distribution of the connections in the lid. Guidelines were given in the previous chapter assessing the best locations for the connections. But the interface with the thruster may restrict the available space for the connectors. This is why the holes in the Abaqus model can be easily modified so that a simulation can be carried out when the final connectors and their locations are chosen. With the obtained results, there should be no need for redesign with whatever configuration. However, the lid thickness may be modified to cope up with the stress changes if needed, only affecting slightly the mass and internal volume budgets.

Another point which could not be assessed during the Finite Element Analysis is the change of thickness in the lid in the bolted joints. Part of the lid stays inside de tank to accommodate the sealing. However, the bolted joints are done outside the tank, so the thickness changes and the lid overlaps the walls of the tank. So far in the design, this thickness is 1 mm, while the total thickness of the lid is 4 mm. A meeting with the workshop experts is required to augment the overlapping thickness without increasing the total thickness and making sure that the groove for the sealing is still manufacturable.

6.2. TECHNICAL DRAWINGS AND 3D MODEL

A 3D printed model was manufactured for better visualisation of the Detail Design. Figure 6.1 shows this model, as well as the CAD model.

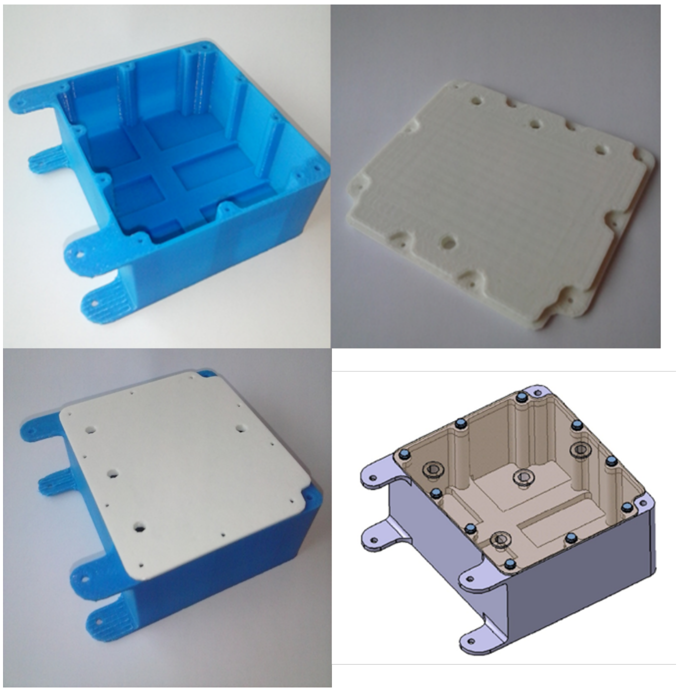


Figure 6.1: 3D Printed model of the Detail Design and CAD model

Appendix E shows the technical drawings of the Assembly (with the Part List) as well as the Lid and Tank parts.

6.3. VERIFICATION & VALIDATION PLAN

A preliminary V&V (Verification and Validation) plan has been established. A brief overview is given on this section, but a major revision of the plan is required before the start of the testing campaign.

V&V is a process to be followed during all stages of the design. The starting point is the requirements document [6]. Each requirement has to be verifiable in order to ensure the compliance. There are various methods of verification, but the ones used for the Propellant Tank Requirements include Inspection, Analysis and Testing.

Inspection consists in measuring a certain characteristic of the Propellant Tank to see if it meets the requirement. It has a close relation with keeping track/ controlling the budgets (mass, volume, etc.). Analysis involves the use of models. A model is a simplification of the physical reality in which parameters and performance can be assessed. As far as the Propellant Tank is concerned, two different models have been developed: a CAD Model and a Finite Element Model. The former helps to visualise the design, and is validated when the manufacturing process is completed. The latter is used to perform a structural analysis of the assembly. The validation of this tool as well as the results obtained is of utmost importance, as the simplifications and assumptions made may not be the appropriate ones. Should the testing campaign obtain the same results, these would be verified and the Model would be validated. Finally, Test is the most visual and intuitive verification method. A previous analysis is normally performed so as to estimate the order of magnitude of the different parameters, and to plan the testing campaign efficiently.

On Appendix A, in the Compliance Matrix, it is possible to see how each requirement will be verified. The verification methods on the baseline at the moment in which this Thesis is written are:

- Finite Element Analysis
- MEOP test
- Leakage rate test
- Budget Control
- Inspection
- Vibrations test (subsystem level)
- Thermal cycle test (subsystem level)
- Propellant Tank readiness test

A more detailed V&V plan is to be elaborated before the start of the testing campaign, defining each exact test to be carried out, as well as the validation process for the models. Even though the problem of validating the model is out of the scope of this Thesis, a few guidelines can be defined in order to help this task. First of all, the testing should make use of strain gauges located on interesting points of the Propellant Tank. As far as the FEA model is concerned, the stress on the tank walls and the middle point of the lid are of the utmost importance. These locations are accessible, and should be measured with pairs of strain gauges pointing in perpendicular directions. Although the behaviour of the bolts should be assessed, it will not add information to the model validation, as they were simplified into simple constraints. It is also advisable to look into the validity of the simplifications made, as well as the assumptions, all available in the previous chapter.

