Chair of Astronautics
Prof. Prof. h.c. Dr. Dr. h.c.
Ulrich Walter

Master's Thesis

Analysis and Development of a System Life Cycle for CubeSat Missions that are Unrestricted by ECSS Compliance

RT-MA-2019/13

Author:
Moustafa Elhag

Supervisor: Dipl.-Ing. Martin Dziura
Chair of Astronautics
Technische Universität München

Acknowledgements

I would like to thank *Martin Dziura* for his support and guidance, *Martin Langer* for sharing his vast network of contacts in the SmallSat industry with me, *Michael Weisgerber* for his guidance and for proof reading the thesis in the week following the birth of his firstborn and *Caroline Lösch* for continuously dealing with a preoccupied mind.

Lastly, I would like to thank all of the interview partners for their cooperation and the valuable insights they shared regarding satellite development.

Disclaimer

This thesis does not aim at critiquing the valuable work conducted by far more experienced engineers in the standardisation of conventional satellite development. It merely tries to highlight the fact that a new emerging and privatised market might require a different approach.

Zusammenfassung

Das New Space Zeitalter bietet zahlreiche neue Möglichkeiten im Bereich der Satellitentechnologie mit geringeren Hürden besonders für den privaten Sektor. Insbesondere die Technologie der Kleinsatelliten wächst über ihren ehemaligen Zweck als reines Technologie-Testbed hinaus und entwickelt einen eigenen Markt parallel zu den größeren Pendants aus dem Old Space Zeitalter. Die neuen Standards für die Entwicklung von Kleinsatelliten und insbesondere der System Life Cycle (SLC) sind von den Old Space Standards abgeleitet, welche mit der Absicht entworfen wurden, komplexe Missionen der bemannten Raumfahrt abzudecken. Jedoch haben diese unvergleichbare Randbedingungen hinsichtlich Entwicklungszeit und Ressourcen, was die Anwendbarkeit dieser Standards auf Kleinsatellitenmissionen mit generell beschränkten Ressourcen in Frage stellt.

Das Ziel dieser Arbeit ist es, die Implementierung von SLCs in europäischen Kleinsatelliten-Missionen zu analysieren und mit den bestehenden Standards abzugleichen. Dazu wurde eine digitale Umfrage sowohl mit Teams wissenschaftlicher Universitätsprojekte, als auch mit privaten Unternehmen, die Kleinsatelliten entwickeln, durchgeführt. Anschließend wurden Interviews mit den Teilnehmern, zugeschnitten basierend auf ihren jeweiligen Antworten im Rahmen der Umfrage, durchgeführt, um weitere Einblicke in die Thematik zu erhalten.

Die gesammelten Daten und Erkenntnisse sind in dieser Arbeit präsentiert, diskutiert und zusammengefasst und dienten als Grundlage für den Entwurf einer SLC Implementierung in Kleinsatellitenmissionen. Der vorgeschlagene SLC hat das Ziel durch die Entwicklung und den Betrieb eines Kleinsatellitensystems zu führen und eine Basis für weitere Diskussionen über die Standardisierung der Kleinsatellitentechnologie zu schaffen. Er umfasst die zu durchlaufenden Entwicklungsphasen, die Reviews zum Übergang in die nächste Phase, sowie die erwarteten Ergebnisse in jedem Review und schlägt mögliche Prozessmethodiken auf der Grundlage der in den Interviews gewonnenen Erkenntnisse vor.

Basierend auf den Ergebnissen wird das oben genannte SLC beispielhaft für das Kleinsatellitenstartup Orora Tech unter Berücksichtigung deren Randbedingungen implementiert. Abschließend wurden die Ressourcen und die Expertise der BERNS Engineers GmbH genutzt, um eine Vorgehensweise für die Standardisierung der Kleinsatellitenentwicklung, auf Basis der etablierten Standardisierung anderer Industrien, zu gestalten.

Abstract

The New Space era offers novel opportunities with reduced entry barriers for the private sector with regard to satellite technology. Specifically, SmallSat technology is stepping out of its former purpose of being merely a technology testbed and is developing its own market parallel to that of its larger Old Space counterparts. However, the standards addressing SmallSat development and specifically the SLC thereof are derived from Old Space standards. Those standards were designed with the intent to cover complex missions encompassing manned space flight which have incomparable boundary conditions regarding development time and resources. This raises the question of their applicability onto resource-constrained SmallSat missions.

The purpose of this thesis is to analyse the implementation of SLCs in European SmallSat missions and to understand their compliance to existing standards or lack thereof. In order to do so, a digital survey was filled out by both scientific university projects and private companies that develop SmallSats. Additionally, a tailored interview was conducted with the participants based on their survey answers, in order to gain further insights into the subject matter.

The gathered data and insights were presented, discussed and summarised in this thesis before they served as a basis for the design of a proposal for SLC implementation in SmallSat missions. The proposed SLC aims at guiding through the development and operation of a SmallSat system and offering a basis for further discussions on the standardisation of SmallSat technology. It covers the development phases to be undergone, the reviews used to phase-shift, the expected deliverables per review and advises on applicable process methodology based on the insights gathered during the interviews.

Based on the results, an example of the implementation of the afore mentioned SLC at the SmallSat Startup Orora Tech is given, based on their boundary conditions. Lastly, due to the inapplicable Old Space standards the resources and expertise from BERNS Engineers GmbH were used to propose a road map for the standardisation of SmallSat development based on the established standardisation of other industries.

Contents

List of Figures

List of Tables

Acronyms

ADCS Attitude Determination and Control System

AM0 Air Mass Zero

CDR Critical Design Review

CDS CubeSat Design Specification

COTS commercial off-the-shelf

DIL Deliverable Items List

ECSS European Cooperation for Space Standardisation

ELR End of Life Review

EM Engineering Model

ESA European Space Agency

EU European Union

FM Flight Model

FRR Flight Readiness Review

INCOSE International Council on Systems Engineering

IOCR In Orbit Commissioning Review

IOD in orbit demonstration

ISIS Innovative Solutions in Space

ISL Innovative Space Logistics

ISS International Space Station

KDP Key Decision Points

LEO Low Earth Orbit

MD Mission Design

MOEs Measures of Effectiveness

MOPs Measures of Performance

MOVE-II Munich Orbital Verification Experiment II

MRR Manufacturing Readiness Review

NASA National Aeronautics and Space Administration

NCRs None Conformance Reviews

NPR NASA Procedural Requirements

OEM original equipment manufacturers

PCB printed circuit board

PDR Preliminary Design Review

PM Project Management

P-POD Poly Picosatellite Orbital Deployer

QA quality assurance

RIDs Review Item Discrepancies

SAR System Acceptance Review

SDR System Design Review

SE Systems Engineering

SIR System Integration Review

SLC System Life Cycle

SpaceX Space Exploration Technologies Corp

SVCM System Verification Control Matrix

TL Top Level

TPMs Technical Performance Measures

TRB Test Review Board

TRR Test Readiness Review

TUM Technical University of Munich

USA United States of America

USSR Union of Soviet Socialist Republics

V0 Version 0

WBS Work Breakdown Structure

1 Introduction

This chapter aims at introducing the subject matter to the reader in order to elaborate on the motivation behind conducting the research and work that comprises the content of this thesis.

In the New Space era the privatisation of the space industry has lead to lower entry barriers for the development and operation of space systems. Specifically, the development of satellite systems has seen an increase and acceleration of the development process through the development of responsive systems with innovative process methodology and novel technologies by private entities which develop smaller more responsive satellite systems with less resources. [2, 3, 4, 5]

However, the standards governing satellite development stem from conventional satellite development in which governmental agencies were the main developers of satellite systems. This has the result that currently established standards were set by governmental agencies which had different boundary conditions with respect to available resources and development time. Further, existing standards describe the development process to rigorous detail. This stands in contrast to the flexibility and innovativeness of the methodology applied during the development process of responsive satellite systems in the New Space era. [4, 6, 7]

Thus, a discrepancy between standards governing the development process and applied methodology for the development of responsive systems can be assumed to exist. Hence, it requires research into the subject matter in order to understand the necessity and challenges of applying exiting standards, the novel development methodologies and to propose a solution that negates an existing discrepancy in standardisation.

The work conducted during the course of this thesis aims at doing so for systems engineering implementation of system life cycles of responsive satellite systems. This is done through literature research, collecting insights from satellite development through the conduction of reviews, proposing a solution based on both methods of research and validating the applicability of it.

2 State of the Art

This chapter aims at providing the reader with insights on the state of the art in satellite development, SLCs of satellite missions and the standardisation thereof. Specifically, it aims at developing an understanding of the New Space trend and its influence on satellite development while elaborating on the current standardisation thereof.

2.1 New Space

In order to lead up to the current state of the art in satellite development an understanding of the New Space trend is developed in this section for the purpose of placing the content of this thesis into both a temporal and a contextual frame.

2.1.1 Historical Background and Standardisation

The innovation in the space industry was commenced by the 'Race to space' and the subsequent 'Race to the moon'. During this time, the United States of America (USA) and the Union of Soviet Socialist Republics (USSR) were politically motivated to achieve scientific and technological progress that would enable them to be the first to orbit the earth and land on the moon respectively. [8]

After the landings of the Apollo missions and the collapse of the USSR, space lost its importance as a competitive domain for garnering international prestige [2]. At that time the communication and navigation satellite businesses started getting lucrative and a prioritisation of profit over prestige occurred. Thus, a more sustainable business model started being implemented in the space industry [2, 9]. The start of which forced governmental agencies to show that their programs had economic payoffs. Said payoffs motivated large cooperations to become parts manufacturers and subsequent satellite developers enabling the private sector to enter the space industry [2]. In the USA, the NASA has been responsible for the development of conventional space projects. They outsourced development services to the private sector, while providing detailed work descriptions and holding ownership of all vendor development activities and parts [10, 5, 11].

The rate of innovation and risk acceptance of the early space races had to a certain degree resulted in catastrophic failures and the loss of human life. As a consequence, standards were developed to reduce known risk factors, by describing the development process and the results thereof in rigorous detail and further evolving into a norm for both development by government agencies and for the cooperation between government agencies and the private sector. Upholding those standards would assure a risk adverse space industry which on the one hand ensures mission success but on the other hand leads to long and expensive development processes. Expensive development processes and the cost of launching the final product into space made the space market an endeavour only governmental agencies or large cooperations could dare to undertake [12, 11].

However, as innovations in other industries lead to technologies becoming exponentially better, smaller and more reliable the space industry had to be influenced. For example, as the computing power of mobile phones in the early 2000s was becoming as powerful as desktop computers of the 1990s, so too was the computing power achievable onboard of modern satellites in comparison to their predecessors [5, 13, 14, 15].

The aforementioned lower costs to enter space activities motivated federal agencies, academic institutes and companies to concentrate on smaller satellite projects with increasing frequency [14]. These so called SmallSats (See subsection 2.1.4) are a product of the shift caused by the New Space Philosophy on the financial aspect of satellite development as well as on the developmental process itself which are both further illustrated in the next sections.

2.1.2 Financial Parameters

> *"The days where commercial access to space is limited to a commercial company's absolute cost advantage, a sole source contract, or government funding are over."* [3]

Since the turn of the century an exponential increase of investment in space industry has been made by large banking entities, investment fonds, angel investors as well as private investors funding their own space ventures [16]. The most lucrative entry point for investments in the space industry are SmallSat missions with their relatively low investment requirement that recently allowed for the usage of crowdfunding platforms to secure funds [5, 3].

In 2015, the global space industry accounted for a spending of $323 billion. Commercial space products, services and the support industry thereof accounted for 77% of this global spending, while the U.S. government and its federal agencies accounted for 14%. The remaining $32.3 billion are composed of government spending by other countries [10].

Between 2014 and 2020, the European Union (EU) alone planned to invest over EUR 12 billion in space activities. The EU owns space systems with 33 satellites currently in orbit and over 30 planned in the next 10–15 years. Currently, space technologies, data and services have become indispensable in the daily lives of European citizens. [12]

> *"It [Space] has [...] improved our everyday life in many ways — the European Space Agency estimates that for every Euro spent in the sector there has been six Euros benefit to society."* (Werner Hoyer, President of the European Investment Bank) [12]

While globally an increasing number of governmental bodies are acknowledging that the space sector has become an established component of their fiscal strategies, the private sector has established itself as an indispensable partner in the space industry without whom the public sector can no longer solely compete on an international market. The best example of this is Space Exploration Technologies Corp (SpaceX) and further private companies allowing the USA to regain transportation capabilities to the

International Space Station (ISS) and thus loosing the dependancy on Russian Soyuz missions that had become the norm after the end of the Space Shuttle Program [10].

Furthermore, market research shows an increasing demand for space technologies applicable for earth and weather observation, as well as communication and space exploration [17, 18, 19]. New Space companies are focusing on said customer needs and developing solutions independent of the public sector [5]. Today, there are established private companies for every aspect of the satellite industry. Meaning that, the process starting from the need for a satellite to the development and launch of the system, as well as the financial backing and parts supplied, can be undergone without the direct involvement of any government entity.

Specifically, the satellite bus market being the “most competitive segment of the space enterprise”, is a product of private companies rapidly increasing their efficiency by using commercial off-the-shelf (COTS) standardised parts and building modular and reconfigurable satellite buses. This increases their share of profit generated in the space industry while outcompeting the public sector. [20]

Further components influencing the development process of satellites are illustrated in the next section.

2.1.3 Parameters of the Development Process

Research specifically addressing the satellite development process in the frame of the New Space era is still in its infancy, but certain characteristics are observable that distinguish the development process from conventional approaches.

First of all, in the conventional space industry the private subcontractors of NASA would get detailed description for every development process in the form of standards to be followed (See subsection 2.2.2). In New Space times the subcontractor bares more responsibility during the development of a system and thus shares both risk and costs [10]. This is called Supplier Integration in Lean Management Philosophy. Supplier Integration is a trend in multiple global industries and is gaining influence on the space industry [21, 22].

Further, the responsiveness of a system is becoming a significant New Space characteristic. Responsiveness describes the ability of a system to rapidly respond to uncertainties, whether they are of technical or environmental nature or due to demand and launch uncertainties as well as funding stream uncertainties [4].

Brown acknowledges that ”larger monolithic spacecraft of today are notoriously unresponsive” [4] and hence he highlights the fractioning of satellite systems as the solution to the unresponsiveness. Fractioning occurs when “a satellite is decomposed into a set of similar or dissimilar component modules which interact wirelessly while in cluster orbits” [4]. Launching multiple smaller satellites to fulfil an objective allows for multiple iterations in the development process where risk - due to uncertainty - can be mitigated to multiple spacecraft instead of a sole one.

.

"Today's spacecraft are designed for requirements. A more responsive solution is to design spacecraft for uncertainty." [4]

Although fractioning is a relevant solution for unresponsiveness in respect to the grand mission goal, the fractioned satellite system components are becoming more responsive themselves, because of further factors that accelerated technology advances and enabled novel design methodology. Additive manufacturing and the use of novel materials allow for more precise production methods which have led to the development and vast availability of miniaturised component parts, more specifically the fields of microelectronics, telecommunication instrumentation and sensors have been greatly impacted [5, 13, 14, 15]. Thus, these globally available and reasonably priced COTS components were adapted to the space industry's needs and used in small satellite production lines [23].

Furthermore, the usage of COTS components, common bus components and the fact that software can be updated after the launch, opens up the field of modular structures which adds a core capability to the development process allowing it to become, in some instances, one of reconfiguration rather than one of redesign [20].

These New Space characteristics clearly distinguish the development process from conventional satellite development and most importantly minimise costs and time to market [18]. They are summarised in Figure 2–1. [24]

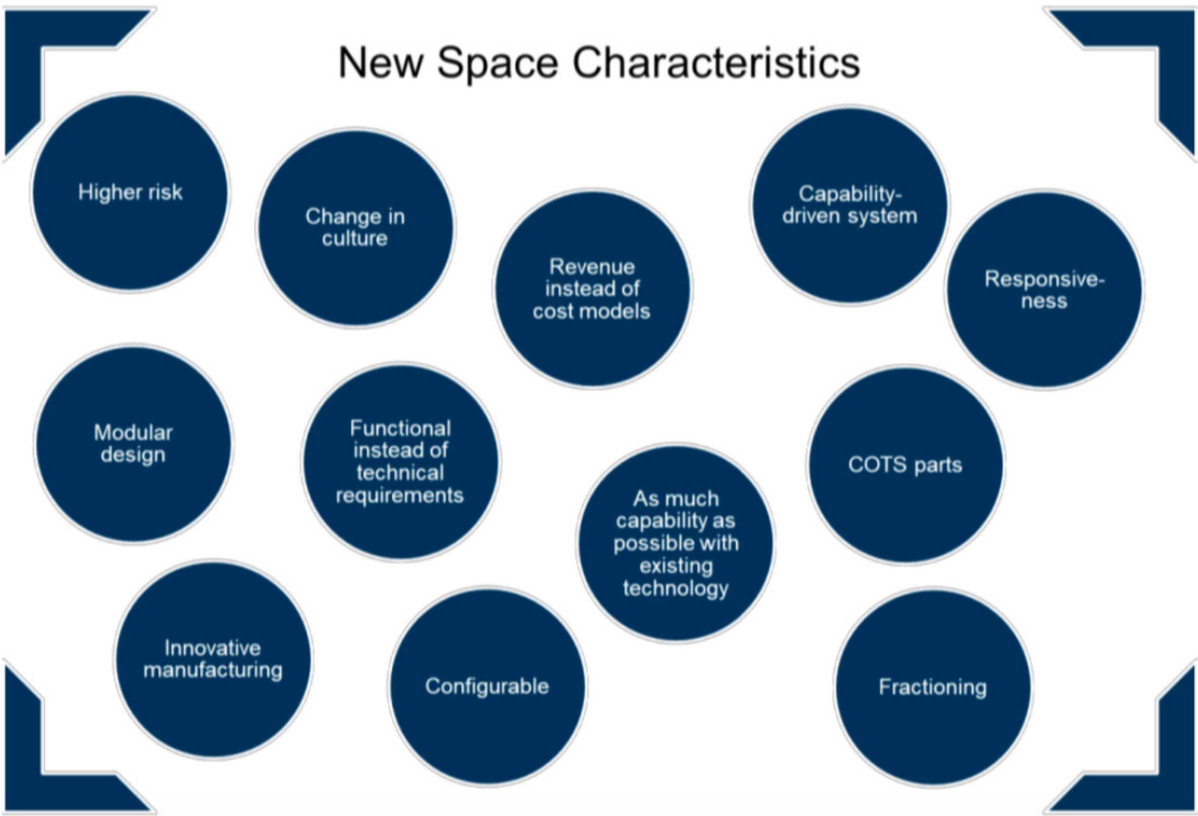


Fig. 2–1: New Space Characteristics [24]

.

Finally, these New Space characteristics allow not only young but also established private companies to operate with novel approaches in system development. They are agile, innovative, economical, take on higher risks and capable of showing a competitiveness not previously common in conventional satellite development as illustrated in the previous section [25, 3]. This holds especially true for companies developing SmallSats which are presented in the next section.

2.1.4 Definition of SmallSats and CubeSats

> *"Were it just the actual spacecraft mass, the changes from this trend would be limited in scope, but the trend is encompassing of more than just a single design parameter. Used colloquially, the term 'Small Satellites' or 'SmallSats' describes not just a focus on lower mass satellites, but also on a different approach to building, operating, financing, and managing risk for satellite systems."* [5]

SmallSats are a class of satellites resource constrained by mass, power, volume, delivery timelines and financial cost relative to their larger counterparts [26]. As advances in different technologies make components for space missions smaller, lighter and more power efficient, the market niche for SmallSats is not only becoming profitable for university projects but also for industrial application. This is specially relevant for developing nations, gaining access to space technology and promoting education and technology utilisation [14, 24].

SmallSats started out as a "petridish" or experimental test beds for novel space technology [5]. An example of this is the Munich Orbital Verification Experiment II (MOVE-II) ongoing at the Technical University of Munich (TUM). Although the project had multiple scientific and educational mission objectives, the mission objective of flying novel solar cells and gathering their data can be taken as an example of a test bed. MOVE-II's payload consisted of a solar cell characterisation system, a system capable of measuring the I-V characteristic curve of solar cells, their temperature and the sun angle. The payload characterised a novel four-junction solar cell and its corresponding single-junction cells against degradation in the space environment. It is not possible to gather information of equal quality on the ground. State of the art solar simulators fail at reproducing an Air Mass Zero (AM0) spectrum and there is no apparatus to reproduce cosmic radiation [27].

Aside from the educational benefit for the universities themselves, such platforms allowed for the mitigation of risk from larger satellites with lower barriers to entry for developers [28]. Thus, allowing many non-traditional entrants, whether they're universities or both public and private companies, to explore new ideas on how they would satisfy their mission requirements or deliver a novel product. Enabled by lower development and launch costs and supported by an ecosystem of vendors, technologies are quickly attempted and refined. The resulting effect is that the small satellite market is serving as a laboratory for rapid evolution of approaches on both the business and technology fronts of the space industry [5].

.

Rivers applies an accurate analogy of “bullets” versus “cannonballs” in the testing of new concepts. Derived from research by Collins and Hansen on what makes companies successfully thrive in their industries during changing times and how those companies used small experiments, or bullets, versus large scale experiments or changes – cannonballs [29]. He argues that SmallSats satisfy the criteria that Collins and Hansen lay out for a bullet and that three key patterns of this technology give it a laboratory nature: the excessive use of COTS parts, the implementation of extendable open-source software, and both modularity and standardised interfaces [5].

Through these key patterns, a different type of space innovation than with conventional satellites is possible. SmallSats operating in Low Earth Orbit (LEO) have a shorter orbit lifetime and the development time is shortened to a few years. Therefore, rapid advantages of new-cutting-edge technology can be utilised. [25, 30, 31]. Hence, SmallSat projects have shorter lifecycles than conventional satellite projects. So in the sense of the analogy, multiple SmallSat ”bullets” can be fired in the time a conventional satellite project - a canon shot - completes a cycle. For each bullet or iteration, the chance to adjust the aim affords the SmallSat domain a pace of change that reinforces its role as a laboratory for the space industry as a whole [5].

Also of crucial importance is the fact that SmallSats are providing acceptable reliability for a weighted reduced mission cost and lifetime [19, 30, 31, 32, 33]. However, SmallSats have recently grown beyond the limitations of technology test beds. Today, established private companies are offering mission development based on SmallSat technology which creates an own market and technological path. Rivers compares them to machine guns with the conventional satellite domain model being the heavy artillery [5].

That does not mean that SmallSats are replacing conventional satellites, but rather that they are developing their own technological path. The innovative disruptive force – successful concepts from the SmallSat petridish - has a deep and lasting impact on the conventional satellite market, but rather than replacing the traditional satellite industry path, the two paths started forming a symbiotic relationship. They feed off the technology, market and culture of each other and benefit the industry as a whole. This symbiosis is noticeable through the migration of technology and business practices [5, 34, 25].

One analysis of SmallSats with respect to cost, power and utility, suggests the optimal satellite size to result in roughly 42 kg [35]. The accumulation of single CubeSats to the extend of larger CubeSat units, e.g. 27U with a mass up to 54 kg, is getting close to this optimal size [24].

