MSc Thesis

Mass optimization of PocketQube structures and deployers

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A method demonstrated on the DelfiPQ PocketQube mission

TU Delft

Mass optimization of PocketQube structures and deployers

A method demonstrated on the DelfiPQ PocketQube mission

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TU Delft

Preface

This document is submitted as the final thesis of the MSc Aerospace Engineering of Delft University of Technology (TU Delft). The research presented has been supervised by Ir. Jasper Bouwmeester of the Space Systems Engineering section of the faculty of Aerospace Engineering (TU Delft). The document is to the best of my knowledge original and references have been made to previous work by other authors.

This thesis presents the research performed at TU Delft with respect to small satellites and in particular their structures and deployers, all in the frame of reference of the DelfiPQ PocketQube mission. The research presented is a culmination and continuation of previous work done by other researchers who have been referenced throughout. The thesis itself aims to benefit both the PocketQube community as a whole and the DelfiPQ mission in particular. I submit this as the final part of my graduation as a master of science.

Gratitude where it is due. First and foremost I would like to thank my supervisor, Ir. Jasper Bouwmeester. His guidance has been invaluable throughout this entire process. From coming to the right topic to excite me, to pointing out my flaws and strengths and how best to optimize them, Jasper has gone above and beyond, and for that I cannot be more grateful.

Another prime help has been Dr. Javad Fatemi, of Airbus Defense & Space, who with his expertise in the field served as an outside consultant to sharpen my thesis.

Praise goes out to Prof. dr. Pim Groen, who aided in some of the final experiments to be performed at the faculty on prototypes.

Special gratitude goes out to CRP Technology for generously providing me with a 3D printed prototype free of charge in order to run experiments on.

Thanks go out to my fellow students, previous authors and PocketQube community members. Without their availability to discuss topics and ideas with regards to this research, my thesis would not be as complete as it is today.

A final word of thanks goes out to my loved and close ones, who served as motivation and confirmation for the path I was on.

Tano S. Spronck
Delft, August 2017

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Executive Summary

This thesis presents a research method into mass optimization of the PocketQube, applied on the DelfiPQ project of the TU Delft. The PocketQube is a picosatellite of which a single unit consists out of a five centimeter cube. Currently its main mission objectives are commercial, tech demonstrations and to serve as learning tools for universities. Its primarily focused on earth imaging and other types of measurements. When ordering a premade PocketQube one should expect the cost to be in the range of <$100.000. However its cost effectiveness is currently lower than that of a CubeSat (one format larger), meaning that a CubeSat has a higher performance to cost ratio than a PocketQube.

As a step towards increasing this cost effectiveness, the main question addressed here is the mass optimization of both the PocketQube's structure and its deployer. In order to achieve a better understanding of this, sub questions have been formed detailing; requirements, needs, constraints, design considerations, scaling properties and innovative conceptual methods.

Forming a list of requirement, first the stakeholders are identified and categorized as universities (or governments), companies and radio-amateurs/enthusiasts. The requirements have been classified as facilitation or needs, constraints, interface and considerations, which have been summarized in compliance with the DelfiPQ project. Special attention is given to a radiation analysis from which it can be concluded that no extra structural requirements need to be established in order to prevent radiation damage to the project. This is of importance because it allows for skeletonized structures, which have greatly reduced mass when compared to conventional boxed structures. Additionally the components to be attached to the structure are presented.

Furthering the design considerations, the mechanical loads subjected to the PocketQube are presented as referenced from launch providers. These are found to be a maximum of 6.2g as quasi-static loads, but mainly vibrational loads up to 2000Hz. Other loads such as transport or thermic are presented but found to be insignificant compared to launch loads.

Subsequently the current dimensional standard is investigated. Through examination it is determined that the standard allows for too large design margins. It is imperative for these to be minimized, as the smaller the design margins of the standard become, the smaller the deployer standard dimensions can become and thus greatly reduce mass of deployers that have to be created. This thesis, in compliance with a proposal to the PocketQube community, suggests a 6.5mm design margin. This would allow for all components to be placed on the sides, and still leave 1.0mm free space.

Additionally investigated is the current state of inefficiency in scaling down to smaller satellite formats. Judging by the disproportionate differences between PocketQube and CubeSat masses, it is determined, that not enough mass is currently being saved in most structural designs. It can be concluded that when scaling down for structural rigidity, a structure can be scaled down to the fifth power.

A crucial aspect in achieving mass optimization is material selection. Different materials have been compared. It is concluded that Windform XT 2.0 is the preferred material as, being specifically designed for aerospace applications, it has a high strength to weight ratio, combined with a relatively low cost and great ease of manufacturability as it is 3D printable. Thus allowing for more design freedom than conventional fabrication methods.

The design ideology is presented for both the PocketQube structure as the deployer. When unnecessary material is removed from a reference structure, altering a boxed design to a wireframe design, over 90% of the mass can be reduced. Noted is that for deployers it is currently prohibited to step off from the box design, in order to comply with explosion hazards and general launch provider compatibility.

Resulting from the aforementioned analysis, two final concepts for the structure, and one for the deployer are presented. Firstly a traditional one devised through topology optimization for the Windform XT 2.0 material, having a mass below eight grams. Secondly a relatively revolutionary concept, in which the outside structure is replaced with the PCB's (printed circuit boards) that conventionally went inside the structure, thus theoretically having negligible structural added mass. For the latter concept, various approaches of attachment are considered, such as adhesives, brackets, etc. Regarding the deployer, whilst abiding with explosion hazard guidelines, an optimization by reducing dimensions and revising the deployment mechanism into an unfolding box is presented.

Both concepts have been prototyped and tested. Applying static and vibrational loads, the goal of the tests was twofold; proving that the software by which they were designed is valid, but most importantly illustrating both structures do not yield under representative loads.

The results of analysis and testing lead to the conclusion that the PCB outer structure concept, with brackets instead of adhesive connections is the most suitable option for the DelfiPQ mission. It is however noted, that for large scale production of traditional structured single use PocketQubes the Windform XT 2.0 topology optimized concept is preferred. Both concepts present a mass optimized solution for their own respective use.

Nomenclature

Abbreviations and acronyms

1/2/3P	single/double/triple unit PocketQube
1/2/3U	single/double/triple unit CubeSat
ABS	Acrylonitrile Butadiene Styrene
AM	Additive Manufacturing
CVCM	Collected Volatile Condensable Material
EPS	Electrical Power Subsystems
ESA	European Space Agency
FDM	Fused Deposition Modeling
FEM	Finite Element Method
FR	Flame Retardant
GAUSS	Group of Astrodynamics for the Use of Space Systems
ISRO	Indian Space Research Organization
LEO	Low Earth Orbit
MAM	Metal Additive Manufacturing
MPPT	Maximum Power Point Tracking
MRFODS	Morehead Rome Femtosatellites Orbital Deployer
NLR	Netherlands Aerospace Centre
PCB	Printed Circuit Board
PLA	Polyactic Acid
PQ	PocketQube
PSLV	Polar Satellite Launch Vehicle
PVA	Polyvinyl Alcohol
RAM	Random Access Memory
SEU	Single Event Upset
SPENVIS	Space Environment, Effects, and Education System
TCS	Thermal Control Subsystems
TML	Total Mass Loss
UAV	Unmanned Arial Vehicle
UCS	Ultimate Compressive Strength
USS	Ultimate Shear Strength
UTS	Ultimate Tensile Strength

Latin symbols

E	Elasticity modulus
F	Force
G	Shear modulus
I	Inertia
k	Stiffness
K	Bulk modulus

L / l	Length
N	Newton
n	Number of vibrations
U	Axial Displacement

Greek symbols

α	Coefficient of thermic expansion
δ	Deformation
λ	Scaling factor
μ	Friction coefficient
ν	Poisons ratio
ρ	Density

Indices

F	Full scale
f	Friction
M	Model
S	Surface
x	X-axis
y	Y-axis
z	Z-axis

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1. Introduction.

The field of small satellites, picosatellites in particular, is experiencing an exponential growth since the introduction of the PocketQube. The PocketQube format, a five centimeter cube satellite, originating in 2009 from Morehead State University, has since been demonstrated by various successful missions starting from 2013. Therefore there is currently a need for optimization of its various aspects. This thesis focuses on the mass optimization of both the PocketQube's structure and its deployment system. Formulating a methodology applied on the TU Delft's own PocketQube project, the DelfiPQ.

In the Aerospace industry mass is always aimed to be reduced. Accordingly, in the small satellite sector it is of vital importance as launch providers charge relative to mass. Despite this, the previously launched missions have somewhat disregarded the mass of the satellite's structures and deployers, deemed merely payload supporting subsystems. Even though the structure generally accounts for more than a quarter of a small satellite's mass, and similarly its deployers amount to two thirds of the total project mass. Currently ongoing missions are making first steps through skeletonization (Rochus, 2008) or alternative outer structures (Dudás, 2014), however no in depth optimization research has been performed. As such the thesis presented here aims to address and solve this issue. During this research, various factors involved with a PocketQube's structure and deployer are investigated. This is done in order to explore the possibilities for mass reduction, and thus increase its cost effectiveness.

Initially the findings of a general PocketQube literature study are presented in chapter 2 in order to make the reader more familiar with the subject "PocketQubes". This leads up to the primary research question and sub questions as included in chapter 3, aimed at a mass reduction design methodology, serving as a red thread for this thesis. This roughly divides the research presented into three global themes; That which is desired from a picosatellite, the possibilities in order to achieve mass reduction, and the proposed design concepts with their respective testing. Subsequently these are broken down into a number of chapters, the outline of which is illustrated as follows:

A stakeholder analysis is performed in chapter 4, in order to emphasize the parties involved with a PocketQube mission and what their respective needs or uses are. Hereafter requirements for a structure and deployment system are formalized and tabled in chapter 5 in correspondence with the actual DelfiPQ PocketQube mission.

The loads to which a PocketQube is subjected are presented and investigated in chapter 6.

After this the current standards and dimensions for PocketQubes and their deployers are investigated in chapter 7, and a new standard is proposed, by which a further step towards mass optimization can be taken. Attention is given to scaling of multiple structural properties in chapter 8 when going from

CubeSat (the ten centimeter cube format) to PocketQube, providing further insight into mass reduction by material omission.

Suitable materials are compared and have their properties and qualities with respect to a small satellite mission explained in chapter 9.

A design ideology follows from this and is presented in chapter 10, in which mass reductions are shown for each configuration of material and dimension.

From here on innovative design concepts are presented in chapter 11, either through topology optimization or more inventive means. Prototypes of two concepts are made and tests have been performed as shown in chapter 12.

Finally the results are traded-off against each other in chapter 13 and from this conclusions are drawn as to what design considerations and philosophy should be upheld to reach a mass optimized structure and deployer.

2. Findings of literature study.

In this section the findings of the preluding literature study are summarized and presented. This is done for different aspects regarding PocketQubes, in order for the reader to expand his view of the field of study.

During the literature study (Spronck, 2016) the currently available PocketQube documentation has been examined. Initially the merit of the format itself is investigated and from this it can be concluded that it is possible through standardization, turn-key (plug and play) technology and mass production that there will be missions for which the PocketQube format is the most cost effective one. When scaling down to smaller satellite formats, such as CubeSats, it can be seen that the masses of the payload, EPS (electrical power subsystems) and the TCS (thermal control subsystems), decrease, while the other respective masses increase. This same trend is to be expected when scaling further down to PocketQubes.

In terms of cost, an average PocketQube mission for 1P (single unit) including launch is approximately $35.000. For enthusiasts, looking to purchase a plug-and-play package from PocketQubeshop, prices vary between $35.000 and $75.000 per package. Of this cost, the launch is about $20.000. It can be concluded that although the cost is significantly lower than that of a CubeSat, the cost effectiveness is still not comparable due to the current state of utility. Meaning for example that images from a CubeSat have a higher resolution with respect to their mission cost when compared to a PocketQube mission.

The involved parties have been identified and categorized, these have been split into three groups: universities, companies, and radio amateurs/enthusiasts. These groups have different goals for their respective PocketQube projects, as is further divulged in the Stakeholders section.

The mission goals have also been identified and categorized into three (sometimes overlapping) branches: A learning tool, a tech demonstration and a commercial purpose. As part of its commercial purpose, included are niche missions, such as inspector satellites accompanying larger missions.

Of the subsystems analyzed the most crucial part of any space mission is the payload. Currently PocketQubes are primarily being used for Earth imaging. Apart from this, spectrometry and other atmospheric or ionospheric measurements are being done through PocketQubes. Further payloads consist out of magnetometers, radios and gravity gradient measurements. A large portion of the payload in a less traditional sense is the PocketQube itself, viz. the tech demonstration of space testing its components to prove the validity of the format.

As a launcher the Russian DNEPR (named after the Dnepr river) launcher system has been used in cooperation with the MRFODS deployer for which the UNISAT-5 was the intermediary platform. This same configuration is the launcher of choice for most currently developing missions.

In conclusion, the PocketQube and small satellite field in general are still in a development stage, and as such many aspects remain to be optimized. The focus of this thesis is on the structural aspect of small satellites and their deployers, and devising a method for mass optimization.

3. Research question.

Here the aim of this thesis has been formulated as a set of questions, consisting out of a primary research question and sub questions to serve as a guiding line for this research paper. The questions are presented below:

3.1 Research Question:

How can the combination of PocketQube structure and PocketQube orbital deployer be optimized for mass?

3.2 Sub Questions:

- What are the requirements, needs, constraints and design considerations for the PocketQube structure and orbital deployer from DelfiPQ-PQ, potential launch providers and other major PocketQube stakeholders?
- How do mass, stiffness and other structural properties scale down from CubeSats (1U-3U) and their orbital deployers to small PocketQubes (1P-3P)?
- Which innovative structural design and production methods can be implemented to achieve a mass-optimized design compliant to the requirements and needs?

Over the course of the following sections, the sub questions, leading up to the primary research question, are addressed.

4. Stakeholders.

In this section the parties involved, stakeholders, are examined. First general stakeholders are presented, with their respective needs, followed by the specific stakeholders concerning the DelfiPQ mission. This is done in order to get a better grasp of who the PocketQubes are being designed for and what their respective roles and needs are for a small satellite project.

The stakeholders identified in the literature study are found to be universities (often associated with governments), companies and radio-amateurs and enthusiasts. To give an idea of the parties involved in small satellite missions, for CubeSat missions these are displayed in Figure 1:

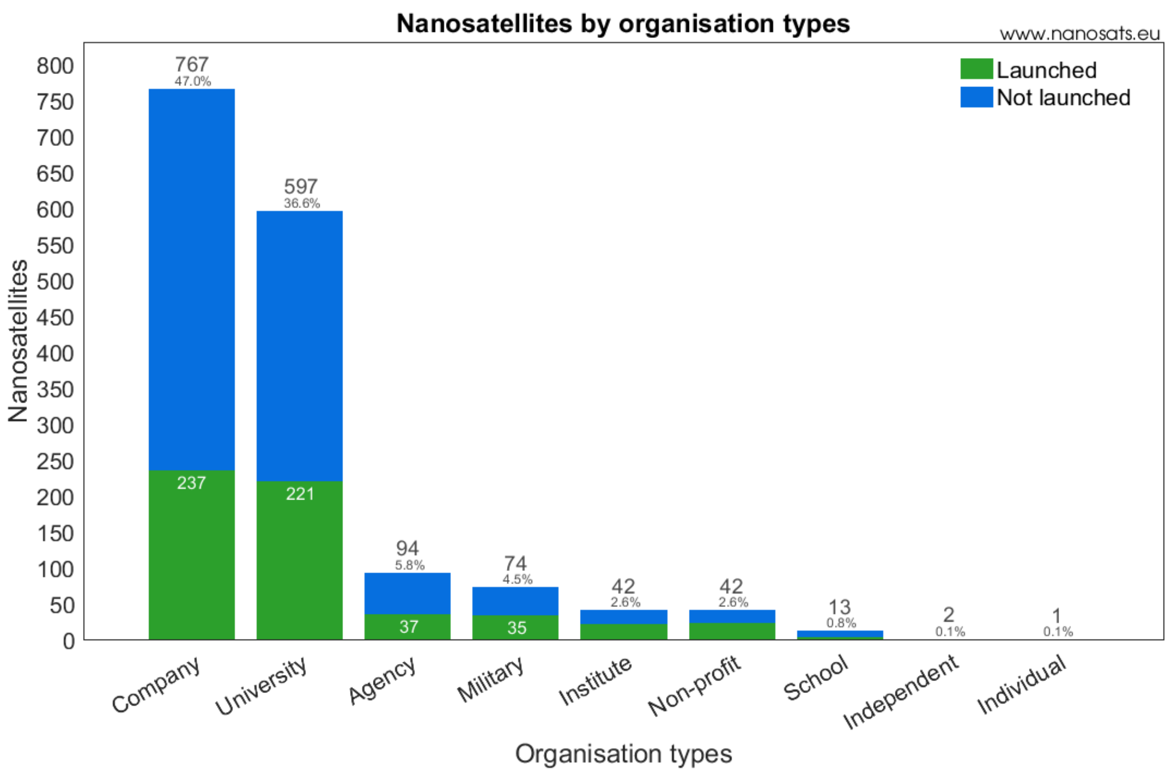


Figure 1 Nano satellites by organization types (Kulu, 2017).

For all three of these aforementioned groups intent on devising small satellite missions the following needs are recognized while performing mass optimization of the structure and deployer:

- Reduction in material costs.
- Reduction in launch costs.
- Equal or better structural properties.
- Compliance with hardware components.
- Compliance with launch provider.
- Compliance with the desired format.

The following stakeholders are found to be relevant for the structural elements and deployer of the DelfiPQ project:

- The TU Delft.

"TU Delft collaborates with a large number of other educational and research institutes within the Netherlands and abroad and has a reputation for high-quality teaching and research. TU Delft has extensive contacts with governments, trade organizations, consultancies, the industry and small and medium-sized companies." (Delft, n.d.)

The university is the crucial stakeholder and main backing force of the project. It provides not only the team of engineers participating in the project, but also the means (both financial and legislative) through which the mission is realized.

- Airbus Defense and Space.

Airbus Defense and Space is a company that is "Europe's No. 1 in defence and space, among the top 10 defence companies worldwide, World-leading player in the space industry, World-renowned range of products including Eurofighter, A400M and Ariane launcher" (Space, n.d.).

For the DelfiPQ project's structure these are relevant as they are likely manufacturing the SPS ring on which the deployer is to be mounted to the launcher.

- ISRO.

"The Indian Space Research Organization is the space agency of the Government of Republic of India headquartered in the city of Bengaluru. Its vision is to "harness space technology for national development", while pursuing space science research and planetary exploration." (ISRO, n.d.)

For the DelfiPQ project's structure these are relevant as they are an alternative potential launch provider DelfiPQ could be using.

- GAUSS.

"The Group of Astrodynamics for the Use of Space Systems (G.A.U.S.S. Srl) is an Italian limited liability company based in Rome, founded in 2012 as a spin-off of the *Scuola di Ingegneria Aerospaziale* of *Sapienza* University of Rome, carrying on the school's more than twelve years tradition in the field of microsatellites. Active in the space technology field, its aims are the research, the development and the implementation of aerospace projects, plus the educational aspect and the execution of related cultural initiatives."

For the DelfiPQ project's structure these are relevant as they are the only company which has created a deployment container for past successfully flown PocketQubes, and thus might require DelfiPQ to conform to their specifications.

- NLR.

“NLR is the Netherlands Aerospace Centre for identifying, developing and applying advanced technological knowledge in the area of aerospace. Their activities are relevant to society and market-oriented. They thus strengthen the innovativeness, competitiveness and effectiveness of government and business.” (NLR, n.d.).

For the DelfiPQ project’s structure these are relevant as they will most likely manufacture parts for the DelfiPQ project, as well as further help towards completing the mission successfully. In this thesis, attention is focused on the capability to 3D print possible structures for the DelfiPQ project.

- Alba Orbital/PocketQubeshop.

“A startup based in Glasgow, Scotland, PocketQube Shop (Alba Orbital Ltd) wants to get more people building and launching their own satellites. We want to provide a hub for the fledgling class of PocketQube satellites by offering a one stop shop with the largest selection of parts available anywhere.” (PocketQubeShop, n.d.).

For the DelfiPQ project’s structure these are relevant as they might be a platform to purchase hardware from for the DelfiPQ project. Other than that they are one of the parties providing an advisory role and can be consulted to benefit the DelfiPQ mission.

- The PocketQube community.

Apart from the major corporations and universities, the PocketQube community also consists of a large number of interested individuals. The community has a stake in every PocketQube project as it simply furthers the field and provides research. Their past insights and further consultation are at the disposal of the DelfiPQ team for use during the project.

- External payload providers.

Currently t.b.d. , one or more payload providers might be called upon to construct a payload for the DelfiPQ project. One can think of imaging and radio systems, technology demonstrations etc.

- Launch provider.

Currently t.b.d , a company is requested to provide a launch vehicle, date and ground station in order to get the DelfiPQ project into a Low Earth Orbit.

In conclusion, over the course of this section an image has been sketched of the parties involved in the DelfiPQ mission, and what their desires or roles are regarding it. In the following section these desires are translated as requirements for the DelfiPQ mission.

5. Requirements and considerations.

In this section attention is given to the requirements pertaining to the DelfiPQ mission, these have been split up into “Facilitation or needs” as driving, “Constraints” as binding, and “Interface and considerations” as additional. What follows is an extra analysis regarding radiation for the structure, and a summary of currently known components to be attached. Achieving a mass optimized structure for the DelfiPQ project, demands a clear definition of its requirements. In accordance with (Boerci, 2017). In Table 1, Table 2, and Table 3, these are given with their reference code for the DelfiPQ mission:

5.1 Facilitation or needs:

Requirement	Code
The Structural System shall be able to host PCBs designed following the PQ9 standard	SAT.1.4.4-F-01
The structure shall accommodate space for at least one kill switch.	SAT.1.4-C-01
The satellite shall be compatible with body-mounted solar panels	SAT.1.4-C-02
The structure shall accommodate venting holes.	SAT.1.4-C-04
The Structural System shall allow for grounding of the radio.	SAT.1.4-C-09
The Structural System shall facilitate the placement of thermal sensors externally on the top, bottom and lateral panels.	SAT.1.4-F-02
The Structural System should facilitate the placement of thermal sensors internally on the top, bottom and lateral panels.	SAT.1.4-T-01
The Structural System shall allow for openings in the outer panels for the payloads requiring an aperture to space.	SAT.1.4-C-07
The satellite structure shall allow for feedthroughs to accommodate electrical connectors between the external and internal surfaces of the panels.	SAT.1.4-C-11
The top, bottom and lateral panels shall internally allow for placement of thermal control measures.	SAT.1.4-F-04
Each lateral panel shall have an out-of-plane stay-out zone equal to 2 mm for possible placement of MPPTs	SAT.1.4.3-C-01
Each lateral panel shall have a dedicated in-plane 5x5 cm internal area for possible placement of MPPTs.	SAT.1.4.3-C-02

Table 1 Facilitation or needs.

5.2 Constraints:

Requirement	Code
The structure and deployer shall cost less than [10.000,-] euro to be developed.	
The structure and deployer shall cost less than [10.000,-] euro to be produced.	
The structure shall have no solar cells on the faces at ends of the longitudinal direction.	SAT.1.4-C-03
The Total Mass Loss (TML) shall be ≤ 1.0% for the material used for the Structural	SAT.1.4-C-05

System.	
The Collected Volatile Condensable Material (CVCM) shall be ≤ 0.1% for the material used for the Structural System.	SAT.1.4-C-06
The choice of material for the Structural System shall prevent spacecraft charging.	SAT.1.4-C-10
The structure of DelfiPQ shall follow the form factor characteristics of the MRFOD standard.	SAT.1.4-I-01
The satellite shall not have structural modes at frequencies <60 Hz in hard mounted configuration.	SAT.1.4-P-01
The center of mass of the Structural System shall lay within a radius of 10 mm from the geometrical center of the system.	SAT.1.4-P-02
The satellite structure shall withstand the quasi-static loads induced by the launch.	SAT.1.4-P-03
The satellite structure shall withstand the sine vibration loads induced by the launch.	SAT.1.4-P-04
The satellite structure shall withstand the random vibration loads induced by the launch.	SAT.1.4-P-05
The satellite structure shall withstand the shock loads induced by the launch	SAT.1.4-P-06
All Structural System components should have a lead time for manufacturing and/or delivery equal to maximum 8 weeks.	SAT.1.4-T-02
The solar panel substrate material choice shall have properties such that the thermal induced stresses in the Temperature range [-40° C, +60° C] will not result in detachment from the solar cells	SAT.1.4-C-08
The outer structure of the satellite shall be compatible with a sliding back plate according to the MRFOD standard	SAT.1.4-I-03
The inner structural configuration shall be a stack of PCBs hosting the subsystems and payloads.	SAT.1.4.4-C-01
The two extremities of the internal stack shall be the antenna board and the antenna release board.	SAT1.4.4-C-02
The Structural System shall have a mass not larger than 150 g	SAT.1.4-C-12
The Structural System should have a target mass equal to 100g	SAT.1.4-T-03

Table 2 Constraints.