7

CONCLUSIONS AND RECOMMENDATIONS

7.1. CONCLUSIONS

The conclusions should be the crucial part of the Thesis, as they summarise the outcome of the research or work performed. Given that this Thesis in particular is mainly project-oriented, most of the conclusions consist in deliverables rather than confirmation of hypotheses. Moreover, the simplifications and assumptions made can only be fully validated after the testing. Be that as it may, all the conclusions drawn from this work are exposed herein.

To begin with, and following the order of the chapters, this Thesis concludes that changes should be made on the Propellant Tank Requirements. These changes affect requirements PROP-TNK-300 and PROP-TNK-321 (requirements on the mass and the size, respectively). The former should include the 50 grams of supporting structure in the propellant storage structure, as the design of the tank does not require additional parts in the interface with the bus. The latter should change the boundaries to 90 x 96 x 41 [mm], as these are the dimensions of the Detail Design, which, due to its interface with the bus structure, will require a larger size.

Moving forward, the design process resulted in important conclusions. The major one is the proved effectiveness of the design trades method, applied as a 10-step process by following reference [12]. The method resulted in successful design choices, generating a Preliminary Design which was slightly modified after the Finite Element Analysis. From the trade-off studies, titanium is concluded to be the best performing solution for companies or agencies, where its cost is affordable and the assumable risks are lower. It is also affirmed that the Additive Manufacturing options available in TU Delft are not suitable for such a structurally loaded assembly, but a promising future is envisioned. Together with this, cast is impractical for the small quantity of models, as well as the complexity related to achieving high structural performance. Furthermore, the cylindrical shape poses less difficulties than cubic shapes in terms of structural analysis, as more literature is available.

As far as the analytical study is concerned, it is possible to conclude that the simplifications and assumptions made resulted in an accurate estimation of the order of magnitude of the stress levels generated by the load cases. Firstly, considering the side walls of the Propellant Tank as plates [10] resulted in an accurate result, proved by the stresses obtained during the Finite Element Analysis. Secondly, the equations from [33] for maximum stress in plates loaded in the thickness direction, as well as the assumptions made to turn the g-accelerations problem into a loaded plate problem proved to estimate the correct order of magnitude for the stresses, as seen in the Finite Element Analysis. Finally, the approach to computing the stress on the bolted joints still has to be proved true by the testing campaign.

From the Finite Element Analysis, it is concluded that the Beam + Shell Model (modelling the walls with shell elements and the stiffeners with beam elements) is not a correct approach. Neither it is modelling the tank without simplifications. However, in order to confirm the validity of the Shell Only Model (stiffeners are changes in the thickness of the shell), the testing results have to be obtained. This will also verify the assumptions and interpretations of the results, concerning the stress concentrations or the unrealistic deformations.

Finally, the main conclusion of this Thesis work is that it is possible to create a feasible Propellant Tank with the expected performance and budgets. However, the testing campaign will confirm that the structural analysis was performed correctly.

7.2. RECOMMENDATIONS

The development of this Thesis has encountered situations from which lessons shall be learned, resulting in piece of advice for future work. In addition to this, the limitations of the work performed call for a further development of the topic, addressing the points that fell out of the scope of this Thesis, and with the aim to generate a successful design of a Propellant Tank, to be used in the Water Resistojet as well as any other Propulsion System which may require a pressurised tank.

Firstly, certain concepts applied on this work are recommended for similar design processes. These include traceability of all decisions made and parametrisation of designs in order to save time in redesigns and modifications. Moreover, including at least three people in the decision making process helps the objectivity and reduces the possibilities of overlooking problems or making mistakes in calculations. Even though the person developing the Thesis is likely to become the expert on the topic, explaining the decision to others helps to develop an argumentative line for the decision taking. Finally, it is crucial to include the opinion of manufacturing experts from the beginning of the design process. If this is not done early enough, redesigns take place and work may be done twice.

Secondly, the work carried out leaves space for further investigation and development, to be performed by other students as subject of their theses. The most critical part to be taken care of at the moment is the manufacture and testing campaign of the propellant tank. In order to validate the results of the Finite Element Analysis, it is necessary to test the assembly in a representative environment. Given that the highest stresses are achieved with the internal pressure load case, it is extremely interesting to verify these results experimentally. Furthermore, the model used for the structural analysis (Shell Only Model) may be used in other applications if it is validated by the testing campaign. In addition, the vibrations load case has not yet been studied. Given the possible impact on the design, the testing campaign should also include a vibrations test as stated on the requirements. Further meetings with the Workshop will inevitably lead to small redesigns or changes in radii or thickness. The FEA models are sufficiently straight forward so as to complete a simulation after each change in the desing.