CubeSats are a form-restricted version of a SmallSat that have a standardised cubic shape of 10 x 10 x 11 cm, with a mass of up to 1.33 kg which is considered one unit (1U) and is defined in the CubeSat Design Specification (CDS) [36]. They are further extended to a multiple of the cube unit ranging from 2U up to 27U. This standardisation is a basis for further developments of efficient and modular products, e.g. the standardised Poly Picosatellite Orbital Deployer (P-POD) which is an interface between a rocket and a CubeSat. This launch integration allows for more compact satellite missions to be accomplished per launcher. Proving that CubeSats are an initiator and accelerator for space industry modularisation and standardisation [5]. Additionally, adhering to the CDS form standard and the development of interfaces based on it allows for CubeSats to have a novel flexibility. A CubeSat can be launched with any interface that is based on that standard which decouples the the development processes of both and ads flexibility regarding the launch opportunities, as an interface won't need to be developed specifically for every CubeSat.

Furthermore, launch opportunities mostly existed in the form of secondary payload missions, with launches often subsidised by the government. However, SpaceX's SSO-A launch in December 2018 which launched MOVE-II into orbit was one of the largest single ride share missions to date and was nicknamed the 'SmallSat Express'. The Falcon 9 rocket launched 64 spacecraft onto a Sun-Synchronous Low Earth Orbit, proving that the demand of the new emerging market of SmallSats is sufficient to finance a launch on its own [37]. This establishes the SmallSat market as the initial frontier of space access for governmental bodies as well as universities independently from the conventional market. Another company called Rocketlab is catering to that market with maximal payload capacity designed to launch SmallSats into orbit [38].

Research conducted by Köchel presents Table 2–1 as an exemplarily satellite classification by mass range [24]. Her classification is derived from both a more scientific source which is Ley [39] and an industrial view by Doncaster, et al. [40]. Historically, satellites have been classified by mass because mass-to-orbit has been the cost driving factor in this industry [41].

Tab. 2–1: Satellite classification based on mass range

Satellite classification	**Mass range [39]**	**Mass range [40]**
Conventional Satellite	More than 500 kg	-
SmallSat	-	100 – 500 kg
MiniSat	100 – 500 kg	-
MicroSat	10 – 100 kg	10 – 100 kg
NanoSat	1 – 10 kg	1 – 10 kg
PicoSat	Up to 1 kg	Up to 1 kg
FemtoSat	-	10 – 100 g

During the course of this thesis, the term SmallSat is used to encompass all satellites under 500 kg. Thus including Mini-, Micro-, Nano-, Pico- and FemtoSats in order to make this thesis easily readable. However, CubeSats will accurately mean one or a multiple of the 1U form restriction standard.

After presenting the novelties of New Space on multiple fronts, the state of the art on the aspects not yet sufficiently innovated under the New Space era is presented. This builds the framework for a suggested innovating of the aspects discussed above during the course of this thesis.

2.2 Standards and System Life Cycles

This section aims at providing an insight on the state of the art in SLCs. Specifically, the traditional SLC implemented by Systems Engineering (SE) in the space domain.

After presenting the terminology used for describing a SLC and its components - according to the most commonly used sources - the standards used for traditional European missions are presented, before a standardisation example from another industry is introduced.

As mentioned, this section aims more towards defining the terminology used during the course of this thesis rather than representing the state of the art in SLC implementation to great detail. This is due to to the fact, that the work conducted in this thesis includes interviews on the state of the art in SLC implementation and is elaborated upon in chapter 5).

To define the term system the International Council on Systems Engineering (INCOSE) definition is used and presented below. The INCOSE is the largest professional society in the field of SE.

> *"A system is an integrated set of elements that accomplishes a defined objective. These elements include products (hardware, software, firmware), processes (policies, laws, procedures), people (managers, analysts, skilled workers), information (data, reports, media), techniques (algorithms, inspections, maintenance), facilities (hospitals, manufacturing plants, mail distribution centres), services (evacuation, telecommunications, quality assurance), and other support elements."* [7]

2.2.1 Traditional System Life Cycles and Terminology Definition

> *"In a similar fashion to human physiology, it is useful to think of a system as progressing through a succession of stages known as a life cycle."* [11]

The term system life cycle is not a standardised term in literature. Often the term Product Life Cycle, Project Life Cycle or Project Phase Concept is used to mean the same thing [6, 42, 43]. As this thesis deals with the development process of SmallSats, the term system life cycle is chosen as the most suitable because the managerial aspects of a project are touched upon during the course of this thesis but only in respect to their direct influence on the development process and not in their proceedings as such. Further, the term product could be understood as the physical satellite itself. However, the development process addressed in this thesis does encompass ground communication segments and satellite operation. Thus, the term system life cycle is chosen to reflect the following quote:

> *"System life cycle is a conceptual model that is used by system engineers [...] to describe how a system matures over time. It includes each of the stages in the conceptualisation, design, development, production, deployment, operation, and retirement of the system."* [11]

The main literature used as a basis for the content of this thesis are:

- The **NASA System Engineering Handbook**: as it is the most commonly used and referenced literature dealing with the topic of SLCs [6]
- The **INCOSE Systems Engineering Handbook**: as it is the official handbook by the INCOSE and also widely referenced and used [7]
- The **European Cooperation for Space Standardisation (ECSS) standards**: as it's the official standard for SLC implementation in Europe which is the focus of this thesis (Further elaborated upon in subsection 2.2.2).

Further, the book "Decision Making in Systems Engineering and Management" by the The Department of Systems Engineering at the United States Military Academy is chosen because it aims to be a "useful undergraduate textbook focusing on the practical application of systems engineering techniques to solving complex problems [...] on the highest levels of government (and) military service". In order to do so, it offers a comparison of SLC implementation and presents it in an educational content for students who do not have a formal education or practical experience in systems engineering while also drawing on SLCs from the above mentioned sources [11].

Considering these sources, terminology can be defined that does refer to the same component of the different, referenced SLCs.

System Life Cycle Phases

> *"One of the fundamental concepts used within NASA for the management of major systems is the program/project life cycle, which categories everything that should be done to accomplish a program or project into distinct phases that are separated by KDP"* [6]

All models of SLCs divide them into such phases with a distinct category for the objectives of the phase. However, the amount of distinct phases vary depending on the source. Figure 2–2 shows a comparison of different SLCs.

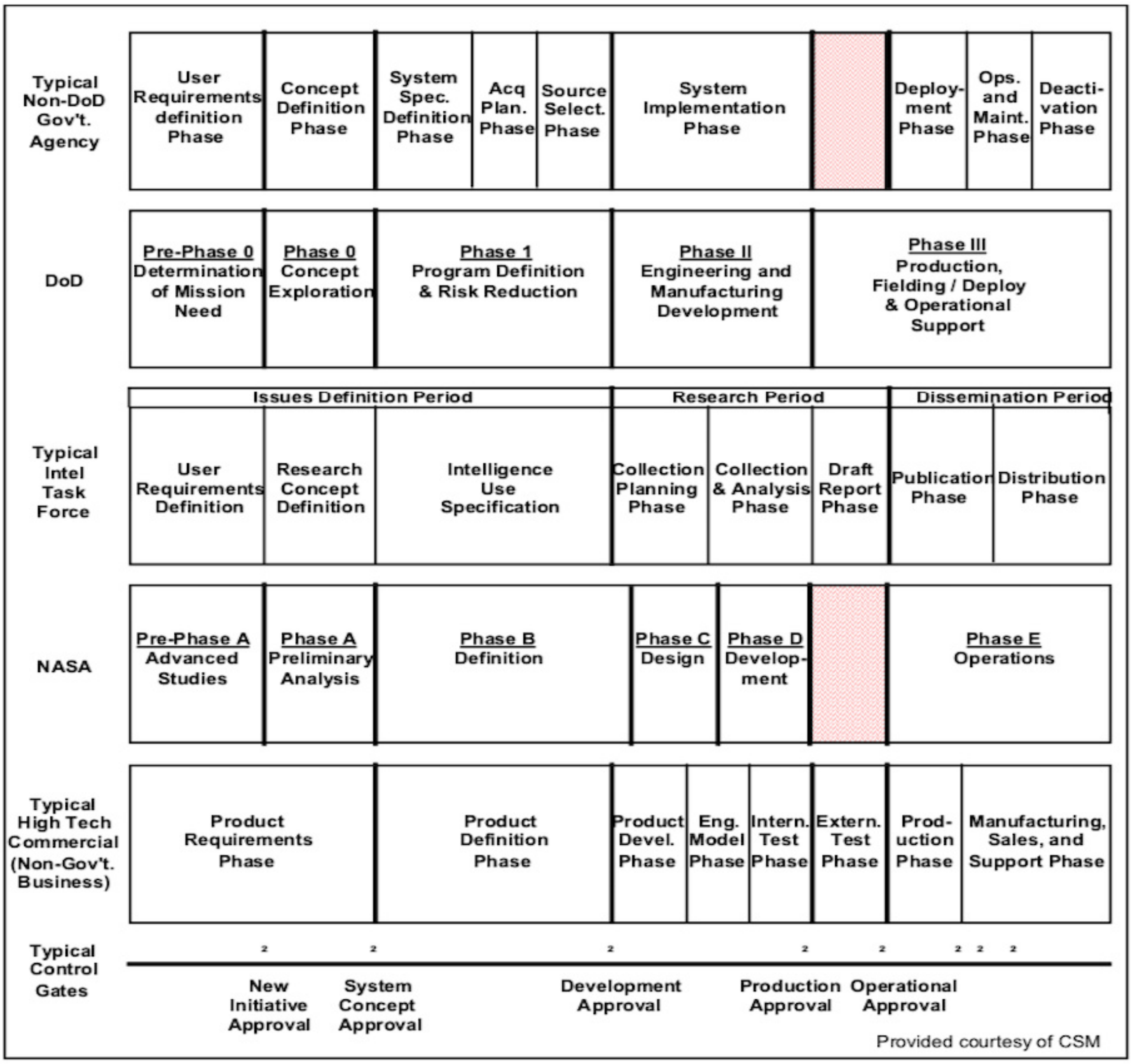


Fig. 2–2: Comparison of SLCs showing the difference in phase devision, terminology, superordinate periods and objectives [7]

As presented, a SLC can be divided into various different phases with defined objectives, with the phases often categorised by superordinate **Periods** and often ending in **Reviews** and **KDPs** (See Figure 2–3). For the contents of this thesis the SLCs from the NASA and the ESA will be taken as the basis for traditional SLC implementation. Figure 2–3 shows a comparison between both and their common denominators.

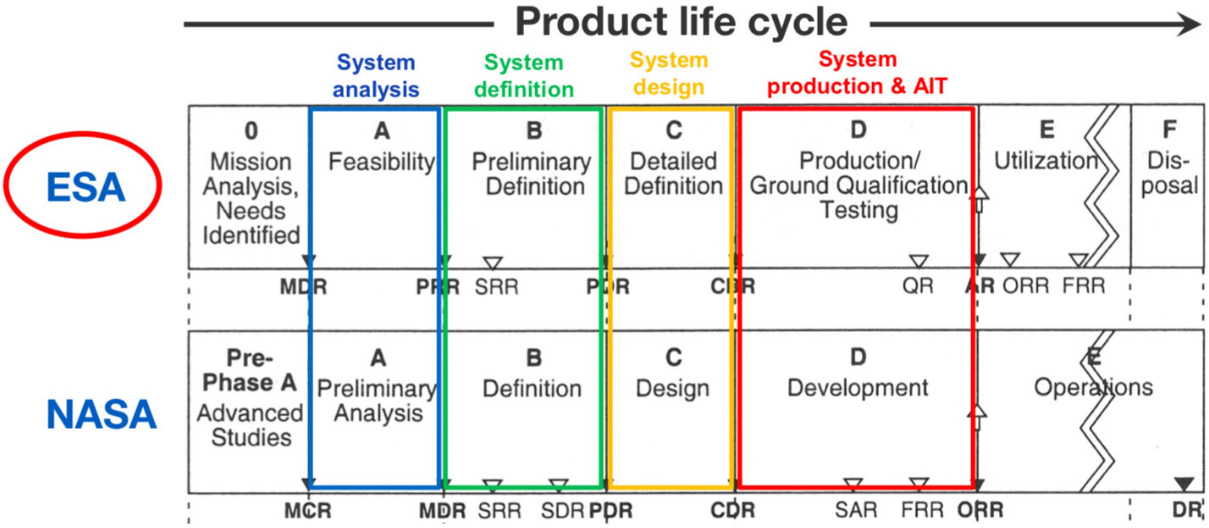


Fig. 2–3: Comparison of NASA's & ESA's SLCs with the ESA's selected as it presents the context of this thesis [42]

The following terminology is chosen as a basis for traditional SLC Phases during the work conducted for this thesis [6]:

- **Pre-Phase A**: Concept Studies
- **Phase A**: Concept & Technology Development
- **Phase B**: Preliminary Design & Technology Completion
- **Phase C**: Final Design & Fabrication
- **Phase D**: System Assembly, Integration & Test, Launch & Checkout
- **Phase E**: Operations & Sustainment
- **Phase F**: Closeout & Disposal

Key Decision Points

> *"KDPs are the events at which the decision authority determines the readiness of a program/project to progress to the next phase of the life cycle"* [6]

During the course of this thesis KDPs are defined as the prelusive quote intends them to be and are synonymous with the term Decision Gate (DG) known from other industries. They are located between phases allowing management to take decisions over the continuation, discontinuation or adaptation of the project.

Reviews & Milestones

Reviews are defined as a report with a specific purpose - in whichever form of conduction - that is conducted in front of a reviewing board which then gives feedback that shall be implemented. The form of conduction and the composition of the review board are further researched during the course of this thesis. However, **Review Item**

Discrepancies (RIDs) are defined as the feedback given by the review board which is expected to be implemented before the review is considered finalised. The positioning of reviews is highlighted for both SLCs in Figure 2–3 in form of triangles.

The term milestone is not defined in literature but is defined during the course of this thesis as a certain desired maturity grade of the system being developed.

The relationship between KDPs, reviews, RIDs and milestones is further researched during the course of this thesis before a final proposal is submitted.

Requirements, Deliverables & MOEs

Requirements describe "how the system must perform during its life cycle" [7]. How requirements are acquired, defined and traced is briefly touched upon in this thesis but will not be the main focus as it is out of the scope of this thesis. This thesis draws on the requirements when explaining the components and relationships of the SLC.

The term deliverables is used in order to encompasses all possible outputs of a phase that are submitted to a second party which can be various types of technical or non-technical documentation, a physical product at a certain maturity or a finalised review.

Further the following degrees or levels for requirements can be found in traditional SLC implementation.

- Measures of Effectiveness (MOEs) are the measures of success that are designed to correspond to the accomplishment of the system objectives as defined by the stakeholder's expectations [7, 6].
- Measures of Performance (MOPs) define the performance characteristics that the system should exhibit when fielded and operated in its intended environment. MOPs are derived from the MOEs but are stated in more technical terms from the supplier's point of view [6].
- Technical Performance Measures (TPMs) are physical or functional characteristics of the system associated with or established from the MOPs that are deemed critical or key to mission success [7, 6].

Stakeholders

> *"A stakeholder, in the context of systems engineering, is a person or organisation that has a vested interest in a system or its outputs [...]. [F]or any systems decision problem, stakeholders will care about the decision reached because it will in one way or another affect them, their systems, or their success."* [11]

The different forms of vested interest in a system are referred to as the **stakes** of the stakeholder. Hence, every group or individual having a stake in the system is considered a stakeholder.

The topic of stakeholders and stakeholder management is also not entirely covered by the scope of this thesis, but is rather elaborated upon when explaining influences on the SLC and specifically the development process, conduction of reviews and the role of the stakeholders on a reviewing board.

Methods

During the course of this thesis the term method will mean process methodology that advises on how the development process should be conducted. While the SLC divides the development process into phases with KDPs, the method often describes the process of going through the phase itself and the relationship between the design, conceptualisation, testing and verification of a system, which in turn can describe the relationships of multiple phase objectives to one another [44].

The main exemplary methods referred to during the course of this thesis are:
(Further elaborated upon in chapter 6 regarding content and choice)

- The V-Model [44]
- The Spiral Model [45, 11]
- Agile methods (mainly in the form of Scrum) [46]

Tailoring

> *"The requirements defined in the series of ECSS Standards are generally applicable to all actors working on space projects, but are intended to be viewed from the perspective of a specific project context, and tailored to match the genuine requirements of the project"* [47].

Thus, the term tailoring means the adaptation of a standard or guideline to meet specific project requirements. Those requirements can be in the form of the environment, technology maturity, product class, cost and risk constraints, organisational complexity and the procurement approach [11].

The NASA SE Handbook for example presents adjusted SLC designs depending on the type of space mission they are intended for and recognises the need to accommodate the unique aspects of each project to achieve mission success in an efficient and economical manner through tailoring. [6]

What the state of the art on that matter is in Europe, is presented in the next subsection.

2.2.2 ECSS standards

> "The European Cooperation for Space Standardisation ECSS is an initiative established to develop a coherent, single set of user-friendly standards for use in all European space activities" [47].

The series of ECSS Standards is intended to be applied for the management, engineering and product assurance in space projects and applications. The ECSS is a cooperative effort of the European Space Agency, national space agencies in Europe and European industry associations for the purpose of developing and maintaining common standards. The standards define what shall be accomplished, rather than the specific terms of how to organise and perform the necessary work.

Analog, NASA has its collection of NASA Procedural Requirements (NPR) defining "what" must be done to properly and successfully manage NASA programs and projects However when it comes to SE, NASA offers a SE Handbook detailing the implementation of a SLC and guiding SE best practices [6]. The same can not be said for the ESA. The INCOSE SE Hanbook can be used for the implementation of the ECSS standards but it does not reference them directly and thus it does not give direct guidance on ECSS implementation [7].

What is meant here by guidance on implementation is a description of the components of the SLC, the positioning of reviews and the expected deliverables of each review as well as a a description on how to show compliance with the standards.

The ECSS standard ECSS-E-ST-10C Rev.1 gives brief guidance on said implementation and does reference other standards with respect to documentation templates [43].

As previously mentioned, space missions used to be exclusively an endeavour governmental agencies could undertake. Thus, these standards were developed as a compliance requirement for suppliers from the private sector. Meaning that complying with these standards was a requirement for cooperating with these governmental agencies. Hence, complying with standards was a prerequisite for being part of a space mission.

ECSS Standards for SmallSats and CubeSats

The ESA provides the TEC-SY/128/2013/SPD/RW document which lists tailored ECSS standards applicable for CubeSat IOD missions [1].

The aforementioned document is comprised of a table highlighting applicable standards and underlines sections that are truly applicable and others that are to be taken as a guideline. Table 2–2 depicts the standards deemed applicable in this document.

Tab. 2–2: Standards deemed as applicable by TEC-SY/128/2013/SPD/RW [1]

Standard ECSS Number	Standard Title
ECSS-E-ST-10-02C [48]	Verification
ECSS-E-ST-10-03C [49]	Testing
ECSS-E-ST-10-04C [50]	Space environment
ECSS-E-ST-20C [51]	Electrical and electronic
ECSS-E-ST-20-08C [52]	Photovoltaic assemblies and components
ECSS-E-ST-31C [53]	Thermal control general requirements
ECSS-E-ST-32C Rev.1 [54]	Structural general requirements
ECSS-E-ST-32-01C Rev.1 [55]	Fracture control
ECSS-E-ST-32-02C Rev.1 [56]	Structural design and verification of pressurised hardware
ECSS-E-ST-32-08C [57]	Materials
ECSS-E-ST-33-01C [58]	Mechanisms
ECSS-E-ST-35-01C [59]	Liquid and electric propulsion for spacecraft
ECSS-E-ST-50C [60]	Communications
ECSS-E-ST-50-05C Rev.2 [61]	Radio frequency and modulation
ECSS-E-ST-60-30C [62]	Satellite attitude and orbit control system (AOCS) requirements

Furthermore, the referred document acknowledges that [1]:

- “For such activities, the majority of the standards contained in the ESA approved list of standards may not be relevant and only a few may be selected as applicable.”
- ”The verification process shall be adapted to reflect the reduced complexity of work and the absence of one or more disciplines.”
- ”[I]t is clear that the design, development and verification process cannot follow a classical ESA project approach to management, engineering, reviews[.] [...] Furthermore, the majority of the standards documents are not relevant/suitable for this type of project.”

This leaves CubeSat developers with a selected few standards that were originally not designed for their innovative technology and that they only have to comply with when working directly with the ESA. Furthermore, the standard describing the SLC and its components is not among the selected applicable standards. The implications of this for SmallSat development is further researched during the course of this thesis.

2.2.3 Automotive SPICE

As previously elaborated, the standards for space missions are mainly established by governmental agencies. However, in the automotive industry an example exists of private companies collaborating on developing a simplistic and implementable industry standard from a previously existing standard in order to suit their specific needs.

Automotive SPICE was developed 2001 as a variant of ISO 15504 (SPICE) by the Automotive Special Interest Group (AUTOSIG). This group consists of the SPICE User Group, the Procurement Forum, and german automotive manufacturers: Audi, BMW, Daimler, Porsche, Volkswagen, and other international automotive manufacturers like Fiat, Ford, Jaguar, Land Rover, Volvo. The listed original equipment manufacturers (OEM)s founded the initiative to define a minimal set of processes for a process reference model [63, 64].

The process reference model (PRM) defines all Automotive SPICE processes to be applicable in well-defined automotive software and embedded systems development. The process reference model is a schema that guides one in a specific field of application to perform certain activities and to produce related work products. On the work floor level, it is a set of base practices (BP) and resulting work products (WP) as deliverables [63, 64].

Automotive SPICE describes the life cycle of electronic products with three different process areas [63, 64]:

- **Primary Life Cycle Processes** — Acquisition (ACQ), Supply (SPL), and two engineering groups: System Engineering (SYS) and Software Engineering (SWE).
- **Organisational Life Cycle Processes** — Management (MAN), Reuse (REU): project and risk management, measurements, process improvement and operational reuse management.
- **Supporting Life Cycle Processes** — Supporting (SUP): quality assurance, verification, documentation, configuration management, change request management, and problem resolution management.

This standard has become a common framework for the assessment of suppliers in the automotive industry and only through it do suppliers qualify to be suppliers for the OEMs [63, 64]. This underlines its success in being a standard defined by the private sector for its specific needs.

During the course of this thesis this will be referred to as the example of private companies coming together to develop a standard to suit their needs.

Figure 2–4 shows the standardised disciplines in the form of a V-Model.