5.3 Interface and considerations:

Requirement	Code
The solar panel substrate shall allow for easy assembly of the solar cells.	SAT.1.4-F-03
The Structural System shall include the interfaces to allow the satellite to be tested a system level after integration.	SAT.1.4-I-02
The choice of material for the interface rail shall ensure no jamming of the satellite inside the deployer.	SAT.1.4-I-04
The Structural System shall enable integration and removal of subsystems from the inner stack.	SAT.1.4.4-F-02
The battery shall have a protective structure.	SAT.1.4.5-C-01
The dimensions of the battery protection bracket in the longitudinal direction of the satellite (-Z,+Z) should not exceed 2 mm in total.	SAT.1.4.5-T-01
The Structural System shall allow for quick and non-destructive integration and de-assembly of the satellite	SAT.1.4-F-01

Table 3 Interface and considerations.

5.4 <u>Radiation analysis.</u>

A requirement that deserves extra attention is the potential need for radiation shielding. The importance is readily demonstrated when comparing a 2.0mm aluminum shielding to no shielding for the DelfiPQ project. The resulting difference for a 3P PocketQube is a mass of 314,5 grams, which for a picosatellite is a substantial amount as these generally range between 0.1kg and 1.0kg. Apart from this, also a larger deployer has to be created for a thicker shielded cube, which in turn results in a higher mass.

The focus of this analysis is to answer the question: <u>Should the DelfiPQ mission have radiation shielding at all?</u>

Initially it serves to answer, what are radiation effects on electronics and what causes them?

According to (LaBel, n.d.), the detrimental effects are the following:

- Degradation of micro-electronics
- Degradation of optical components
- Degradation of solar cells
- Data corruption
- Noise on Images
- System shutdowns
- Circuit damage

According to the same paper, of the radiation sources in question - protons, electrons and neutrons - protons are the main cause of damage and undesirable effects. These sources are generated by:

- Solar particles
- Free-space particles ("for earth-orbiting craft, the earth's magnetic field provides some protection")
- Trapped particles

By (Omid Zeynali, n.d.) in depth spacecraft shield design and the factors it depends on have been researched. The preferred metals suited for a PocketQube, due to their mass to structural strength properties, are aluminum and titanium. A shielding test has been performed (for a larger orbit of 1600km) to demonstrate the effects of aluminum thickness on incoming radiation as displayed in Figure 2:

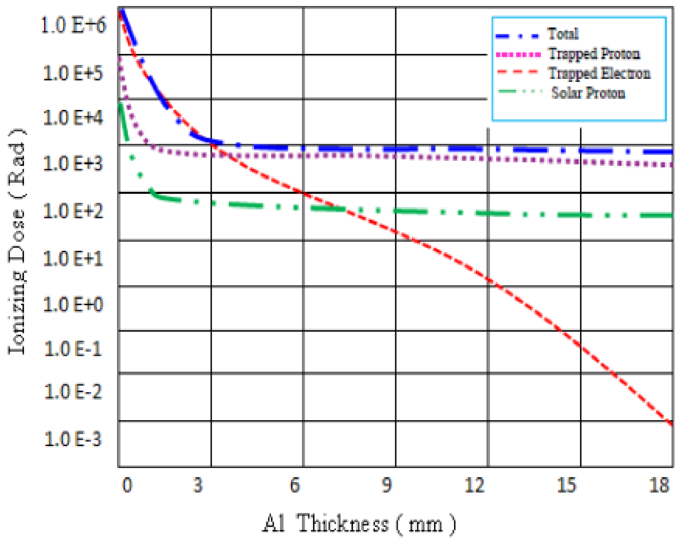


Figure 2 Ionizing Dose vs. Aluminum Thickness (Omid Zeynali, n.d.).

As can be seen in Figure 2, with a thickness of more than 3.0mm, the total radiation coming through barely decreases, as such this serves as an upper bound. In the paper a statement is made that most harmful effects become apparent from $2 * 10^{10}$ flux of protons 10 MeV. This can be checked in the SPENVIS software package (ESA, n.d.) for orbits ranging between 300km and 700km altitude, which corresponds with previously launched PocketQubes that were released at 700km altitude. The results are shown in Figure 3 and Figure 4 for thicknesses of only aluminum below 3.0mm:

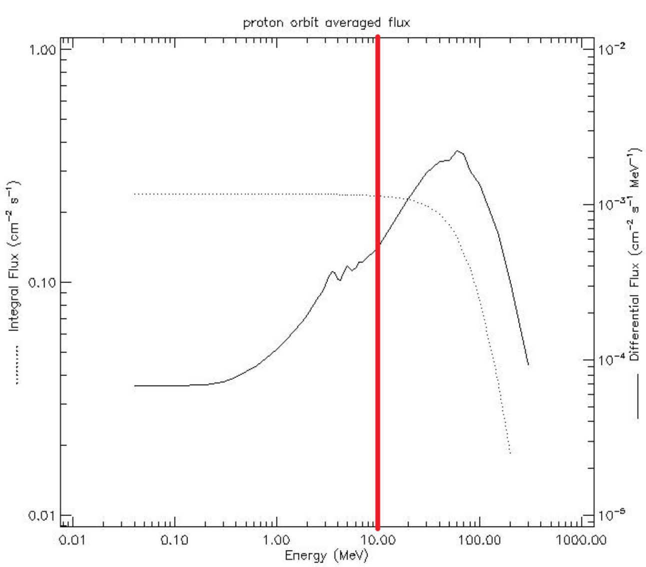


Figure 3 Flux for 0.370 aluminum shielding.

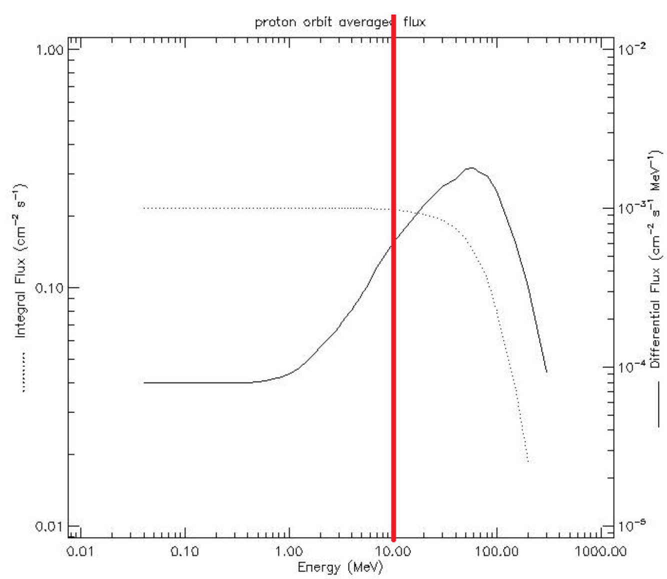


Figure 4 Flux for 1.853 aluminum shielding.

Simulating the radiation effects, results in Figure 3 and Figure 4. From which it can be concluded that for the protons hitting our desired PocketQube mission, the threshold of $2 * 10^{10}$ of both integral flux $[cm^{-2}s^{-1}]$ or differential flux $[cm^{-2}s^{-1}MeV^{-1}]$ is never hit for protons of 10 MeV.

However, these are the larger effects seen in the degradation of components, the single event upset effects (such as data corruption, bit flips etc.) always take place, so it serves to investigate what the effects of radiation shielding are on these.

On this particular type of shielding for low earth orbits, research has been done by ESA (Kiri L. Wagstaff, n.d.). Simulations have been run through their lightweight SEU (single event upset) software simulator, BITFLIPS (basic tool for fault localized injection of probabilistic SEUs). The software radiation simulator injected errors (SEUs) into RAM while the program is running, the data then requested by the algorithm from RAM was inspected for its level of corruption. As illustrated in Figure 5:

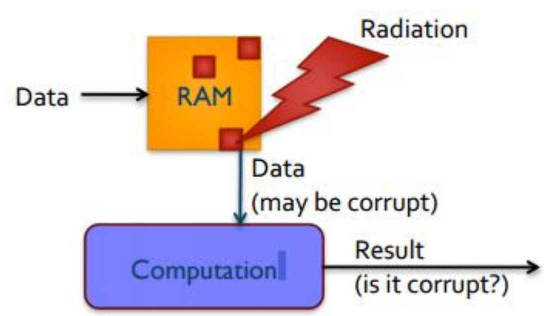


Figure 5 Data processing representation (Kiri L. Wagstaff, n.d.).

During these simulations it was found that “for operation in low Earth orbit, even commercial RAM provides more than enough protection for both classification and clustering algorithms to produce correct results despite ongoing SEUs.” A further interesting find was that “simpler algorithms (regular k-means clustering, linear support vector machines) have less sensitivity (more tolerance) than more sophisticated versions (kd-k-means, Gaussian support vector machines).” As is shown by Figure 6:

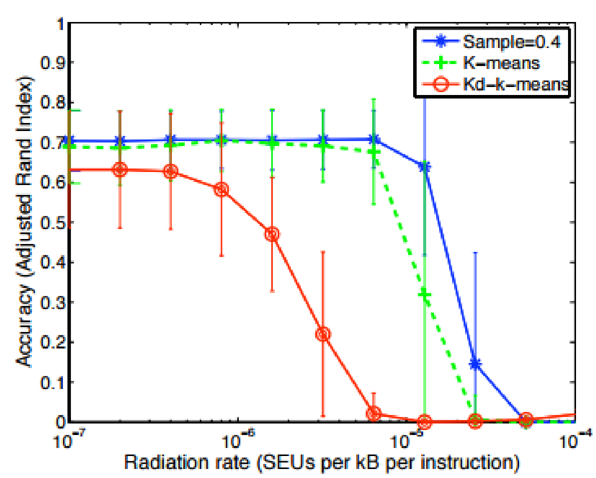


Figure 6 Radiation rate versus accuracy for different algorithms (Kiri L. Wagstaff, n.d.).

Furthermore the SEUs are of such a small degree in low earth orbit that even without radiation hardened components, software options are available that would provide the same level of reliability.

A final worthwhile investigation is to inspect CubeSat missions with no structural shielding. According to (Rochus, 2008), the structure of the sides of CubeSats has evolved from solid (ISIS structure), to skeletonized (Pumpkin structure) and eventually to open sided, where the only thing attached to the side are the PCBs used for the solar panels ,etc. A number of CubeSat missions have already been successfully launched with this type of “skeletonized” or “open side” structures covered by PCB’s (Space, n.d.). Shown in Table 4 are the mission names and their respective mission launch date and lifetime:

Mission name	Launch date	Mission lifetime
ITU-pSAT1	September 23, 2009	6 months
Caerus/Mayflower	December 8,2010	13 days
GOLIAT	February 13, 2012	3 years
HawkSat-1	May 19, 2009	2 years
Libertad-1	April 17, 2007	>2 years
RAX	November 2010	2 months
RAX-2	October 28 2011	2 years
CSSWE	September 13, 2012	1 year

Table 4 Previous missions with respective lifetimes.

All of these missions had Pumpkin open or skeletonized structures, with only PCBs as a form of radiation shielding. From this can be concluded that for LEO CubeSat missions an open or skeletonized structure covered by PCB’s provides such radiation shielding as to allow for a satisfactory lifetime (in the range of years).

This agrees with a statement from (Omid Zeynali, n.d.) saying “for orbits below 1000km almost no additional shielding is required”, and the further general consensus is that radiation shielding is intended for missions with a longer desired lifetime (five to ten years). Also important to note is that the CubeSat requirements standard (NASA, n.d.), has no requirement pertaining to radiation shielding whatsoever.

All the above concludes the radiation analysis and answers the question regarding PocketQube radiation shielding; there is no need for a requirement for extra shielding against radiation on a PocketQube structure.

5.5 Components to be attached to the structure:

In this section another dictating design characteristic is presented: the components that need to be attached to the structure. Technical drawings of the structure with its attached components together, and individually, are presented in Figure 7.

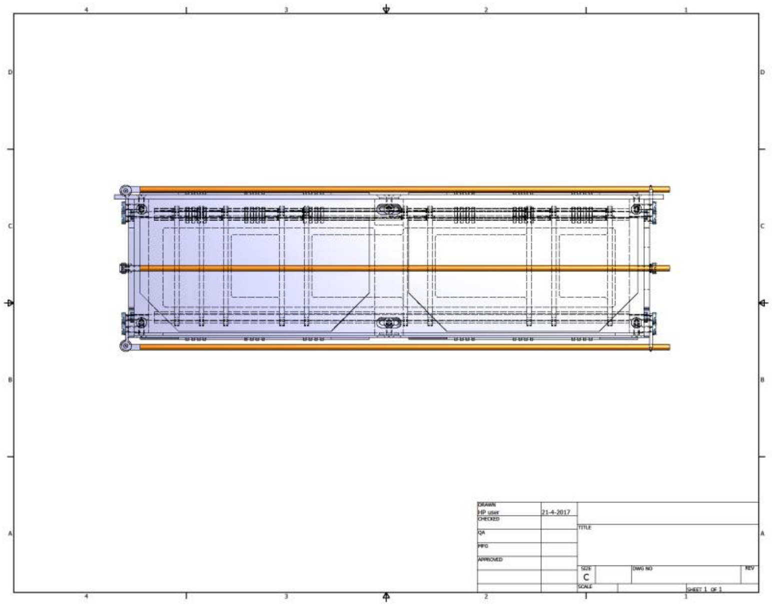


Figure 7 3P DelfiPQ see-through undeployed.

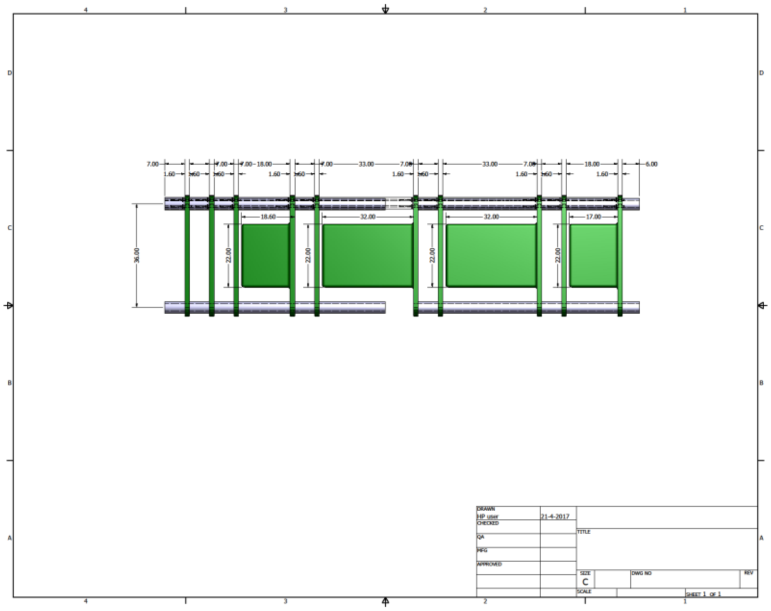


Figure 8 DelfiPQ current PCB stacking.

Presented in Figure 8 is the inner layout of the PCB stacking. There are three different sizes of PCB's, from here on referred to as respectively standard, medium and large PCB.As can be seen the stacking consists of six standard, two medium and two large PCB's, in the order as shown above. The stacking and configuration of the PCB boards is subject to change, and might be outdated at the time of reading as the project progresses.

Presented in Figure 9 and Figure 10 are a solar cell and one of its connectors.

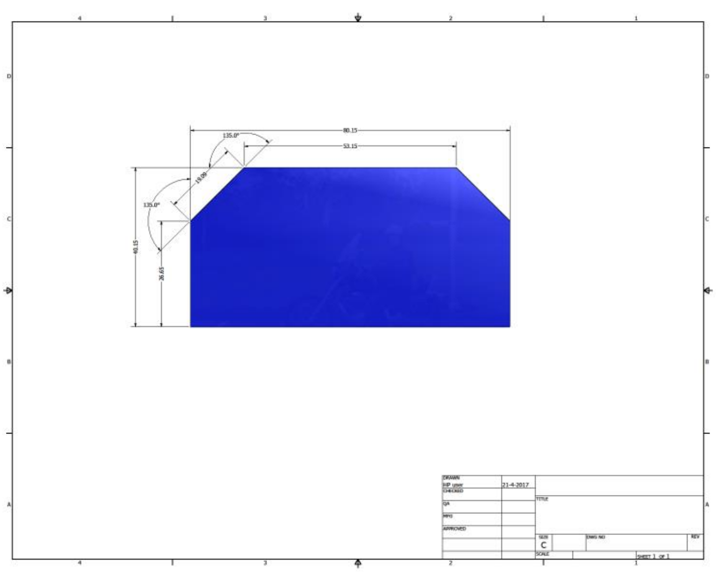


Figure 9 DelfiPQ solar cell.

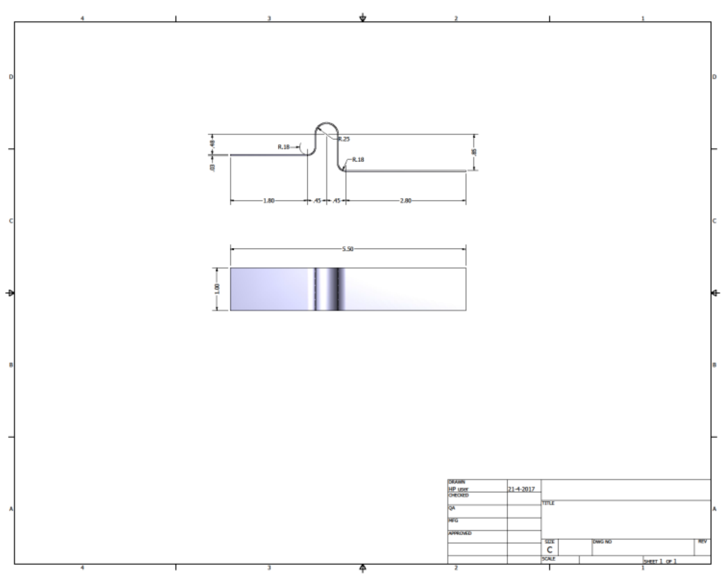


Figure 10 DelfiPQ solar connector.

The DelfiPQ mission has two solar cells per side, so a total of eight, with each 12 connectors, making a total of 96 connectors. It should further be noted that the solar cell itself is considered as the functional component and the solar panel to which it is attached seen as supportive.

Presented in Figure 11 and Figure 12 the mounting board and the antennas.

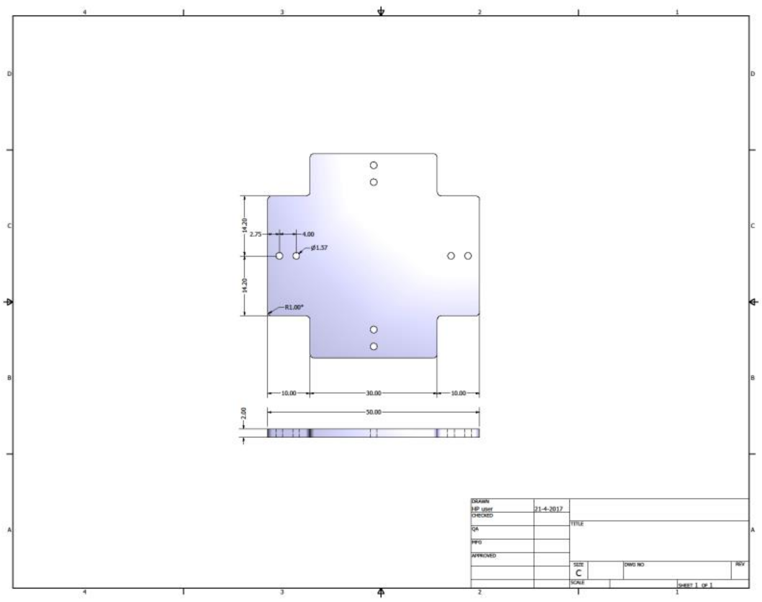


Figure 11 DelfiPQ antenna mount.

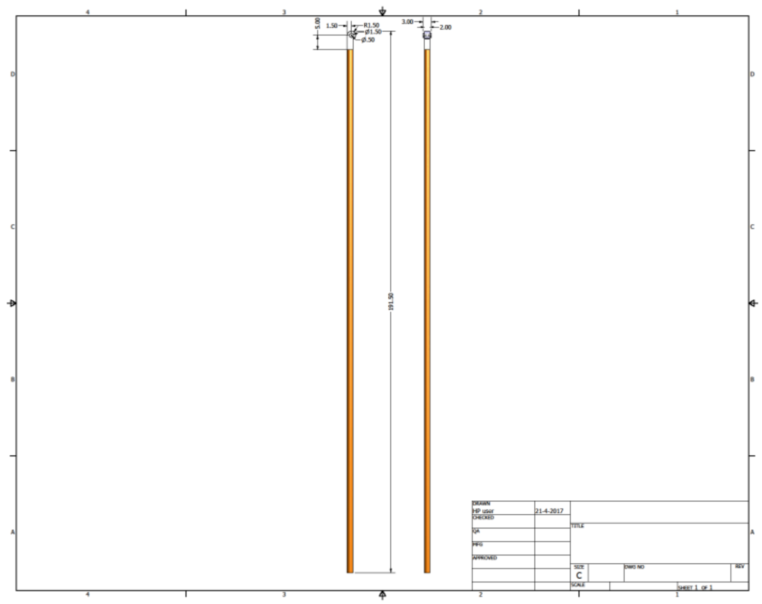


Figure 12 DelfiPQ antenna.

The DelfiPQ mission has four antennas, one for each side, and two mounting boards on the ends of the structure. The mounting board is used on one side to facilitate the hinge for the antenna, and on the other side to facilitate the release mechanism for antenna deployment.

Presented in Figure 13, Figure 14, Figure 15 are respectively, the standard, medium and large PCB.

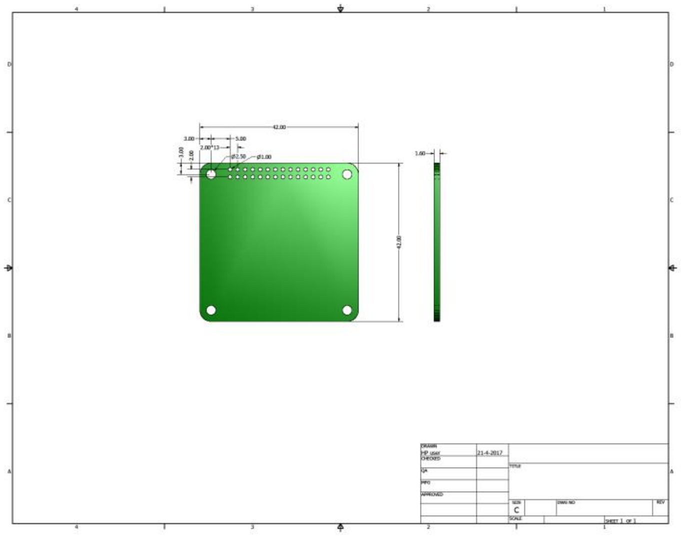


Figure 13 DelfiPQ standard PCB.

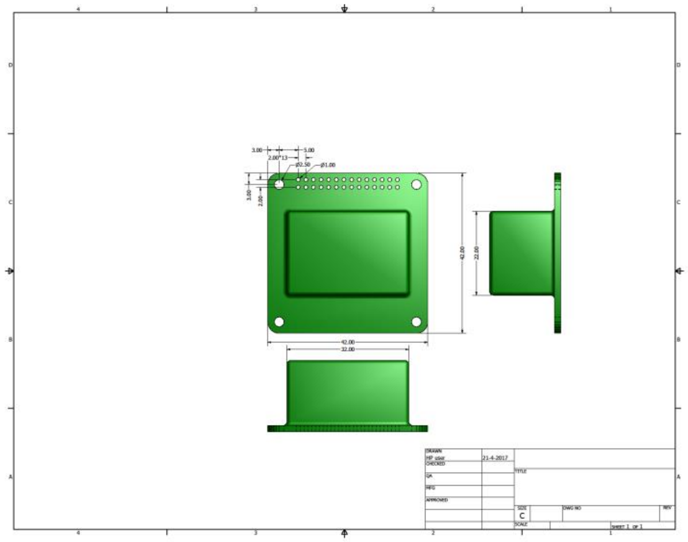


Figure 14 DelfiPQ medium PCB.

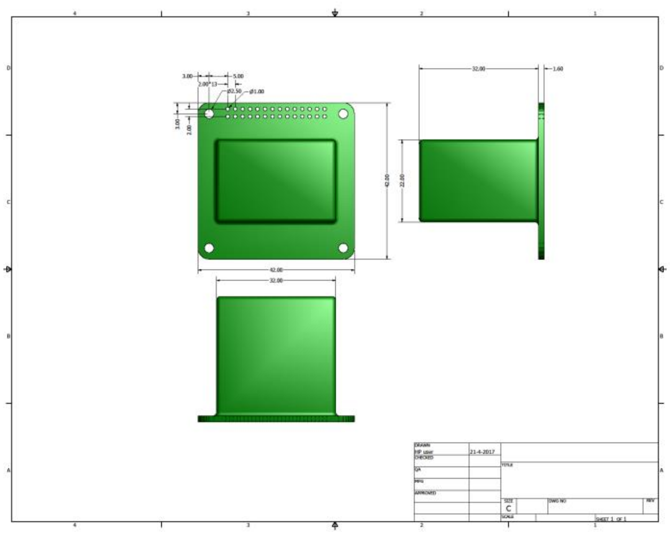


Figure 15 DelfiPQ large PCB.