Finally, other research possibilities arise from the work performed in this Thesis. The influence of the temperature variation on the structural performance is a subject to analyse, as, for example, the high CTE of aluminium will cause higher displacements, and the modulus of elasticity will change. These changes should be assessed in order to assure the correct performance of the Propellant Tank within the range of temperatures stated on the requirements. Furthermore, a structural analysis of the PCB could be carried out. This would not only increase the design options for the Propellant Tank, but also generate a model which could be used in applications where large components should be attached to a PCB. The investigation on the PMD and the conncetors will already be carried out by other team members of the DelFFi Propulsion Team.

A

COMPLIANCE MATRIX

Propellant Tank Compliance Matrix 1.0

Requirement Types
F = Functional
P = Performance
B = Budgets
I = Interface
S = Safety
E = Environmental
P&M = Production & Materials
A&I = Assembly & Installation
T = Test

Requirement		**Description**	**Compliancy**				**V&V**	**Comment**
Numbering	*Cat.*		*Design*	*FEM Analysis*	*Test / Manufacture*	*Delivery*		
PROP-TNK-100	F	The propellant storage system shall be able to contain non-toxic, non-corrosive, non-flammable propellant in both liquid and gaseous form.	Compliant					
PROP-TNK-101	F	The propellant storage device shall allow for possible integration of Propellant Management Devices or Propellant Expulsion Devices.	Pending					
PROP-TNK-200	P	The propellant storage device shall be able to withstand a MEOP of 10 bars when using liquid propellant.	Compliant				FEM analysis + MEOP test	
PROP-TNK-201	P	The propellant storage device shall be able to withstand a MEOP of 20 bars when using purely gaseous propellant.	No Compliance				FEM analysis + MEOP test	This requirement should be reconsidered, as it drives the design to a high mass for a functioning mode which may not be used.
PROP-TNK-202	P	The maximum leak rate shall be 10E-5 GN2 (TBC) [scc/s] at maximum operating pressure.			Pending		Leakage rate test	
PROP-TNK-300	B	The propellant storage structure, including possible PMD, shall have a mass less than 200 grams.	Partially compliant				Budget control + Inspection	Actual mass budget is 259 grams. Including the 50 grams of structure mass into the budget and reducing the 50 grams assigned to PMD would result in compliance.
PROP-TNK-320	B	The internal storage volume shall be ≥ 200 ml.	Compliant				Budget control + Inspection	Current volume is 205.3 ml.
PROP-TNK-321	B	Propellant storage device volume shall not exceed the boundaries of 80 x 80 x 40 mm. (XYZ)	No Compliance				Budget control + Inspection	The "direct to structure" configuration needs a bigger volume in order to be attached to the structure bars.
PROP-TNK-380	B	The cost of the propellant storage device shall be ≤ TBD €.				Pending	Budget control	
PROP-TNK-400	I	The propellant storage device material shall not affect the composition of the propellant and/or pressurant.			Pending			
PROP-TNK-401	I	The propellant storage device shall allow for propellant fill and drain port(s).	Compliant					
PROP-TNK-440	I	The storage device shall allow for the capability of electronic sensing of propellant temperature and pressure inside the tank.	Compliant					
PROP-TNK-500	S	The storage device shall have a design factor of safety higher than 1.6 for yield load.		Compliant	Pending		FEM analysis + MEOP test	
PROP-TNK-501	S	The storage device shall have a design factor of safety higher than 2.0 for ultimate load.		Compliant	Pending		FEM analysis + MEOP test	
PROP-TNK-600	E	The propellant storage device shall be capable of withstanding lateral loads ranging from ±1.8 g.		Compliant	Pending			
PROP-TNK-601	E	The propellant storage device shall be capable of withstanding longitudinal loads ranging from -5 g to +1.8 g.		Compliant	Pending			
PROP-TNK-602	E	The propellant storage device shall be capable of withstanding the sine equivalent dynamics experienced during launch.			Pending		Vibrations test (subsystem level)	
PROP-TNK-603	E	The propellant storage device shall be capable of withstanding the random vibrations experienced during launch.			Pending		Vibrations test (subsystem level)	
PROP-TNK-620	E	The storage device shall be capable to perform its functionality function within a temperature range from -10 °C to +50°C.			Pending		Thermal cycle test (subsystem level)	
PROP-TNK-750	P&M	The propellant storage device material characteristics shall not be altered by liquid H_2O and gaseous N_2.			Pending			
PROP-TNK-800	A&I	The propellant storage device shall be compatible with the standard ISIS CubeSat structure.	Compliant					
PROP-TNK-801	A&I	Fill and drain port(s) on the storage device shall be accessible after integration into the CubeSat.	Compliant		Pending		Inspection	
PROP-TNK-802	A&I	The structural support should be such that it will allow connection of the tank and integration into DelFFi satellite.	Compliant					
PROP-FDS-900	T	The MEOP of propellant storage device as defined by requirement PROP-TNK-200 must be experimentally validated.			Pending		MEOP test	
PROP-FDS-901	T	The expulsion of propellant from the storage device shall be experimentally validated.			Pending		Readiness test	
PROP-FDS-902	T	The leakage characteristics of the propellant storage device as defined by requirement PROP-TNK-202 shall be experimentally validated.			Pending		Leakage rate test	