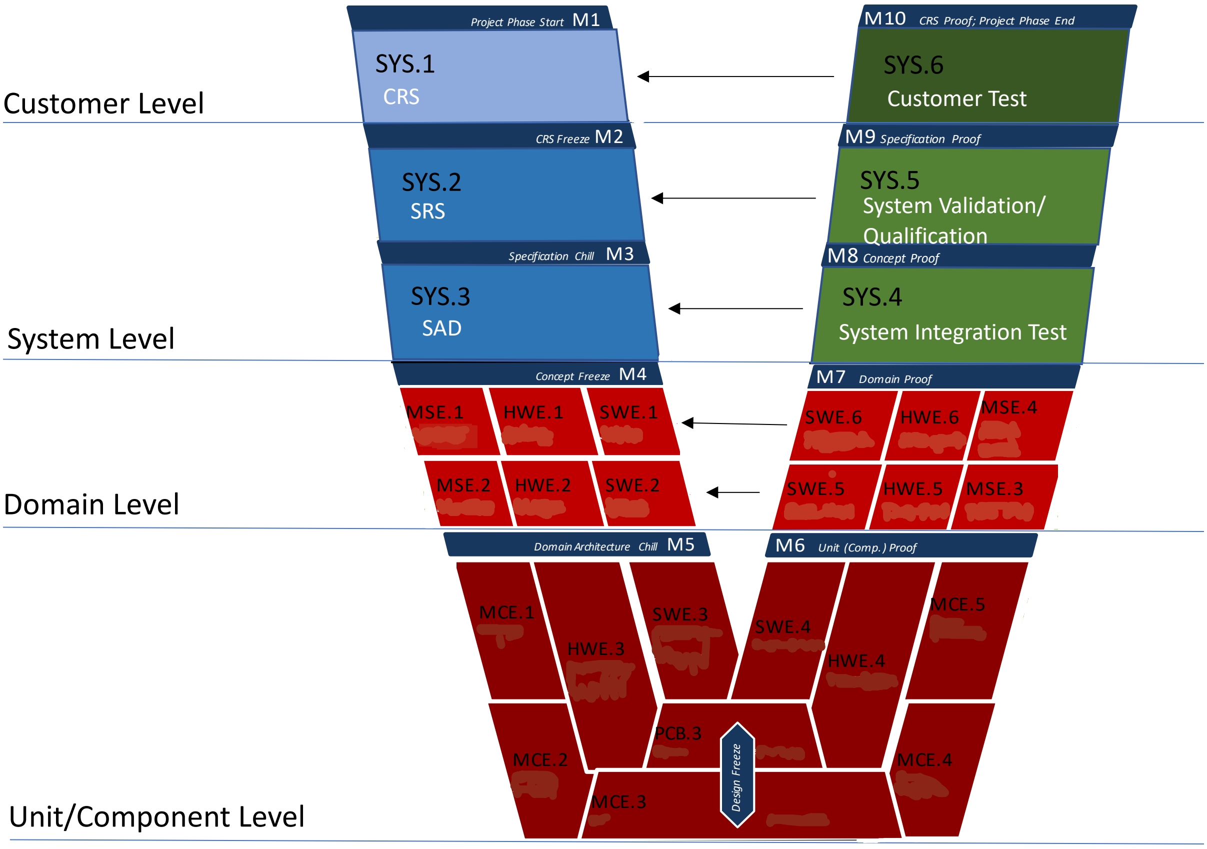


Fig. 2–4: The ASPICE standard depicted as a V-Model of the different disciplines it encompasses

2.3 Conclusion of the State of the Art

The state of the art presented underlines the innovative progress attributed to SmallSat technology in the New Space era. Both the novel financial parameters of the New Space era as well as the adapted parameters of the development process have impacted said innovation. SmallSats are developing their own, highly-responsive technological path which enables them to be the most tangible entry point to the space industry, resulting in novel approaches at a previously unobtainable speed of innovation.

However, standards describing the implementation of a SLC for satellite development were defined to standardise conventional space missions in rigorous detail, which had different characteristics both on the technical as well as on the monetary aspect of development.

If and how these standards can be implemented in the developmental process of a SmallSat, what comprises the components of such a designated SLC and what the relevance of compliance is, are questions that are tackled during the course of this thesis, as is illustrated in the next chapter.

3 Goal of the Thesis

The goal of this thesis is to analyse current implementations of SLCs in SmallSat missions and to develop a proposal for a SLC fitted to SmallSat development in the New Space era. As the European basis for SLC implementation is standardised by the ECSS, the goal includes analysing compliance with said standards.

In order to reach this goal, an analysis of SLC implementation in different SmallSat missions is to be conducted and evaluated. The different SmallSat missions are comprised of scientific university projects and private company products. The reason behind doing so is to analyse SLC implementation in teams with different characteristics in order to be able to gain as many insights as possible about the subject matter.

Furthermore, it is to gain insights about ECSS compliance depending on the team characteristics as well as both the ESA's stake in the mission or lack thereof. Hence, this analysis has the purpose of gaining an understanding of the reality of SLC implementation in such missions in order to integrate solutions to existing challenges in the proposed SLC, thus ensuring future applicability of it.

The goal is to identify and propose a SLC with:

- **Phases** defined by their objectives
- Clearly positioned **KDPs** as phase completion which are detailed to the extent of their **deliverables**
- An example of a **methodical approach** of going through the phases
- An argumentation regarding its **ECSS compliance**

After the development of a proposed SLC, the application of it onto the development process at the SmallSat startup Orora Tech is the case study chosen to validate the applicability of it. The aim is to describe the application of the SLC for the complete development process as well as for the current development process of the optical payload and launch thereof in cooperation with another private company.

Lastly, a goal of this thesis is to use the SE resources of BERNS Engineers in order insure the applicability of it on new SmallSat missions in the form of SE consultancy.

4 Methodology

This chapter presents the methodology used for literature research and interview conduction during the course of this thesis. It aims at giving the reader the fundamental understanding of how the contents of the next chapters came to be.

4.1 Literature Research Methodology

As previously stated the following documentation is the basis for research on SLC implementation and combined presents the state of the art in that matter:

- NASA System Engineering Handbook
- INCOSE Systems Engineering Handbook
- ECSS standards

The methodology behind it is plainly simple and summarised by the fact that any literature dealing with space SLC implementation references these documents. This is due to the history of the space industry being solely a domain of governmental agencies and thus they defined and standardised all proceedings for this industry. Additionally, SE began to evolve as a branch of engineering during the late 1950's during the race to space as the INCOSE Handbook states [7]. Hence, the INCOSE Handbook guides on SLC implementation that is not just applicable but originates from the space industry.

Moreover, the widely referenced book "Decision Making in Systems Engineering and Management" is additionally taken into account because of its educational nature and the coverage of other literature.

Lastly, the standards listed in ESA's TEC-SY/128/2013/SPD/RW document titled "Tailored ECSS Engineering Standards for In-Orbit Demonstration CubeSat Projects" are the official guideline for SLC implementation for CubeSat missions in Europe [1]. Thus, the research conducted in this thesis incorporates its contents and the output is compared to it regarding applicability and hence the necessity of compliance or lack thereof.

4.2 Interview Methodology

As the literature on SLC implementation in space missions covers the theory, additional practical input for a development of a SLC is required. This input is obtained through the conduction of interviews with both university projects as well as private companies.

The methodology behind the conduction of the interviews is as follows:

1. A digital survey is sent out to the interviewee to collect a wide variety of data covering SLC implementation
2. An interview is tailored based on the collected data of the survey

3. The tailored interview is conducted with the interviewee to gain a deeper understanding of the SLC implementation and the relationship of the components to one another

In order to insure the comprehensibility of the questions in the survey, it was sent to members of the MOVE-II team that were not system engineers and unfamiliar with the detailed SE terminology. Their feedback was incorporated before the first round of interviews was conducted with project leaders and systems engineers from the MOVE-II team. Finally, their feedback, regarding the survey as well as the tailored interviews, was also incorporated before this methodology was used on external interviewees.

The disadvantage of surveys is the lack of interaction with the interviewee. When completing a digital survey, the complete understanding of the survey questions by the interviewee cannot be guaranteed. There is no possibility to adapt questions or to check answers with the interviewee to verify his replies. Further, demanding for more information on a specific question is not possible. This is why the survey is merely a tool to paint a picture of the subject matter. The semi-standardised way for the conduction of surveys was chosen. The sequence of the questions stays the same. But in contrast to fully standardised questions, which provide all possible answers, most questions require the formulation of own answers. This is done in order to cover all aspects of SLC implementation as some aspects can be implemented in a variety of ways but some aspects are either conducted or not.

The tailored interview was then designed in order to further analyse deviations from the norm. The norm here being SLC implementation as found in the selected literature. The survey questions have been designed after the thorough familiarisation with the state of the art and thus represent conventional SLC implementation. Hence, the interviewee could select if the implementation was according to the norm or deviated from it. The deviations are then selected for the tailored interview and additional questions are designed to further investigate the deviations during the interview.

Furthermore, the interviews were conducted, transcribed and referenced during the collective analysis of SLC implementation in praxis and further in the development of a SLC. The documentation of the results is presented in chapter 5 while a summarisation and discussion of the results is presented in chapter 6.

Lastly, the discussed results were implemented in a proposed SLC in order to allow it to be fitted to SmallSat development in the New Space era and the validation of applicability is conducted in the form of a case study encompassing two distinct application scenarios at a SmallSat startup (See chapter 7). Hence, the the summarisation and interpretation of the results was conducted with the development of the SLC and application at a private company in mind. Thus, the results relevant for these scenarios are the ones highlighted in this thesis.

5 Results of the Digital Survey and the Interviews

In this chapter the results of the interviews are presented chronological to the interview process itself. The data of the survey is presented in the chronological order of the survey questions and then further complimented by extracts of the interviews. The complete transcripts of the interviews can be found in Appendix C. Afterwards, some points are presented that have surfaced during the interviews but were not part of the original survey questions. The next chapter is a discussion of the presented results and a summarisation thereof.

The interviewees and the information they shared about themselves are listed in Table 5–1.Table 5–1 presents what role the interviewees had in their respective missions and if that mission was part of a university science project or an industrial product by a private company. The abbreviated roles are Attitude Determination and Control System (ADCS), Project Management (PM), Systems Engineering (SE) and Mission Design (MD). Additionally, the type of the project is indicated by either the given university name or company name.

Table 5–1 further presents if the interviewees completed the digital survey which is marked as an ”X” in ”S.” and if they were available for an interview afterwards which is marked as an ”X” in ”I.”.

As previously mentioned (See section 4.2), the MOVE-II team members and Partick Lux were part of the the development of this survey and thus their feedback was incorporated in the final version of the survey. The data presented in this chapter only consist of the final iteration of questions in order to ensure consistency. However, the transcripts of their interviews hold valuable information that is incorporated in this chapter.

On the other hand, Bertels and Papadeas have filled in the survey but it was not possible to conduct a followup interview during the temporal frame of this thesis.

Lastly, it shall be noted that the interview with Innovative Space Logistics (ISL) yielded important insights on multiple fronts of the development process, the standardisation thereof and the perspective of a launch provider. However, nearly all ”not applicable” (n/a) answers in the survey are from ISL and are thus not further detailed or explained in this chapter. This is due to the discrepancy of the questions being specifically for satellite development and ISL being a launch provider which does not directly develop satellites.

Tab. 5–1: The interview partners

Name	Mission	Role	Institut or company	S.	I.
David Messmann	MOVE-II	ADCS & Student Lead	Tech. Uni. of Munich	-	X
Florian Schummer	MOVE-II	SE Lead	Tech. Uni. of Munich	-	X
Patrick Lux	LuxCube	SE	Uni. of Luxembourg	-	X
Andris Slavinskis	ESTCube-1&2	ADCS Lead & MD	Uni. of Tartu	X	X
Kelly Antonini	Multiple	SE & PM	GomSpace	X	X
Jasper Bouwmeester	Delfi-C3 & -n3Xt & -PQ	SE & PM	Tech.Uni. of Delft	X	X
Michiel van Bolhuis	Multiple	Launch Mission Manager	Innovative Space Logistics (ISL)	X	X
René Fléron	DTUsat & DTU Space	PM	Tech. Uni. of Denmark	X	X
Jaan Praks	Aalto-1&2	PM	Aalto University	X	X
Merlin Barschke	Multiple	PM	Tech. Uni. of Berlin	X	X
Laurynas Mačiulis	LituanicaSAT-1	SE	Vilniaus Gediminas Tech. Uni. & NanoAvionics	X	X
Inna Uvarova	PW-Sat2	PM	Warsaw Uni. of Technology	X	X
Marcos Compadre	Multiple	Tech. Lead	Clyde Space	X	X
Hong Yang Oei	Multiple	PM	Innovative Solutions in Space (ISIS)	X	X
Eric Bertels	Multiple	SE	Innovative Solutions in Space (ISIS)	X	-
Pierros Papadeas	UPSat	PM	Libre Space Foundation	X	-

5.1 Chronological Interview Results

This section chronologically presents the collective data gathered through the digital survey and extracts from the interviews in which the same point has been further investigated. The chronological order of the survey's sections is presented in Table 5–2.

During the answering of the digital survey the interviewees were free to fill in the survey for one mission that they were involved in or for multiple missions. However, during the interview they were asked to focus on one mission and use additional missions

Tab. 5–2: Sections of the survey and their purpose

#	Name	Short Description of the Purpose of the Section
1	General Questions	Collecting general information about the interviewee, the mission, the orbit etc.
2	Stakeholder	Understanding who the stakeholders were, how they influenced the development and how they were managed
3	ECSS standards	Understanding the implementation of the standards in the project
4	Methods for Processes Implemented	Understanding the methodology behind the development processes
5	Milestones, Deliverables and Reviews	Understanding their conduction, relationship to one another and to the SLC phases
6	System Life Cycle	Understanding the phases themselves, MOEs, MOPs and the placement of KDPs
7	Feedback	Collecting feedback about the survey and the CubeSat community as a whole

when asked to further elaborate a specific point. In the case of university projects this was useful for understanding how lessons learned from one project influenced the next. Moreover, in the case of companies this was useful for understanding how standardised processes were adapted depending on the mission itself.

The data is presented here collectively. A possible representation would be to illustrate which interviewee chose which answer. However, the goal of the thesis and the agreement reached with the interviewees, is to analyse the implementation of SLCs without giving out too much information about a specific mission. This is why some specific partners are merely referred to as ”costumers” or ”suppliers”. This is also the reason why some examples of misconduct are presented without direct citation. Gathering data in an industry ruled by Nondisclosure Agreements (NDA) is a sensitive matter, that I tried to undertake to the best of my knowledge and with the utmost respect for my interview partners.

In this thesis, the interview partners are called “interviewee” and “he”, which also includes female questionnaire partners. Further, the usage of the verbs ”choose” or ”select” in this chapter, means that the interviewees selected a presented option as an answer. However, the usage of the verb ”write” indicates that they wrote down an answer in the digital survey.

In this chapter the single choice answers are presented as a pie chart and multiple choice answers are presented with horizontal bars indicating the amount of interviewees that selected them. Further, a question that was answered with a rating from ”1” to ”3” is presented with vertical bars as well as questions regarding phase and review conduction. For phase and review conduction the answers that were selected by more than two interviewees are highlighted in order to allow for an interpretation based on sufficient entries.

5.1.1 General Questions

The purpose of the first section of the digital survey was to collect general information about the interviewee, his role in the mission, the developed satellite, the orbit and ESA's involvement in the project. The data collected from the interviewees on their role in the mission and the name of the mission is presented in Table 5–1.

When asked what their mission was part of, the interviewees responded with:

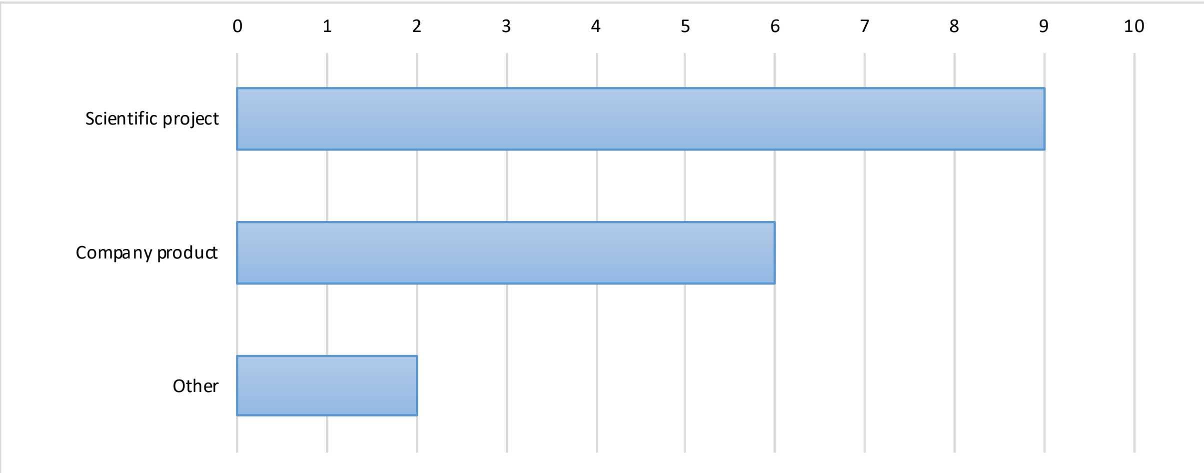


Fig. 5–1: Mission type as selected by interviewees: The horizontal axis indicates how often the answer was selected by the 13 interviewees who responded to the question.

As a justification for choosing "Other" the interviewees wrote "Non Profit Foundation" and "Start-up".

Figure 5–2 shows the categorisation of the developed satellites by the interviewees which were all intended for LEO.

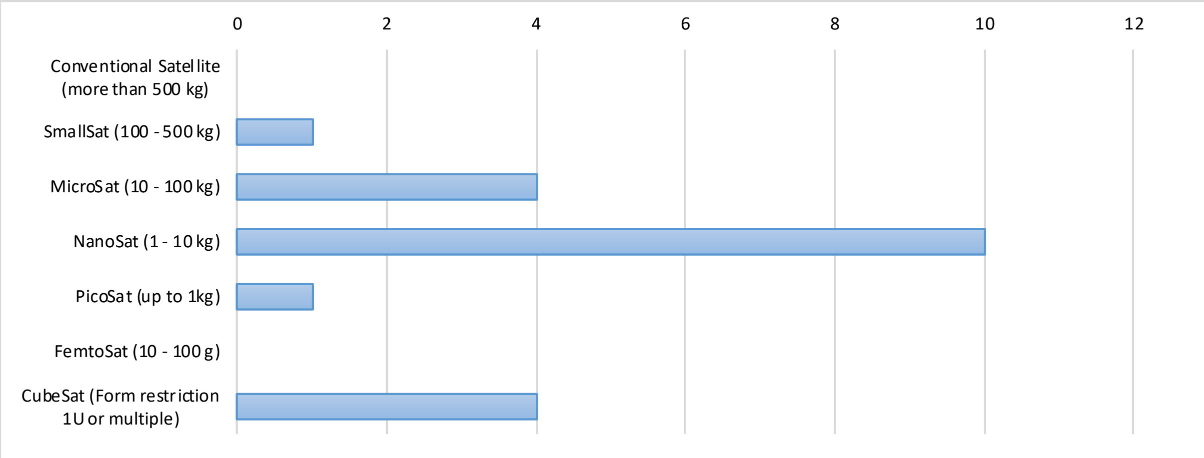


Fig. 5–2: Satellite classification based on mass and the CubeSat form restriction: The horizontal axis indicates how often the answer was selected by the 13 interviewees who responded to the question

Further, 10 interviewees have selected that their satellite or satellites have been launched into space while three selected that they haven't yet been launched. Upon further investigation during the interviews, interviewees clarified that a current satellite that they are working on has not yet been launched but previous satellites have been. Thus, all interviewees have previously participated in the development of a satellite that was launched into orbit. (Hong Yang Oei - ISIS, Jasper Bouwmeester - TU Delft, Marcos Compadre - Clyde)

The interviewees wrote down the the following answers as their mission objectives:

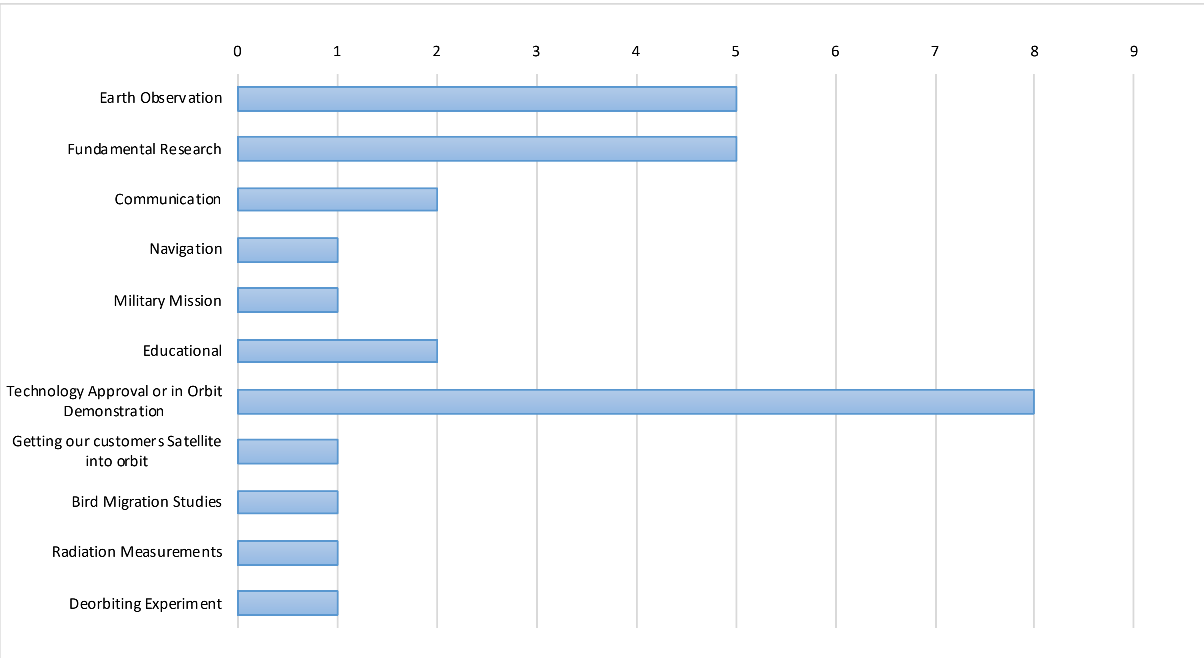


Fig. 5–3: Mission objective as given by interviewees: The horizontal axis indicates how often the answer was selected by the 13 interviewees who responded to the question.