In this section the current components including PCB's with their stacking configuration have been shown. These components including their respective ways of mounting might still be subject to change as the project progresses.

In conclusion: In this chapter both driving and binding requirements have been presented for the DelfiPQ mission structure. Additionally, further analysis proves that it should not have extra shielding against radiation, so no requirements pertaining to this are in order. The next chapter provides insight into the loads a PocketQube structure will come to bear.

6. Loads.

6.1 Mechanical loads.

In this section one of the most important design elements is displayed: the loads the structure is susceptible to. The relevance of this comes from the simple fact, that the higher the loads are, the stronger and thus thicker the structure must be. So in order to get a structure as light as possible it is important to get clear values for these loads. The load cases presented below are taken from the launch manuals of two potential launch providers, VEGA (arianespace, 2014) and PSLV (ISRO, 2000) (Boerci, 2017), respectively.

Vega

Mechanical Loads Envelope

Eigenmodes

Type	Description/Value
Minimum Fundamental Frequency	60 Hz
Occurrence	LV longitudinal axis

Table 5 VEGA Eigenmodes.

(Quasi-Static) Acceleration Loads

Type	Description/Value
Maximum Acceleration	-7 [g]
Occurrence	3rd stage maximal acceleration (on LV longitudinal axis)
Safety Factor	1.25
Acceptance Value	7 [g]
Qualification Value	8.75 [g]

Table 6 VEGA Acceleration loads.

Sine Vibration Loads

Frequency Range [Hz]	Acceptance Level [g]	Qualification Level [g]
1 – 5	0.40	0.50
5 – 45	0.80	1.00
45 - 110	1.00	1.25
110 – 125	0.20	0.25
Occurrence	LV Longitudinal axis	
Sweep Rate (Qual.)	2 oct/min	
Qualification Factor	1.25	

Table 7 VEGA Sine vibration loads.

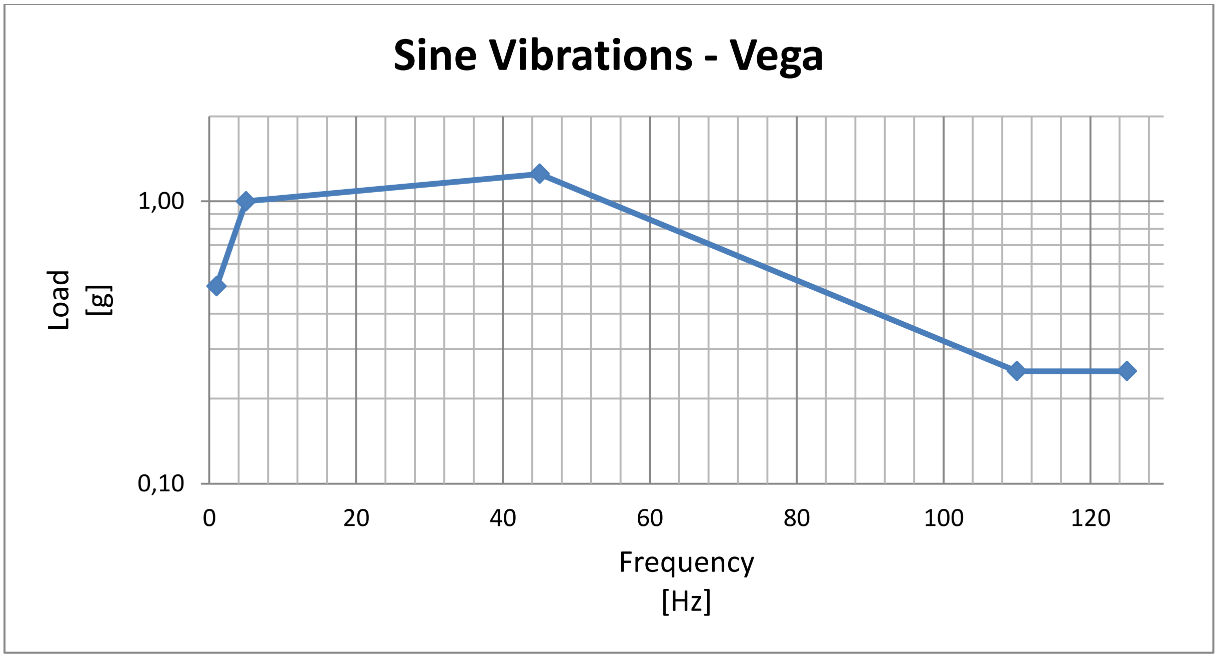


Figure 16 VEGA Sine vibrations plot.

Random Vibration Loads

Frequency [Hz]	Power Spectral Density $[g^2/Hz]$	Power Spectral Density (Qual.) $[g^2/Hz]$
20	0.013	0.026
2000	0.013	0.026
g_{RMS}	7.175 g	
Duration per axis (Qual.)	120 sec*	
Qualification Factor	2*	

Table 8 VEGA Random vibration loads.

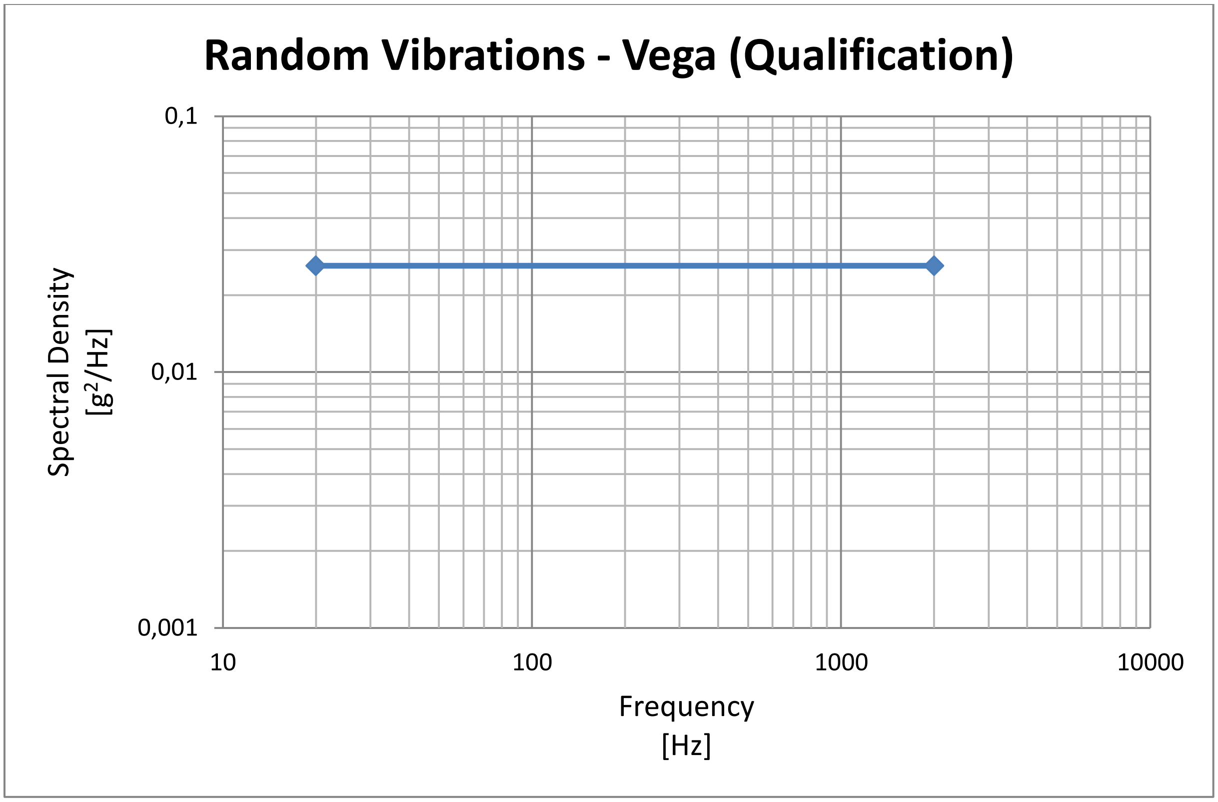


Figure 17 VEGA Random vibrations plotted.

PSLV

Mechanical Loads Envelope

(Quasi-Static) Acceleration Loads

Type	Description/Value
Maximum Acceleration	6.2±0.2 [g]
Occurrence	Stage III (LV Longitudinal axis)
Safety Factor	
Acceptance Value	6.4 [g]
Qualification Value	

Table 9 PSLV Acceleration loads.

Sine Vibration Loads

Frequency Range [Hz]	Acceptance Level [g]	Qualification Level [g]
5 – 11.5	0.22 - 1.20	0.33
11.5 – 20	1.20	1.80
20 – 25	1.20 - 2.50	1.80 - 3.75
25 – 33	2.50	3.75
33 – 35	2.50 - 0.50	3.75 - 0.75

35 – 100	0.50	0.75
Occurrence	N/A	
Sweep Rate (Qual.)		
Qualification Factor	1.5	

Table 10 PSLV Sine vibration loads.

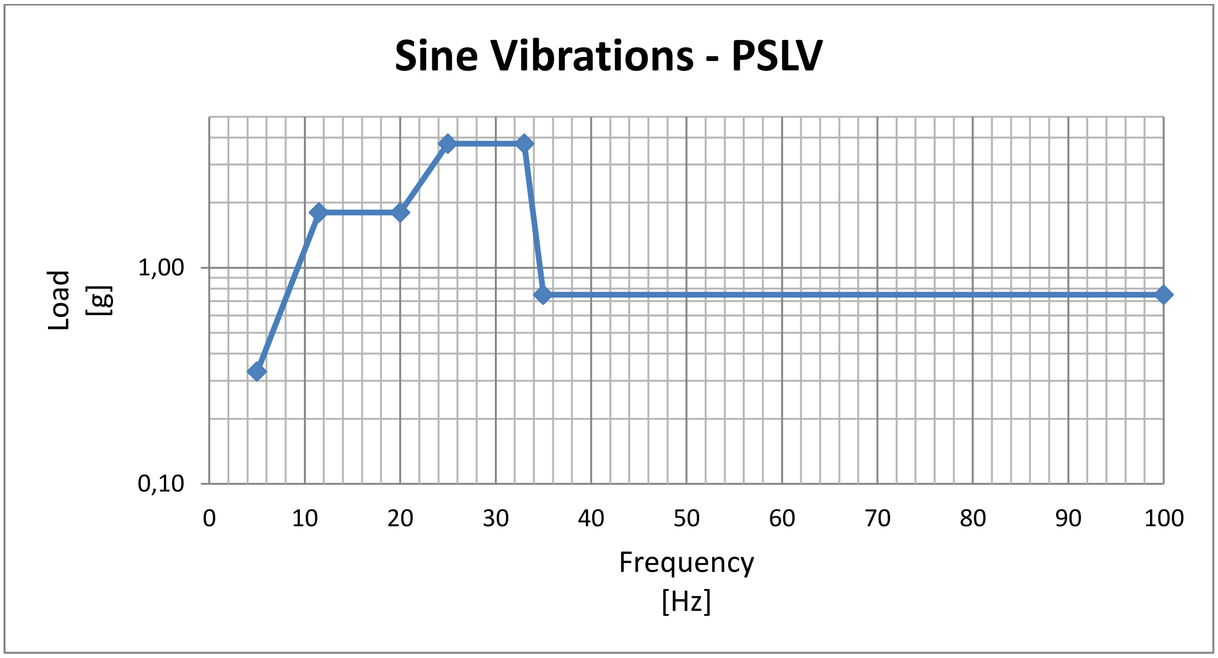


Figure 18 PSLV Sine vibrations plotted.

Random Vibration Loads

Frequency [Hz]	Power Spectral Density [g^2/Hz]	Power Spectral Density (Qual.) [g^2/Hz]
20	0.001	0.002
110	0.001	0.002
250	0.015	0.034
1000	0.015	0.034
2000	0.004	0.009
g_{RMS}	6.692 g	
Duration per axis (Qual.)	120 sec	
Qualification Factor	2.25	
Frequency [Hz]	Power Spectral Density [g^2/Hz]	Power Spectral Density (Qual.) [g^2/Hz]

Figure 19 PSLV Random vibration loads.

For the optimization to be done, the loads are initially taken as the envelope of the maximum values of each subsection put together, and then checked for failure for each individual value. The Eigenmodes are calculated up to 2000Hz through a plug-in of the optimization software. The first 20 Eigenvalues are given in Table 11:

Frequency [Hz[	n_x	n_y	n_z
57.2	1	0	0
114.3	2	0	0
171.5	3	0	0
171.5	0	1	0
171.5	0	0	1
180.8	1	1	0
180.8	1	0	1
206.1	2	1	0
206.1	2	0	1
228.7	4	0	0
242.5	3	1	0
242.5	3	0	1
242.5	0	1	1
249.2	1	1	1
268.1	2	1	1
285.8	5	0	0
285.8	4	1	0
285.8	4	0	1
297.0	3	1	1
333.3	5	1	0

Table 11 first 20 Eigenmodes.

To illustrate, the first Eigenvalue is shown for the reference frame (attachables made invisible) in Figure 20:

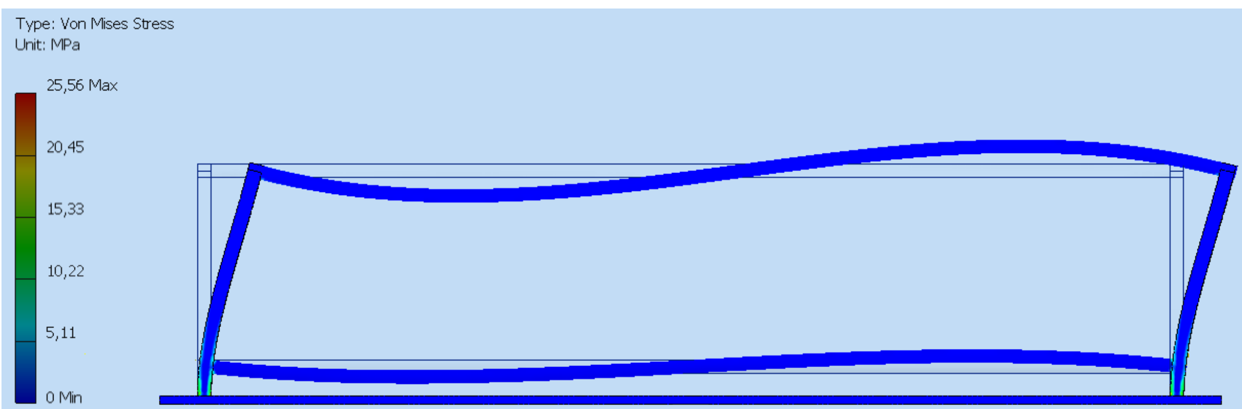


Figure 20 First Eigenmode illustration.

As can be seen in (exaggerated deformation) Figure 20, the first Eigenfrequency of 57.2 Hz, causes a vibration in one plane in the x direction, specifically the four attachments of the wireframe to the guiding plate. A maximum stress of 25.56MPa is registered.

To give an idea of what the pressure points are where most tensile loads are placed, a simulation is run for the new structure containing the stacks (considered the bulk of the mass). Shown in Figure 21 is an exaggerated image, showing where forces during launch apply:

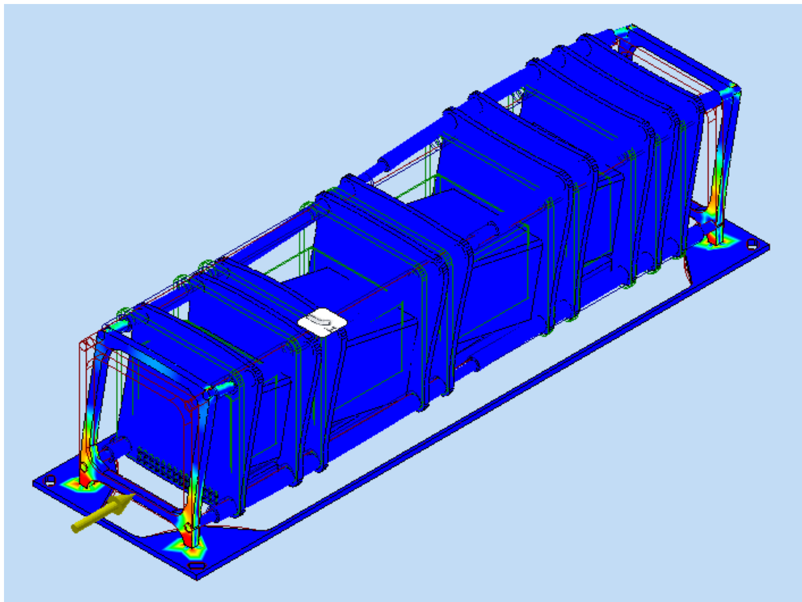


Figure 21 Windform structure with internal stacks exaggerated loads display.

The image presented is a result from the topology optimization performed in the chapter 11. However it serves to show that the bulk of the forces are situated at the attachment between the end rods and the bottom plate.

6.2 Transport loads

Another factor that needs to be taken into account is the loads that are brought upon the PocketQube during transport, as it is also not allowed to mechanically fail during this stage of the mission.

Transport loads by cargo trucks are regarded by (Maheras, 2013), and generally found to be well below 2.0g acceleration and 30Hz vibrations.

Transport loads by cargo airplanes are regarded by (Boeing, n.d.), and generally found to be well below 3.8g acceleration and 40Hz vibrations.

As both types of transportation loads are significantly lower than the loads during actual launch, these are considered negligible henceforth.

6.3 Thermic expansion loads

Another type of loads is the thermic expansion and contraction of the material. Considering the low earth orbit temperature range of 103.15K to 396.15K (Israel, n.d.). The software used does not allow straight implementation into the topology optimization, however it does allow checking the stresses for the finished product.

Shown in Figure 22 and Figure 23 are the maximum stresses for respectively the maximum and minimum temperature, given in exaggerated deformation views:

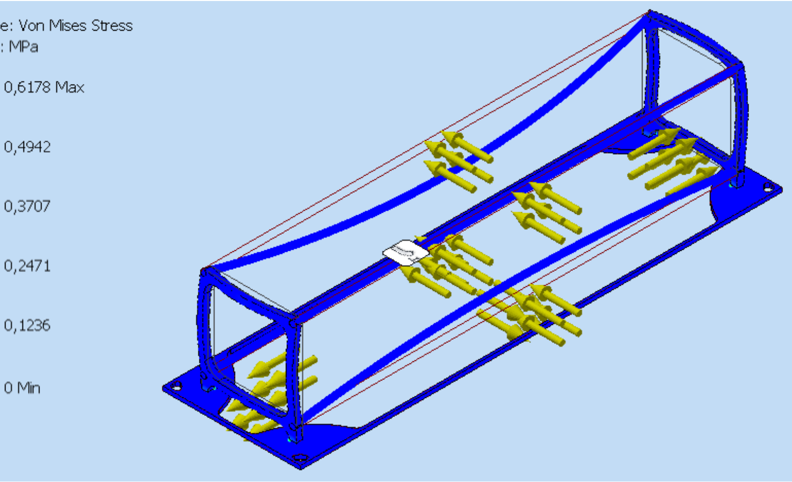


Figure 22 Maximum temperature expansion stresses.

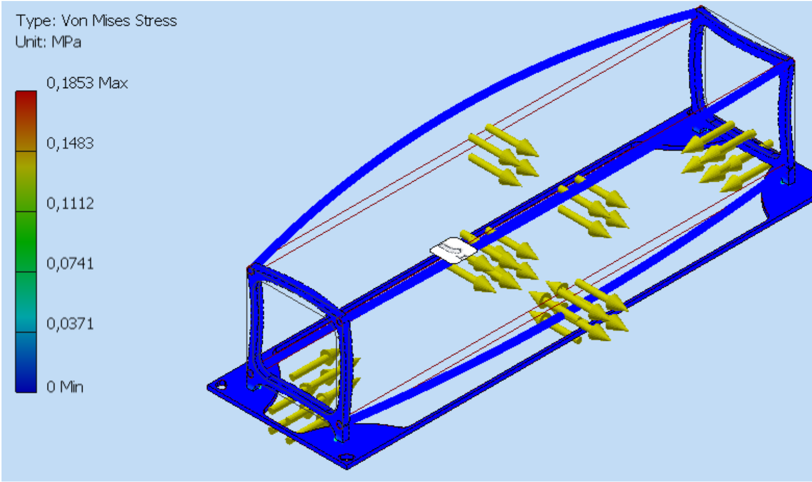


Figure 23 Minimum temperature contraction stresses.

The stresses for the Windform structure, going from maximum to minimum temperature respectively, are 0.6178 and 0.1853 Mpa. Both not causing the structure to yield, therefore from here on out, the thermal expansion and contraction loads are considered negligible for the structure.

With the requirements, considerations, attachables and loads known the first sub question has been answered in chapters 5 and 6. However before the actual design process can start, first the format standard of PocketQubes has to be investigated to serve as a reference point. In the following section this is researched and a more suitable standard is suggested, from which designing continues.

7. Format standard.

In this section the original, or current, standard of both the PocketQube structure and deployer format is presented through technical drawings. Explanation is given as to the differences with CubeSats and other aspects. After which a smaller format is presented in order to save mass.

In order to optimize the structure of the DelfiPQ project, a good starting point is the currently abided standard for PocketQubes. Here the three general variants are displayed for a 2P and a 3P PocketQube, the variants differ solely in the Z-axis, currently the “option 1” variant is the ongoing choice as to allow for mounting space on the ends without touching the deployment systems.

The 2P variants:

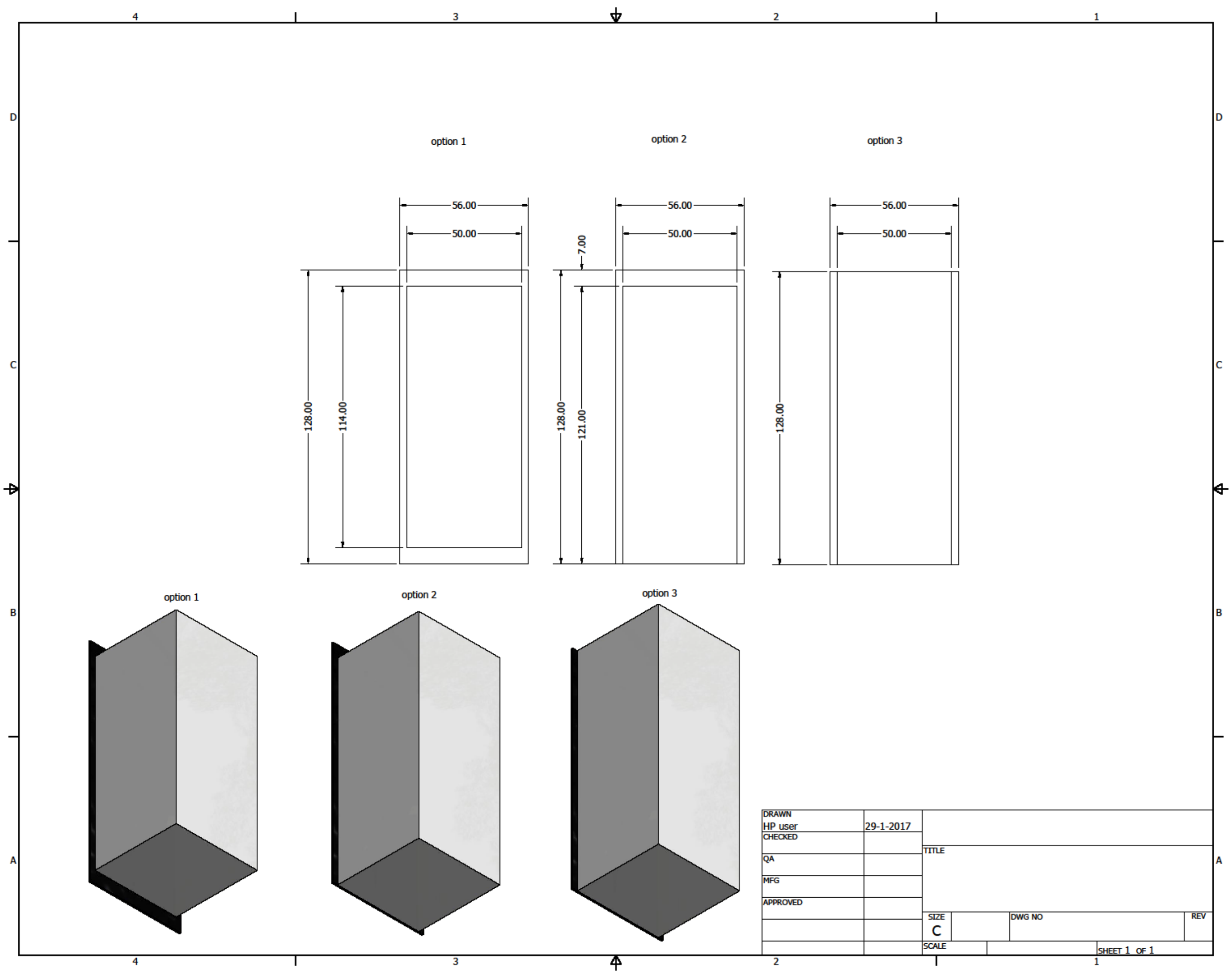


Figure 24 2P PocketQube options dimensions.