Figure A.1: Compliance Matrix for the Propellant Tank

B

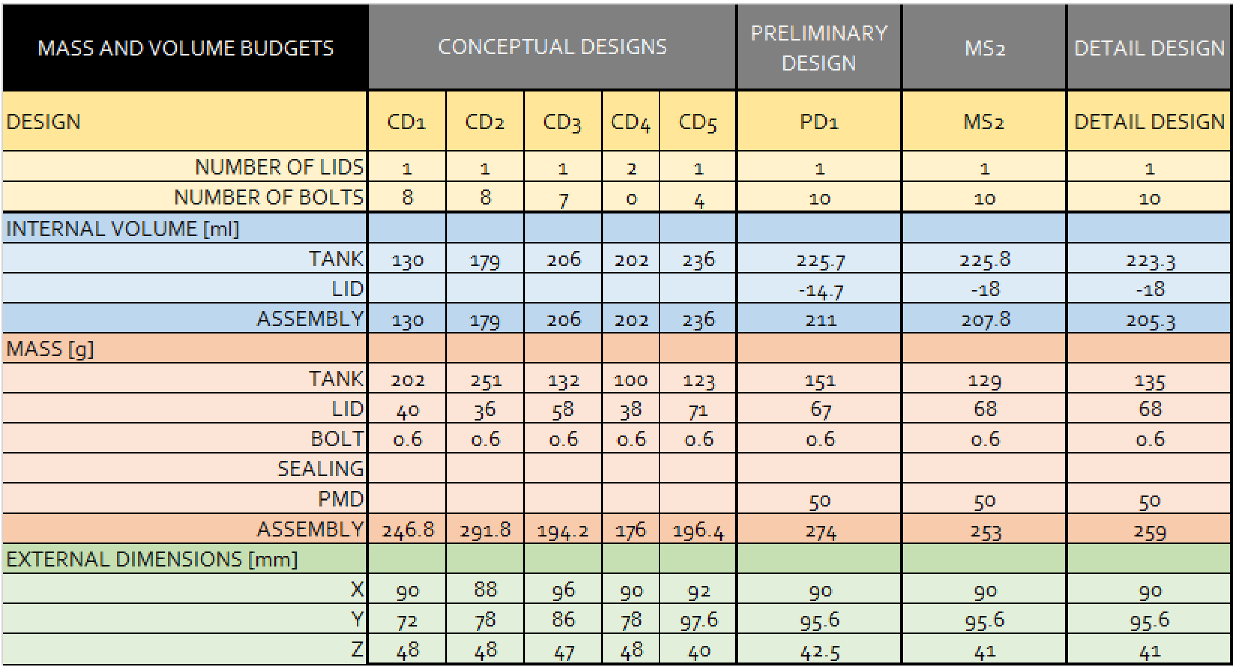
RELATIVE COST OF METALS

Metal	Price $	£1000/tonne	£1000/m^3	Relative cost (weight)	Relative cost (volume)
Steel HR (A56)	6	3,2	24,7	1	1
Steel CD (12L40)	7,4	3,9	30,5	1.23	1.23
Alloy Steel (4130)	9,99	5,3	41,2	1.66	1.66
St.Stl (304L)	15,34	8,1	63,2	2.6	2.56
St.Stl (316L)	20,61	10,9	84,9	3.4	3.44
Aluminium (2011-T3)	8,58	13,1	35,4	4.2	1.43
Copper (C110)	37,91	17,5	156,2	5.6	6.32
Brass (C360)	25,3	11,7	104,3	3.7	4.22
Bronze	42,09	19,5	173,5	6.2	7.0
Titanium (6AL-4VG5)	107	98	441	31	17.8

Figure B.1: Relative cost of metals (Source [35])