For the planned mission life time the interviewees wrote down:

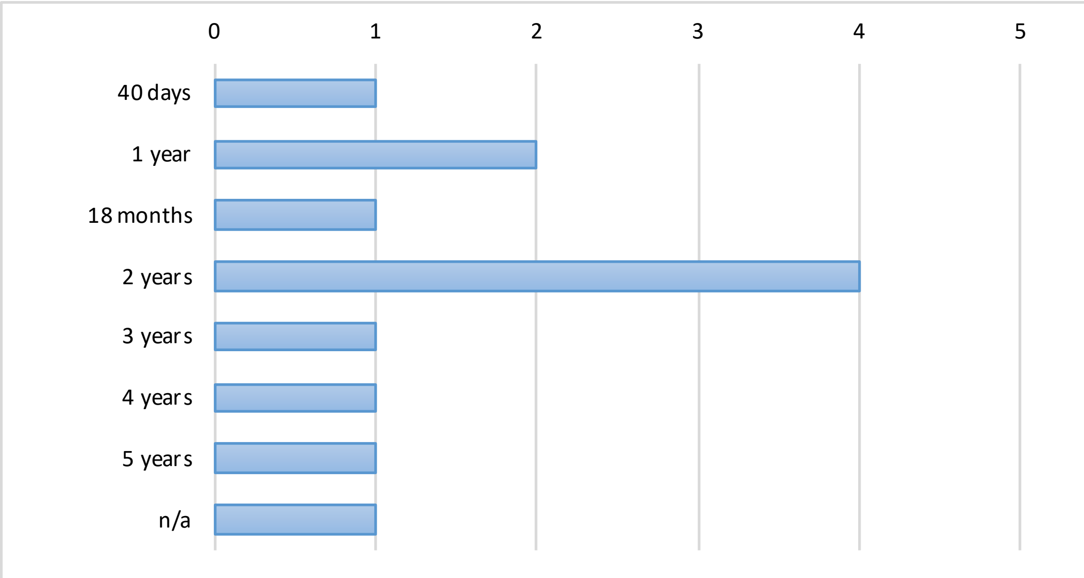


Fig. 5–4: Planned mission lifetime as given by interviewees. The horizontal axis indicates how often the answer was selected by the 12 interviewees who responded to the question.

This averages 1,97 years which is common for SmallSat missions with the previously presented masses in LEO [65].

Lastly, the interviewees selected the following, as an answer to if the ESA was involved as a stakeholder for their mission:

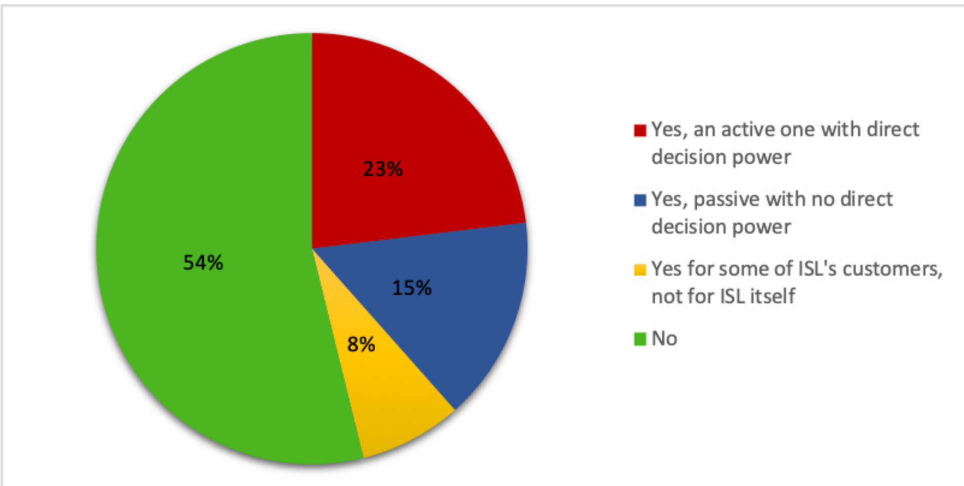


Fig. 5–5: ESA's involvement as an active or passive stakeholder for the missions: The percentage indicates how many interviewees selected that option out of 13 responses to the question.

In the case of the launch provider (ISL), the interviewee chose a fourth option to clarify that ESA's involvement was based on them being a stakeholder in the mission through the costumer. The costumer in these cases could be the launched satellite using ISL hardware or a launch vehicle using ISL hardware (Michiel van Bolhuis, Launch Mission Manager - ISL). This is further elaborated upon in subsection 5.1.3.

5.1.2 Stakeholder

When asked who the stakeholders were for their mission and what their ”stake or motivation for support was” , the university projects mainly listed:

- The university itself as the main financier or as having an interest in the educational value for students and researchers
- A national government agency as the main financier
- The payload providers because of their interest in the scientific data collected from the payload
- The engineering team consisting of students and researchers who are interested in the scientific output that can be published as well as the motivation gained from achieving progress

In the case of the ESTCube-1 the ESA was a stakeholder in the form of the Plan for European Cooperating State (PECS) Arrangement for Estonia. They then required one report of the test campaign before the launch and a final report after the launch from the developing team. They did not go into detail about the development process itself with the developing team. (Andris Slavinskis, ADCS Lead, University of Tartu)

In the case of the Aalto-1 mission the ”ESA was paying the development of the technology until qualification (...) but they are not interested in the launch” (Jaan Parks, Assistant Professor, Aalto University). Thus, the ESA financed the development of the ”camera technology” but afterwards the project was financed through a different source.

The interviewed companies answered the afore mentioned question with:

- The suppliers of the components that make up the satellite as they have an interest in knowing the performance of the satellite
- The launch providers as they have an interest in the performance of the satellite during the launch
- The costumer as the party who initiated the development and makes use of the satellite in space
- The ESA only when the agency was the costumer itself or part of a constellation representing the costumer

As a response to the specific question if they considered their engineering team as a stakeholder:

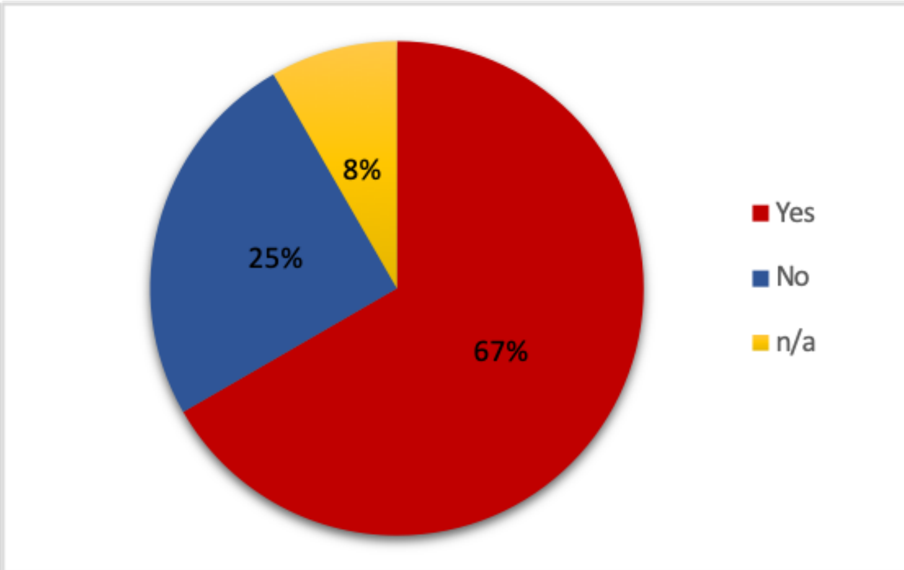


Fig. 5–6: Consideration of the engineering team as stakeholder: The percentage indicates how many interviewees selected that option out of 12 responses to the question

When asked if a stakeholder analysis was conducted, none of the interviewees selected ”Yes, with a concrete method”. The interviewees selected:

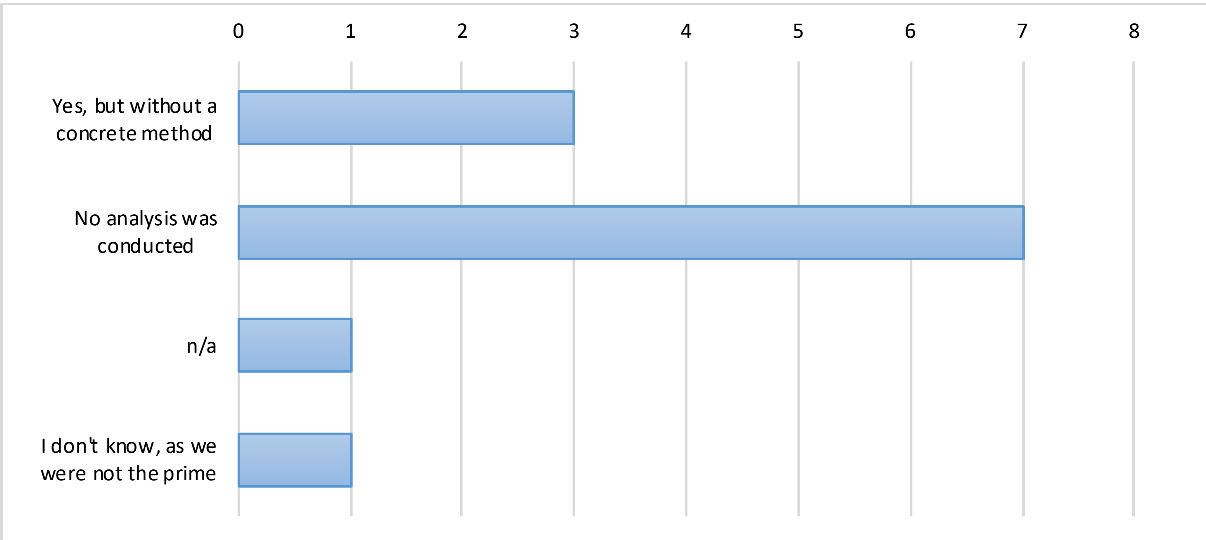


Fig. 5–7: Method for stakeholder analysis: The horizontal axis indicates how often the answer was selected by the 12 interviewees who responded to the question.

Further, during the interviews the interviewees explained that no structured approach is usually implemented but that it is known in the teams who the main stakeholders are, what their stake is and what their decision power is in the sense of influence on the development process. The most detailed description of an approach was:

> *”Of course, there is a difference between stakeholders and stakeholders. A supplier is important, but the customer is more important in that sense. [...] If you talk about the customer, it is structured. We have a formal kick-off,*

> *like most of our teams we have formal progress meeting reports, we have other meetings with the customer - internally discussion their stakes. If you talk about suppliers, its most of the time known. Our teams are small and the suppliers that we work with are well known, so its implicit in the whole (process). We don't make it very explicit - like rank and characterise them, but we do know what to discuss with them, where they are within the picture. [...] Before you start a project, you try to ask the right questions to find out who is behind the order and what their objectives are in their order. [...] I discuss that for example with my systems engineers a lot, because they are responsible for the technical system."* (Hong Yang Oei, Project Manager - ISIS)

Additionally, an example was given that elaborated how a motivated systems engineer starting discussing ideas in a meeting with the stakeholders which then decided that they want the idea implemented. However, after the meeting, the engineering team had to clarify that the idea was not feasible with the available resources and figure out how to communicate that to the stakeholders who at that point were highly motivated to see the idea implemented. (Jasper Bouwmeester, Project Manager - TU Delft)

However, no direct method of writing down the process and managing the stakeholders was mentioned from any interviewee.

When asked if the stakeholders executed on their decision power in the form of influence during the development and design of the mission, the interviewees selected:

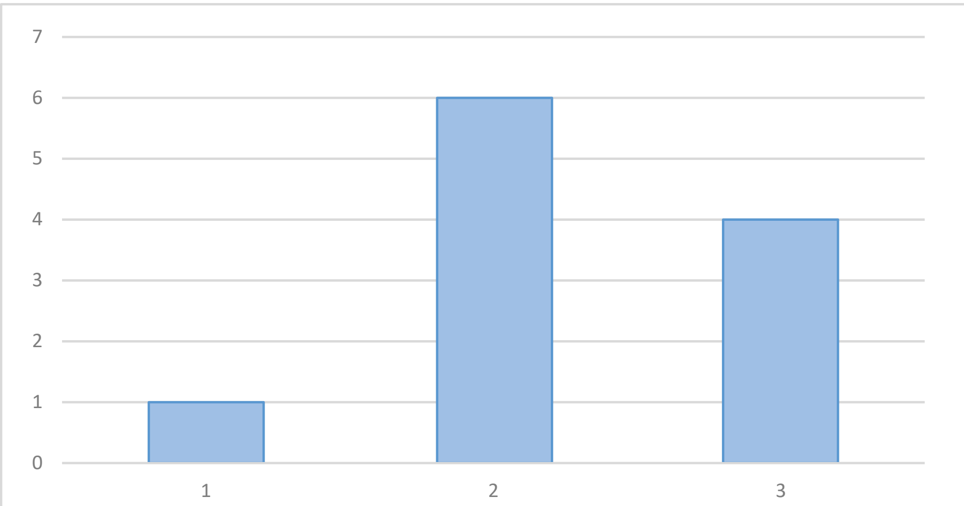


Fig. 5–8: Execution of decision power by the stakeholders: The bar's vertical hight indicates how many interviewees selected that option out of 11 responses to the question; "1" meant "They did not have any influence on development" and "3" meant "They did have a lot of influence".

And when asked if the stakeholders executed on their decision power adequately to their stake, interviewees selected:

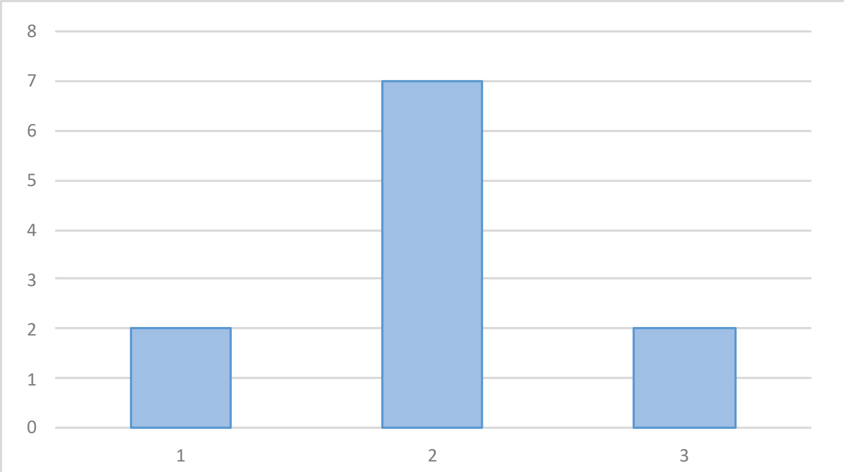


Fig. 5–9: Execution of decision power by the stakeholders adequate to their stake: The bar's vertical hight indicates how many interviewees selected that option out of 11 responses to the question; "1" meant "They executed their decision power adequately to their stake" and "3" meant "They executed their decision power inadequately to their stake".

5.1.3 ECSS standards

This section of the survey aimed at understanding the implementation of the ECSS standards in the respective projects.

When asked to rate their knowledge of ECSS standards the interviewees selected:

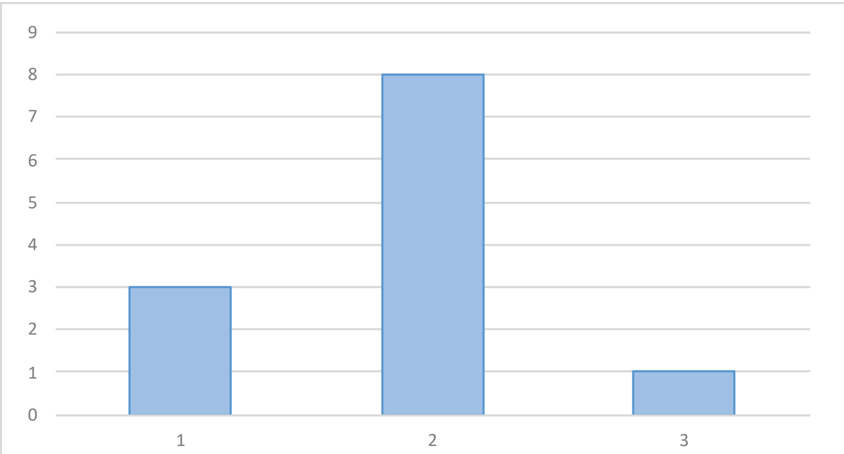


Fig. 5–10: Interviewee's knowledge of ECSS standards: The bar's vertical hight indicates how many interviewees selected that option out of 12 responses to the question; "1" meant "poor" and "3" meant "excellent".

When asked if they complied with ECSS standards or the specifically tailored standards for CubeSat IOD missions as defined in TEC-SY/128/2013/SPD/RW [1], the interviewees selected:

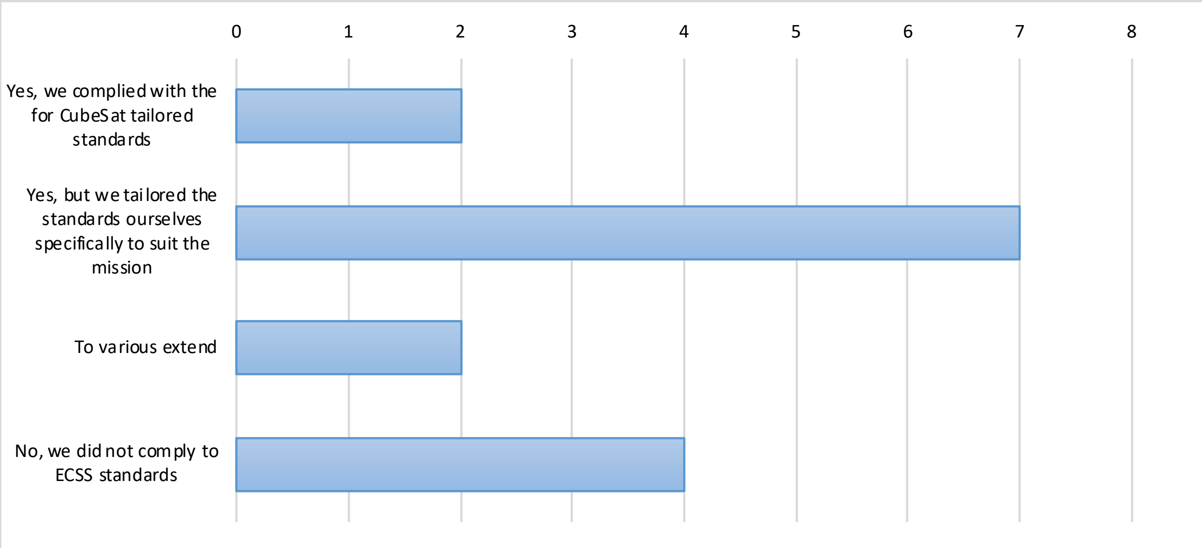


Fig. 5–11: Compliance with ECSS standards: The horizontal axis indicates how often the answer was selected by the 13 interviewees who responded to the question

None of the interviewees chose ”Yes we complied with ECSS standards” or ”Yes we tailored the standards in compliance with the tailoring standard ECSS-M-00-02A”.

One of the interviewees that chose ”To various extent” elaborated:

> *”We followed for a large part NASA standards for manufacturing. CDS Rev 13 for physical [design] and a mix of ESA and NASA for test and qualification.”* (Merlin Barschke, Project Management - TU Berlin)

When asked to give the motivation behind doing so, the interviewees wrote in the digital survey:

- *”The ECSS standards specifically tailored for CubeSat IOD missions are too complex and sometimes confusing to follow by the letter. If they were followed by the letter we would not be able to offer a competitive price.”*
- *”Applicability”*
- *”ECSS was not ”first stop” when searching for ”How to do” answers.”*
- *”Main motivation was to fly the mission with existing resources. ECSS compliance was not possible.”*
- *”It was a low-cost ESA mission, so full ECSS compliance was not affordable.”*
- *”ECSS is in many cases too stringent for the project and mission.”*
- *”Academic mission, no need to implement fully ECSS”*

Interviewees further elaborated during the interviews:

> *”I am tempted to say that the standards are developed for more mature platforms than we actually have in the CubeSat industry.”* (Kelly Antonini,

Project Management - GomSpace)

"Sometimes, they have useful guidelines. But we are very pragmatic with it. If it helps us, if we can do it quicker, better in our own belief then we use it but if we think that this is just a lot of red tape or forcing us in a technically not best direction, then we just ignore it. (Jasper Bouwmeester, Project Management - TU Delft)

"But defining the whole procedure and documenting it is not productive for small missions at all because you just don't need it. [...] If you can design the whole satellite with one white board, then making the entire ECSS standards documentation is over head. It is just not economically feasible." (Jaan Praks, Project Management - Aalto University)

"Probably, they are good for these type [large with multiple teams working for the ESA] of projects, because one can agree on such a standard. For a start-up, for a small company, I would suspect they are probably not so fit." (Laurynas Maciulis, Project Management - Vilniaus Gediminas TU)

When asked how they estimate the time spent on implementing, discussing how to implement, discussing why not to implement and documenting of ECSS standards by their team, out of 12 responses 10 interviewees chose less than 10%, one interviewee chose 20% and one chose 30%.

Further, when asked if the SE team or the subsystem teams conducted the documentation, 23.1% (3) wrote the subsystem teams, 30.8% (4) wrote the SE team, 30.8% (4) wrote that both shared the responsibility and 15.4% (2) wrote "not applicable". This was out of 13 responses.

Lastly, when asked what their opinion is on the necessity of new standards for the New Space era, the interviewees selected:

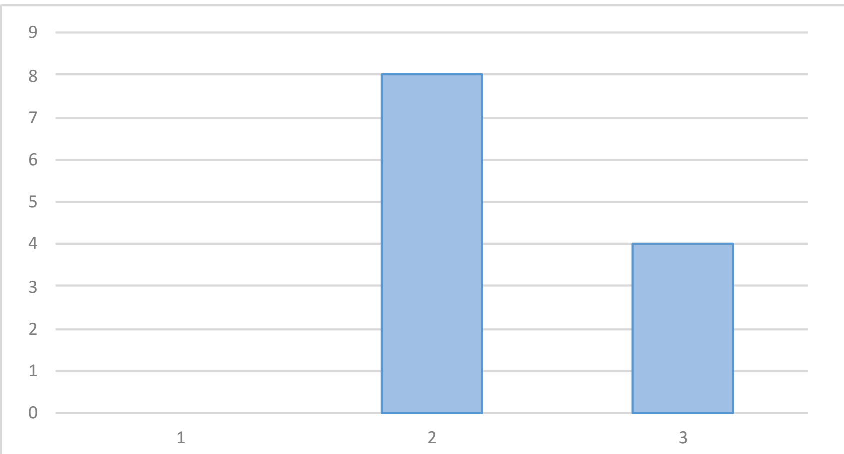


Fig. 5–12: Necessity for new standards: The bar's vertical hight indicates how many interviewees selected that option out of 12 responses to the question; "1" meant "Not necessary. Exiting standards are sufficient" for New Space and "3" meant "Highly necessary".

Interviewees further elaborated during the interviews:

> *"20-30% as an estimate was used on having to justify, having to write, having to put down to develop a procedure and so on. What you need to understand is the CubeSats are not meant to follow ECSS standards, this is the problem. A CubeSat is 200.000 – 400.000 Euro. The full mission. That by definition should be a way to decouple from ECSS. If you want to follow ECSS, this is because you spend a certain amount of money on something that has to be fully redundant that you have a one-of shot, that is 100.000.000 Euro mission, how can you apply the same regulation to the CubeSats? By definition, they should be decoupled."* (Marcos Compadre, Tech. Lead - Clyde Space)
>
> *"We have the ECSS tailored standard [company internal], so that is already a tailored standard. In the specific case, that we are now addressing or the project I have in mind, the customer doesn't care too much about what ECSS said itself. They have their own requirements. They don't have any standards. They just want a system up flying there meeting a certain lifetime. They want us to produce and define that. They put a lot more effort and link a lot more payment to this end goal that you can show that you delivered a system that is actually up to the specs. And they don't care about how you get there"* (Hong Yang Oei, Project Management - ISIS)
>
> *"[T]he first satellite [at their university] was launched in 1991 and the first CubeSat was launched in 2009, so we started to make up our mind about standards and tailoring way before ESA started to think about CubeSat ECSS [...] Software is also a topic where there is not too much to gain from the ECSS."*(Merlin Barschke, Project Management - TU Berlin)

5.1.4 Methods for Processes Implemented

This section of the survey aims at understanding the methods that were used for the processes during the development of the satellite.