The 3P variants:

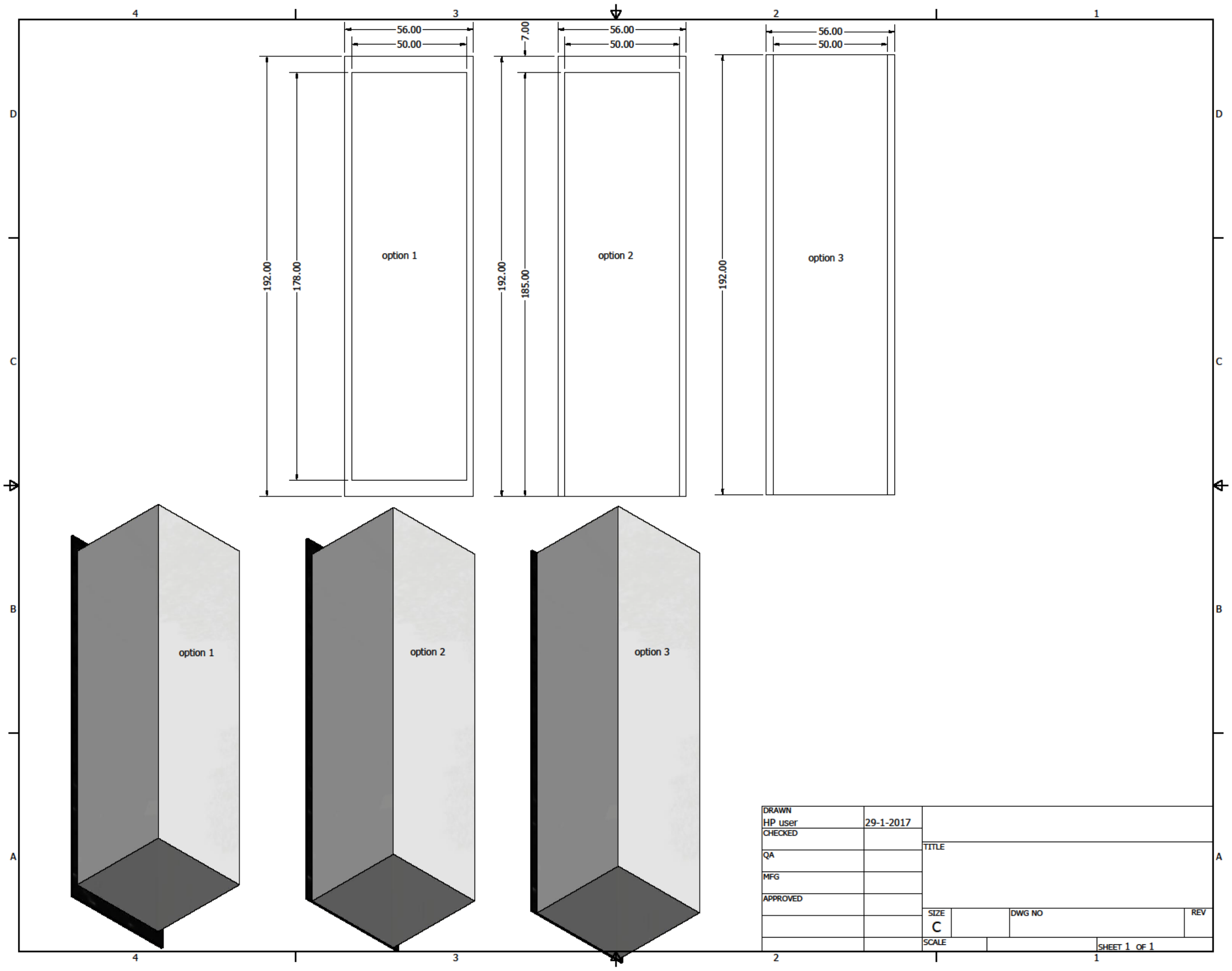


Figure 25 3P PocketQube options dimensions.

The DelfiPQ project aims for a 3P setup, in order to provide as much space for payload and other subsystems as possible. This is a common trend, also seen in CubeSat launches. To illustrate the distribution of units taken on CubeSat missions, Figure 26 is shown:

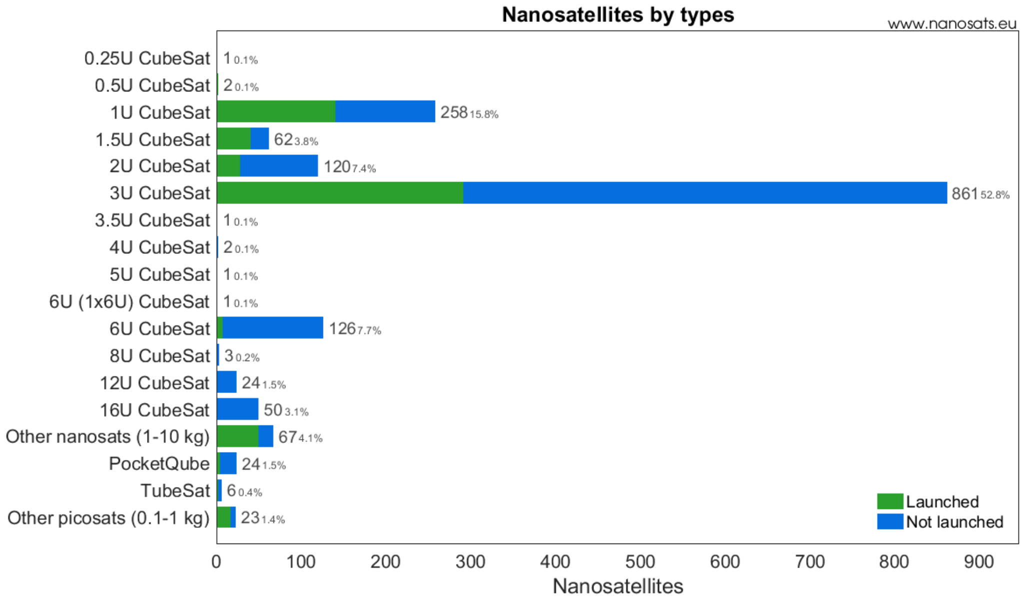


Figure 26 Nanosatellites by types (Kulu, 2017).

The amount of units of which the project consists, only affects the dimensions, but not its design margins. Below, as viewed directly on the Z-axis the currently maintained margins for PocketQube expansion are shown in Figure 27:

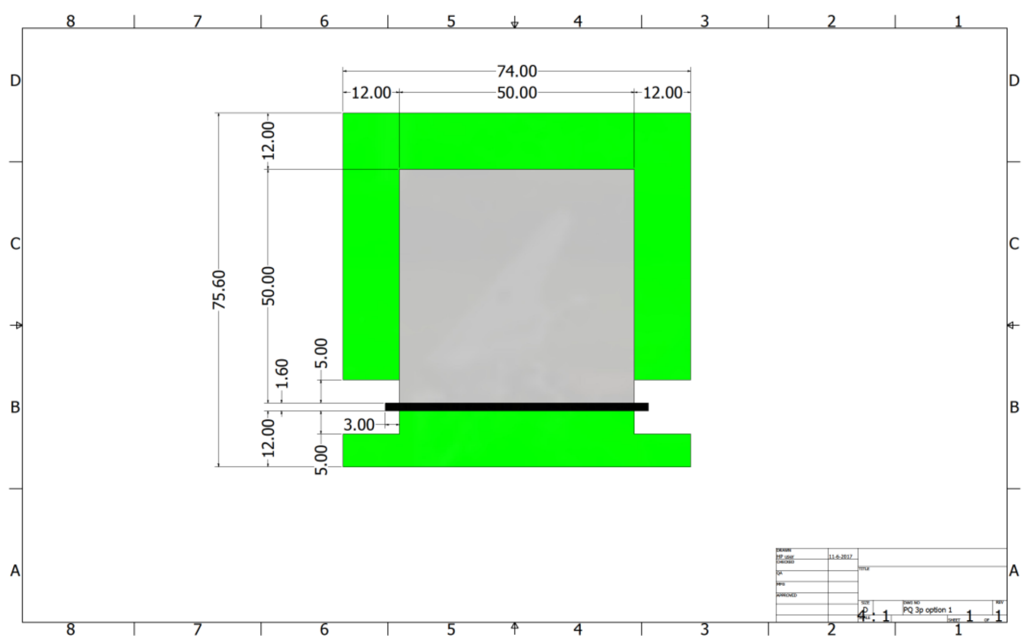


Figure 27 Original PocketQube standard margins.

Set in 2014, the standard theoretical margins for a PocketQube are indicated as $2 * 12$mm (both sides) or $\frac{12}{50} = 24\%$ (per side).

To give a clearer image of the magnitude of the margin currently available by the PocketQube standard an isotropic view is presented in Figure 28:

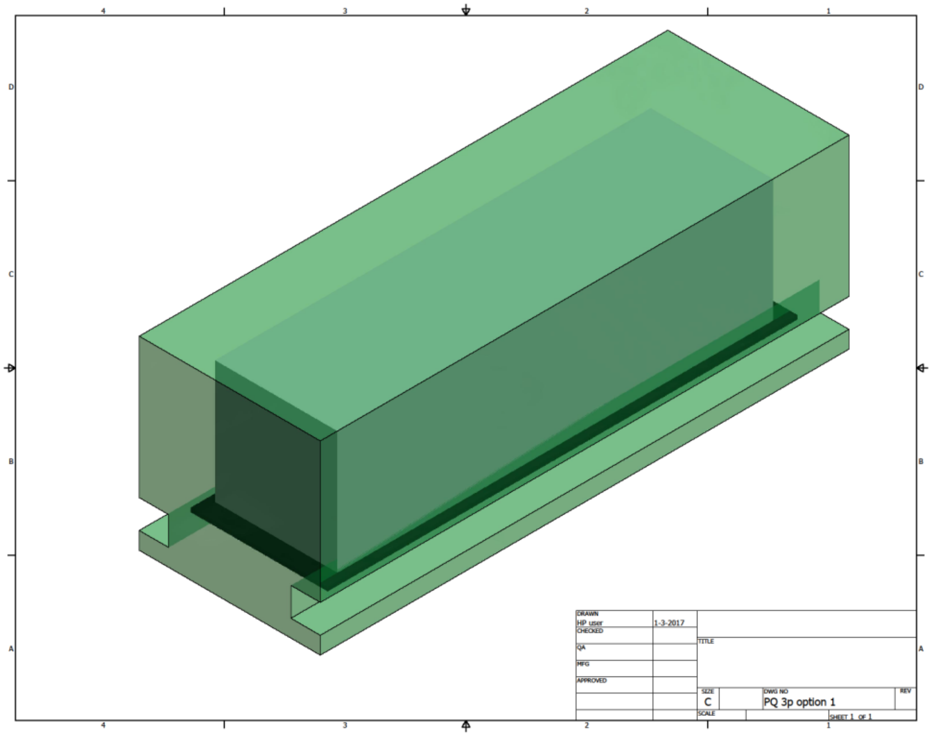


Figure 28 Isometric view of PocketQube standard with margins.

In the Figure 28, the margin is represented by the transparent green sections.

In comparison, CubeSat standard (Puig-Suari, n.d.) theoretical margins are 2*6.5mm or $\frac{6.5}{100} = 6.5\%$ of its dimensions, while for example the TU Delft CubeSat mission Delfi-C3 had used a margin of 10.0mm or $\frac{10}{100} = 10\%$ (Brouwer, 2008). Other missions had their margins mainly dictated by the solar arrays. A typically used panel, for example, is the one offered by ISIS, which uses a margin of 2*2.5mm (excluding harnessing) (ISIS, 2015).

As can clearly be seen, the current standard for PocketQubes and its protrusions has margins that are relatively high, this requires a larger deployer and thus incurs higher mass. A final dimension for the DelfiPQ and thus collaboration with its deployer is yet to be confirmed, however the current proposal is shown in Figure 29:

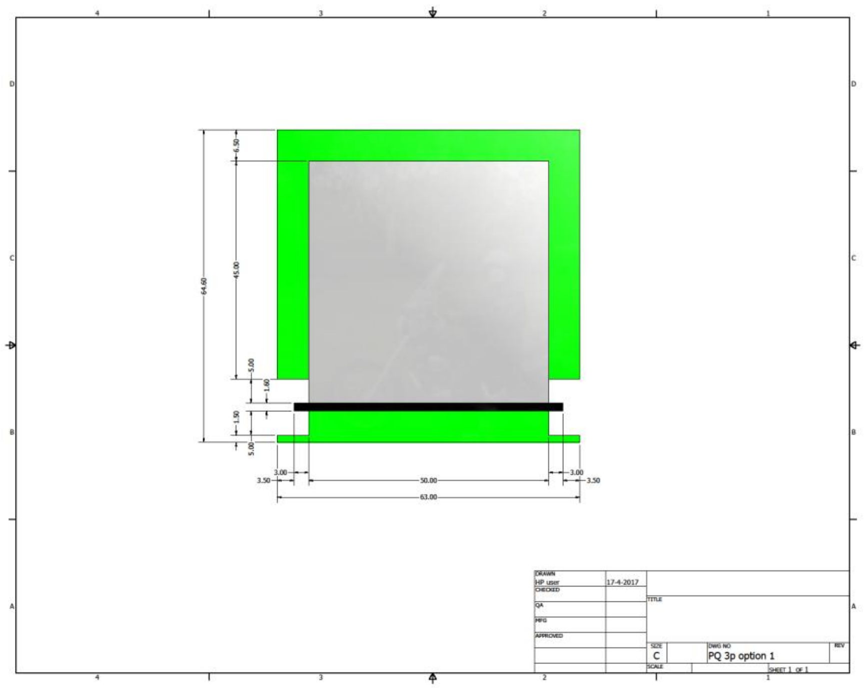


Figure 29 Proposed PocketQube standard margins.

In essence all the margins have been set to 6.5mm. This number has been chosen based on the following two reasons: Firstly it is the same design margin as the CubeSat standard maintains (SLO, n.d.). Secondly this would allow for a PCB (1.6mm), solar cells (0.9mm), antenna rod (2.0mm), hinge extension + hold down wire (1.0mm) and 1.0mm of open space (team, n.d.). Through decreasing this margin, a deployer can already have a lower mass, as is described in the following section.

Presented is the current PocketQube deployment system, PQOD, in consideration by the DelfiPQ project group as shown in Figure 30:

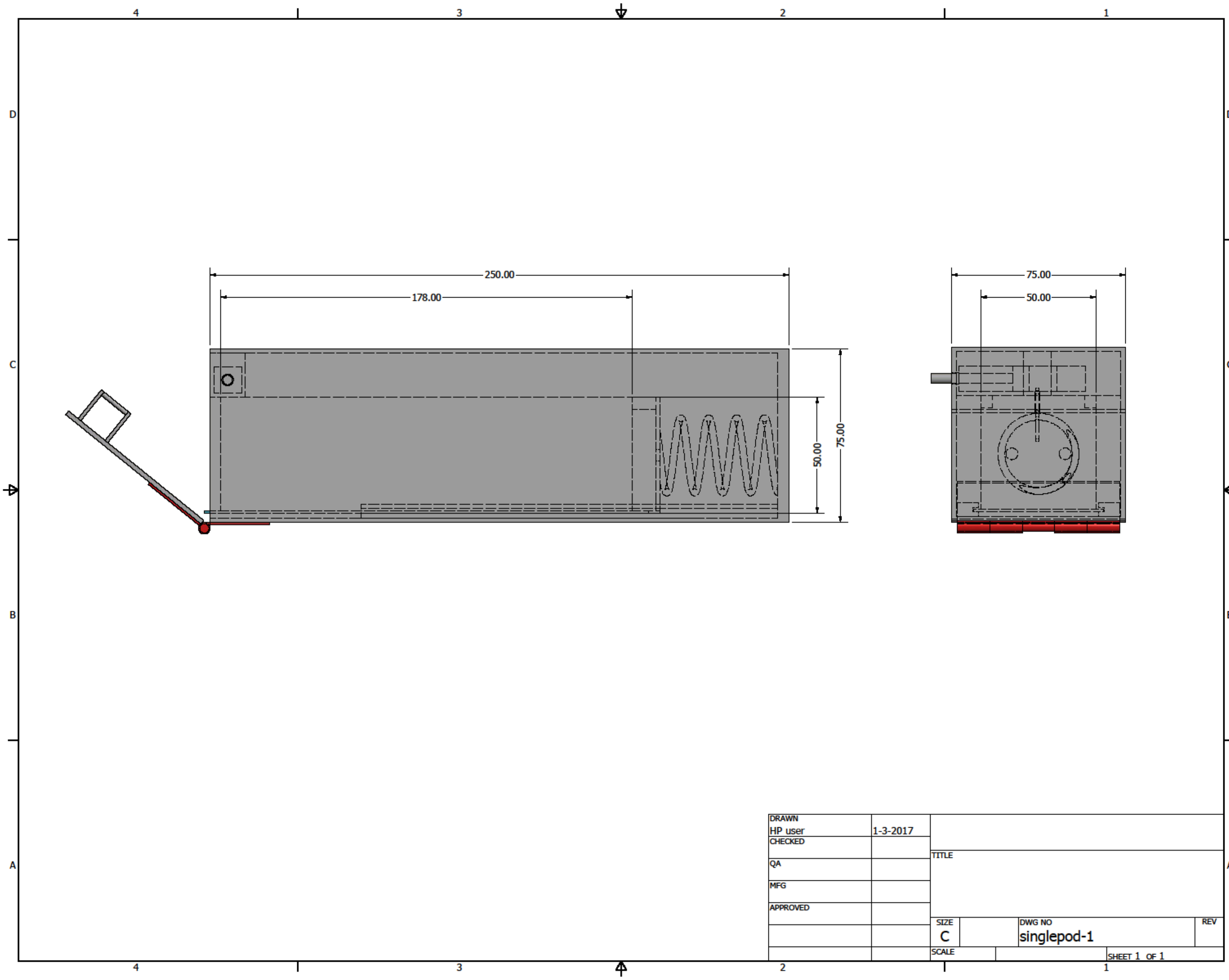
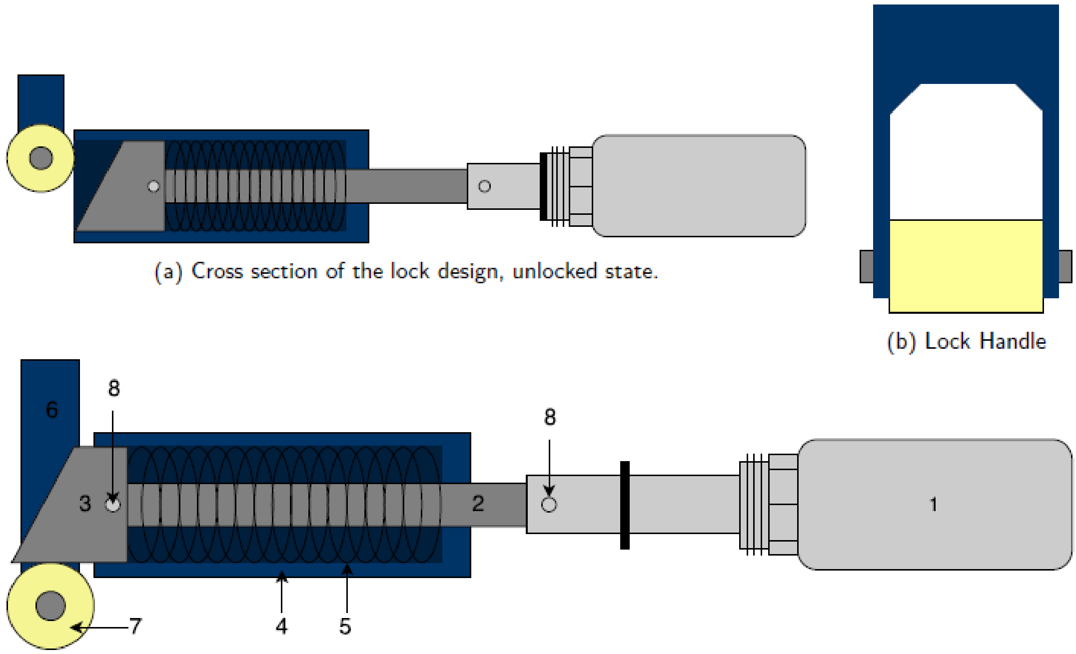


Figure 30 Reference deployer.

The deployer consists of 2.0mm anodized aluminum plates with a total dimensions of 75*75*250mm, with a total mass of around 950g (Snijders, n.d.). In the drawing, outer measurements of the deployer and the actual PocketQube are given in order to demonstrate the inefficiency of the current design. As can be seen, the deployer could be made significantly smaller whilst still housing the PocketQube, and thus achieve a reduction in mass.

A spring-loaded deployment mechanism has been devised as shown in Figure 31:



(a) Cross section of the lock design, unlocked state.

(b) Lock Handle

(c) Cross section of the lock design, locked state.

No.	Part
1	Solenoid Actuator
2	Rod
3	Lock pin
4	tube, hole in backside
5	Spring
6	Handle
7	Wheel at handle
8	Assembly pin

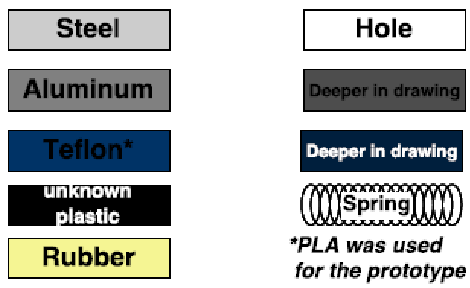


Figure 31 Reference deployment mechanism (Hoogelander, 2016/2017).

Both the deployer and the deployment mechanism now serve as a “starting point” for further development and mass optimization.

In conclusion, both the structure and the deployer benefit from tighter design margins, as the mass of these both can now be smaller while still standardized.

In this section the current standard has been presented as a reference point and a new standard has been proposed. After researching the dimensions of the satellite, in the following section, scaling down to a PocketQube format is investigated in order to explore the possibilities of mass optimization.

8. Scaling.

In this section scaling is examined, firstly by looking at what happens to mass when scaling from CubeSat down to PocketQube. Secondly specific attention is given to the mechanical properties, followed by a FEM analysis comparison.

8.1 Mass differences CubeSat to PocketQube

In order to get a better understanding of the development of a PocketQube structure and deployment mechanism, it is a useful tool to research the scaling from CubeSat to PocketQube.

An important parameter is mass, this is seen to scale as follows.

Assessing structures, taking the TU Delft missions as an example for three unit missions, for the Delfi-n3xt CubeSat structure, a mass of around 791g is found (Delft, n.d.). An average structure CubeSat mass is 0.89kg per U (Kulu, 2017). The DelfiPQ PocketQube structure however is currently estimated to have a mass of around 185g.

Assessing deployers, for the Delfi-n3xt mission the deployer used was the ISIPOD by ISIS, a commonly used deployer, which has a mass of two kilograms (Space, n.d.). Another commonly used deployer, which has also been recommended as the standard in the past, is the P-POD, which has a mass of 1.5kg (Puig-Suari, 2001). To illustrate, the current design for the deployer of the DelfiPQ mission has a mass of around one kilogram (Snijders, n.d.).

Now these mass differences are notable, as the format decreases by a factor 0.5 in three dimensions, so a mass of $\frac{1}{8}$th would be expected, however the mass reduction is about $\frac{1}{4}$th for the structure itself and $\frac{1}{2}$th for the deployer. This leaves room for improvement.

8.2 Dimensioning.

Further untapped potential whilst scaling from CubeSat to PocketQube are the design margins as described in the previous section. Also there seems to be a discrepancy as both the absolute and the relative design margins are smaller for the CubeSat standard than for the PocketQube standard. Summarizing, the PocketQube standard allows for $2 * 12$mm or 24% margin, while the CubeSat standard only allows for $2 * 6.5$mm or 6.5% margin.

These margins are important as they determine what can be fitted onto the outer walls of the PocketQube and thus determine the internal dimensions of the deployer, as such they strongly correlate with total mass. General protrusions on the outer walls include sensors, antennas, hinges, and (generally the largest for PocketQubes) solar panels. Now in the current setting, the margin is 12mm, and the deployer is set at 75mm outer diameter, resulting in a mass of 950grams. In a scenario where the margin was set to the thickness of a standard solar panel, 2.5mm, providing 1.15W. And given a more effective use of the space of the pod, whilst keeping a similar mechanism, its outer dimensions could be reduced to 59mm, resulting in a mass of 701.6 grams. This would already be an improvement, but further improvements can be made when changing the mechanism itself to achieve a lower mass.

Another notable difference between CubeSats and PocketQubes is the guiding railing into the deployer. For the PocketQube standard this is a back plate with two sides contacting with the deployer, for the CubeSat standard these are four sliders on each corner, all contacting the deployer (Puig-Suari, n.d.).