C

Mass and Volume Budgets

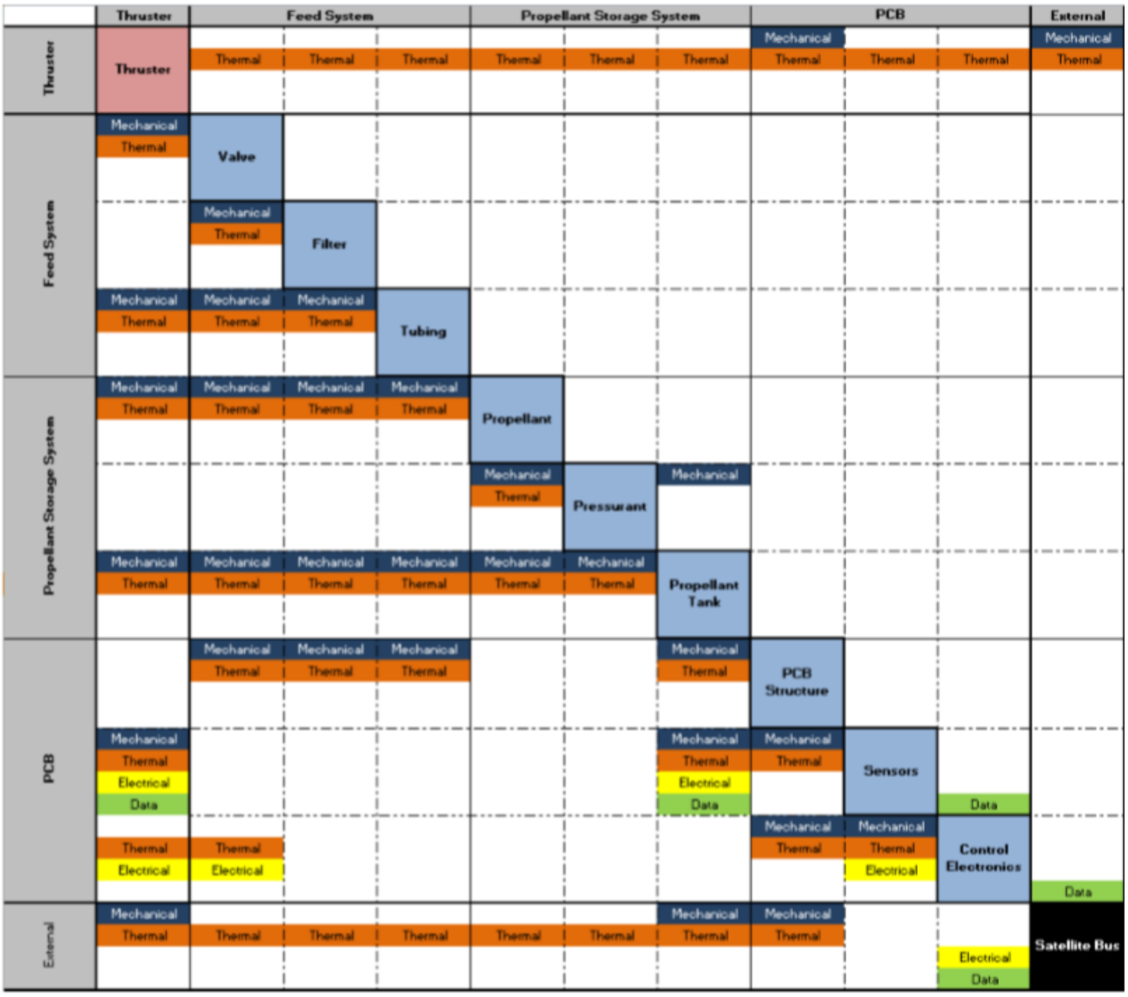


MASS AND VOLUME BUDGETS	CONCEPTUAL DESIGNS					PRELIMINARY DESIGN	MS2	DETAIL DESIGN
DESIGN	CD1	CD2	CD3	CD4	CD5	PD1	MS2	DETAIL DESIGN
NUMBER OF LIDS	1	1	1	2	1	1	1	1
NUMBER OF BOLTS	8	8	7	0	4	10	10	10
INTERNAL VOLUME [ml]								
TANK	130	179	206	202	236	225.7	225.8	223.3
LID						-14.7	-18	-18
ASSEMBLY	130	179	206	202	236	211	207.8	205.3
MASS [g]								
TANK	202	251	132	100	123	151	129	135
LID	40	36	58	38	71	67	68	68
BOLT	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
SEALING								
PMD						50	50	50
ASSEMBLY	246.8	291.8	194.2	176	196.4	274	253	259
EXTERNAL DIMENSIONS [mm]								
X	90	88	96	90	92	90	90	90
Y	72	78	86	78	97.6	95.6	95.6	95.6
Z	48	48	47	48	40	42.5	41	41