When asked which methods were used for the processes during the development, interviewees wrote in the digital survey:

- *"Agile Methods"*
- *"Agile chaos"*
- *"Beautiful chaos (agile?)"*
- *"V-Model"*
- *"V-model (though not deliberately). We used the CDIO teaching approach which resembles V-model."*
- *"Design - build - test - repeat (test early and often)"*

When classifying the mentioned iterative process as an agile method and grouping together the various descriptions of agile methods, then agile methods were the answer of seven interviewees and V-model was the answer of four interviewees while one chose "not applicable". This was out of 12 responses.

> *"The principles were all the same, that you chop it up in smaller pieces and leave the team more interactively working. If I speak for myself, I don't believe in one single standard to be perfect or complete enough. I feel most of the time you can combine them. So, in this case the V-Model has a nice structure on how to develop on a higher level, while the agile method is much more focused on the steps in between"* (Hong Yang Oei, Project Management - ISIS)

When asked what the main barriers for the implementation of the method were, interviewees answered with:

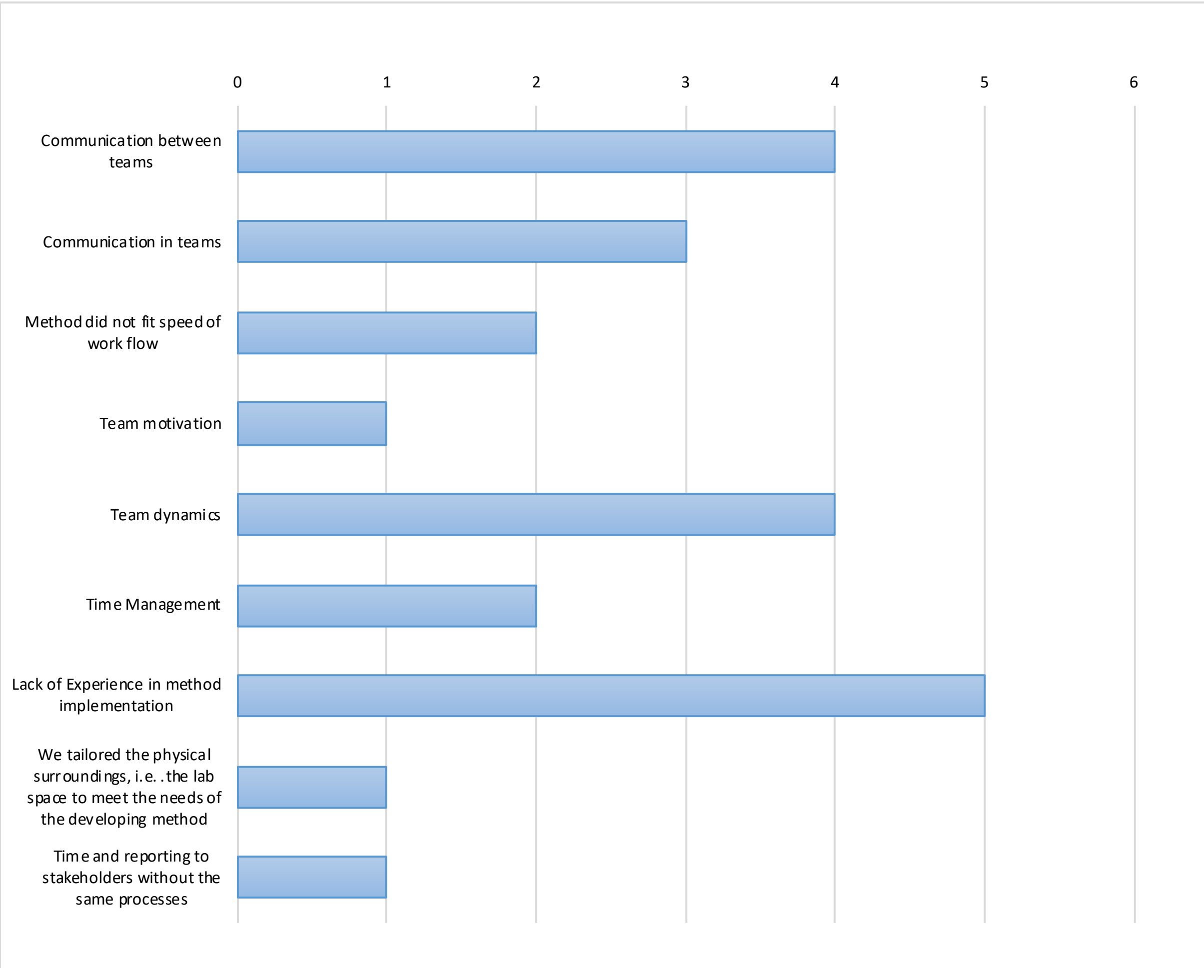


Fig. 5–13: Barriers for method implementation: The horizontal axis indicates how often the answer was selected by the 11 interviewees who responded to the question.

When asked how applicable they thought the method to be in hindsight, the interviewees answered with:

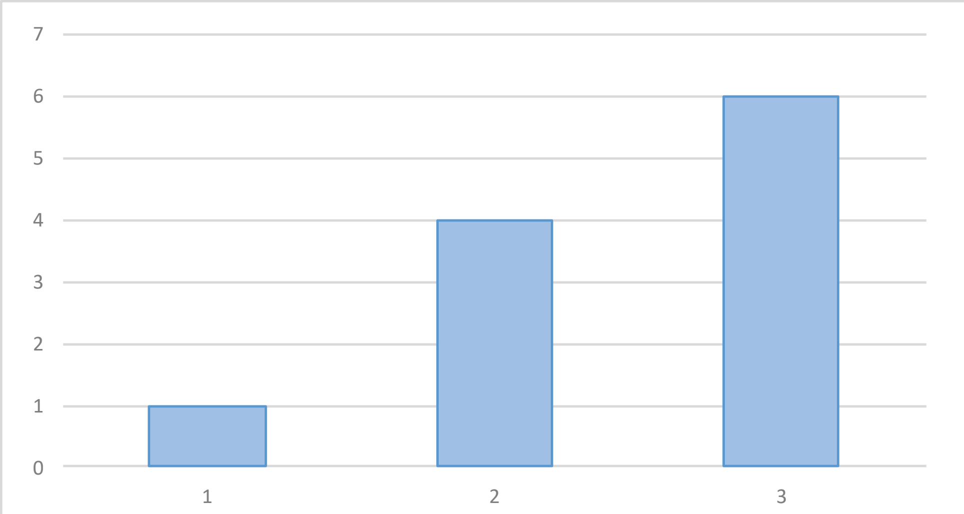


Fig. 5–14: Applicability of method in hindsight: The bar's vertical hight indicates how many interviewees selected that option out of 11 responses to the question; "1" meant "It was the wrong method for the desired outcome" and "3" meant "It was completely applicable ".

When asked if they would have chosen another method, three interviewees selected "Yes" while seven selected "No". The interviewees that selected "Yes" further elaborated:

- *"For Delfi-PQ (the next mission) we started with an iterative approach"*
- *"Document requirements (...) and interfaces, test more"*
- One interviewee did not offer an explanation

Interviewees further elaborated during the interviews:

> *"[T]he agile approach, so small iterations with less documentation. Of course, you do some requirements and especially interfaces, budgets and things like that, but it is more the design and prototyping which gives you the input -"What is rather required" than a top-down derived list. [.....] So, basically that was the idea and I still believe in it and you see good examples of where it actually worked with Planet where they have, since a few years ago, already 20 iterations of the satellite. Of which maybe 8 iterations have actually flown"*(Jasper Bouwmeester, Project Management - TU Delft)

> *"[W]e also had a pilot project in software where we implemented specifically agile methods to see whether it would work with our size of software group [...] We did all the stuff you usually due to have fast and efficient development in a university environment, but also we had a [...] pilot project, where we really tested, defined all the different roles and having these two-week cycles [...] specifically to find out whether this would be something for the future, which we would implement, first to the software, but also hardware development."* (Merlin Barschke, Project Management - TU Berlin)

Similar arguments towards agile development and prototyping were also made by David Messman, Florian Schummer Kell Anonini, Rene Fleron and Laurynas Maciulis.

5.1.5 Milestones, Deliverables and Reviews

This section of the survey aimed at understanding how milestones, deliverables and reviews were conducted in the respective projects. Further, it aims at understanding their relationship to one another and to the SLC phases.

When asked how they conducted reviews for their mission, interviewees replied with:

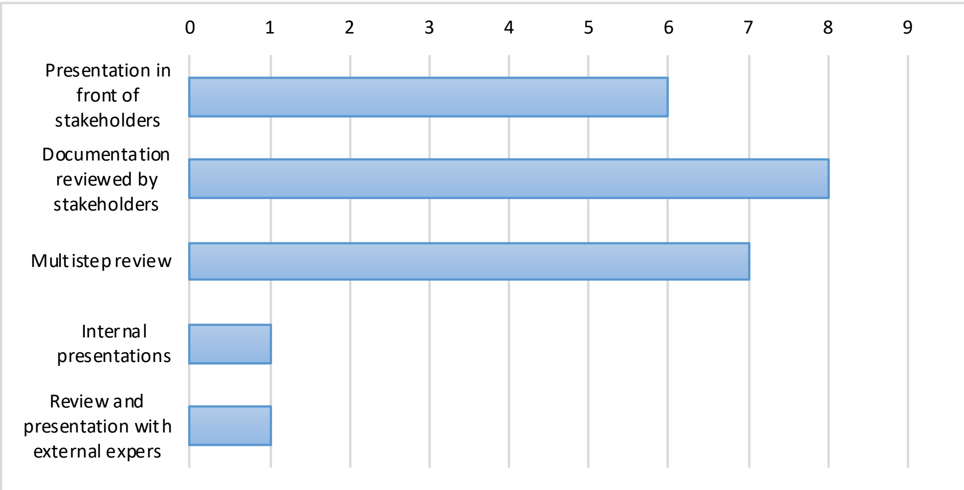


Fig. 5–15: How reviews were conducted: The horizontal axis indicates how often the answer was selected by the 13 interviewees who responded to the question

When asked if they set milestones during their project or if they kept on developing until the final product was finished, interviewees replied with:

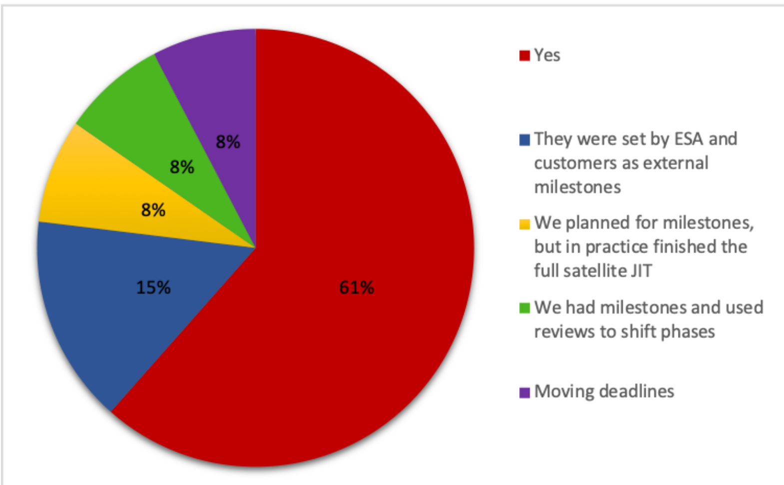


Fig. 5–16: Setting milestones versus continuous development until final product: The percentage indicates how many interviewees selected that option out of 13 responses to the question

Interviewees further elaborated during the interview:

> *I personally think it also makes sense to have some specific milestones and to finish stuff up to some certain milestone to prevent that you repeat questioning all the stuff you already have defined due to various reasons along the way all the time and then it would really delay your development process. [...]Also, you will have to speed up working before the milestone and there will be a stressful time if you haven't finished it.* (Merlin Barschke, Project Management - TU Berlin)

When asked if milestones and deliverables were always part of or product of reviews during the development, interviewees replied with:

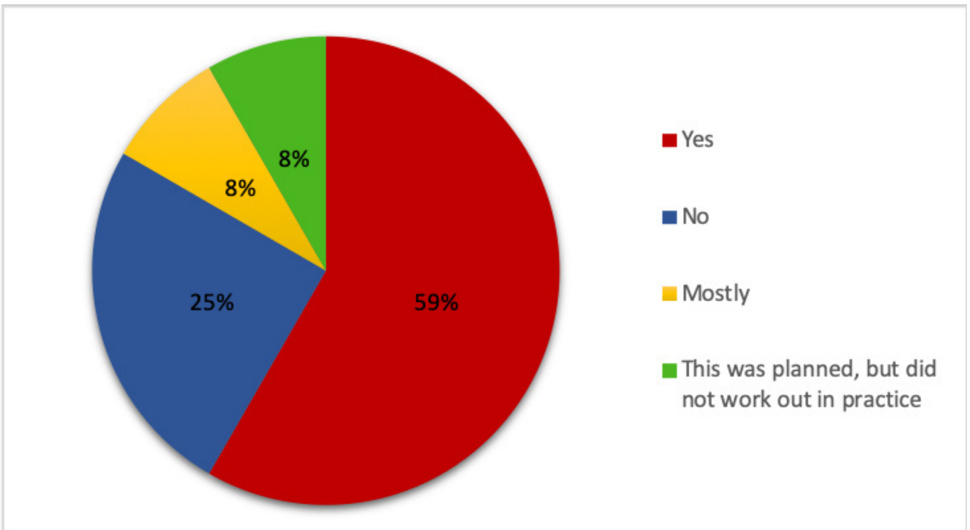


Fig. 5–17: Milestones and deliverables as part of or product of reviews: The percentage indicates how many interviewees selected that option out of 13 responses to the question

Afterwards the interviewees were presented with the following reviews to select which ones were conducted during the mission:

Tab. 5–3: The reviews that were provided to interviewees as options to select from

Acronym	Name	Acronym	Name
MCR	Mission Concept Review	ORR	Operational Readiness Review
SRR	System Requirements Review	LRR	Launch Readiness Review
SDR	System Definition Review	MRR	Mission Readiness Review
MDR	Mission Definition Review	FRR	Flight Readiness Review
PDR	Preliminary Design Review	PLAR	Post-Launch Assessment Review
CDR	Critical Design Review	CERR	Critical Events Readiness Review
PRR	Production Readiness Review	DR	Decommissioning Review
SIR	System Integration Review	PFAR	Post-Flight Assessment Review
SAR	System Acceptance Review	DRR	Disposal Readiness Review

The reviews that were selected as ”conducted” or ”partially conducted” by more than two interviewees were:

- SRR - System Requirements Review
- PDR - Preliminary Design Review
- CDR - Critical Design Review
- PRR - Production Readiness Review
- SIR - System Integration Review
- FRR - Flight Readiness Review

While the reviews with the most responses (greater than 7) were the PDR, the CDR and the FRR. Further, interviewees clarified that ”Milestones can be called differently across the industry” and that ”Partially other terms are used (...) such as Manufacturing Readiness Review (MRR) Integration Readiness Review (IRR), In Orbit Commissioning Review (IOCR)”. Additionally, they wrote that sometimes smaller ”progress meetings were held with the stakeholders, or ”subsystem [specific] reviews” were conducted.

When asked if they had different stakeholders for different reviews and how that influenced the conduction of the review, interviewees wrote:

- *”Yes. It was harder to anticipate the maturity level desired.”*
- *”some reviews were internal, some with all stakeholders”*
- *”The external review team did vary throughout the project, however focus was always competences with respect to the review task.”*
- *”yes. not the best idea but worked.”*
- *”No we didn’t. Always ESA and the customer”*

- *"Yes, sometimes repeating the same questions"*

When asked how useful the feedback collected during the reviews was, interviewees replied with:

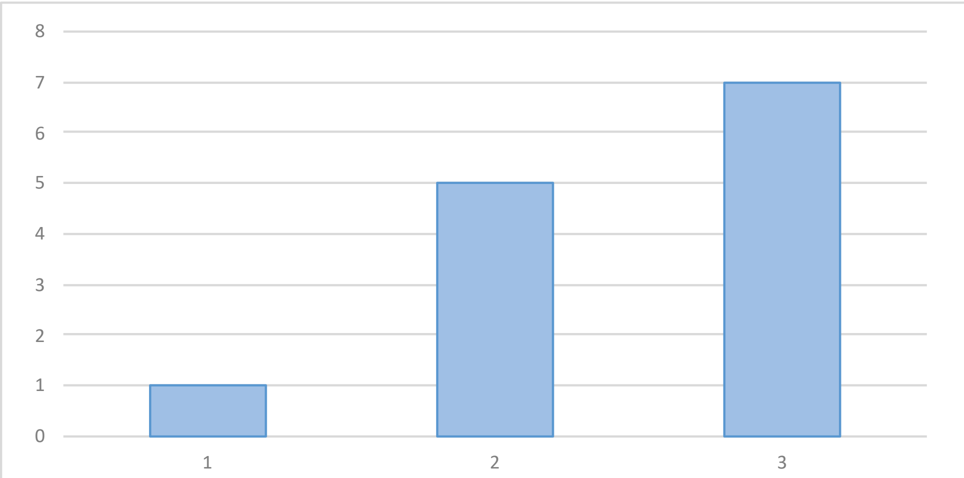


Fig. 5–18: Usefulness of feedback collected during reviews:The bar's vertical hight indicates how many interviewees selected that option out of 13 responses to the question; "1" being "not useful and "3" being "very useful".

When asked how well their team implemented the feedback collected during the reviews, the interviewees replied with:

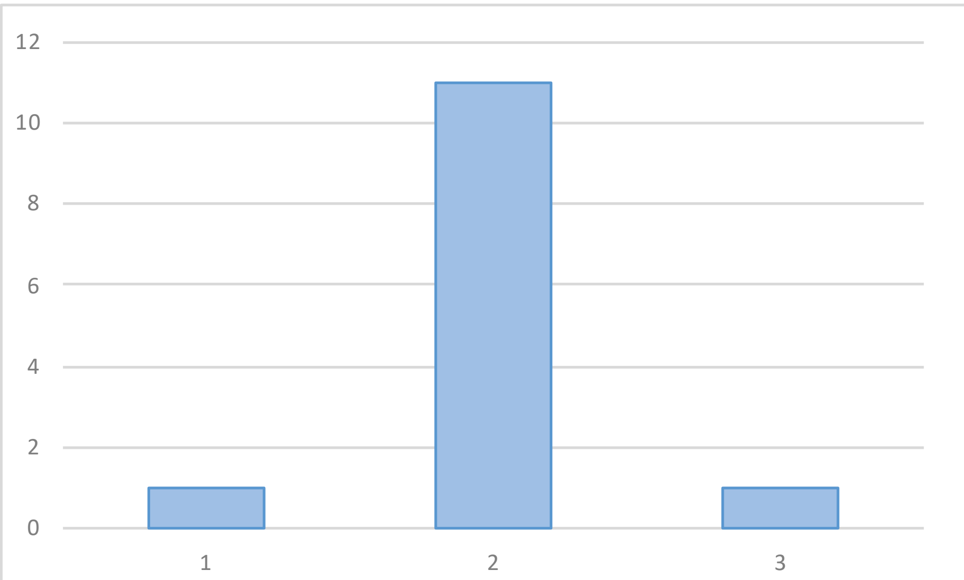


Fig. 5–19: How well the team implemented the feedback collected during reviews: The bar's vertical hight indicates how many interviewees selected that option out of 13 responses to the question; "1" being "implemented it loosely" and "3" being "implemented it to the letter".

When asked how they defined their KDP for the project phases, interviewees chose:

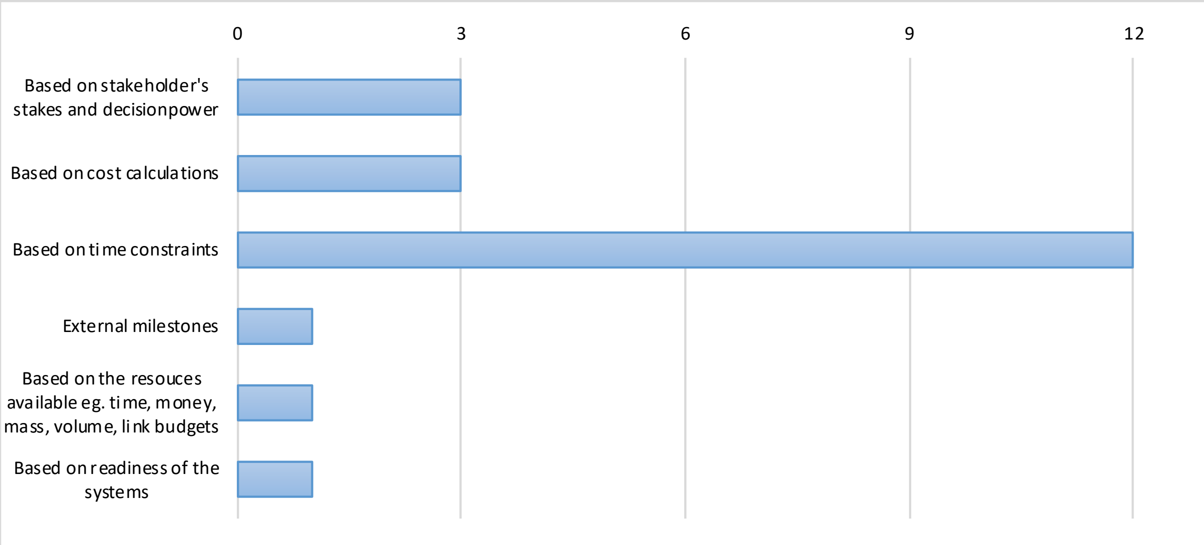


Fig. 5–20: Basis for KDP definition: The horizontal axis indicates how often the answer was selected by the 13 interviewees who responded to the question.