8.3 Mechanical properties scaling

Another important aspect of structural scaling are the mechanical properties. A common notion of structural scaling is described by the Froude Scaling Laws (NTNU, 2017) in which λ is used to describe the scaling factor of a length of the full scale divided by a length of the model. So:

$$\lambda = \frac{L_F}{L_M}$$

Which gives the following general scaling mechanisms presented in Table 12:

Physical parameter	Unit	Multiplication factor
Length	[m]	λ
Structural mass	[kg]	$\lambda^3 * \frac{\rho_F}{\rho_M}$
Force	[N]	$\lambda^3 * \frac{\rho_F}{\rho_M}$
Moment	[Nm]	$\lambda^4 * \frac{\rho_F}{\rho_M}$
Pressure	$[Pa = \frac{N}{m^2}]$	$\lambda * \frac{\rho_F}{\rho_M}$

Table 12 Froude Scaling Law formulas.

This means when scaling elasticity, as seen in a simplified beam example:

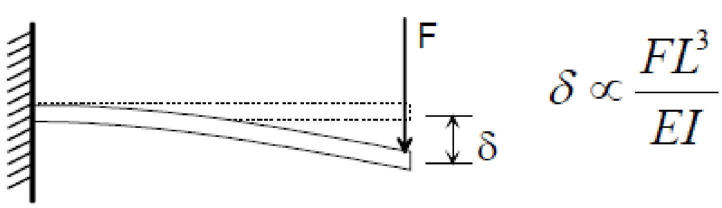


Figure 32 Cantilever beam with deformation.

This gives for the deformation at the end:

$$\delta_F = \lambda \delta_M$$

From (Ghosh, 2011) with stiffness k defined as:

$$k = \frac{F}{\delta}$$

As such, stiffness of a cantilever beam scales as the length scale (l) of the beam. So:

$$k \propto l$$

From this, regarding the stiffness property under the beam's exerted mass, the deflecting force is proportional to its mass that scales as l^3. Since I (inertia) scales as l^4. This gives:

$$\delta \propto l^3 * l^3 * l^{-4} \propto l^2$$

And thus the requirement to the structural rigidity:

$$\left(\frac{U^2L^4}{EI}\right)_F = \left(\frac{U^2L^4}{EI}\right)_M \rightarrow (EI)_F = (EI)_M \lambda^5$$

Thus, smaller beams behave stiffer than the larger ones, relative to their size.

For PocketQubes this is a beneficial trait when scaling down from CubeSats, as this is one of the factors allowing for extra mass reduction. This means, that although the volume of a 1P PocketQube decreases by a factor of $\frac{1}{2}^3$, the thickness of the structure can decrease by even more in order to have an appropriate stiffness.

This is illustrated by the following simulation as presented in Figure 33 and Figure 34, in which both a PocketQube and CubeSat are subjected to $\frac{0.1N}{cm^2}$:

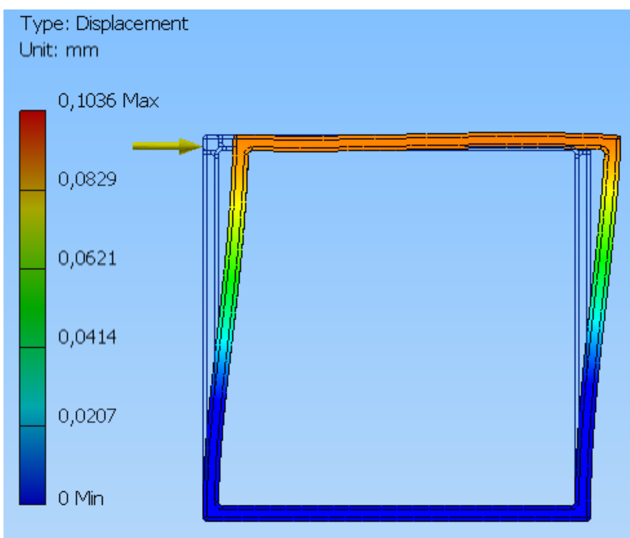


Figure 33 Structural deformation CubeSat.

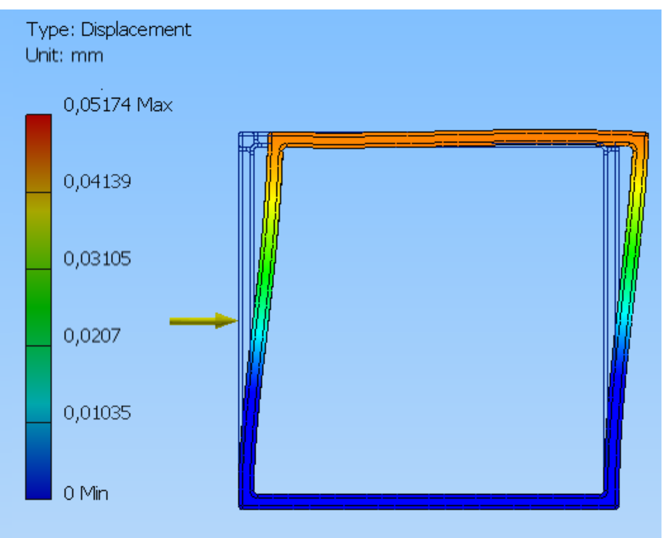


Figure 34 Structural deformation PocketQube.

As shown in Figure 33 and Figure 34, with the same load per surface, and a proportionally scaled frame, the CubeSat displacement is 0.1036mm while the PocketQube is almost half that with 0.05174mm. This further confirms that a PocketQube can have a much thinner structure than would initially be suspected when downscaling from a CubeSat, and thus additional mass can be saved. To validate the importance further, theoretically when designing purely for stiffness this means that a 75% mass reduction can be achieved when scaling down with a fifth power, with respect to simply scaling down the dimensions proportionally.

In conclusion, by scaling down the structure up to the point where it yields for the loads presented, more mass can be saved than by simply scaling down with a third power with respect to CubeSats for instance. This, in combination with chapter 7, answers the second research question.

In this section the potential of scaling down a structure has been examined. In the following section, a step further is taken to reaching the design process: the material selection.

9. Material selection.

In this section the type of material to be used is examined. First the mechanical properties of potential materials are set out in a table. Then metals and plastics are compared. Attention is then given to performance (through FEM analysis), manufacturability and surface smoothness.

9.1 Material properties.

A vital part of structural mass optimization is the material selection, different materials have different properties that are to be considered with respect to their density. In this section both conventional metals, as well as 3D-printed plastics are investigated. Given is Table 13 with relevant properties for both material types (Callister & Rethwisch, 2011), (Fenner, 2000):

Material	$\rho \left[\frac{kg}{m^3}\right]$	$E \left[\frac{GN}{m^2}\right]$	$G \left[\frac{GN}{m^2}\right]$	$K \left[\frac{GN}{m^2}\right]$	ν	$\alpha\ [10^{-6} * °C^{-1}]$	Yield stress $\left[\frac{MN}{m^2}\right]$	UTS $\left[\frac{MN}{m^2}\right]$	UCS $\left[\frac{MN}{m^2}\right]$	USS $\left[\frac{MN}{m^2}\right]$	Melting point [K]	Friction coefficient $[\mu_S]$
Steel	7850	207.0	79.6	172.0	0.30	11	400	650		240	1644	0.8
Aluminum alloy	2720	68.9	26.5	57.5	0.30	23	350	400		220	933	1.05
Titanium	4430	114	45	143	0.31	8.6	1103	1172	1080		1878	0.34
ABS	1040	2.28					44.8	73.1			373	0.46
PLA	1240	3.3	3.3	5.7	0.38	126	72	70	86.4		418	
PVA	1190	4.07						81.8			473	0.2
FR4	1900	12			0.136	22	70	75			411	
Windform XT	1097	8.9		7.3		4.3		83.84		133	453	

Table 13 Mechanical properties of structural materials.

9.2 Conventional metals:

The metals discussed here are steel, aluminum and titanium. All three have different properties that have various uses for space applications.

High purity stainless steels (Duval, n.d.), are, as one of the most common materials, a good reference point for metals. Steel has its advantages in its strength and stiffness, but also in its manufacturability; it is however often deemed simply too heavy for space applications.

Aluminum-Lithium (Al 2195) (McGill, n.d.) alloys are another common material, much more used in space applications. Aluminum, compared to steel, is less strong and stiff, but has even greater ease of manufacturability. Its main advantage however is that the density of aluminum is such that for desired applications it is simply much lighter than steel.

Titanium (Ti-6A1-4V) is a less common material (for small satellite structures), but one still useable for space applications thanks to its interesting qualities. Titanium, compared to steel, has similar strength and stiffness, but a much lower density and thus mass for its applications. A large disadvantage however is the difficulty and cost of manufacturing that comes with it.

9.3 Plastics (some 3D-printable):

The plastics presented are all unconventional materials to be used in space (except for PCB's). They are generally weaker and less stiff than the metals mentioned before, however due to their low density still an interesting option in order to save mass (Beginners, 2017). Manufacturability of this material is the most convenient, as any 3D-printer, such as those at the TU Delft, is available to create a structure from this in a short amount of time.

A concern with plastics however is the possibility of outgassing. This is the release of a gas that was dissolved, trapped, frozen or absorbed in some material. As a result plastics can become brittle and lose their stiffness, causing structural failure. Further problems of outgassing are the condensation onto lenses and other visual sensors, adverse effects on solar cells, thermal radiators and electronics. For space application it is paramount to use materials with at least low vacuum outgassing properties (Strong, 1938). As a reference for outgassing, NASA has created a database in which materials have been tested, and are considered to have low and acceptable levels of outgassing if they have a TML (total mass loss) below 1.0% and a CVCM (collected volatile condensable materials) below 0.1%

ABS, "short for Acrylonitrile Butadiene Styrene, a petroleum-based thermoplastic used to make filament for FDM-type 3D printers. Being petroleum-based, ABS is non-biodegradable, but it can be recycled. ABS is very strong, is soluble in Acetone and can easily be post-processed. Its melting temperature lies around 210-230°C and due to its shrinkage properties (a.k.a. warping) the use of a heated print bed is recommended." This has (borderline) acceptable levels of outgassing, with a TML of 0.94% and a CVCM of 0.08% (Powers, 2017). ABS however would melt in the most extreme temperatures of Low Earth Orbit, so it would require additional temperature control.

PLA, "Short for Polyactic Acid. A biodegradable thermoplastic polymer made from plant starch, used as a 3D printer material. Often PLA is used as a short form, actually referring to filament made of PLA." A 3D printable plastic. This has acceptable levels of outgassing, with a TML of 0.56% and a CVCM of 0.01% (Powers, 2017).

PVA, "Short for Polyvinyl Alcohol. A water-soluble filament often used as support material in 3D printing". Outgassing properties unknown.

FR-4 glass epoxy "is a popular and versatile high-pressure thermoset plastic laminate grade with good strength to weight ratios. With near zero water absorption, FR-4 is most commonly used as an electrical insulator possessing considerable mechanical strength. The material is known to retain its high mechanical values and electrical insulating qualities in both dry and humid conditions. These attributes, along with good fabrication characteristics, lend utility to this grade for a wide variety of electrical and mechanical applications." This is the main material used for PCB's which, as demonstrated with

PocketQubes such as SMOG-1, can be used as a structural supporting element as well. This does not suffer from outgassing with an TML of 0.26% and a CVCM of 0.00% (Powers, 2017)

Windform XT. " is a ground breaking carbon fiber reinforced composite 3D printing material known for its mechanical properties. It is particularly suitable in demanding applications such as motorsports, aerospace, and UAV sectors." Apart from its structural properties, it is also 3D printable and thus easily manufacturable, on top of that its outgassing properties are also good with a TML of 0.42% and a CVCM of 0.00% (Powers, 2017)

9.4 Performance.

Considering the low earth orbit temperature range of 103.15K to 396.15K (Israel, n.d.), only ABS would require extra coolant when exposed to the extreme temperatures of space. As such, for the other materials this is regarded as a non-issue. Further attention to the effects of thermic expansion is given in section 6.3.

In order to get a better grasp of how different materials react on forces exerted, a FEM analysis is done, in the Autodesk Inventor Professional 2017 software package, for the three common forces: shear, torsion, compression. This is done for all of the materials, for a skeletonized 2.0mm thick wireframe of single unit PocketQube dimensions. The displacements are shown in Figure 35, Figure 36, and Figure 37, they are amplified to show differences between materials.

Shear:

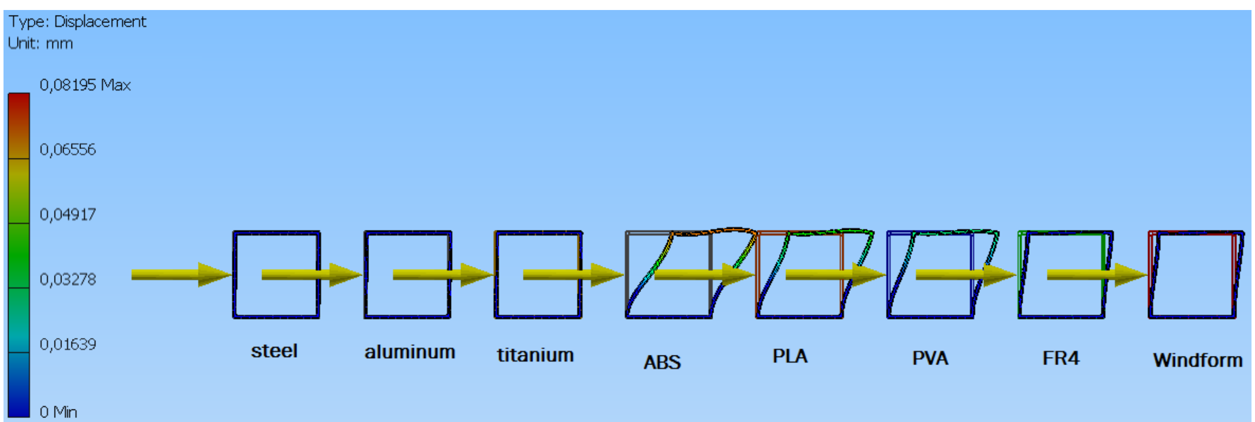


Figure 35 Material comparison for shear.

Torsion:

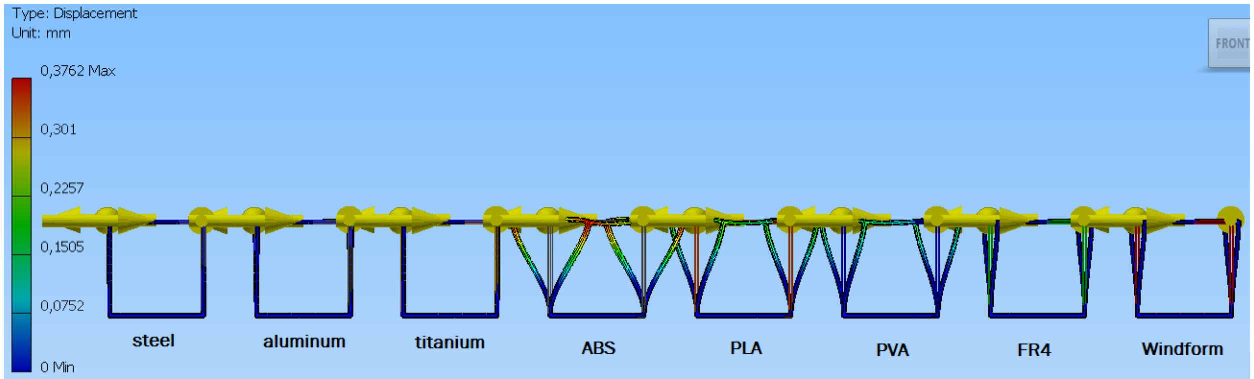


Figure 36 Material comparison for torsion.

Compression:

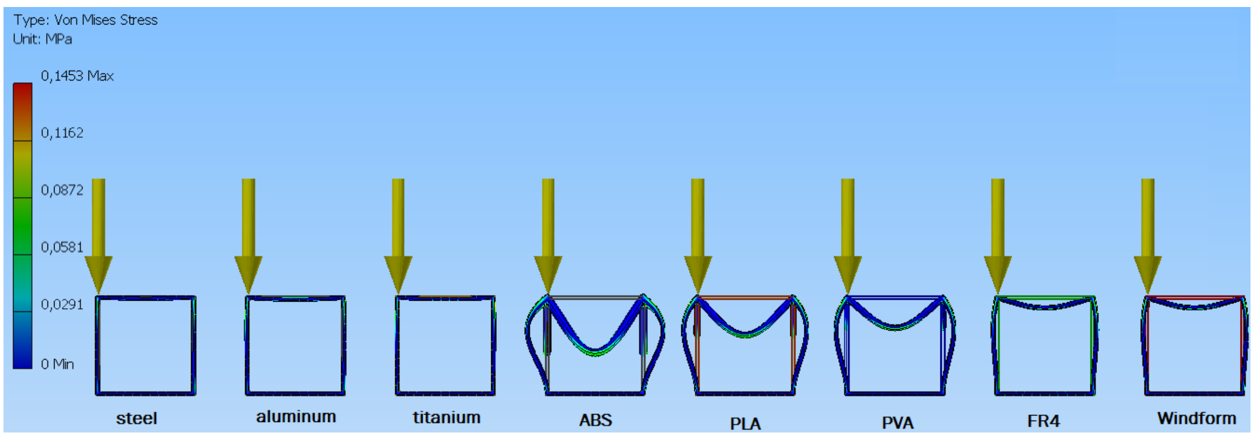


Figure 37 Material comparison for compression.

Although this already illustrates the difference between materials, in Table 14 are the actual maximum deformations for an (arbitrary) force of 1.0N on a 2.0mm skeletonized PocketQube frame:

Displacement of	Shear in [mm]	Torsion in [mm]	Compression in [mm]
Steel	0.007393	0.03406	7.717E-4
Aluminum	0.0207	0.09568	0.00216
Titanium	0.01253	0.05805	0.001308
ABS	0.636	2.955	0.06637
PLA	0.4317	2.006	0.04505
PVA	0.3506	1.615	0.03659
FR4	0.1191	0.5376	0.01245
Windform	0.1603	0.7386	0.01673

Table 14Displacement per material type.

9.5 Manufacturability.

Another important aspect when selecting materials is the manufacturability. Special attention is given to two prominently distinct methods of manufacturing: conventional milling versus 3D-printing.

“Milling is the machining process of using rotary cutters to remove material from a work piece by advancing (or feeding) in a direction at an angle with the axis of the tool.” (Sharpe, 2013). Milling is generally more suited for metals than it is for plastics, as plastics have a higher tendency to tear or be damaged otherwise. Milling has an accuracy of 0.0254mm and better (Cookbook, n.d.)(for very high end machines).

“3D printing, also known as additive manufacturing (AM), refers to processes used to create a three-dimensional object in which successive layers of material are formed under computer control to create an object.” (Excell, 2013) 3D printing is generally more suited for plastics, however metal 3D printing is possible although generally at a much higher cost of both time and money. 3D printing techniques generally have an accuracy at 0.155mm and better (Grieser, 2015).

Through correspondence with NLR (Smit, n.d.), the 3D printing of metals has its advantages and disadvantages with respect to conventional milling. Its major advantage is that the method of Metal Additive Manufacturing (MAM) is especially suitable for complex structures, like those which originate through topology optimization, where milling might prove impossible to produce a prototype. Another advantage is a wider use of metals such as magnesium, aluminum, steel, titanium and nickel alloys, of which some are not suited for milling.

Disadvantages compared to milling however are the large manufacturing time (both machine time as man-hours), and its resulting high cost. A further disadvantage is that the design needs to accommodate correct support struts and ground plate attachments, for which there are no general guidelines but a “case by case” approach has to be devised. And in general, without post production, milling produces better surface smoothness than 3D printing.

A further concern is post manufacturing. Once the general structure is made, often during assembly extra manufacturing is done. For example drilling holes, threading, chamfering, smoothing surfaces etc. In general metals are more suited for this than plastics. There are also, for both metals and plastics, post manufacturing techniques dedicated to increasing surface smoothness. For example, the Windform XT2.0 manufacturer offers surface finishing process that increases the smoothness to 1.8 μm (Technology, n.d.).

An advantage of conventional metal structures versus innovative 3D printed structures is the ease of assembly and disassembly, where metal structures often exist out of multiple components, 3D printed structures often exist out of a single work piece.

9.6 Surface smoothness:

Apart from the manufacturing techniques explained above, surface smoothness is also determined by the maximum friction coefficient a dry and clean material has. Since the aluminum has the highest friction coefficients (Table 13) of the selected materials, and it is also the traditionally used material, it is assumed that none of these materials are too rough for the gliding plate to function properly (for some materials that does however require post manufacturing to increase surface smoothness).

However it is important to know what friction the guiding plate encounters, because the friction force determines the spring required to overcome it. So in order to save mass, a smaller spring is desired and thus a smaller friction force.

A friction between guiding plate and deployer of $F_f = \mu * N \approx 1.05 * 6 \approx 6{,}3N$ is found (assuming the reference structure). This serves as an upper limit of the force required by the spring, for the original deployer concept. Once the deployers' allowed dimensions are known, the spring required can be calculated.

Given above were the friction coefficients for different materials, but these can be deceiving as they do not take the manufacturing process into account. For instance, in reality plastics have a higher friction than aluminum. Because aluminum is viable for milling, which gives a smoother surface finish than 3D-printing. However even 3D printable plastics can be post manufactured to have more than sufficient surface smoothness, as such this is regarded a non-issue when selecting materials.

A further point to take into consideration when judging aluminum, is that from a certain surface smoothness, the phenomenon "cold welding" can occur (Dunn, 2009). Cold welding is a mechanical failure, occurring when smooth surfaces of a similar metal impact or fret among each other, causing a solid-state welding process to occur that is only achievable in a vacuum. This means that when minimizing friction, metals must have a lower boundary but plastics do not.

9.7 Currently preferred options:

Although many materials are well suited for a PocketQube, in order to optimize for mass a selection has to be made. The first and preferred option would be the Windform XT2.0 material, as it is optimized for aerospace applications it has a high strength to density ratio and very low outgassing. On top of that, it is 3D printable so manufacturing cost and ease are both satisfied. When comparing this to titanium or aluminum the following has to be noted. Although both these metals have a higher strength to density ratio, for 3D printing purposes they are far more expensive (about a factor 50) making this is an undesired choice for a PocketQube project. Although aluminum is affordable for conventional manufacturing such as milling, this restricts design possibilities when compared to 3D printing to such an extent that effectively mass is gained. As such, from here on out, Windform XT2.0 is taken as the material of choice.

Another option would be to use the PCBs which are already being used to house hardware, as the actual structure itself. The material properties and ease of manufacturing are subpar compared to Windform XT2.0, however if by clever sectioning the PCBs already present can serve multiple use as a structure, mass is still reduced through this option. This option is further explored in section 11.4.

In conclusion, if a traditional structure (framework with internal rods to which components are attached) is selected, Windform XT2.0 is the preferred material. A more provocative option, is using the PCB's already on the DelfiPQ as structural elements.

In this section materials have been presented and compared to each other, from which preferences are selected. In the next section, the design process and the methodology behind it are presented in order to explore the mass reduction possibilities.

10. Design ideology.

In this section the design process is presented. For both structures and deployers it is shown how much mass can be saved if it were not for restrictions. Some ideas for deployment mechanisms are presented, followed by some general comments. Adhesives are examined with respect to their uses for the DelfiPQ mission.

In order to demonstrate how much mass can be reduced by omitting unnecessary material, 2.0mm wall thickness is assumed initially, both for the structure itself and the deployer. Here it is noted that in reality this thickness is thinner, for example a standard CubeSat frame has a wall thickness of 1.27 mm (Kit, n.d.). However in order to demonstrate the relative mass reduction when removing material, 2.0mm wall thickness serves properly.

10.1 Structure:

Reference structure (3P):

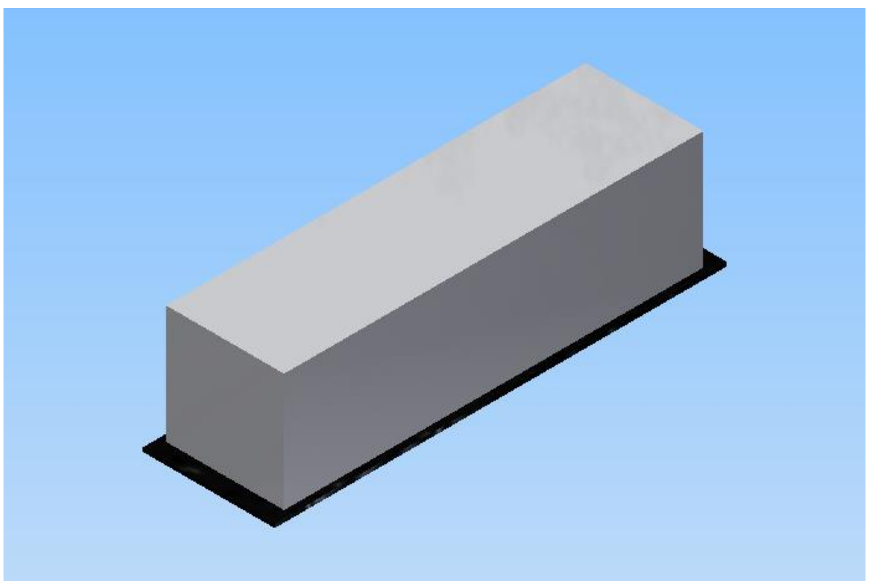


Figure 38 Reference structure.