Figure C.1: Mass and Volume Budgets

D

N2 Chart of the Propulsion System Interfaces

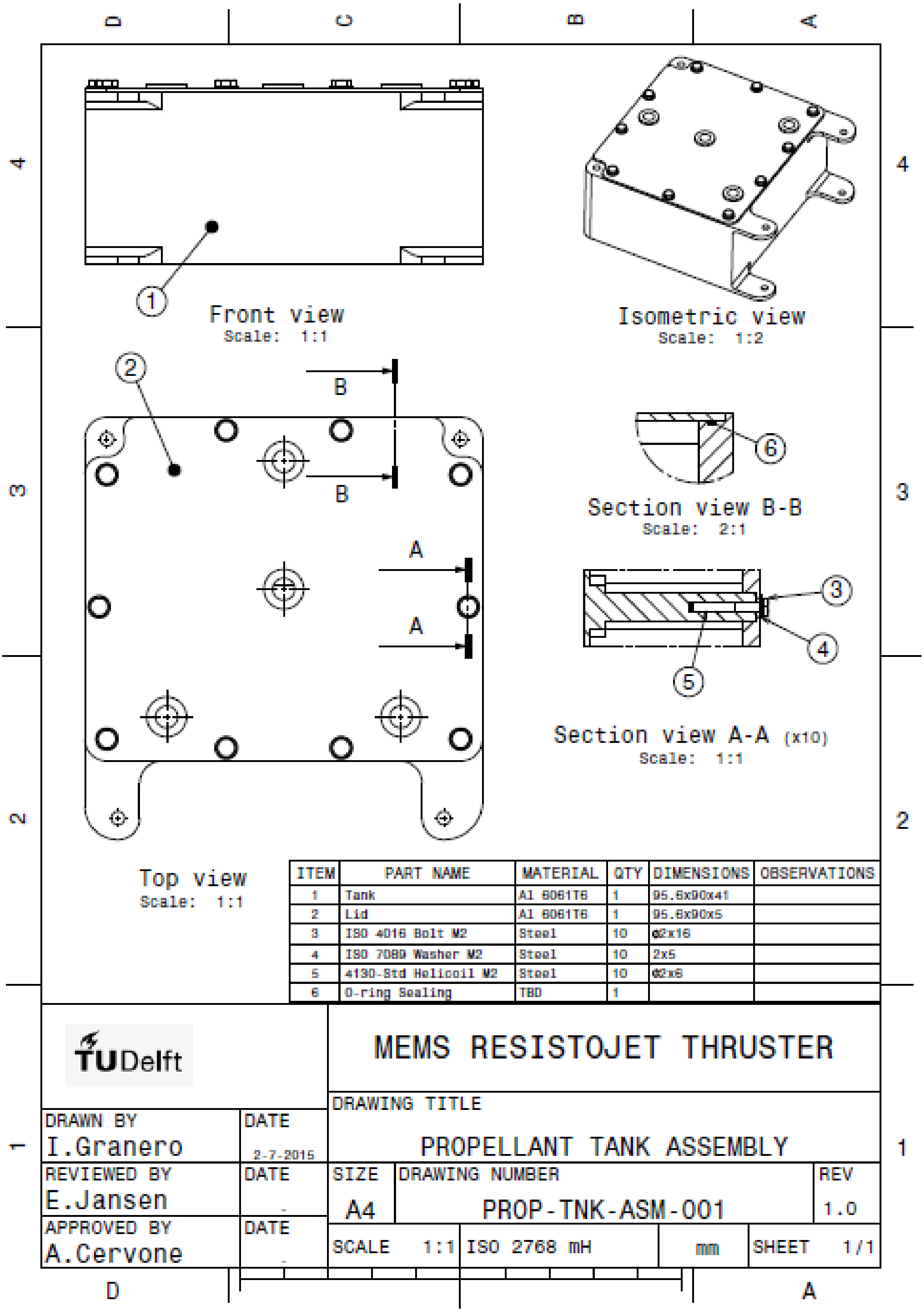


	Thruster	Feed System			Propellant Storage System			PCB			External
Thruster	**Thruster**	Thermal	Thermal	Thermal	Thermal	Thermal	Thermal	Mechanical Thermal	Thermal	Thermal	Mechanical Thermal
Feed System	Mechanical Thermal	**Valve**									
		Mechanical Thermal	**Filter**								
	Mechanical Thermal	Mechanical Thermal	Mechanical Thermal	**Tubing**							
Propellant Storage System	Mechanical Thermal	Mechanical Thermal	Mechanical Thermal	Mechanical Thermal	**Propellant**						
					Mechanical Thermal	**Pressurant**	Mechanical				
	Mechanical Thermal	Mechanical Thermal	Mechanical Thermal	Mechanical Thermal	Mechanical Thermal	Mechanical Thermal	**Propellant Tank**				
PCB		Mechanical Thermal	Mechanical Thermal	Mechanical Thermal			Mechanical Thermal	**PCB Structure**			
	Mechanical Thermal Electrical Data						Mechanical Thermal Electrical Data	Mechanical Thermal	**Sensors**	Data	
	Thermal Electrical	Thermal Electrical						Mechanical Thermal	Mechanical Thermal Electrical	**Control Electronics**	Data
External	Mechanical Thermal	Thermal	Thermal	Thermal	Thermal	Thermal	Mechanical Thermal	Mechanical Thermal		Electrical Data	**Satellite Bus**