When asked if a reduction in documentation would have been in order or if a reduction in time invested in documentation would have resulted in more output of their team, interviewees replied with:

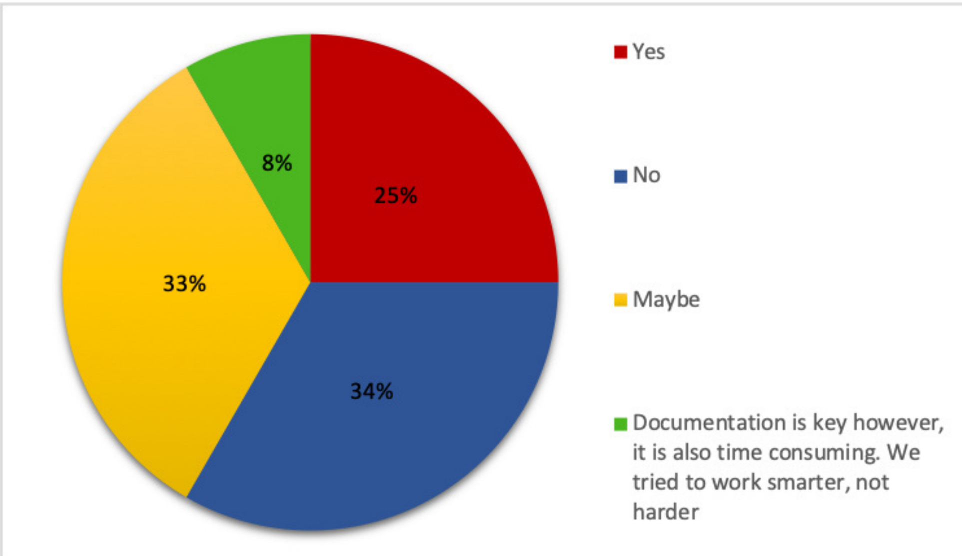


Fig. 5–21: If a reduction in documentation would have been in order: The percentage indicates how many interviewees selected that option out of 12 responses to the question

Interviewees further elaborated:

> *"But the thing is that you end up with 400, 500 comments and it is quite a small team to deal with them. Some of those comments are good, but you have this process in place where you have to deal with all of them. for many students it felt like this huge bureaucratic monster without really seeing the*

purpose of it all. While 10 % were useful, they are overshadowed by the other 90 % which were not too useful. [...] Testing is the real proof of the body. You will not fully find the design flaws through documentation. But if you do a test and did not work then hopefully you know a bit more about it." (Jasper Bouwmeester, Project Management - TU Delft)

5.1.6 System Life Cycle (SLC)

This section of the survey aimed at understanding more holistic components of SLC.

When asked if they specifically tailored an SLC for their project, interviewees wrote:

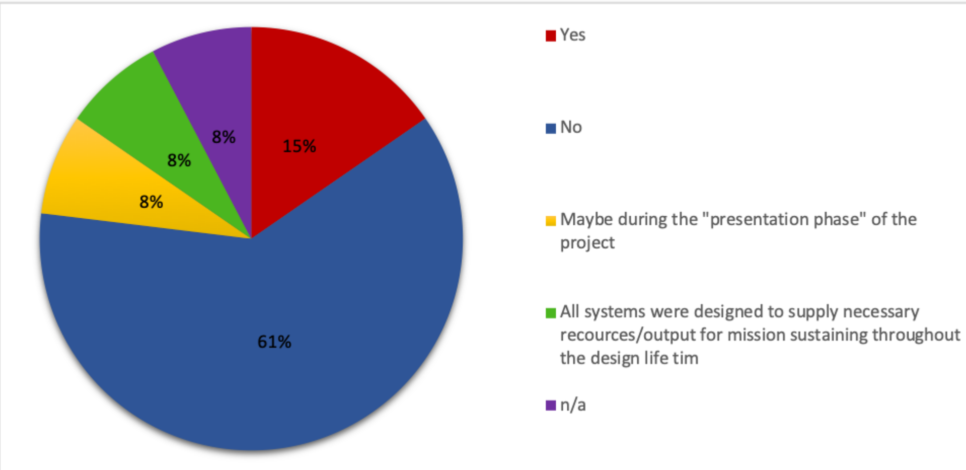


Fig. 5–22: Tailoring of SLC to the mission: The percentage indicates how many interviewees selected that option out of 13 responses to the question. While the presentation phase was meant to mean the initial concept studies.

When asked if the milestones at the end of each project phase were reviews followed up by KDPs, the interviewees replied with:

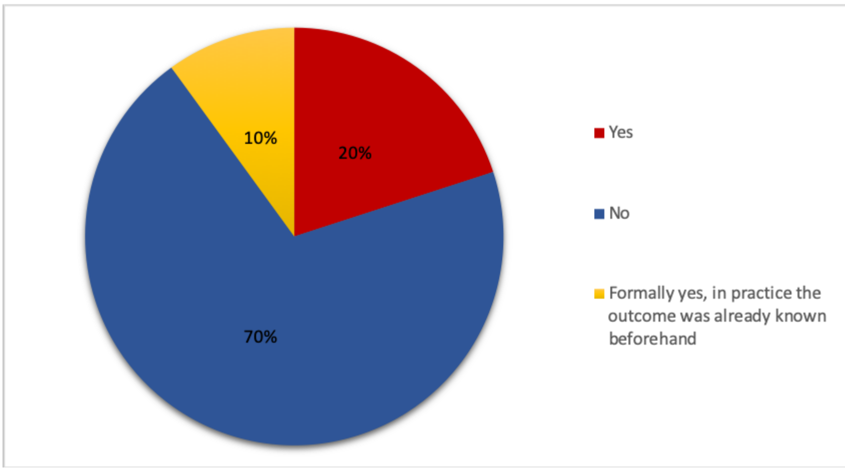


Fig. 5–23: If the milestones at the end of each project phase were reviews followed up by KDPs: The percentage indicates how many interviewees selected that option out of 10 responses to the question

Further, interviewees were asked to select which phases were applied form the following project phases:

- Pre-Phase A Concept Studies
- Phase A: Concept & Technology Development
- Phase B: Preliminary Design & Technology Completion
- Phase C: Final Design & Fabrication
- Phase D: System Assembly, Integration & Test, Launch & Checkout
- Phase E: Operations & Sustainment
- Phase F: Closeout & Disposal

The interviewees selected:

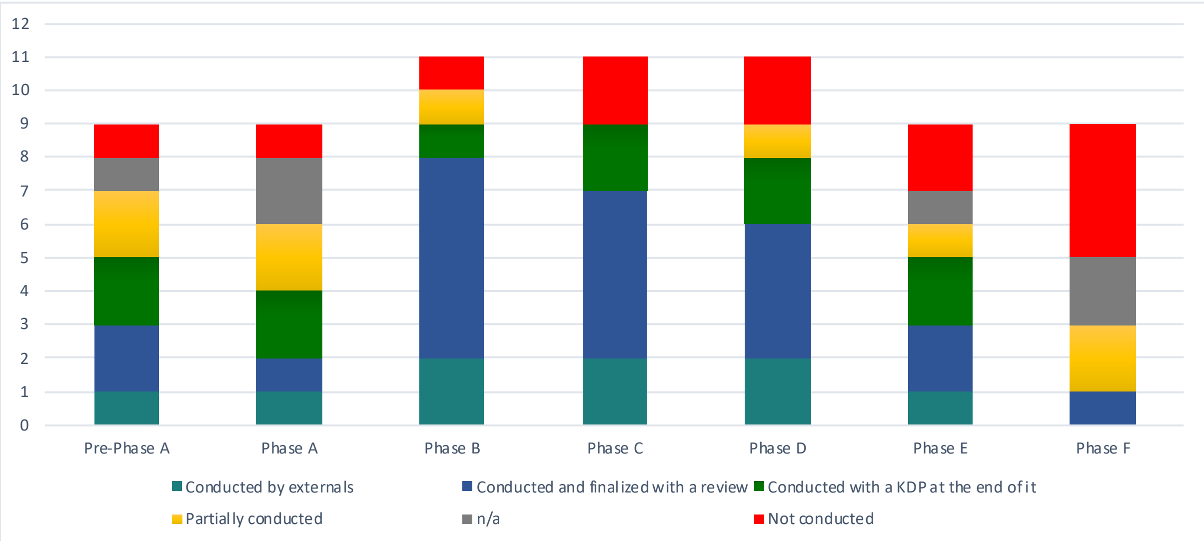


Fig. 5–24: Application of SLC phases: The vertical hight of the bar indicates how often the answer was selected by the 11 interviewees who responded to the question.

The phases that got more than two responses for the ”conducted and finalised with a review” option are B,C & D.

As a further elaboration on this some responses were that they ”used standard ECSS phases” because ”It was the way ESA conducted it” or because it was ”In line with industry standard”. But for most interviewees the ”definitions were loose” or rather the phase definitions were not as prioritised as the definition of the reviews.

When asked if their subsystems were always working on the same project phases and how they would conduct the reviews otherwise, the interviewees responded with:

- *”We didn’t follow phases strictly.”*
- *”No, no at all. That’s why the reviews never really met the criteria to have them.”*

- *"We tried to keep them in same phases. When step backs occurred other system were held back till next review."*
- *"Internal review"*
- *"Some developments were concluded later than others"*
- *"It depends, COTS products can skip phases, and long lead items can be procured in different phases of the project, sometimes driving the design"*

When asked if they used a specific method for requirements management, the interviewees replied:

- *"Interface Control Document"*
- *"just a plain list with codes to show the derivations"*
- *"The system engineering group defined the system requirements following the payload selection. System design did not start until after sys.req. document had passed review."*
- *"system engineering table"*
- *"Magic Draw"*
- *"Compliance Matrix"*
- *"ISIS tailored requirements process"*

When asked if they established a set of MOEs from their requirements 91% (11) chose "NO" while one wrote: "Partially. System budgets are driven by requirements and have set high and low parameters which we cannot exceed". Further, all interviewees chose "NO" for the tailoring of specific MOEs for specific stakeholders, dividing them down to MOPs and TPMs and if their stakeholders used them to take decisions during the KDPs.

However, during the interviews all interviewees confirmed that they had written down requirements and specified them to at least a subsystem level although the verification was then neglected over the course of the development. (Florian Schummer, Kelly Anotnini, Jaan Parks and Jasper Bouwmeester)

5.1.7 Feedback

When asked if they think that the CubeSat community in Europe is well networked, interviewees responded with:

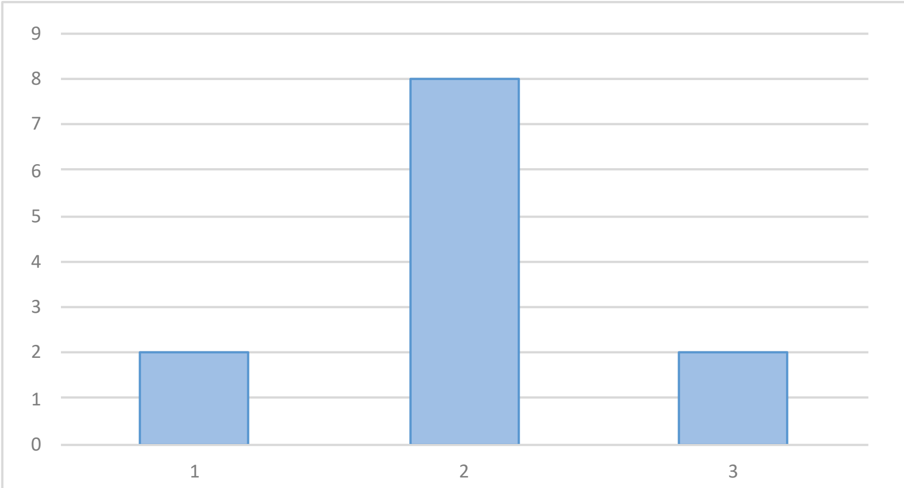


Fig. 5–25: CubeSat network in Europe: The bar's vertical hight indicates how many interviewees selected that option out of 12 responses to the question; "1" being "no existing network" and "3" being "strong community network".

When asked if know-how transfer and developmental cooperation occur between different CubeSat missions in Europe, interviewees responded with:

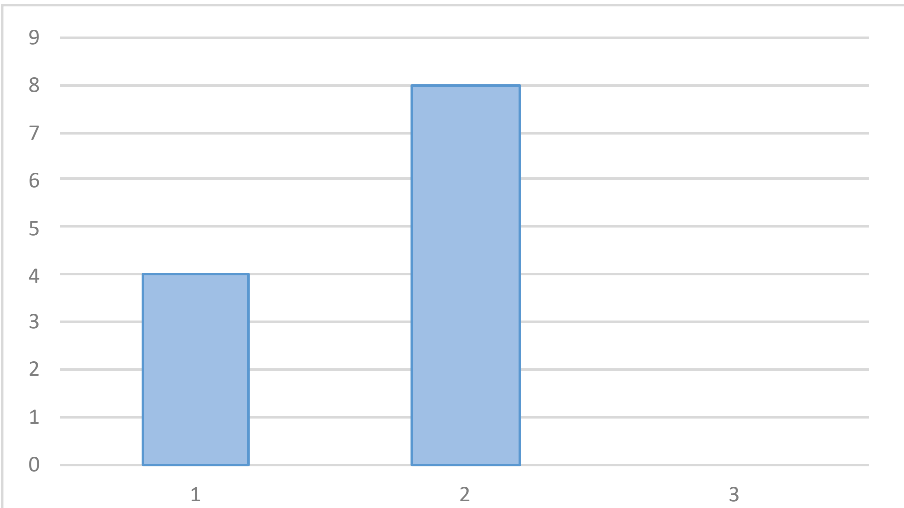


Fig. 5–26: Know-how transfer and developmental cooperation between different CubeSat missions in Europe: The bar's vertical hight indicates how many interviewees selected that option out of 12 responses to the question; "1" being "No, cooperation barley occurs" and "3" being "Yes, continuous cooperation is the norm".

Finally, when asked if they think that more platforms, events and conferences for CubeSat missions are required in Europe, interviewees responded with:

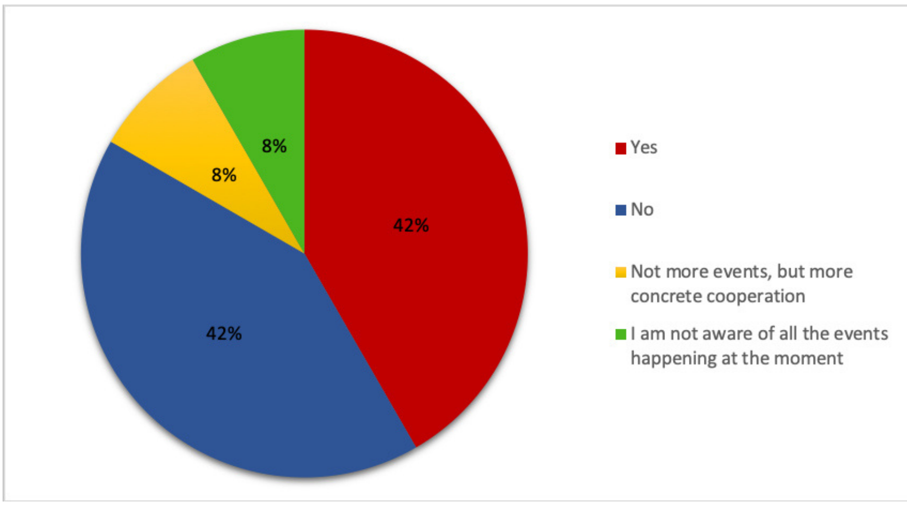


Fig. 5–27: Requirement for platforms, events and conferences for CubeSat missions in Europe: The percentage indicates how many interviewees selected that option out of 12 responses to the question

> *"It can be interesting. We do recognise that we all need to tailor ECSS in another way to make it compatible with the CubeSat industry."* (Hong Yang Oei, Project Manager - ISIS)

5.2 Additional Points Derived from Interviews

In this section some points raised by the interviewees are presented that were not part of the survey questions but are incorporated in the discussion in the next chapter.

A point raised by Patrick Lux was that confirming the compliance of COTS products to ECSS standards is not possible. If any supplier has compliance written in a description sheet, he can be sure that SmallSat teams will take his word for it as they won't have the resources to completely investigate on that matter. They will conduct tests regarding the COTS component's performance for their specific mission requirement but other than that they will trust the supplier that the components are space worthy. Without complete validation options by SmallSat teams and no entity regulating the usage of the term ECSS compliance, this situation will not change.

A further point raised regarding collective launch contracts was:

> *"In an ideal CubeSat world there could be a less static market where, for example you were a CubeSat provider who can launch, but you know that if that launch is delayed then you can automatically go on some other launch in the same orbit. But within the quarter that you were promised.[...] Because that is something, we are suffering a lot from. We have multiple Units for more than a year waiting for certain orbit to launch. And it is just dragging the project, it is meaning that the customer, if it is not ESA, it is just a private costumer, that does not get any data and therefore does not revenue and has the risk to go bankrupt and if they go bankrupt they will never launch and we built them for nothing. [...] So, that is a big risk that*

> *we see in the industry. [...] MOVE was (1) Unit, right? So for something that small, there are now more and more rockets joining the market, so that could be an idea [...] All the 1Us, that want to launch in this quarter have like a common contract for it if it passes you. When there is a delay, I would not say guaranteed, because there is nothing guaranteed, but you have another launch opportunity."* (Kelly Antonini, System Engineer & Project Manager - GomSpace)

Also a relevant point raised regarding the modularity of SmallSat development:

> *"That means that at the beginning a lot of it is still open for our own decision and certain subsystems that we fly are under development. Then the key point could be "do we continue implementing this new subsystem, which is under development, or do we switch to a flight-proven system?" [...] Very simply said, if something is already qualified from another mission then we do not have to qualify it again. We just do the acceptance on it. [...] So, we try to develop this thing as a separate thing for other platforms as well. So, we have the mission requirements coming from the launching mission, the first mover, and we might have other requirements from future missions, we want to say general things that we would like to implement. In that sense, the PDR/CDR milestones might also be separate from the PDR/CDR from the mission. [...] Sometimes it means that there are two subsystems that can fit the requirements and the decision is still to be made which one to use."* (Hong Yang Oei, Project Manager - ISIS)

Furthermore, the interviewee representing the launch provider elaborated on the requirements set by the launch provider:

> *"Essentially what you need is something from a government agency that shows that your satellite is allowed to be launched and operated in space. You need to show that you are allowed to use the radio frequencies to communicate with your satellite. You need a general description of your satellite, what the payload is and what the mission is. Another important one is an End-User Statement which is a document that certifies that your satellite is operated by whatever entity and that it is intended for peaceful purposes and not for military use or non-friendly activities. Then you end up in technical details, such as mass properties, RF properties, environmental loads test reports. And that's mainly it."* (Michiel van Bolhuis, Launch Mission Manager ISIL)

Laslty, the point of end of life or end of operations agreements was raised by Florian Schummer by stating that no agreements exist on what to do with SmallSats that are operational beyond their defined mission lifetime and that there should be agreements allowing for useful solutions for those cases.

6 Discussion of Results

In this chapter the previously presented results of the interviews are discussed in the same chronological order. Both survey data and interview extracts are summarised in the argumentation lines presented in order to further integrate them in the SLC proposed in the next chapter. Further, this chapter includes insights from the interviews that were obtained through asking a long elaborative question or making a complex analogy to which interviewees have merely answered with a positive affirmation and thus the insights were not quotable in the previous chapter. Additionally, the results of comparing obtained internal company documents with declassified documents from the ESA are presented in this chapter.

The first section of the interview focused on collecting data about the interviewees and their respective mission and does not require a great deal of discussion. It showed that:

- All interviewees had a leading role in their respective missions and thus could give valuable insights on SLC implementation.
- The missions had a variety of objectives but the most commonly selected option is in orbit demonstration (IOD) which allows for a comparison to the proposed implementation in ESA's TEC-SY/128/2013/SPD/RW document [1].
- The majority (76.9%) of the missions surveyed developed NanoSats (1-10kg) which leaves the contents of this thesis well in the frame of the New Space Philosophy defined in the state of the art.
- All satellites were launched into LEO and had a mission lifetime averaging slightly less than two years (1,97) which is common for CubeSat missions with the presented mass range in LEO [65].
- All interviewees have been part of a mission that was launched into space.
- The interviewed missions are split between having the ESA as a stakeholder. This occurs in different configurations and allows the contents of this thesis to explore a variety of SLC implementation with and without ESA's direct or indirect involvement.

Lastly, although the amount of interviewees (16) is not sufficient for a survey of the complete SmallSat industry, it is counteracted by the fact that all have held leading positions in their respective projects, in total could give insights regarding current development and development starting from the early 2000s and half were part of multiple missions with different stakeholder configurations.

6.1 Stakeholders

As the data showed and the interviews confirmed (See subsection 5.1.2), no specific method was used for stakeholder management or categorisation based on decision power.

In the case of university projects the stakeholders differed greatly but a categorisation into the university, a national agency, the payload providers and the engineering team can be made. University projects considered their engineering team as a stakeholder because of the awareness of the direct correlation between the continuous output and progress of the mission and the published papers and theses. This is a novelty to satellite development when compared to conventional satellite development in which solely the novel satellite was the output of the engineers who were hired by governmental agencies to specifically accomplish that task. For university projects the engineering team has a larger stake due to the additional output. Additionally, the influx of man power is a dominant issue for these type of university projects and thus the correlation between progress made and motivation for the team is also noticeable.

In the case of company products the situation is clearer in the sense that the product is being developed for a costumer who placed an order. In some cases the constellation is expanded to one party paying for the mission while another - often the ESA or another governmental agency - is handling the technical oversight. To do so, they organise the experts who make up the reviewing board. Further, companies do recognise their suppliers as stakeholders but due to the repetitive engagement with them they are not prioritised as the costumers are prioritised for one single mission. In scientific university projects agreements with the supplier can lead to reduced procurement costs in exchange for a stake in the project in the form of data collected about their product which in turn raises their prioritisation as a stakeholder compared to private companies.

Further, companies have policies on how to deal with costumers which even when not written down are taught to system engineers on the job. There are documents detailing the deliverables per project phase which define the contractual part of an SLC between company and costumer. How to and who should engage with the stakeholders is often defined outside of SLC documents in designated PM plans or quality assurance (QA) plans. However, there is an awareness throughout the whole team of the decision power of the stakeholders, as payment is often coupled with the conduction of the reviews and the passage of the review to the satisfaction of the stakeholder (Further elaborated upon in section 6.4).

In all cases, the launch provider has a significant stake in the development of the satellite because the launch provider has a responsibility to meet requirements set by the launch vehicle operator. Thus, the launch provider needs to ensure that these requirements are met by the satellite developer in order to fulfil his responsibilities towards the launch vehicle operator. However, the launch provider does not usually achieve this by being present at reviews and giving feedback but by requesting documentation that fulfils its requirements before the launch of the satellite.

.

In case of the ESA being an active or passive stakeholder in a mission, the developing team is required to comply with ECSS standards. As previously elaborated, in the case of a SmallSat mission those would be the tailored standards as per TEC-SY/128/2013/SPD/RW.

6.2 ECSS Standards

As evident by the data and the interviews (See subsection 5.1.3), compliance with ECSS standards does not occur except in the case of the ESA being a stakeholder. Additionally, the interviewees stated that the tailored standards for CubeSat IOD missions are too complex and require resources greater than what is reasonable for a lean CubeSat mission. Thus, a general consensus exists regarding the lack of their applicability. Further, an argument was made by more than one interviewee regarding the standards not covering factors that lead to the failure of CubeSat missions. How this could be addressed is covered in section 6.6.