The 3P reference structure weighs in at 0.242kg, Partially skeletonized structure, full gliding plate.

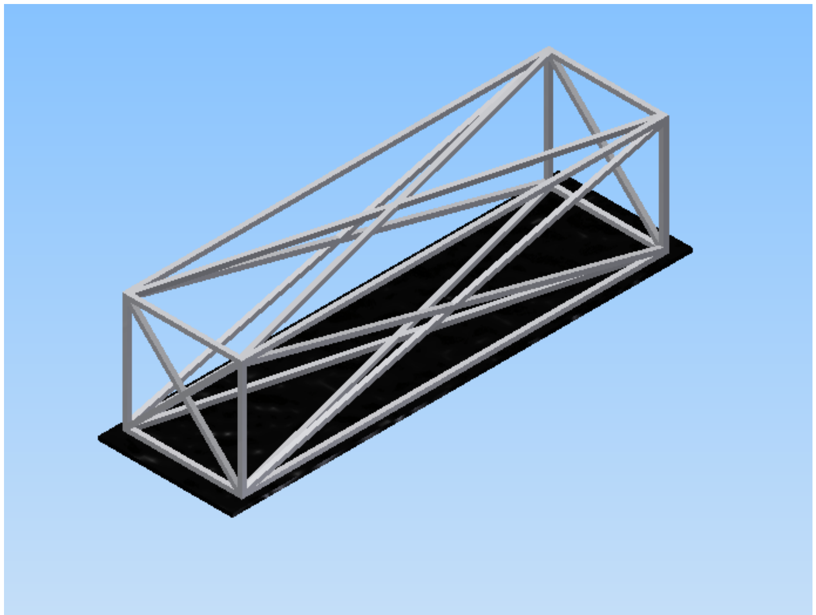


Figure 39 Skeletonized structure.

For the partially skeletonized structure, material has been removed except for the ribs and crossbeams of the PocketQube, the gliding plate has been left intact. The mass is now 0.076kg and has already been reduced by 68.60%.

Fully skeletonized structure, full gliding plate.

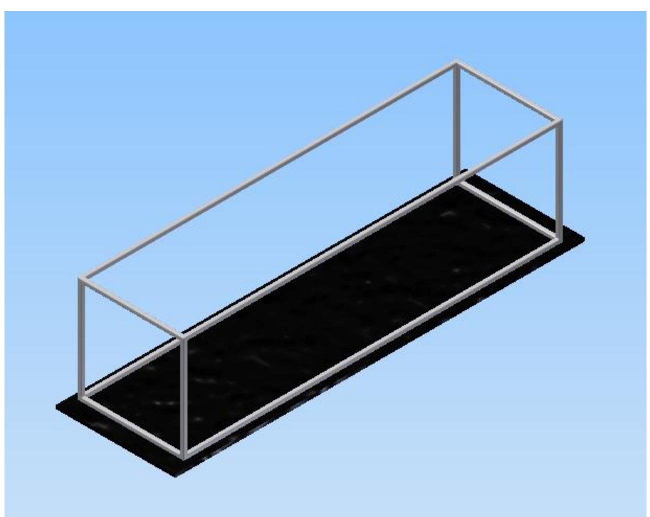


Figure 40 Wireframe structure.

Here the structure has been fully skeletonized to just the ribs (or wireframe), the back plate is left intact. The mass is now 0.057kg or a 76.45% saving.

Fully skeletonized structure, fully skeletonized gliding plate.

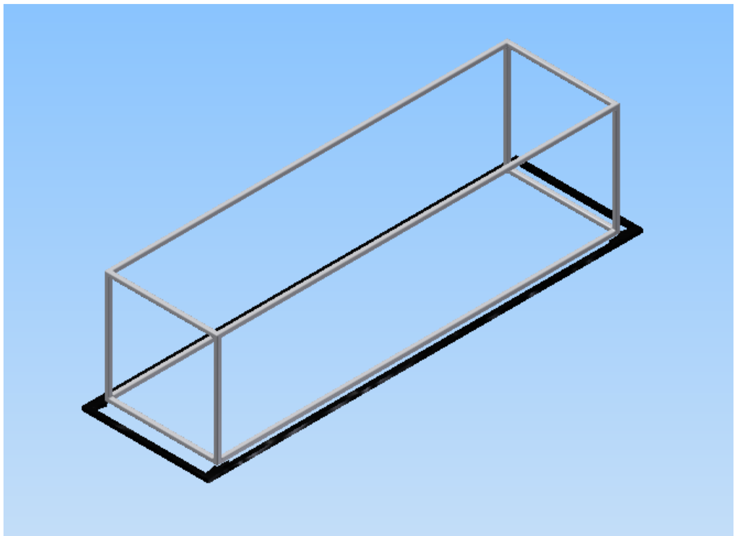


Figure 41 Wireframe structure and gliding plate.

Here apart from the body of the structure, also the back plate has been skeletonized to its ribs. The mass is now 0.015kg or reduced by 93.80%.

“Bare necessities”

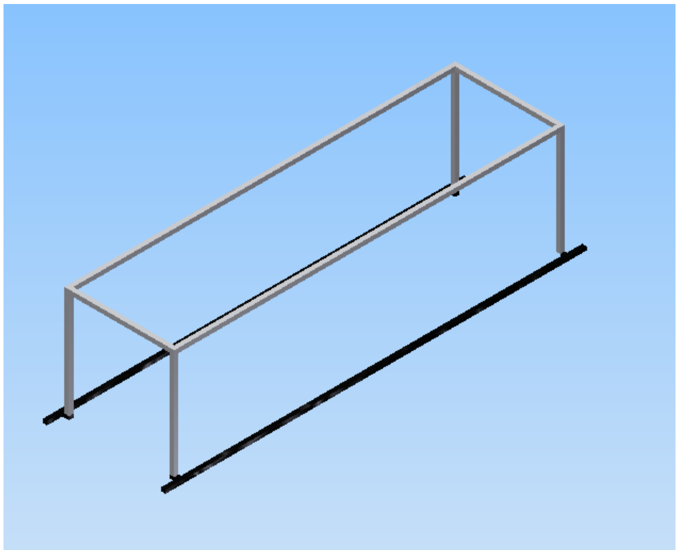


Figure 42 "Bare necessities" wireframe.

This is a concept where the ribs that are not directly used have also been removed. The mass is then 0.010kg or reduced by 95.87%. Although this structure still needs to be confirmed for mechanical properties it is not unlikely that a final topology optimization yields a result similar to this, therefore giving a valid impression of the potential mass reduction the PocketQube structure may achieve.

10.2 Deployer:

Reference deployer (3P):

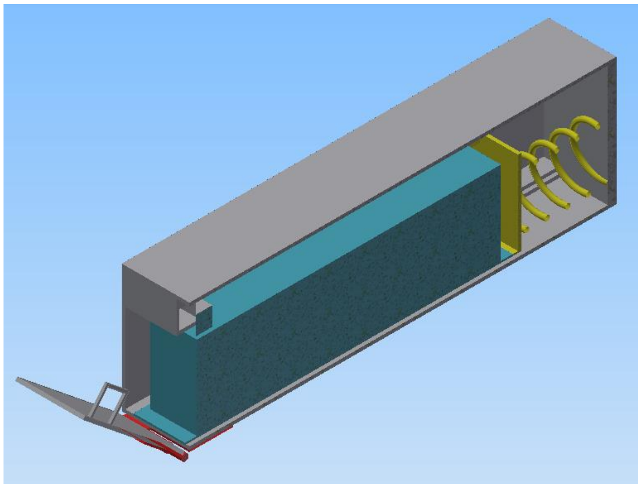


Figure 43 Reference deployer mechanism.

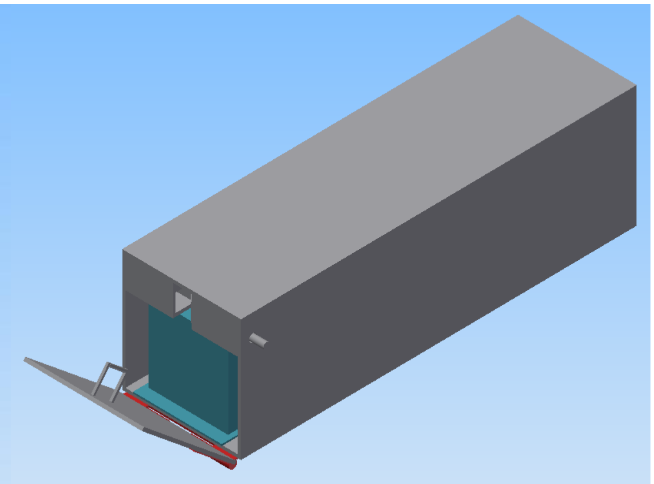


Figure 44 Reference deployer box.

Initially attention is focused on the “box” of the deployer, and eventually on the mechanisms inside it. At this point the mass is 1.854kg.

Deployer box, shortened for current margins:

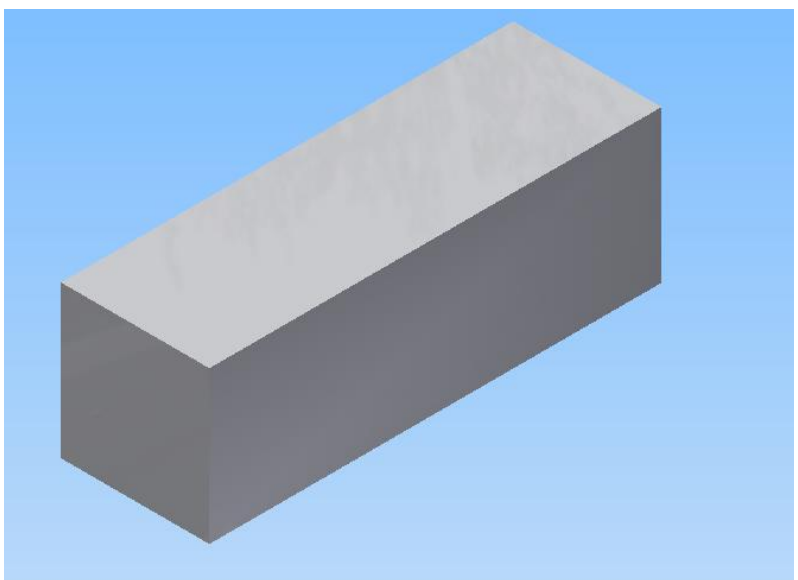


Figure 45 New margins deployer box.

Here the structure of the box has simply been cut down to the minimum size allowing the structure and its margins, and only the guiding rail mechanism is retained. This gives a mass of 0.361kg or already a reduction of 80.53%.

Deployer skeletonized:

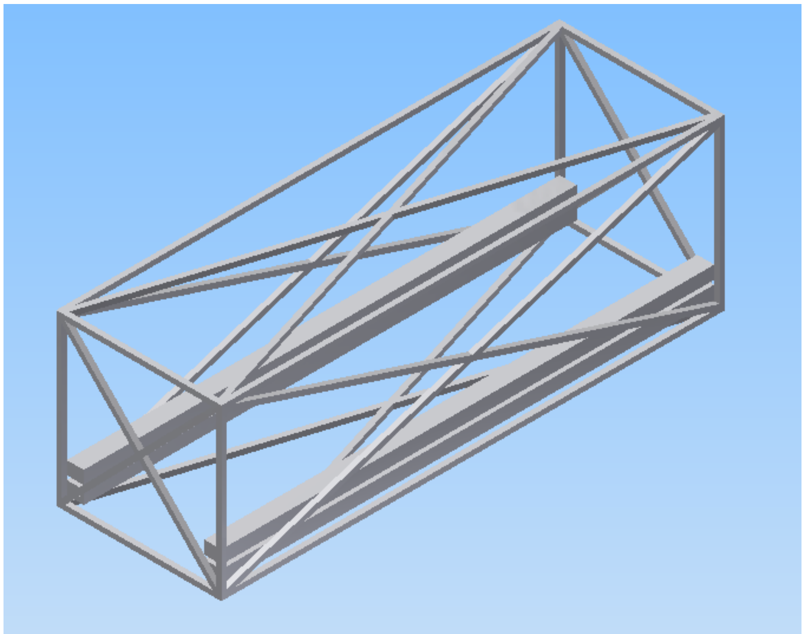


Figure 46 Skeletonized deployer box with guiding rails.

Here the deployer has been skeletonized to a rib construction with crossbeams kept intact and gliders, the mass at this point 0.100kg, or reduced by 93.80%.

Gliders:

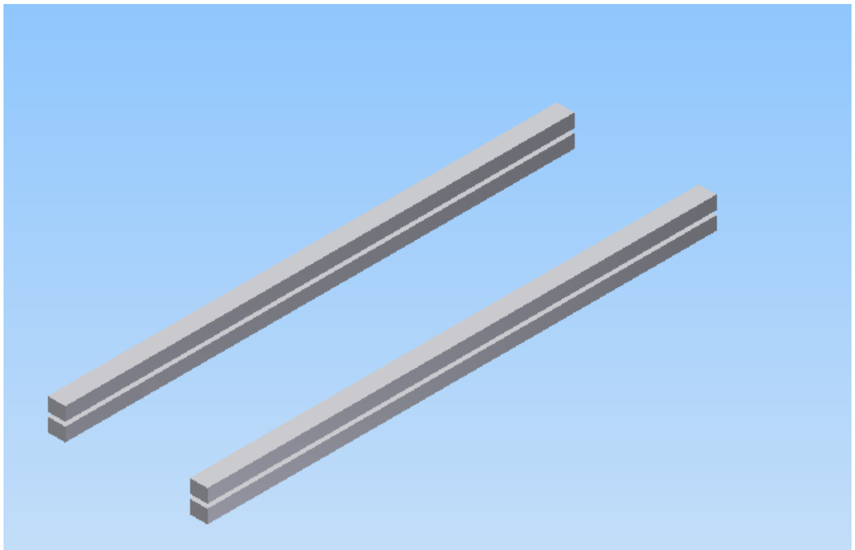


Figure 47 sole guiding rails.

Here the entire box is scratched and only the gliders are left, this greatly reduces mass to 0.066kg, or by 96.44%.

<u>“Bare necessities”:</u>

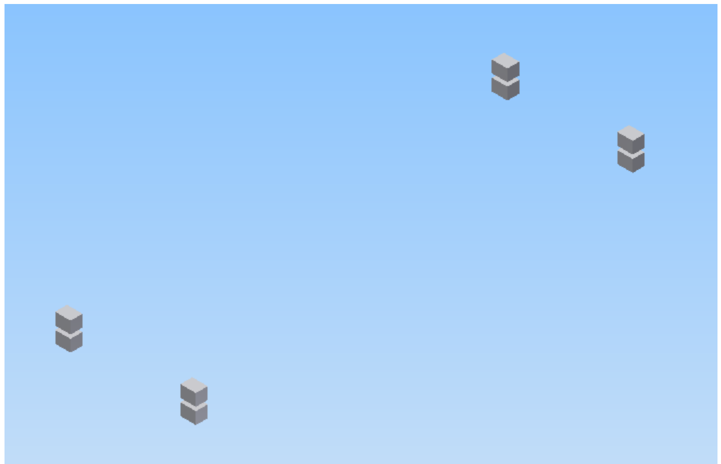


Figure 48 Clamps on corners replacing guiding rails.

In this last concept, the gliders have been replaced by simple “clamps”, only having a mass of 0.004kg and thus having a mass reduction of 99.78% with respect to the standard original box idea. The idea is that no gliding motion actually take place, but the clamps simply open up to release the PocketQube.

These are not a binding or final concepts, but what they serve to show is that upon getting rid of the “box” idea of a deployer a high mass reduction can be gained. In reality the problem lies not with feasibility of design, but with it being in accordance with the launch provider’s specifications, for example regarding explosion hazard containment. As such from here on out a guiding plate, with a gliding mechanism, and a full box is maintained.

10.3 Adhesives.

In order to achieve a greater mass reduction, the possibility of switching from conventional connections (bolts, screws etc.) to adhesives is considered.

Adhesives, such as glue and tape types do not necessarily lose their function in space (Shiue, 2008). Therefore from here on out the design concepts are also considered to use an adhesive in order to attach components to the structure. This is breaking with traditional design philosophies, because it creates more discomfort in assembling and especially disassembling small satellites components. However the notion is entertained from a mass reduction standpoint, as the mass of the adhesive used is considered negligible and does not require further design alterations to be applicable. When thinking of disassembly it serves to note that chemically soluble glues can be used. Furthermore in order to keep assembly and disassembly for the actual DelfiPQ project feasible, a final design of PCB’s is proposed which returns to actual attachments and disregards adhesives.

In conclusion, in this section an image has been sketched of the ideology involved in coming to a final design for both the structure and the deployer of the DelfiPQ mission. In the following section this leads to concepts being developed and further on prototyped.

11. Concept development.

In this section optimized designs are proposed. This is done through topology optimization both for aluminum and Windform XT2.0. Followed by an unconventional design using only PCB as structure. A new concept is also proposed for the deployer.

11.1 Topology optimizer settings.

In this section of the thesis topology optimization is used in order to come to a design. Topology optimization is a mathematical method that optimizes material layout within a given design space, for a given set of loads, boundary conditions and constraints with the goal of maximizing a desired aspect of the performance of a system. The software package in which this is done is Autodesk Inventor Professional 2017.

All the requirements are known to which the design must uphold: loads, volume constraints, and attachments. These serve as the inputs for the optimizer. The output is the new structure with a decrease in mass. This is done for both aluminum and Windform XT2.0 as material selections.

To provide insight into the optimizer, the following settings have been used:

- Objective function:

The objective function is mass reduction.

- Constraints:

The first set of constraints are the loads (both acceleration and vibration), acting on the x, y and z sides of the guiding plate, as this is the only part touched by the deployer.

The next driving constraint is to not allow for mechanical failing. Meaning in this optimization for the stress not to reach the level of yield stress for the material selected.

- Boundaries:

The boundaries are the maximum allowable loads. For acceleration this is 6.2g, for vibration this goes through all the Eigenfrequencies up to 2000Hz.

Another boundary is set to a maximum mass reduction of 70%, this is a safety precaution advised by the software provider in order to prevent the optimizer from creating infeasible results.

Furthermore the following assumptions have been made in order to come to a final design.

- A wireframe type structure with attachment to the gliding plate.
- Glue and socket adhesion to mount attachments. In this the glue is assumed as a perfect attachment or weld.

- A mesh with a minimum and average element size of respectively 0.004mm and 0.02mm.
- A symmetry plane through the length of the structure.
- The structure cannot detach from itself, meaning to create a “stalactite-stalagmite” formation in the wireframe.
- The mass of the components attached to the structure is regarded evenly distributed per each component.
- Only body mounted solar panels are considered. Not only does this mean that they serve a (negligible) structural purpose, but also that their load is distributed evenly, as opposed to foldable panels.

The optimizer is run for these settings, providing the results displayed, and in the following sections:

11.2 Aluminum.

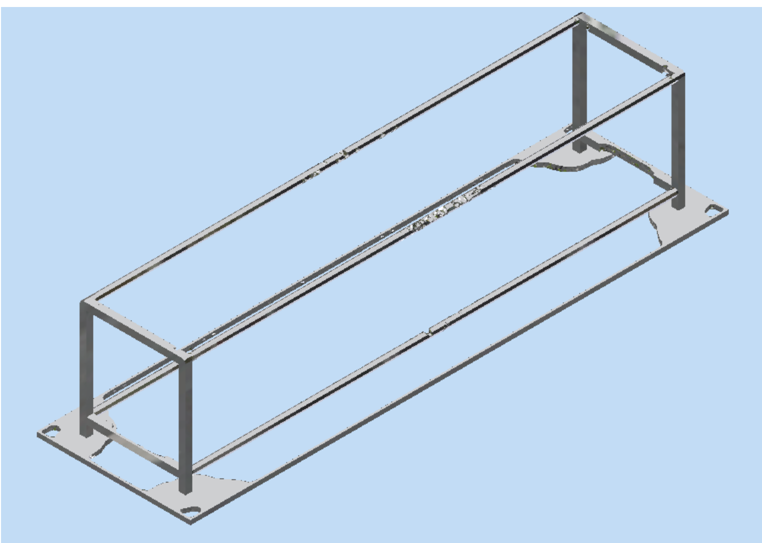


Figure 49 Aluminum structure topology optimized.

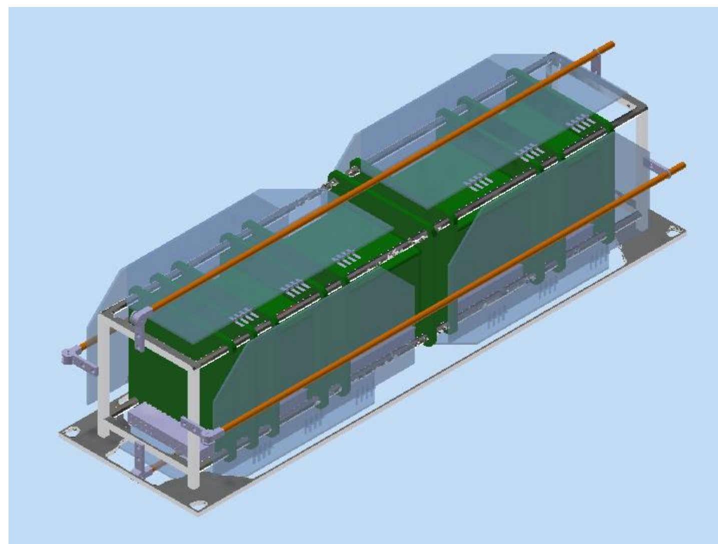


Figure 50 Aluminum optimized assembly.

The aluminum structure has a mass of 0.0555kg. An important note for the aluminum structure is the following regarding the manufacturing techniques. The structure is currently assumed to be 3D-printed, however a comparable structure could also be milled “traditionally”. This is because the major decrease in mass is taken from the guiding plate, and this can also be achieved through milling.

The difference however lies in the wireframe itself, where in some places irregular chunks are taken out in order to save mass. This cannot be done as easily or completely with conventional milling. This only accounts for a negligible difference in mass, therefore (for the sake of mass optimization being the outset of this thesis) from here on out the aluminum design is assumed to be 3D-printed.

11.3 Windform XT 2.0

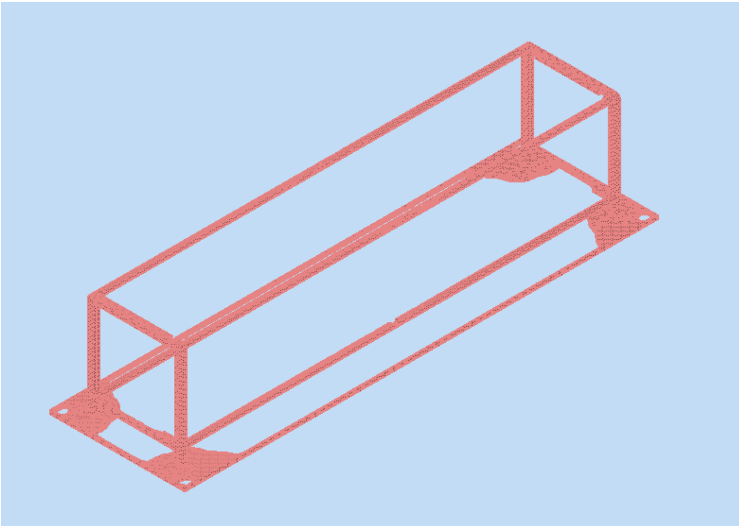


Figure 51 Windform XT 2.0 Topology optimized structure.

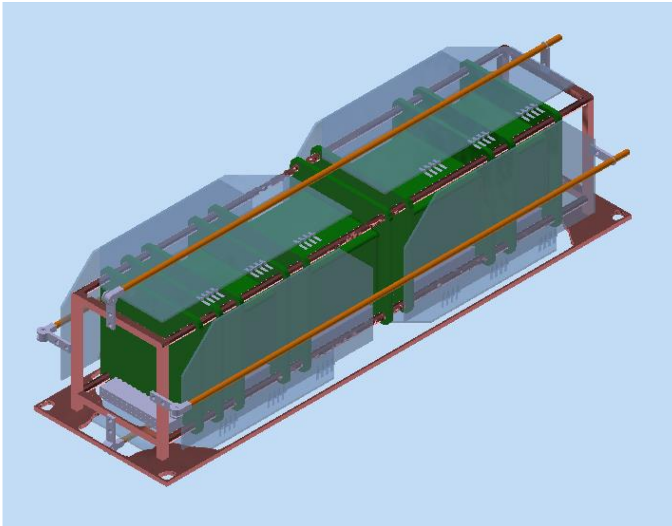


Figure 52 Windform XT2.0 optimized assembly.