Figure D.1: N2 Chart of the Propulsion System Interfaces (Source [1])

E

TECHNICAL DRAWINGS OF THE DETAIL DESIGN



ITEM	PART NAME	MATERIAL	QTY	DIMENSIONS	OBSERVATIONS
1	Tank	Al 6061T6	1	95.6x90x41	
2	Lid	Al 6061T6	1	95.6x90x5	
3	ISO 4016 Bolt M2	Steel	10	Ø2x16	
4	ISO 7089 Washer M2	Steel	10	2x5	
5	4130-Std Helicoil M2	Steel	10	Ø2x6	
6	O-ring Sealing	TBD	1		

MEMS RESISTOJET THRUSTER

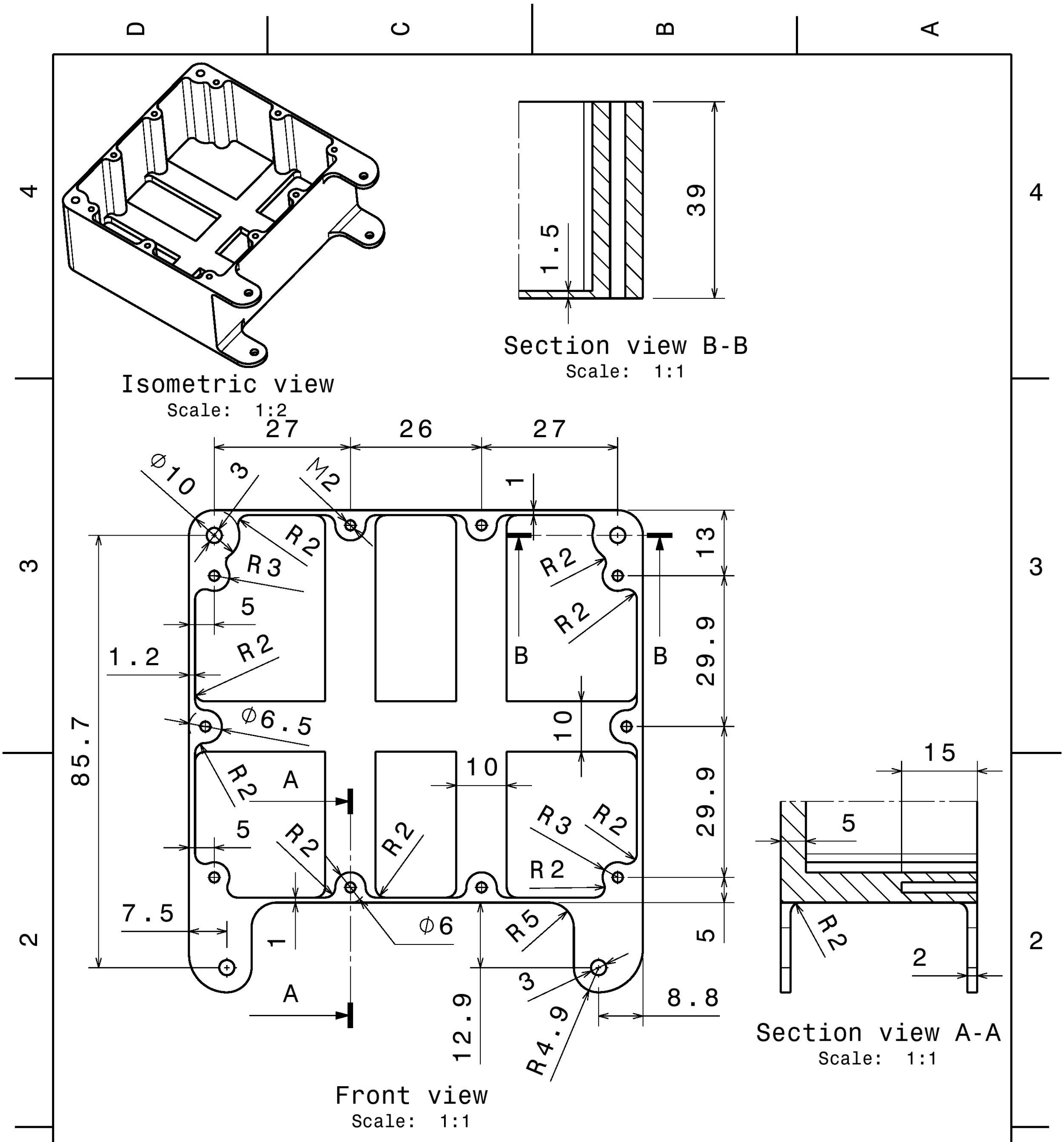
DRAWN BY I.Granero DATE 2-7-2015
REVIEWED BY E.Jansen DATE -
APPROVED BY A.Cervone DATE -