For the scientific university projects that develop CubeSats the first documentation that guides on the development of the physical design is the CubeSat Design Specification Rev. 13 because it is the standard on the form restrictions of CubeSats [36]. Further, NASA & ECSS standards are then referred to as guidelines when searching for a solution for a specific problem. However, an attempt on full compliance is never made by the university teams and is not seen as an ideal to strive for because of the existing awareness of the lack of applicability.

In the case of private companies internal standards for SLC implementation exist. Some examples of revealed standards are partially influenced by the tailored ECSS for CubeSat IOD missions but not tailored according to the ECSS-M-00-02A [47] tailoring standard nor are they covering the same scope. The internal SLC standards that were revealed by the private companies had the following in common:

- A SLC visualisation with phases and decision gates for phase shift
- The detailed design of decision gates. Meaning how the reviews and the subsequent KDPs are conducted
- A Deliverable Items List (DIL) listing the types of documentations and their expected content
- A matrix linking the maturity grade of DIL documents to the reviews

In essence, that which the complete ECSS covers but applied to the use case of SmallSats [1]. What is significant here, is that the documents encompassing the afore mentioned information are no longer than 10 pages. Which means that the interviewed private companies have developed SLC standards for themselves that suffice for successfully developing SmallSats for costumers. Moreover, they have managed to do so with a reduction of resources that is adequate to SmallSat development in the sense of reducing the scope of the standard as well as the tasks to be performed to uphold it.

.

The tailored ECSS for CubeSat IOD Missions aims at doing so. However, rather than selecting the significant factors based on lessons learned from SmallSat development and then combining them to a new standard, it proceeds to tailor standards that are applicable for manned space missions onto the use case of CubeSats. The result thereof is a complexity hindering the applicability of the standards (See section 6.4).

During the interviews the main concern of interviewees who did not know if they should fully support the development of new standards was the complexity and the resulting non-applicability. Interviewees feared that in the SmallSat domain a new standard would hinder flexibility and if so, this would result in the new standard also not being implemented. However, most of these interviewees expressing these fears were from scientific university projects, who have not attempted the tailoring of a standard for themselves and are not aware of the tailored standards by the companies since those tailored standards are kept company internal. The fact that the interviewed companies have internal new standards proves the fact that there is a necessity for a new standard for SmallSat development. How this could be achieved and what the implications of that would be for the SmallSat industry is further investigated in section 6.6.

For the scientific university projects that have motivated and innovative students make up their teams, a new resource-efficient standard would not hinder their flexibility. As clearly stated by interviewed professors and student leads, students will always ignore standards in favour of more simpler and more innovative solutions. Thus, to offer them a new standard is merely to offer them a new basis for their innovative endeavours and a chance to analyse the actuality of the standard and adapt it accordingly. This would only be achievable if a new standard is not a restrictive rigorous requirement but an easily implementable guideline.

6.3 Methods for Processes Implemented

The data of the digital survey showed that agile methods in the sense of an iterative development approach and the V-model in the sense of mirroring testing and verification to the development process are implemented. Mostly, when asked if they used a specific agile method during the interviews the interviewees declined. When then an explanation of what the method entails followed, the interviewees confirmed that a comparable approach is being used in their development process. The further investigation showed that the following methods are used by SmallSat developers.

As innovation in the SmallSat industry is becoming increasingly software-heavy and software offers more agility - e.g. further adaptations after launch - it is logical that methods from that domain are implemented. An example of such is Scrum. Scrum divides the development process into Sprints. A Sprint is usually a defined work package that is undergone in a short time frame. Usually that time frame is one or two weeks. Afterwards the team meets, revises the progress and defines work packages for the next Sprint. Scrum also entails developing a baseline and then adding so-called features onto it. E.g. when a search engine for a database is built, the search function would be the baseline which is programmed as simplistic as possible. Afterwards, use cases like multiple entries, usage by multiple users and none-existing entries are dealt with, which is called adding features to the baseline. This iterative process is repeated and features are added until the final product fulfils all desired requirements and has incorporated solutions of defined test cases. [66, 67]

The same approach from a hardware perspective is the Bread-Brass-Silver-Gold approach of the Air Force Research Laboratory's University Nanosatellite Program. A Bread Model is built that implements primary functions of a printed circuit board (PCB) and is built from plug-in kits. For the next iteration a Brass Model is built that uses commercial parts and does not need to be in the final flight format but allows for further testing and debugging. Afterwards, a silver model is built that is in the flight format and allows for component testing. Lastly, a Gold Model is built in which the tested components are staked to a final model. [68, 69]

This approach combined with recent advancements in additive manufacturing allow for the conduction of individual repetitive functional and performance tests in relevant environments early on at component and subsystem level [70, 71, 72]. This method was not a familiar terminology for the interviewees, except the MOVE-II team that is implementing according to that terminology. However, all interviewed companies and most university projects confirmed that they implement a similar approach.

Further, a common method for the development of space systems is to develop both an Engineering Model (EM) and a Flight Model (FM). This method stems from traditional satellite development and is continued for New Space systems. The EM is built first and rigorously tested. Afterwards, the FM is built and handled relatively gently until it is launched into orbit. Most importantly, it is made sure before the launch that the FM is identical to the final state of the EM. This has the benefit of test conduction with the EM on the ground, of which the results are valid for the FM in orbit which aids greatly in failure analysis and fault identification [73].

Lastly, the method for requirements management was kept rather simplistic in the interviewed missions. Top Level (TL) requirements are defined for the system as a whole and further derived from those are subsystem specific requirements. The sum of these requirements is then traced in a requirements verification matrix.

6.4 Milestones, Deliverables and Reviews

As evident from both data and interviews and logically expectable, all of the interviewed missions set milestones for their development process. Although one interviewed mission finished the satellite just in time for launch, they had also previously set milestones for the development process. Thus, the practice of setting milestones is implemented as can be expected from systems engineers and project managers.

University projects have the flexibility of conducting milestones and reviews at their discretion. Milestones in the sense of a desired maturity grade of the system are set in order to both increase the motivation and work flow towards the milestone and to benefit afterwards from the motivation due to achieved progress. The reviews are set in order to produce documentation of the system and get feedback from a selected pool of experts that make up the reviewing board. The same benefits in the sense of motivation for the team are applicable to reviews. Significant for these cases is the flexibility of setting milestones independently of reviews, the choice of conducting reviews at a desired milestone to increase motivation or documentation progress and the freedom to choose the make up of the reviewing board.

The exception to this is an interviewed case of a scientific university project being a showcase of political agendas and politicians having an influence on the developmental process. In this scenario politicians have influenced the setting of milestones in order to demonstrate the achieved progress to the public and get required approval, e.g. for new laws regulating space endeavours for that country. Understandably, the feedback of the engineering team on that matter was a negative one as the usual flexibility of a university science project was compromised.

The setting of milestones and the conduction of reviews for a company product is a different case. The costumer purchasing the product has an expectation on when he desires the product to be launched and be of use to him. Thus, milestones and reviews are set according to his temporal frame. Even if the costumer does not dictate a temporal frame, the contract between the company and the costumer includes a SLC with set reviews to be held. Hence, from an engineering team's perspective the temporal frame is set.

As the temporal frame of the conduction of the reviews is set, the milestones in the sense of system maturity are thereby also set. The system is developed to have a pre-defined maturity in a fixed temporal frame for which a review is conducted to present the progress to the stakeholders, collect feedback and shift to the next project phase. For this case the stakeholder decides the makeup of the reviewing board. The reviewing boards included both representatives of the costumer as well as invited external experts on the subject matter.

The reviews were conducted by the interviewed companies as follows. The draft documentation at the desired maturity grade of the system is sent to the members of the reviewing board which then send back RIDs. For those, the engineering team has to prepare solutions for the final review presentation in front of the reviewing board. A number of RIDs are highlighted as Blocking RIDs which means that the reviewing board expects these RIDs to be addressed at the final presentation, in order for the engineering team to pass the KDP into the next SLC phase. After the final presentation, a meeting between both parties occurs which represents the KDP. During this KDP it is decided if the review and thereby the project phase is concluded to the satisfaction of the stakeholders and if the project is allowed to continue in the same manner, in a different manner or be terminated. Additionally, contractual payment agreements are linked to the KDPs. Meaning that an agreed upon payment occurs after the successful passage of a KDP.

As presented in subsection 5.1.6 the reviews conducted by most SmallSat missions are:

- SRR - System Requirements Review
- PDR - Preliminary Design Review

- CDR - Critical Design Review
- PRR - Production Readiness Review or
  MRR - Manufacturing Readiness Review
- SIR - System Integration Review or
  IRR - Integration Readiness Review
- FRR - Flight Readiness Review
- IOCR In Orbit Commissioning Review (for company products developed for a costumer)

In the case of ESA being an active stakeholder and expecting full ECSS compliance None Conformance Reviews (NCRs) were conducted in the event of the engineering team developing in a manner that was nonconforming to ECSS. The effort for conducting these reviews was described by the interviewee to exceed an estimated 30% of the effort during the development process. Which is neither in line with the responsive development process of SmallSats nor with the concept of supplier integration in the sense of the New space Philosophy (See subsection 2.1.3).

Lastly, the issue of deliverable documentation needs to be addressed. As previously elaborated (See section 6.2), part of the contractual SLC agreement is a deliverables matrix detailing which DIL documentation is provided by a satellite developer at which maturity grade with respect to the reviews.

The complete ECSS standards offer this matrix of deliverables in ECSS-E-ST-10C Rev.1 - Annex A [43] and further offer document templates attached to the standards detailing the makeup of certain documents. However, the TEC-SY/128/2013/SPD/RW document [1] that details the tailoring of ECSS standards to CubeSat IOD missions does not list ECSS-E-ST-10C Rev.1 as "applicable" but it is marked as most other engineering standards as "guideline".

Further, the TEC-SY/128/2013/SPD/RW document does not advise on which reviews are to be conducted specifically for CubeSat IOD missions nor does it list deliverables' maturity. Additionally, the TEC-SY/128/2013/SPD/RW document advises on fusing together and replacing most of the documentation required in the standards it deems "applicable". Thus, rendering all of the document templates inapplicable.

However, upon request at the Systems and Engineering Support Division (TEC-SY) at the ESA, one can obtain the TEC-SY/127/2013/DRD/RW which is titled "IOD CubeSat Document Requirements Definition" [74]. This document does list the required content of documents as listed by the TEC-SY/128/2013/SPD/RW document but it does not offer templates, a matrix of deliverables' maturity nor insight on which reviews are applicable.

Comprehensibly, company internal documentation is developed which in one case referenced these documents as a source but for most companies it is developed purely based on lessons learned. This also presents an argument for the lack of implementation by innovative student teams.

.

However, the document requirements that any satellite developer must comply with, are the document requirements of the launch provider. Those are document requirements that need to be met by satellite developers and can not be negotiated during reviews or KDPs as the launch provider gets these requirements form the launch vehicle operator. Hence, the launch provider does not attend reviews but merely checks the fulfilment of these requirements before a payload is cleared for the fairing of a rocket.

6.5 Holistic Components of a System Life Cycle (SLC)

As per the design of the survey, so too does this section take a step back and address holistic components of an SLC after specific components have been addressed in detail (See subsection 5.1.6).

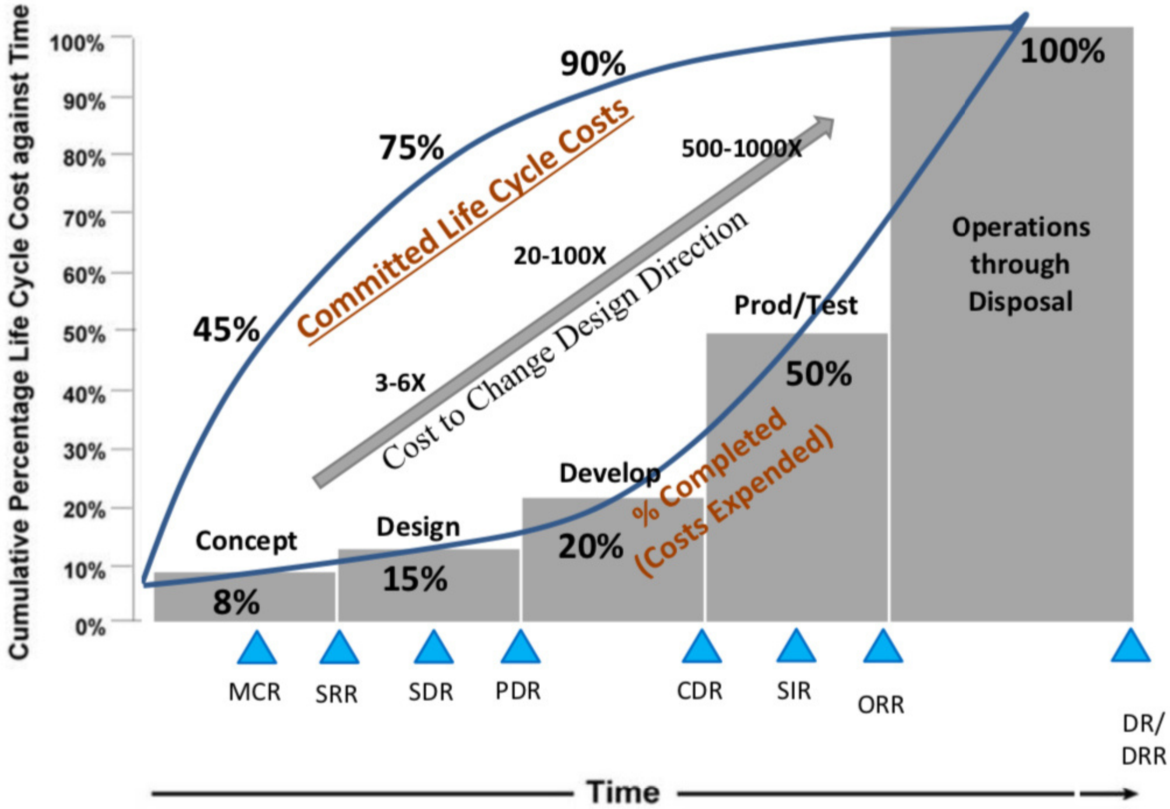
Interviewees explained that the phase terminology was not as significant as the review terminology at the end of it. Meaning that the reviews characterise the phase and not the opposite. However, the interviewees predominantly selected the following phases as conducted:

- Phase B: Preliminary Design & Technology Completion
- Phase C: Final Design & Fabrication
- Phase D: System Assembly, Integration & Test, Launch & Checkout

A paper by the Shiotani at the American institute for Aeronautics and Astronautics at the University of Florida suggests the fusing of Pre-Phase A, Phase A and Phase B to Phase AB. The argument he makes is that in "Phase AB, the process it too early to perform any verification tests or develop mission assurance cases since the design is only at a preliminary stage." He further argues that internal and external MCRs and PDRs should focus on preliminary concept of operations and design processes while satisfying CubeSat standards and that successful reviews will lead to successful submissions of proposals for funding. [75]

His argumentation also includes the role of published papers and student theses in his proposed SLC. Although not directly indicated, it is deductible that his proposed SLC is intended for scientific university products. Taking into account that the majority of interviewees are scientific university projects one can support his claim based on the collected data. Further, approaching a funding opportunity with a system maturity at a PDR level rather than a MCR level is a sound argument.

However, for the case of company products the situation is different. During Phase A mission analysis and engineering activities with the main purpose to establish the mission requirements documentation are conducted. During Phase A different solution concepts are evaluated via trade-off studies and the feasibility is assessed. During Phase B the main purpose is to develop mission requirements into system requirements and to ensure that a feasible solution to the system requirements exists. It is crucial to communicate this information through distinguishable reviews with the stakeholders. That is due to the fact that the stakeholders for the company products are already invested in the project. As opposed to university projects who are applying for funding, these missions already have a costumer paying for the development. The cruciality of that early communication is underlined by the increase in cost to change design direction over time, as Figure 6–1 depicts.



MCR	Mission Concept Review	CDR	Critical Design Review
SRR	System Requirements Review	SIR	System Integration Review
SDR	System Definition Review	ORR	Operational Readiness Review
PDR	Preliminary Design Review	DR/DRR	Decommissioning/Disposal Readiness Review

Adapted from INCOSE-TP-2003-002-04, 2015

Fig. 6–1: Life Cycle Cost Impacts from Early Phase Decision-Making [6]

It is to be noted that Pre-Phase A existed in the documentation shared by the interviewed companies but was outside the scope of the development process and not finalised by reviews. It focused rather on taking the project over from the sales department - after they've secured an agreement with the costumer - and organisational resource allocation as indicated by the terminology "Sales-Takeover" or "Kick-off" phase. In contrast, the focus in Pre-Phase A at governmental agencies by the engineers and scientists, is to convince the agency of the benefit of developing a novel technology in the first place [6].

Regarding Phase E Operations & Sustainment, there are two scenarios for company products:

- The product was developed for a costumer that intends to operate it himself. In that scenario the developing company conducts an In Orbit Commissioning Review (IOCR) which to pass the product needs to be ready to commence nominal operations in orbit. Afterwards, the project is considered finalised from the developing company's point of view and that becomes the end of their commitment to a contracted SLC. With the exception of contractual maintenance agreements.
- The product was developed for a company-internal mission or is entirely operated by the developing company for the costumer. For this scenario the commitment continues beyond commissioning in orbit and the SLC is continued.

Regarding Phase F Closeout & Disposal and what it entails, it is the same for all CubeSats in LEO. CubeSats are designed to burn out during reentry into the atmosphere. For that to happen, no active intervention from an operator is required. This deorbeting happens gradually over time due to orbital disturbances mainly caused by atmospheric drag and solar radiation pressure. Thus, after the end of operations in Phase E the satellite is left to nature's mercy. However, nature's forces can vary in intensity, e.g. low solar activity. As a result thereof, a CubeSat may have achieved its mission objectives, reached beyond its defined mission lifetime and still be operational. How to make use of these CubeSats is not something this industry has concrete plans for and is not usually written in contractual agreements, as one interviewee explained. [76]

Lasty, the issue of requirements management was previously addressed (See section 6.3) but more holistically the issue of requirements communication was also elaborated upon by the interviewees. In the case of the ESA being a stakeholder and full ECSS compliance is required, the ESA will require requirement definitions to be shared for all levels of development to the detail of TPMs and test case requirements. However, interviewees have stated that other costumers are not too keen on knowing those details. For most costumers other than the ESA, the communication of TL requirements suffices. Hence, subsystem level requirements can be kept team internal which adds flexibility to the development process. Thus, emphasising on adequate requirement communication can have a significant impact on the conduction of reviews and on the SLC as a whole. Which is a further argument for a novel standard which negates the discrepancy between what the ESA expects and what satellite developers deem as adequate based on their experiences with private costumers.

6.6 Feedback and Additional Points Derived from Interviews

As discussed in the previous sections, a novel and easily implementable standard for SmallSat development for the European space industry is in order. As companies have already developed internal standards the approach of developing an industry-wide standard would best be suited to follow the approach of Automotive SPICE (See subsection 2.2.3). Instead of relying on the ESA to tailor complex standards down to a SmallSat use case, established companies should come together and develop an industry standard based on their lessons learned, best practices and desired goals.

As elaborated upon in chapter 2, SmallSats have already established their own market that generates innovative technologies applicable for the space industry as a whole. Thus, a standard specifically for SmallSat development is a step towards acknowledging the significance of this technology and aiding its developers in their efforts.

The development of a new standard by established companies would encourage know-how transfer and strengthen cooperation in the SmallSat community. Further, the standard could increase the speed of satellite development by decreasing the time lost due to:

- Testing of unverified COTS components
- Agreeing on content of documentation and correct formats thereof
- Agreeing on best practices for review conduction, requirements tracking and procurement procedures

A depiction of how Automotive SPICE achieves that is shown in Figure 6–2. The standard has grown to be of significance to the degree that assessors investigate the suppliers of the OEMs and if the suppliers are deemed to be not upholding the standards, the OEMs seize the procurement of their product. This has the benefit that, on the upside of this scenario the OEMs can procure from accredited suppliers without wasting resources and time on quality verification and documentation definition. They merely submit their requirements and are ensured quality through the standard. Figure 6–2 depicts the replication of the concept onto a new standard for satellite development for the scenario of component procurement. The same depiction can also be replicated for the role of a new standard in the scenario between launch providers and satellite developers.

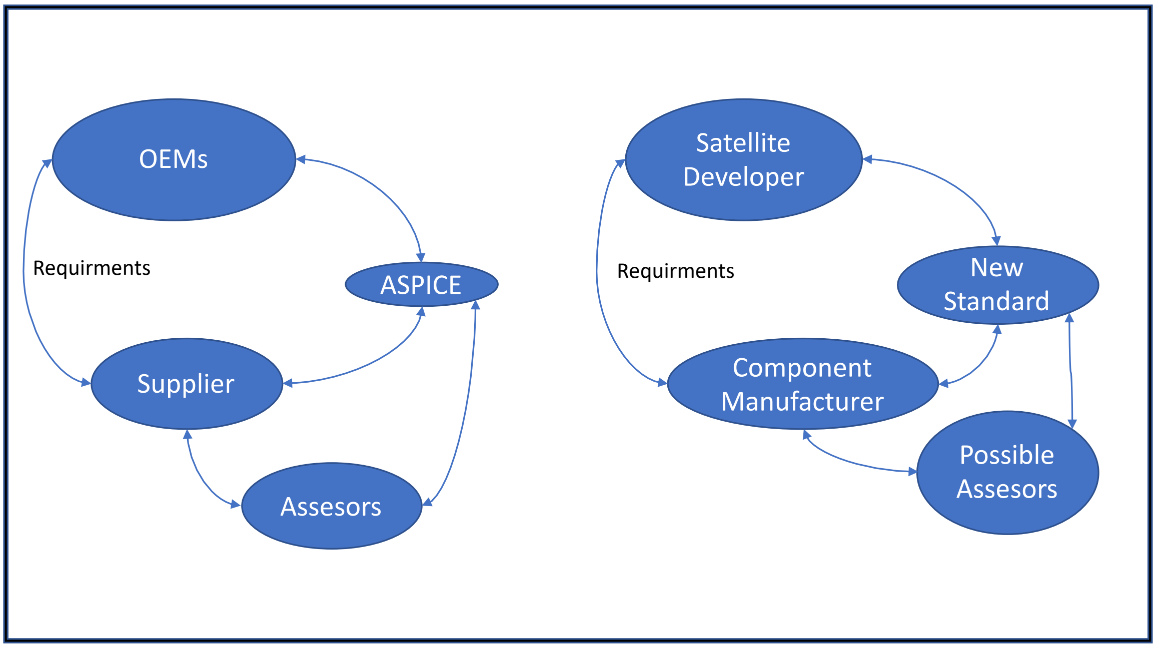


Fig. 6–2: Analogy of the functional of the ASPICE standard to a possible new standard for satellite development

If the SmallSat domain would have an easily implementable standard, it could also profit from saving resources in the same manner. Especially, because the SmallSat domain is a resource-constrained domain, the increase in development speed would be more significant and the allocation of resources to innovative technologies would result in greater outputs.