The Windform XT2.0 structure has a mass of 0.00782kg. However it is to be noted that, this structure is assuming glue connections (for which mass has not been taken into account) which greatly decreases ease of assembly and disassembly. As a theoretical optimum this still serves, but for the DelfiPQ project this disadvantage is deemed too large. This way of coming to an optimum, focused majorly on mass optimization is however very well suited for single use, mass produced satellite missions.

11.4 PCB's as a structure.

A next suggestion would be to have the PCB's already required to simply function as the structure. Either by gluing everything together to the solar panels and PCB's themselves, or by using the PCB's as an outer structure.

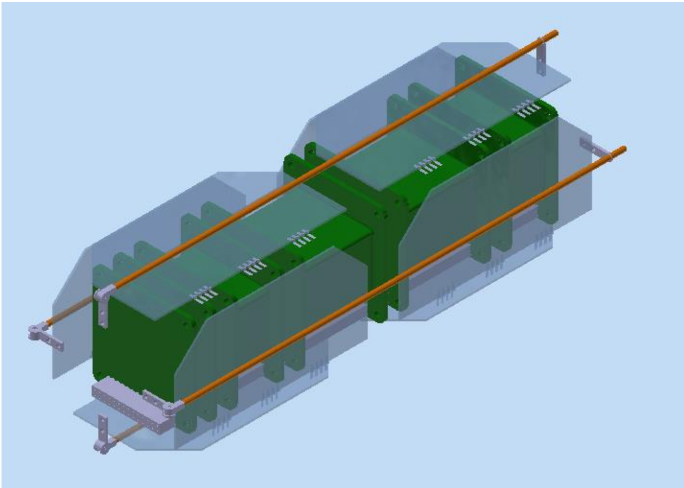


Figure 53 Example pure PCB glued structure.

It should be noted here that the PCB's themselves have a mass of approximately 182grams. This mass is regarded for simulations as if the density of the PCB's is homogeneous. Moreover this is subject to change as the PCB configuration might alter in the course of the project.

This initial concept needs refining as it currently has a great discomfort in ease of assembly and disassembly, also solar panels cannot realistically be used as structural elements, Therefore a version is proposed where the PCB's are used as an outer structure and are connected to each other via a corner bracket.

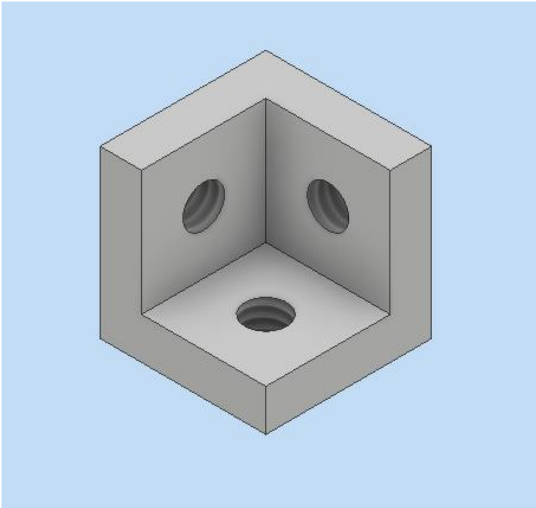


Figure 54 Example corner bracket.

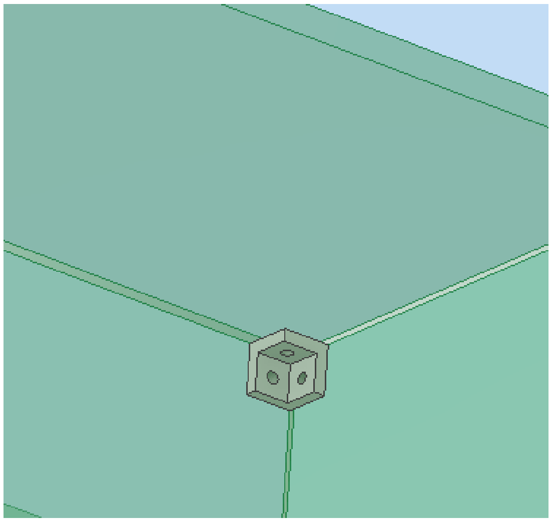


Figure 55 Example corner bracket against PCB's.

In order to guarantee no mechanical failure, a FEM analysis has been done on a bracket to see how it responds to representative loads. The results are shown in Figure 56:

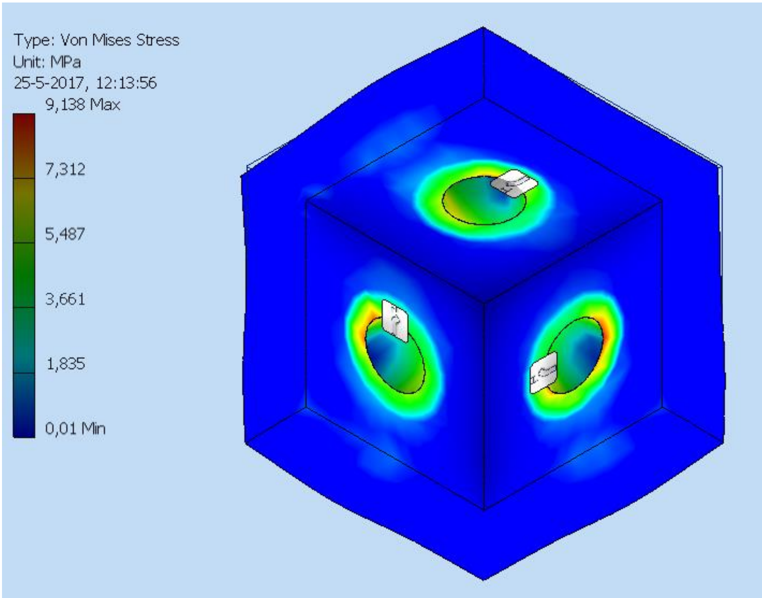


Figure 56 Corner bracket FEM analysis.

Most importantly notable here is, that with a maximum stress of 9.138MPa, the aluminum is far from yielding. Furthermore a maximum displacement (in the image exaggerated) of $6.889 * 10^{-5} mm$, is regarded as acceptably small.

Alternatively, instead of dedicated fabrication of brackets, the following COTS brackets (left full bracket, right Meccano prototype) (Figure 57) would also suffice without substantially altering the concept design:

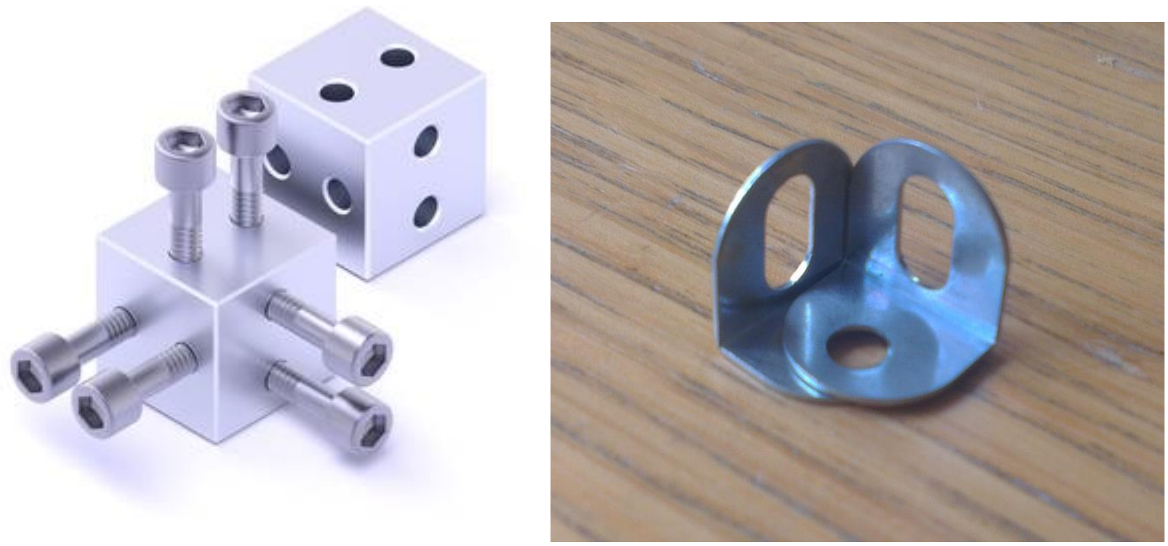


Figure 57 Alternative COTS corner-bracket examples (Uniqb, n.d.).

The differences in price, mass and design, between bracket options are deemed negligible from here on out. By using these brackets the PCB structure is presented as in Figure 58:

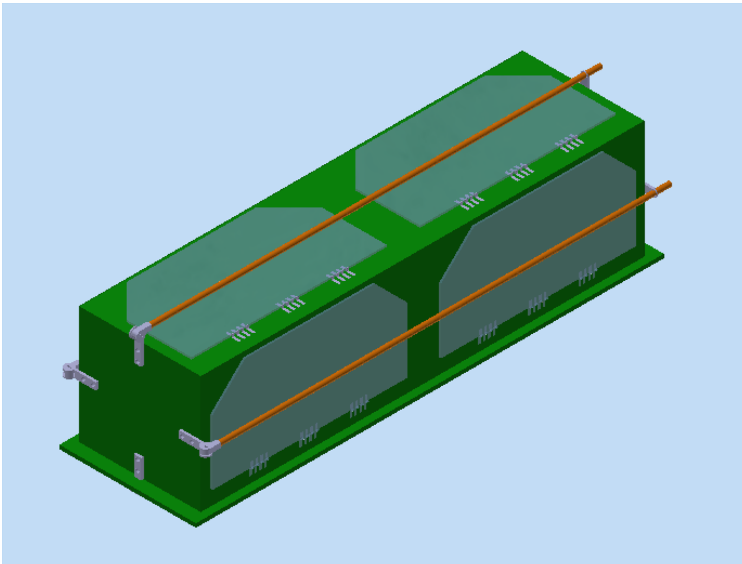


Figure 58 PCB as outer walls structure concept.

The following is noted: in Figure 58 of the structure concept, the PCB's cover the full surface and thus also have a higher mass than the original PCB's. However in actuality, after the placement of the attachables are decided, unused material can be omitted. This is done both for venting of internally generated heat and returning the PCB mass to its original value of approximately 182grams. The only added mass for this structure comes by the eight corner 1.0mm thick brackets and their respective screws. Assuming aluminum for these, this gives a mass of less than a gram. So with a somewhat negligible increase in mass, the ease of assembly and disassembly has greatly increased. It is noted that an undetermined increase in cost results from the redesign of the PCB's.

It is possible to split the six PCB surfaces into more surfaces to ensure higher ease of assembly and disassembly, this would require center brackets to be constructed as well. Although these brackets have almost negligible difficulty of manufacturing, and more importantly mass, for the purpose of the mass reduction focus of this thesis, the eight bracket setup is maintained.

Noted for the PCB concept is, that here only the 1.6mm thickness is regarded, as this is readily available from manufacturers. In actuality it is reasonable that a thinner board can be used in certain locations.

11.5 Deployer optimization:

When regarding the deployer, its entirety can be simplified to the following three subsections:

- The launch adaptor.
- The container or box.
- The deployment mechanism.

The launch adaptor is determined by the requirements of the launch provider, which currently still need to be finalized. In essence this means that currently no optimization of this subsection is regarded.

The box, however still constrained, is to be optimized. The chief constraint on the box is that of an ISIS guideline that the box should be closed around all sides and have a 3.0mm wall thickness to prevent explosion damage (ISIS, 2013). This 3.0mm is also included in the deployer standard (Twiggs, 2015). So although this constraint prevents topology optimization, scaling the box down to its minimum required dimensions, and switching the material can still save mass.

Assuming a 3P PocketQube (including margins) of $64.60 * 63 * 192$mm, a wall thickness of 3.0mm, and Windform XT 2.0 as the material, this gives a container mass of 0.2152kg.

When reducing deployer mass, eventually the deployment mechanism potentially becomes dominant in mass and must therefore be optimized. Regarding the deployment mechanism, the reference mechanism is a pushing spring onto the end of the gliding plate. Already it is important to note that the spring (or other touching components) should only push against the gliding plate and not the PocketQube structure itself, as to prevent bending or deformation of the PocketQube structure.

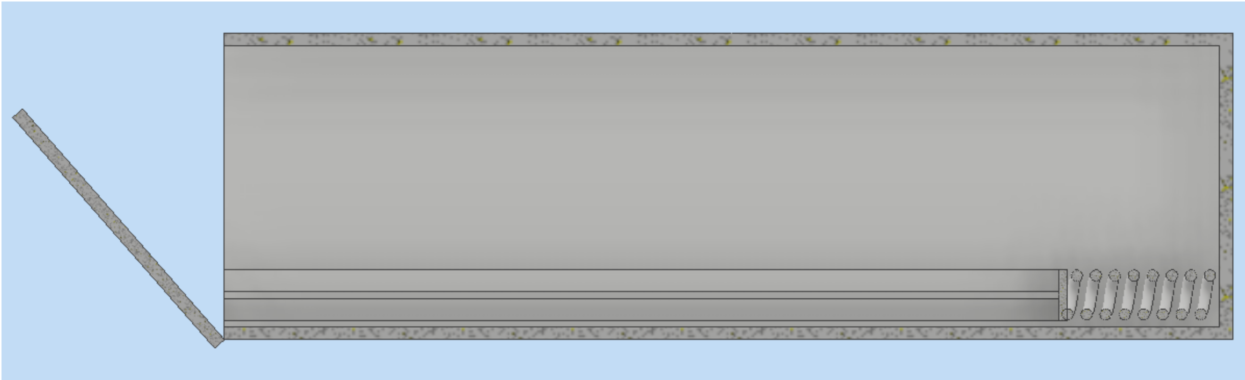


Figure 59 Deployer push spring mechanism.

An obvious downside to the push-spring design is the extra required space for the spring to be stowed in. A simple way of retaining the spring principle but reducing the space used is a pulling spring, or elastic band, with a hooking mechanism underneath the gliding plate, that pulls the PocketQube out of the deployer.

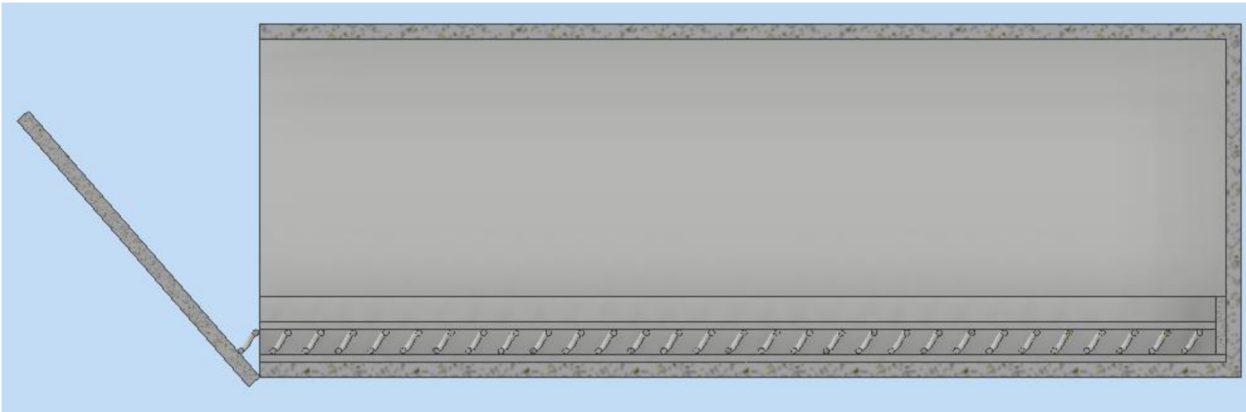


Figure 60 Deployer pull spring mechanism.

As a final suggestion, instead of pushing the PocketQube outside of the deployer container, the possibility is explored of having the box unfold around the PocketQube.

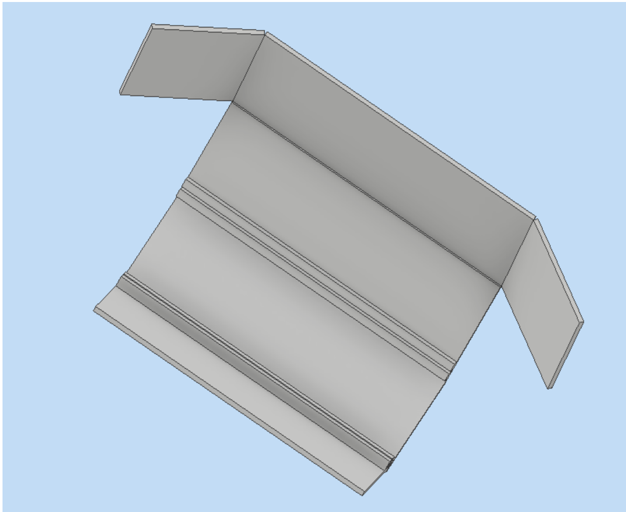


Figure 61 Deployer unfolding mechanism.

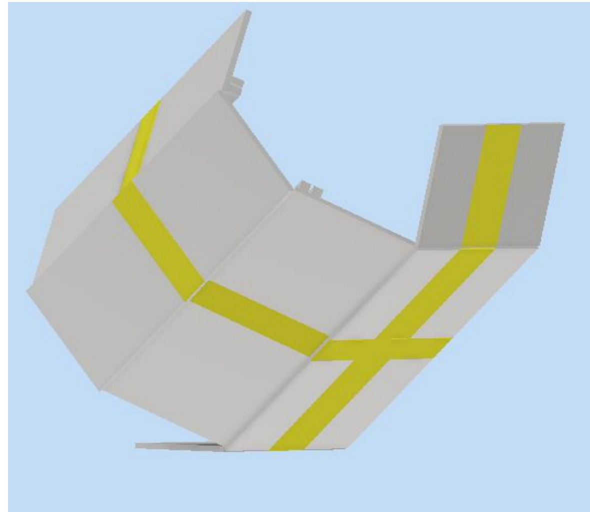


Figure 62 Unfolding deployer measuring tape mechanism.

An advantage of this type of design (in aluminum) is the mass that is being saved, at 562 grams or a 69,69% mass reduction when compared to the reference deployer. Especially when crafted in Windform XT 2.0, giving a mass of 230 grams, or a 87,60% mass saving. The unfolding mechanism is shown in Figure 62. Once the locking mechanism unlocks the top valve, measuring tape on the outside of the deployer unfolds it.

Important to note for this concept, is that in terms of mass optimization (while retaining the box) it is preferred to other designs. However practically it has a major downside, being that it can only be deployed as a singular deployer. Because when surrounded by other deployers or hardware the box cannot unfold, but that is beyond the scope of this thesis as it differs mission to mission.

In conclusion to this chapter, for a traditional structure, made out of Windform XT2.0, a large amount of mass can be saved through topology optimization and the right material selection. However compared to using the PCB's as structure, this design concept has more mass, as theoretically there is no real mass increase for the PCB option. Regarding deployers, due to design restrictions, mass can mainly be saved by redimensioning the box, altering the deployment system and changing material types. A Windform XT unfolding deployment mechanism has been presented. With these concepts, this chapter, in combination with chapter 10, has answered the third sub question.

In the next section, the concepts presented here are prototyped and tests are performed.

12. Prototypes and testing.

In this section, the current prototypes are presented and validating tests are shown, furthermore the current DelfiPQ working concept is also discussed.

12.1 Prototypes.

Working on this thesis, prototypes have been created in order to validate the methodology presented here. A prototype of the Windform XT 2.0, traditional structure (framework with internal rods to which components are attached) concept has been manufactured with thanks to CRP Technology. As is shown in Figure 63:

Figure 63 Windform XT2.0 prototype.

In correspondence with CRP Technology, it was decided that in order for it to be more convenient for (dis)assembly and testing, the structure has been slightly reinforced at connecting points. However the mass increase due to this is negligible. Slightly different from the topology optimized structure as presented above, the structure still weighs in below eight grams as opposed from the actual proposed structure weighing in at about 7.8 grams.

Also a testing mockup prototype of the PCB outer structure concept has been made, as shown in Figure 64:

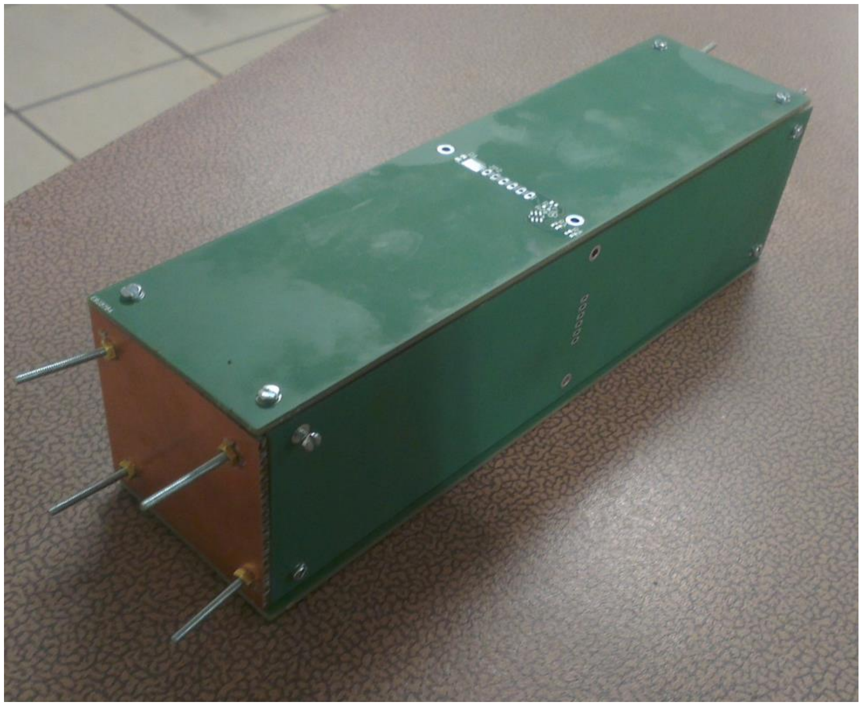


Figure 64 PCB outer structure example prototype.

This first prototype is different from the proposed concept in the following ways. All sides are of equal dimensions. There is no guiding plate. The corner brackets used were temporarily fabricated out of Meccano as shown in Figure 57 (right). There is currently nothing mounted onto the PCB's, they are just blank boards, also without cutouts at unused space. In this concept for testing there are still inner stacks similar to those shown in Figure 68. This structure is deemed representative as the differences between the prototype and the actual model have negligible structural impact.

12.2 Validation testing.

The prototypes are tested in a laboratory environment on a selection of load conditions in order to validate the results from the modeled load responses.

The tests performed were Eigenfrequency, and stiffness measurements. These have been selected as these are also the driving inputs behind the software models.

A series of sine vibration tests have been performed, with thanks to Prof. dr. Pim Groen, using the following setup shown in Figure 65:

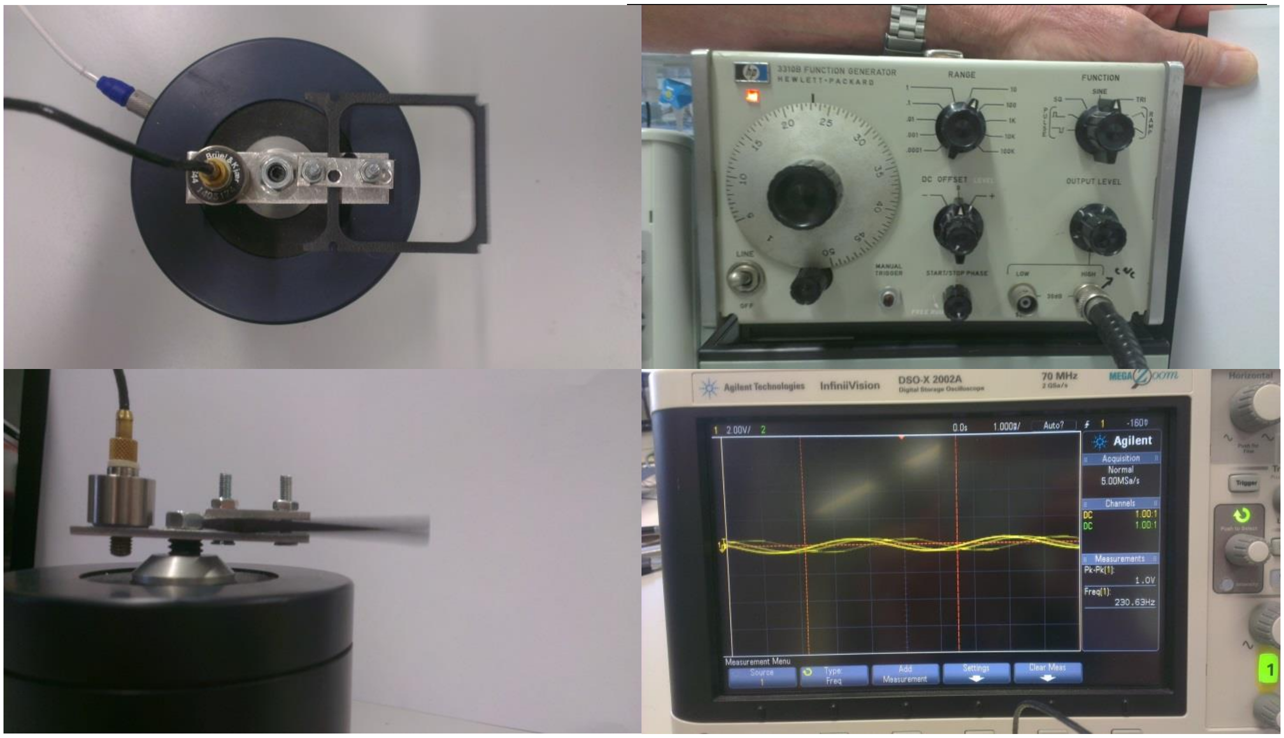


Figure 65 Sine vibration test setup example

In this test, all components were clamped into different positions, and vibrated for frequencies varying up to 2000Hz in order to determine the Eigenfrequency. The setup works as follows, as shown in Figure 65 (top left), the component is fastened on the shaker, through the dials (top right) a frequency is selected, which is plotted on the display (bottom right). When an Eigenfrequency occurs, the component starts visibly vibrating heavily (bottom left) and the sinusoid on the display becomes erratic. Every component was tested with three methods of clamping, three different times for each axis in order to have a more reliable measurement.