DRAWING TITLE
PROPELLANT TANK ASSEMBLY

SIZE A4
DRAWING NUMBER PROP-TNK-ASM-001
REV 1.0

SCALE 1:1
ISO 2768 mH
mm
SHEET 1/1

Figure E.1: Assembly Drawing



MEMS RESISTOJET THRUSTER

DRAWN BY
I.Granero

DATE
2-7-2015

REVIEWED BY
E.Jansen

DATE
-

APPROVED BY
A.Cervone

DATE
-

DRAWING TITLE
TANK

SIZE
A4

DRAWING NUMBER
PROP-TNK-DRW-001

REV
1.0

SCALE 1:1
ISO 2768 mH
mm
SHEET 1/1

D
A

Figure E.2: Tank Drawing

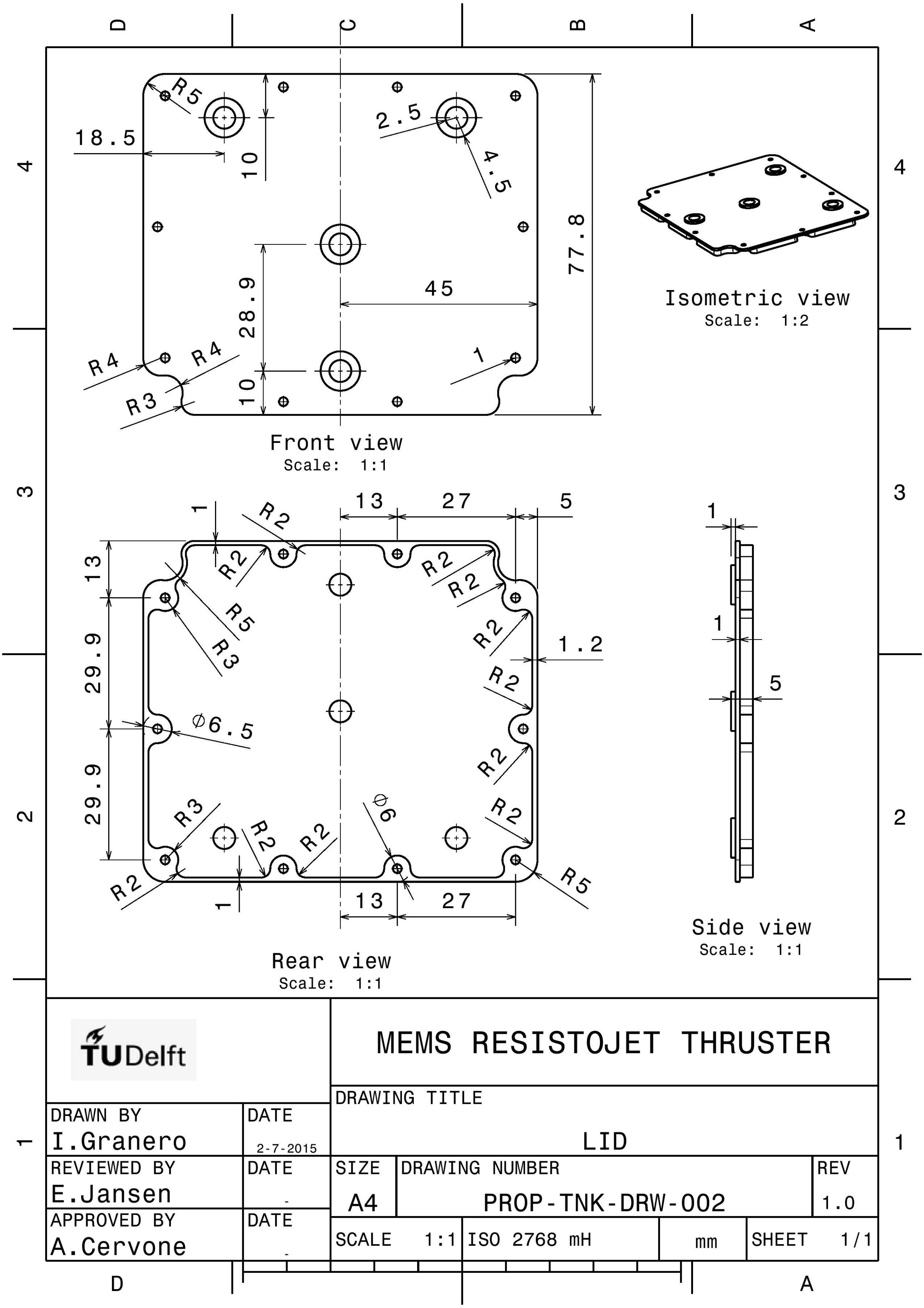


Figure E.3: Lid Drawing

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