Subject.	Measured Eigenfrequency. [Hz]	Modeled Eigenfrequency. [Hz]	Deviation. [%]	Standard deviation of measurement [Hz].
Side x axis	230.63	237.09	2.8	0.66
Side y axis	314.01	308.67	1.7	0.41
Side z axis	339.17	335.44	1.1	0.37
Bottom x axis	79.20	82.61	4.3	1.41
Bottom y axis	107.83	110.53	2.5	0.96
Bottom z axis	54.29	57.98	6.8	2.83
Rod x/y axis	161.89	163.99	1.3	0.39
Rod z axis	287.41	286.26	0.4	0.22

Table 15 Windform single part Eigenfrequency validation results.

Also a series of deformation/force tests have been performed by the following setup shown in Figure 66:

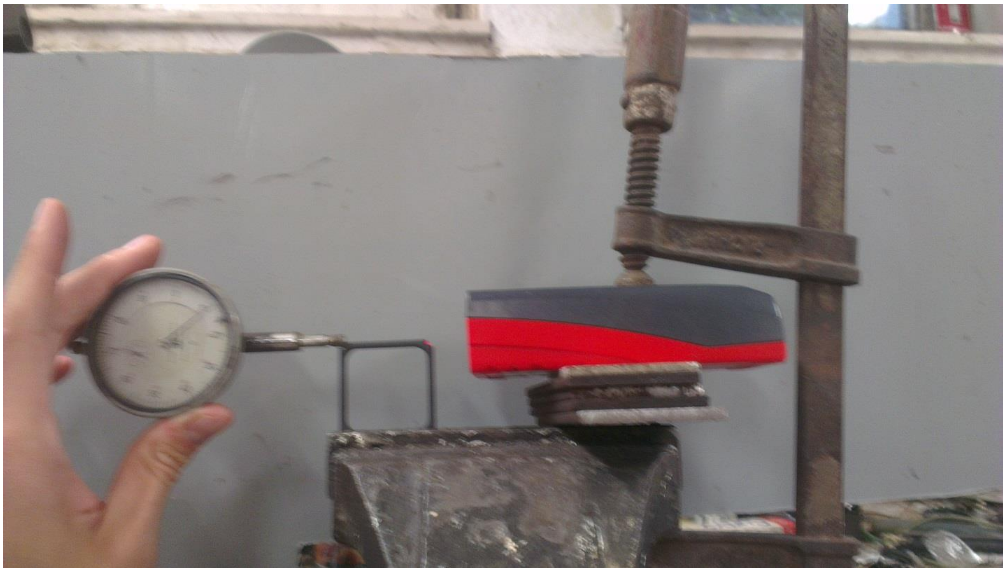


Figure 66 Stiffness test setup example.

In this test, all components have had a force exerted on them, in the ranges of 10.0N to 120.0N, at which point a laser measured the displacement, for different configurations (the clamping always being on the far opposite from the point of load exertion). From this the stiffness could be calculated.

Subject.	Measured displacement. [mm]	Modeled displacement. [mm]	Deviation.[%]
Side x axis (20N)	1.08	1.08	0.1
Side y axis (15N)	0.81	0.81	0.1
Side z axis (15N)	0.69	0.69	0.2
Bottom x axis (20N)	4.17	4.15	0.4
Bottom y axis (10N)	13.88	13.70	1.3
Bottom z axis (10N)	20.41	19.98	2.1
Rod x/y axis (50N)	2.63	2.60	1.1
Rod z axis (10N)	0.50	0.50	0.0

Table 16 Windform single part deformation validation results.

The accuracy of the measuring laser (0.01mm) in combination with the setup clamping and exertion, caused for such similar results that there was no noteworthy standard deviance between sets of three measurements.

All testing setups were remodeled and simulated on their digital counterparts and found to have a maximum of 6.8% deviance. This deviance can be explained both by measuring inaccuracies, as well as slight modeling differences of the simulations. From here on out, the deviance is considered acceptable and the software model is considered validated.

Continuing, it serves to test and validate for failure at Eigenfrequencies in a more realistic full-build setup. To this purpose dummy masses have been created representing the actual internal PCB stack masses, according to a recent DelfiPQ mass budget (Anon., 2017) as shown in Figure 67:

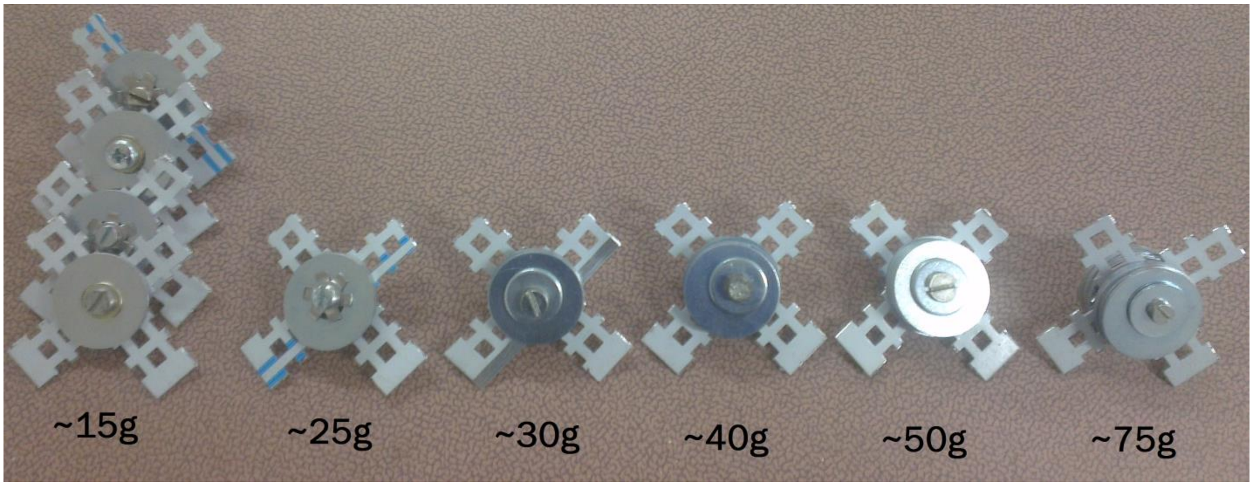


Figure 67 Testing dummy masses.

Dummy masses assembled on structures as shown in Figure 68:

Figure 68 Testing assembled prototypes with dummy masses.

The same deformation and vibration tests have been performed in the setups displayed in Figure 69:

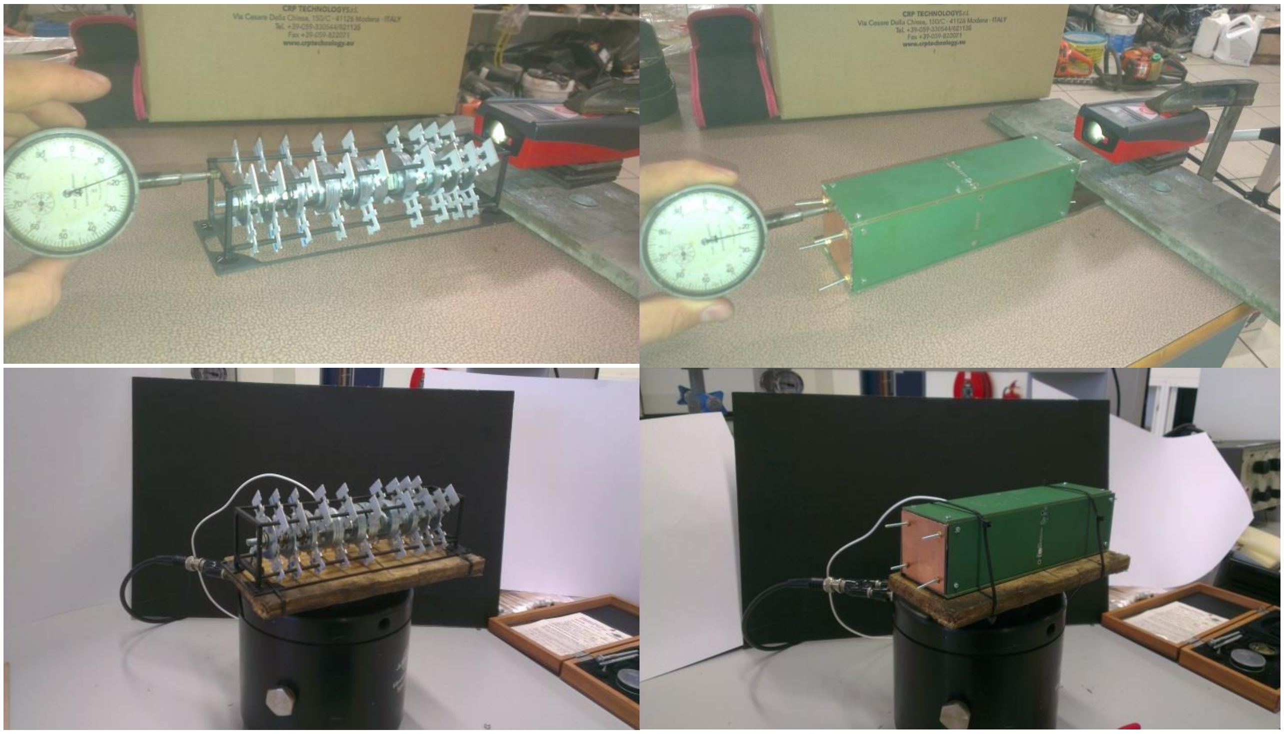


Figure 69 prototype example testing setups.

Test results:

Subject.	Measured displacement. [mm]	Modeled displacement. [mm]	Deviation.[%]
Windform x axis	2.19	2.12	3.2
Windform y axis	6.56	6.31	3.8
Windform z axis	4.60	4.38	4.8
PCB x/y axis	0.46	0.45	2.4
PCB z axis	0.29	0.29	1.5

Figure 70 assembled deformation test results.

Subject.	Measured Eigenfrequency. [Hz]	Modeled Eigenfrequency. [Hz]	Deviation. [%]	Standard deviation of measurement.
Windform x axis	57.41	60.17	4.8	0.70
Windform y axis	163.22	174.81	7.1	0.83
Windform z axis	153.48	174.81	13.9	1.04
PCB x/y axis	221.97	229.74	3.5	0.49
PCB z axis	276.74	285.32	3.1	0.28

Figure 71 assembled Eigenfrequency test results.

The main finding of these experiments is, that under the loads presented, both structures successfully did not yield.

Initially the deviations mostly lie within a 95% deviation range of the modeled structure, however for the Windform Eigenfrequency tests this deviation range is extended to a maximum within 85%. The deviations can be attributed to inconsistencies between the testing setup and the software model.

Meaning that for single parts the software is validated, for the assembled configuration the software does not approximate the experiment to a desired degree (95%, most commonly used). However there is still no yielding, buckling, breaking or permanent deflection of the assembled structure, thus validating the structure itself for its intended purpose.

Currently the process, of prototyping and testing has not been done for the deployer. This is because the deployer can only logically be prototyped after the final structure is known, as such this was deemed too high of an investment for what could be learnt from it, since it could not be obtained as a free sample.

12.3 Current concept of actual DelfiPQ project.

In the actual DelfiPQ project, an adaptation of the PCB structure concept is upheld. In this concept the PCB's do replace the outer structure, including guiding plate, however maintaining an internal rod structure and stacks of PCB's (of which the orientation is currently being decided).

Although this already procures a mass reduction, this still deviates from the concept presented in this thesis and thus requires an explanation. The reasons for deviating from the PCB structure presented in this thesis, where the outside structure is replaced by the internal PCB stacks and glued together or using corner brackets, are twofold. Firstly this offers greater ease of assembly and disassembly than gluing the boards together. And secondly, by maintaining internal stacks as well, this allows more freedom and possibilities in PCB design.

In this section the design concepts have been presented as prototypes and have undergone testing both to validate the software and to test the structure for yielding. The results of this, among others, are presented in the next section where trade-offs are done both for the structure as the deployer.

13. Comparative results.

In this section, trade-offs are held for both structure and deployer. When regarding the “reference” structure and deployer, the original concepts at the start of the DelfiPQ project are considered.

13.1 Structure tradeoff:

Both the structure and deployer values for price and time are procured through communication with manufacturing companies such as CRP Technology, NLR, etc.

As all suggested structures are capable to withstand the loads and hold up to the constraining requirements, a trade-off is made based on the following qualities:

	Mass [grams]	Material cost [€]	Manufacturing cost [€]	Manufacturing time [days]	Ease of assembly.	First Eigenfrequency [Hz[	Stiffness k [N/m]
reference	242	<100	<1000	~1	Optimal		
Aluminum, Figure 49	55.5	<100	~10000	~20	Acceptable		
Windform, Figure 51	7.82	included	~190	<5	Acceptable	57.41	$1.83 * 10^4$
PCB adhesive, Figure 58	~0*	~0*	~0*	~0*	Acceptable		
PCB brackets, Figure 64	<1	<100 t.b.d	<1000	~7	Optimal	221.97	$2.61 * 10^5$

Table 17 Structure tradeoff.

*Note that the assumption is made that when the structure is completely replaced by the PCB’s already in use, the only added mass is the glue used to hold the boards together, and this is considered negligible.

Another note is that the structural properties have only been confirmed for the prototypes. Manufacturing costs have been estimated in accordance with correspondence from manufacturers.

Several important things become apparent. The Windform XT2.0 is the best concept when regarding a traditional structure concept with internal PCB stacks. However the PCB outer structure is the best concept all round, considering its low added mass, structural properties, cost and ease of assembly.

The difference in performance, the PCB outer structure outperforming the Windform structure, is due to the fact that the Windform structure has been optimized (with safety margins) to withstand the maximum loads. While the PCB concept does not have material removed where no loads are placed , rather the material is only removed on unused sections. In the current presented concept they are considered blank PCB’s on which no form of (topology) optimization has taken place yet.

13.2 Deployer tradeoff.

For the deployment mechanisms, the following tradeoff is made (all assuming aluminum as the comparison material):

	Mass [grams]	Material cost [€]	Manufacturing cost [€]	Manufacturing time [weeks]	Ease of assembly.
reference	1854	>500	~1000	<2	Optimal
Push spring, Figure 59	645	<500	~1000	<2	Optimal
Pull-spring, Figure 60	567	<500	~1000	<2	Optimal
Unfolding, Figure 61	562	<500	~1000	<2	Average

Table 18 Deployer trade-off.

The main focus of the deployer optimization is the scaling down of the box, by diminishing dimensions and optimizing the deployment mechanisms. As such material has not been regarded in Table 18. When regarding the unfolding box mechanism (having the lowest mass) and applying Windform XT2.0 as the material of choice, the mass would be 230 grams, another significant improvement.

Considering the box however, the major drawback is the anti-explosion guideline of actually having a containment box with a certain thickness. If not for this, much more mass could be reduced with respect to the reference structure. Considering the Windform XT2.0 material for the unfolding option, the manufacturing cost would be ~1690,- (material included), with a maximum manufacturing and delivery total time of five days. Note however that the unfolding mechanism only works for solo deployers, as it otherwise cannot unfold in certain configurations.

In this culminating chapter, the main research question of this thesis has been answered.

In the following sections all conclusions of the research are presented and discussed, followed by recommendations for further research.

14. Conclusion and discussion.

14.1 Conclusion:

Over the course of this thesis the following research question has been investigated:

How can the combination of PocketQube structure and PocketQube orbital deployer be optimized for mass?

A methodology for this optimization has been presented throughout, investigating various structural aspects, according to the following sub questions:

- *What are the requirements, needs, constraints and design considerations for the PocketQube structure and orbital deployer from DelfiPQ, potential launch providers and other major PocketQube stakeholders?*

In the sections pertaining to this question, the following has been investigated: what does one want from a structure or deployer and what are the possibilities? The requirements, needs and constraints are respectively given in Table 1, Table 2 and Table 3. The potential launch providers and stakeholders are presented in chapter 4. The maximum loads the structure is susceptible to, are found to be up to 2000Hz and 6.2g.The main design consideration when creating a PocketQube or its deployer, after fulfilling all the requirements, comes down to finding the balance between saving mass, ease of assembly and comfort of use suited for the mission at hand.

- *How do mass, stiffness and other structural properties scale down from CubeSats (1U-3U) and their orbital deployers to small PocketQubes (1P-3P)?*

In the current standard of PocketQube structures and deployers the difference when scaling down from CubeSat format is not reaching its full potential. As presented, an average CubeSat structure has a mass of 0.89kg, while a PocketQube structure is set at 0.185kg. The deployers have an even smaller difference, going from two kilograms to one kilogram when scaling from CubeSat to PocketQube respectively. This is already significantly less mass reduction than would be expected by scaling down with proportionally. In chapter 8 detailing scaling, the conclusion can be drawn that structural properties do not scale to a third power as might be expected, but rather scale more than that. Mass reduction is to be achieved by abiding scaling laws. Scaling structural properties generally follows the Table 12 Froude scaling laws. From this it is concluded that while dimensions shrink to the third power, structural rigidity scales down with a fifth power. Meaning that for structural purposes 75% more mass can be saved with respect to simply scaling down its dimensions to the third power. Simply put, the smaller a structure gets, the stronger and more resilient to loads it gets compared to its size.

- *Which innovative structural design and production methods can be implemented to achieve a mass-optimized design compliant to the requirements and needs?*

In the sections pertaining to design, an ideology is presented in which the main aspects are the following: determine the right material, and remove unnecessary mass with respect to loads and attachments. Starting from the reference or standard and leading up to the first prototype and concepts, this yields a methodology which, one designing a small satellite (specifically PocketQube) mission, could follow in order to create a mass optimized design.

Presented are innovative concepts, one giving a topology optimized internal structure made out of the 3D printable material Windform XT2.0 with a mass of about 7.82 grams, having no outer structure whatsoever and relying on glue connections. Whilst the other, preferred concept, is only an outer structure consisting out of PCB's that would otherwise be used for internal stacking, thus theoretically having no net structural mass.

For the deployer the same ideology has been applied, whilst abiding by explosion hazard restrictions. Resulting in a an unfolding box concept, also made out of Windform XT2.0, and having a mass of 230 grams.

14.2 Discussion

Over the course of this thesis the following methodology has been presented to reach a final optimized design for both the PocketQube and Deployer.

Initially the findings of the literature study are reviewed, from this perspective research questions have been formed with respect to the topic at hand: structures.

After identifying the stakeholders, requirements for both a structure and a deployer can be set and investigated. Throughout the thesis, information is gathered concerning the requirements in terms of attachable components, dimensional constraints, mechanical loads ,etc.

At this point attention is given to the current PocketQube standard, with respect to the projects already launched and in the making. Decisions are made and supported for the dimensions of the PocketQube standard to which the DelfiPQ shall abide.

After this, scaling is investigated, both for going down from CubeSat to PocketQube and for picosatellites and their mechanical properties in general.

In order to achieve a final design, a comparison between materials is made. A supported choice is set for Windform XT2.0 for conventional structures. This material is specifically designed for space applications, with a high strength to density ratio, availability for 3D printing techniques, a low cost and close to no outgassing, the material is chosen for both the PocketQube structure and deployer.

When all the requirements are known, the design process is discussed. The main philosophy of removing unused mass is initially demonstrated by different skeletonized designs. After this, where suitable, a topology optimization is performed to exactly this end.

The Windform XT2.0 wireframe structure has a mass of 7.82 grams and relies on glue-socket connections for assembling. The material cost and manufacturing time are respectively ~€190,- and within five days. With respect to the original structure, the mass is reduced by 234.18grams or 96.7 %.

This type of wireframe structure with glue connections has its advantages and disadvantages. The main advantage is the low mass with respect to a small price and low manufacturing time. The disadvantages lie in the glue connections, making assembly and disassembly less practical. In reality this would mean that this type of structure would be mainly suitable for single use, mass produced satellite missions.

An unconventional approach is the use of the PCB's as the actual structure, in this case the added mass of the structure becomes negligible. When using adhesives to attach PCB's to each other the mass is the lowest possible, however a great discomfort of assembly and disassembly is added. In order to compromise, a final design is proposed where corner brackets are used to have redesigned PCB's function as a structure.

What is most important to note here is that a great amount of mass has been saved by these concepts, while still fulfilling all the requirements. The design facilitates all the components that need to be attached or complying with the structure, while abiding by all the constraints set for it, and still resisting all the loads exerted onto it.

Through prototypes, tests could be performed to validate the software approach of topology optimization. After a maximum deviance of 6.8% of the predicted values, the software used as a critical part in the methodology of optimizing a structure, was deemed validated. After which the validation of the actual structures took place, in which representative loads were applied to the prototypes, both not resulting in structural failure of any kind.

Out of the two concepts presented here, it is by trade-off as shown in Table 17 concluded that the PCB outer structure with brackets concept is the final preferred concept. The concept has a negligible structure mass, a production cost and time which are well acceptable, better structural properties and an optimal ease of (dis)assembly.

As the structure itself, likewise the deployer has the same design methodology exerted on it. Although topology optimization through material omission of the box was prohibited due to explosion hazard guidelines, optimization could still take place. The deployer has been shrunk, the material set to Windform XT2.0 and the deployment unfolding mechanism chosen as shown by trade-off in Table 18. Most properties of deployers are similar, e.g. cost, manufacturing time, and ease of assembly, therefore the main focus can go to mass. For this reason a "measuring tape spring" unfolding mechanism is selected, because it requires no added dimensions of the deployer box in order to accommodate the mechanism. When furthermore the material of choice is Windform XT2.0 ,this deployer has a mass of 230 grams, which with respect to the original deployer is a reduction of 1624 grams or 87.6 %. Important to note about the unfolding, by measuring tape, mechanism is the fact that it can only work as a solo deployer. This is due to the fact that when surrounded by other deployers or hardware, the box cannot unfold. However in terms of mass savings, this is the preferred deployer concept.

This issue, as the glue connections for the structure, immediately reveal the inherent flaw for this thesis: the quest for mass optimization. Mass has been optimized to such an extent, sacrificing ease of assembly, disassembly and general comfort of use, while purely pertaining to the requirements specified, that a result is procured that is mainly of use for irreversible integration, single use and series production. This leads to the DelfiPQ project, for which assembly and disassembly is important to such a high degree, that the reality has deviated from the methodology of this thesis, both for the structure as the deployer. This is deemed to be the case for the PocketQubes as a learning tool in general, where students will want to assemble and disassemble its components. As opposed to corporations, who eventually might launch numerous PocketQubes, ready made, “fire and forget”. As such a case by case approach is advised in order to balance mass saving and comfort of use, for each respective mission type.

This concludes this research, throughout which a method or ideology has been presented, which offers a solution with respect to structural mass reduction of small satellites and their respective deployers, contributing to the cost effectiveness of the small satellite field.

15. Recommendations for continued research.

In this section some recommendations are presented which were currently beyond the scope of this thesis, but would be a logical direction in which to continue.

- Thermic performance has currently not been taken into account for the structure optimization. As the structure is mostly open, it is considered to a negligible effect on the internal heating and heat distribution of components.
- For future PocketQube development, it would probably serve to abandon the traditional deployer box idea, which in turn leads to the required guiding plate. During this thesis an insight is given into the mass that can be saved in this way, however due to ISIS guidelines for explosion hazard, the deployer box concept is still adhered to.
- For the PCB structure concept, it would probably save more mass to find out what the minimum thickness required for the PCB's is. During the scope of this thesis, this was limited to available sizes from manufacturers.
- Another interesting thing to add to topology optimization would be stiffness. In other words, what deflection is acceptable for the components attached to the structure.
- The aging of materials in space was not taken into the scope of this thesis, because both concept materials (Windform XT2.0, and FR4 for PCB's) have been space tested. However when regarding new materials in order to fabricate a structure this should be checked.
- Inside the scope of this thesis, at points where glue connections were assumed, these were assumed as perfect welds, which is not too far from reality. However it might serve to investigate more rubbery, perhaps silicone based, glues for their dampening properties in order to deal with vibrational loads.

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