The standard could further offer solutions through know-how transfer and cooperation to points raised by the interviewees such as:

- Novel interfaces: By incorporating new interface into the standard, payloads from other missions could be flown on satellite busses from other companies or institutes, as university projects continuously attempt to do.
- Collective launch contracts: The standard could provide launch providers with the option of interchanging the SmallSats on a launch rapidly because it standardises the fulfilment of the launch provider's requirements. Thus, a SmallSat experiencing delays in its development could be rapidly replaced by another one and further be guaranteed a future launch opportunity.
- Generation of benefits from operational SmallSats beyond their mission lifetime - end of life or end of operations agreements: SmallSats that are operational beyond their mission lifetime could be used by other entities as aspects of the operation are standardised. E.g student operators from universities could be trained on them if the operation software or method is standardised.

An argument could be made that this knowledge transfer and sharing could reduce the competitiveness of the SmallSat domain and thus hinder innovation and advancement. However, as any other standard the competitive advantage of companies will come through their implementation of it. Additionally, by being based on lessons learned and being easily implementable it can only be simple and nonrestrictive to innovation. This in turn is only achievable by an open and inclusive process of standardisation.

As the interviewees have stated, the need for a SmallSat conference for networking is saturated but a conference with a purpose of collaboration towards a definitive goal was welcomed by the interviewees.

The next chapter does not offer a proposal for a complete standard but it rather offers a basis for discussion for one of the sectors of a potential standard. It does so based on the insights gathered and discussed from both scientific university projects, companies and existing standards.

7 The Proposed System Life Cycle

In this chapter a proposal for a SLC is presented based on the insights gathered during the digital survey and the subsequent interviews. A visual representation of the SLC is shown and explained. Afterwards, the phases of the SLC are chronologically elaborated upon before further insight is given on how the results of the interviews are implemented in the SLC.

As previously stated, this SLC aims at being easily applicable and resource efficient. It is designed to be applied by system engineers in resource-constrained SmallSat projects while guiding through necessary steps in a SLC for mission success based on the collected information during the course of this thesis through:

- Established literature [6, 7]
- Declassified ESA documentation [74, 1]
- Existing internal company standards
- Insights collected and points raised during the interviews

If a new standard for SmallSat development is to be developed, then this chapter aims at offering a basis for discussion on the part of it that standardises SE application in the form of SLC implementation. To do so, this SLC aims at covering satellite development in the various mission configurations encountered during the course of this thesis. Hence, it has the objective of covering all the aspects of development of the interviewed missions and being applicable for their development process when tailored according to their mission characteristics and objectives.

Shown in Figure 7–1 is a proposed SLC with distinct phases separated by external milestones, a projection of the the V-Model that shows the relation of the validation process to the development process and cycles indicating the iterative agile development processes which are further detailed in this chapter.

7.1 Holistic and Visual Presentation of the System Life Cycle

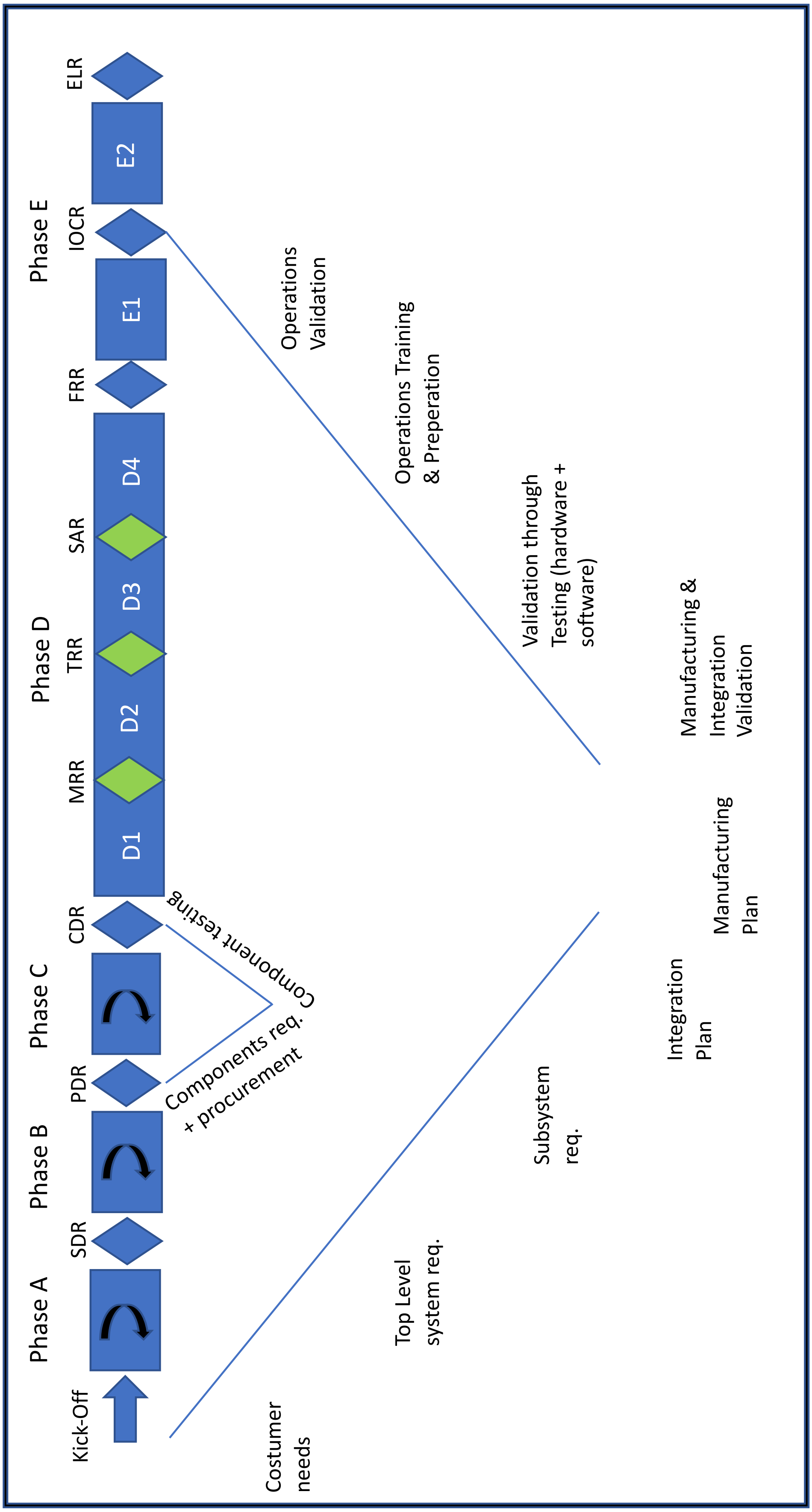


Fig. 7–1: Visual representation of the proposed SLC: Showing the chronological phases, external reviews (blue), internal reviews (green) and the design and validation as a V-Model [66]

The visualisation of the SLC starts at the Kick-Off of the project where engineering development begins. As discussed in section 6.5, prior to that are sales and resource allocation processes that conclude in the Kick-Off of the development process with defined costumer needs and allocated resources.

Afterwards, the proposed phases to go through during the development process are:

1) **Phase A**: Mission Analysis and Feasibility
2) **Phase B**: Preliminary Solution Definition
3) **Phase C**: Detailed Solution Definition
4) **Phase D**: System Manufacturing, Integration, Test & Launch Preparations
   (a) **Sub-Phase D1**: Manufacturing Preparation
   (b) **Sub-Phase D2**: Integration & Test Preparation
   (c) **Sub-Phase D3**: Testing & Validation
   (d) **Sub-Phase D4**: Final Launch Preparations
5) **Phase E**: Operations & Sustainment
   (a) **Sub-Phase E1**: Launch & Commissioning
   (b) **Sub-Phase E2**: Service & Maintenance

Analogical to that is the finalisation of a phase and shift to the subsequent phase through the following reviews:

1) **SDR**: System Design Review
2) **PDR**: Preliminary Design Review
3) **CDR**: Critical Design Review
4) Phase D internal reviews and external D4 review to shift to Phase E:
   (a) **MRR**: Manufacturing Readiness Review
   (b) **TRR**: Test Readiness Review (includes System Integration Review (SIR))
   (c) **SAR**: System Acceptance Review
   (d) **FRR**: Flight Readiness Review
5) Phase E external reviews with E2 review as the end of the mission:
   (a) **IOCR**: In Orbit Commissioning Review
   (b) **ELR**: End of Life Review

The proposed form of review conduction is presented in Figure 7–2.

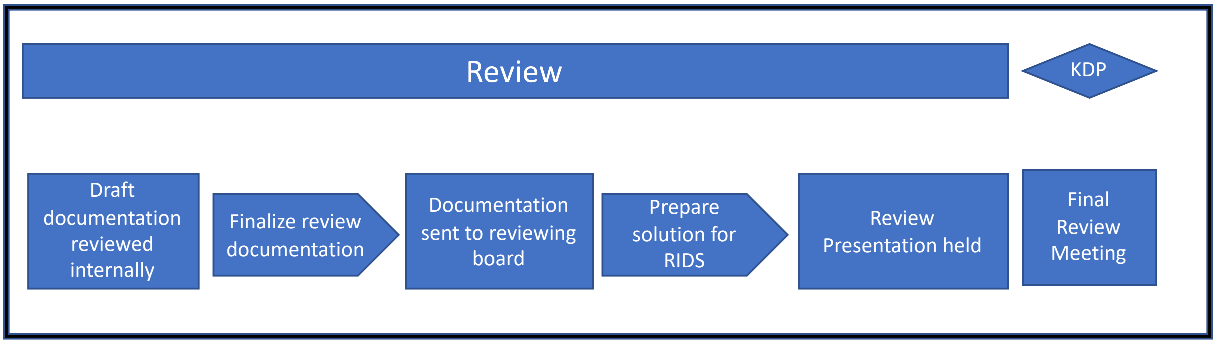


Fig. 7–2: The proposed process for review conduction

The review draft documentation is revised and finalised team internally. Afterwards, the review documentation is sent to the members of the reviewing board which then send back RIDs. For which, the engineering team has to prepare solutions for the review presentation in front of the reviewing board. Specifically, the highlighted Blocking RIDs have to be addressed for the engineering team to pass the KDP into the next SLC phase. After the presentation, a final meeting between both parties occurs - the KDP. During this KDP it is decided if the project phase is concluded to the satisfaction of the stakeholders and if the project is allowed to continue in the same manner. Additionally, this SLC advises on the system engineering team being in control of the structure of the documents and the subsystem teams filling in the content of the sections.

This represents the official medium of progress communication to the stakeholders. For any other information exchange, progress reporting or organisational discussions, the team should define a single point of communication, which is often the task of a single person in the industry (e.g. Key Account Manager [77] or Product Owner [46]).

As for the verification of requirements for a SmallSat mission, companies use and the ESA advises on using a simple System Verification Control Matrix. The purpose of the matrix is to identify verification methods for the requirements and to track the verification status with respect to requirements during the System Life Cycle. [74]

Thus, for this proposed SLC it is suggested to use a matrix and keep requirements and requirement verification at three levels of detail. Meaning that costumer needs are developed into TL requirements which are then specified into subsystem requirements. The third level of detail is the expected results of the defined verification methods. That is to highlight the importance of developing the verification strategy or the right side of the V-Model, as early as possible. Thus, instead of defining a third level of requirements for a subsystem it is suggested to specify the concrete desired outcome of a concrete verification method to fulfil the previously defined requirements. In this case multiple verification methods can be defined to satisfy the same requirement without the need to continue defining sub-requirements that could possibly be neglected. This is then controlled through a System Verification Control Matrix (SVCM).

In essence this is similar to the MOEs, MOPs and TPMs of the NASA (subsection 2.2.1) [6]. The Exception is that the TPMs do not just include physical and functional characteristics to be verified, but also include the verification method itself and further only the

the TL requirements are suggested to be communicated with the stakeholders for this SLC, except if they request more detail. This is due to the fact that private costumers often do not request more detail and thus keeping subsystem requirements and verification methods internal offers the developing team more flexibility. This is in contrast to the conventional communication of all of the MOEs, MOPs and TPMs to the NASA or ESA but in line with supplier integration in the sense of lean production (See subsection 2.1.3) [6]. Further, the depiction of their maturity at SDR and PDR level as in Figure 7–1 is merely a limit to the finalisation but previous definition is at the discretion of the developing team. A template for proper requirements definition is attached to this thesis in Appendix B.

As per the deliverables, Figure 7–3 lists the documents and their purpose and Figure 7–4 lists their required maturity at each review. The shared company internal standards were either based on lessons learned and did not specifically address the content of the deliverables but did use similar terminology for the documentation or they referenced the declassified TEC-SY/127/2013/DRD/RW titled "IOD CubeSat Document Requirements Definition" [74]. Thus, the deliverables for this SLC are based on the afore mentioned document and it is attached to this thesis because it describes the deliverables to great detail. Further benefits of including this definition of deliverables in the SLC are discussed in section 7.3. However, this document does not offer neither information on the required maturity per review nor documentation templates. Thus, the required maturity per review for this SLC is based on the insights gathered from the interviews, the internal company standards and the afore mentioned literature.

Name of document	Porpuse
Mission Requirements Document (MRD)	To specify the mission requirements and constraints, and high level payload user requirements
System Requirements Document (SRD)	To specify the system requirements relating to the spacecraft, payload and ground segment
Mission Analysis Report (MAR)	To describe all of the analysis performed in support of the mission planning prior to launch
System Verification Con- trol Matrix (SVCM)	To identify verification methods to track verification status with respect to requirements during the project lifecycle
System Design Report (SD Report)	To provide a summary technical description of the overall baseline mission, spacecraft system and ground segment, including external interfaces and system
Payload and Platform Interface Control Docu- ment (P&PICD)	To define the payload item interfaces with the platform
Environmental Design Specification (EDS)	To define the launch and space environments that the satellite is expected to be encountered by the spacecraft throughout the mission, and to form an Environment requirements specification for application system design.
Satellite Mechanical Analysis Report (SMAR)	To describe the s/c mass properties, structural analysis setup, assumptions, and analysis results in relation to the relevant requirements
Satellite Thermal Analysis Report (STAR)	To describe the thermal analysis setup, assumptions, and analysis results in relation to the relevant requirements
Satellite AOCS Anal- ysis Report (SAAR)	To describe the AOCS analysis setup, assumptions, and analysis results in relation to the relevant requirements
COTS User Manuals (CTUM)	To describe the Commercial Off The Shelf products to be used in the satellite design baseline
Space-to-ground In- terface Control Doc- ument (SGICD)	To define the interfaces between the spacecraft and the ground segment, including all ground stations
Space Debris Mit- igation Document (SDMD)	To define how the project plans fulfil space debris mitigation re- quirements
Declared Lists for parts, materials and processes (DL)	To identify all types of electrical components, mechanical parts and materials needed for the current design for all system-level models
Satellite AIV Plan	To define and control all assembly, integration, verification and transportation activities
Satellite Integration Logbook (SIL)	To record the actual events of the satellite integration process
Test Procedures	To establish the objectives, organization, setup and constraints of verification tests. To establish the procedures/success criteria used in verification tests and the requirements to be verified
Test Reports	To describe the results of the verification tests at all levels against the specified requirements.
Saftey Data Package (SDP)	To demonstration the compliance with the launch safety requirements as set by the launch provider requirements
Mission Operations Plan (MOP)	To define the full plan of activities immediately preceding and during the mission operations phase, including the Mission Timeline. It shall cover all mission phases, from liftoff from the launch pad until and including the Spacecraft end of life disposal, covering nominal and contingency recovery operations.
Mission Operations Status Reports (MOSR)	To regularly report on the health status of the platform and payload in orbit and the progress with respect to the Mission Operations Plan
Post-flight Analysis Report (PAR)	To summarise the main results of the mission based on the data acquired, and describe the lessons learned
Non-Conformance Reports (NCRs)	To record non-conformances of the system product with respect to requirements in terms of nature, root cause, and corrective actions
Request For Waivers (RFWs)	Request waivers for established requirements.

Fig. 7–3: Deliverable Items list (DIL) and the purpose of the documents [74]; The complete document with the detailed contents of the deocuments can be found in Appendix A

Document	SDR	PDR	CDR	MRR	TRR	SAR	FRR	IOCR	ELR
MRD	B	M	M						
SRD	A	B	M						
MAR	A	B	M	M	M				
SVCM	A	M	B	M	M				
SD Report	A	M	B	M	M				
P&PICD		A	B	M	M				
EDS	B	M	M						
SMAR		A	B	M	M	M			
STAR		A	B	M	M	M			
SAAR		A	B	M	M	M			
CTUM		A	B						
SGICD		A	B			M	M		
SDMD		A	B						
DLs			B	M	M				
AIV Plan		A	M	B					
SIL			A	M	B				
Test Procedures		A	M	M	B				
Test Reports						B			
SDP		A	M	M	M	M	B	M	
MOP		A	M	M	M	M	B	M	
MOSR								B	
PAR									B
NCRs	Appl.	Appl.	Appl.	Appl.	Appl.	Appl.	Appl.	Appl.	
RFWs	Appl.	Appl.	Appl.	Appl.	Appl.	Appl.	Appl.	Appl.	

Fig. 7–4: The maturity of the deliverable Items as per review: maturity indicated as Approach (A), Baseline (B) and Maintain (M)

The maturity indicators in the matrix represent:

- A: Approach. Initial calculation or efforts in the direction. Defining the complete scope of the document and tasks thereof.
- B: Baseline for the project and possible release. Complete documentation effort to the maturity degree of release approval.
- M: Maintenance level. It does not require a full effort but only an update.

7.2 Chronological Presentation of Phases and Reviews

This section aims at elaborating on the proposed phases in a chronological manner. The phases are defined by the review finalising them which represents the set goal of the phase.

Phase A

The purpose of Phase A is to conduct a mission analysis and engineering activities with the main purpose to establish the mission requirements which represent the TL requirements of the system. During the phase different solution concepts are evaluated and their feasibility is assessed.

The main tasks to be conducted during this phase are:

- Generate an understanding of the scope of the stakeholder's stake and decision power and define a single point of communication with the stakeholder
- Derive TL requirements for the system based on mission analysis and derived from the stakeholder's needs
- Conduct trade-off studies for different solution concepts and asses their feasibility
- Define roles and responsibilities in a Work Breakdown Structure (WBS)
- Define validation cases for TL requirements
- Design a TL system architecture
- *Conduct a SDR*

Phase B

The purpose of this phase is to to define the project in enough detail to establish an initial baseline that is a feasible solution capable of meeting system requirements. From this point on, almost all changes to the baseline are expected to represent successive refinements, not fundamental changes as significant design changes at and beyond Phase B become increasingly expensive and should not be implemented without a proper impact analysis (See Figure 6–1).

The main tasks to be conducted during this phase are:

- Detail TL requirements to subsystem requirements

- Design validation cases for the subsystem requirements
- Define system architecture, interfaces and budgets
- Define operations plan
- Finalise risk assessment
- Define procurement strategy
- Run simulations with subsystem components
- *Conduct a PDR*

Phase C

The purpose of this phase is to complete the detailed design of the system (and its associated subsystems, including its operations systems), fabricate hardware, and code software. Generate final designs for each system component (flight and ground station systems) and demonstrate that it will perform in adherence to the system requirements.

The main tasks to be conducted during this phase are:

- Develop and document hardware and software detailed designs
- Perform development testing at the component or subsystem level
- Finalise system architecture, interfaces and budgets
- Finalise integration, verification and validation plans
- Finalise Operations plan
- Build prototype (Silver Model)
- Define Manufacturing plan
- Fully document the final design
- *Conduct a CDR*

Phase D

The purpose of this phase is to manufacture, integrate and validate the system (hardware, software, and operators), meanwhile achieving confidence that it will be able to meet the system requirements. Perform system end product implementation, assembly, integration and test, and transition to use.

In this phase the actual production and qualification of parts are performed followed by the assembly, integration and verification of the actual flight satellites.

Specifically the purpose of the sub-phases are:

- **D1**: The main purpose of the phase is to finalise preparation for manufacturing and integration. Whereas the previous phase focused primarily on what should be produced, this phase focuses primarily on detailing how it should be produced.

- **D2**: In this phase the actual production and assembly of parts are performed followed by the assembly, integration and verification of the actual flight satellites.
- **D3** In this phase the conduction of all predefined test cases occurs in order to validate the system up to the fulfilment of TL requirements
- **D4** In this phase the final operations trainings, ground station calibrations and flight readiness procedures are conducted

The main tasks to be conducted during this phase are:

- Finalise manufacturing plan
- Finalise preparations for manufacturing
- Release Version 0 EM (Gold Model)
- *Conduct MRR*
- Validate the integration plan using the V0 EM
- Manufacture the system and integrate it according to the integration plan
- Finalise preparations for test and validation using the V0 EM
- *Conduct TRR* (includes SIR)
- Conduct tests according to validation plan
- Resolve verification and validation discrepancies
- Document test conduction and results
- *Conduct SAR*
- Finalise operator's handbook
- Finalize maintenance manuals
- Train initial system operators and maintainers (Train on contingency planning)
- Confirm telemetry validation and ground data processing
- Confirm system and support elements are ready for flight
- Confirm launch provider required documentation
- *Conduct FRR*

Phase E

The purpose of this phase is to calibrate and commission the launched system's functionality. Finally, it is more significantly to conduct the mission and meet the initially identified need and maintain support for that need.

- **E1**: During this phase the satellite(s) are launched, and satellite bus and payload functionality is calibrated and commissioned.

- **E2**: During this phase the system are in operation and regular maintenance is performed.

The main tasks to be conducted during this phase are:

- Perform planned on-orbit operational validation
- Document lessons learned
- *Conduct IOCR*
- Provide support and maintenance during operations
- Finalize mission final report
- *Conduct ELR*

Based on the insights from the interviews it is advised to include an end of life agreement if the satellite is operational beyond the defined mission lifetime. This concludes the presentation of the proposed SLC before further correlations between the SLC and the interviews are discussed.

7.3 Justification of the Points Implemented in the Proposed System Life Cycle based on the Interview Results

As previously stated the SLC is designed to be easily applied in resource-constrained teams. Hence, the following is implemented in it, according to the points characterised in chapter 6.

Requirements management is kept as simple and as effective as possible in order to be easily applicable and fulfil its purpose of verification control. This is specifically so in order to avoid the neglect described by the interviewees and ensure the application of the V-model's verification control. However, requirements management is a task that is dependant on the discipline of the tools used and the application by the engineering team, no matter the proposed standard.

The reviews are divided into internal and external reviews. This is in order to ensure that progress validation is communicated to the stakeholders in the case of external reviews. Further, it is in order to verify and control the progress while maintaining a degree of flexibility in the case of internal reviews. Specifically, considering the fact that payment is often linked with the passage of a KDP, it might be wiser to conduct internal reviews that require less resources, do not halt the complete team and the progress thereof.

For the design process up until the CDR agile methods are suggested to be implemented with iterations that are finalised by a subsystem progress meeting which is a subsystem internal review. Ensuring the communication and interfaces between the subsystems is conducted by SE and the reviews presented control the holistic progress of the mission. As for the documentation of the design, the review documentation is suggested to suffice. As documenting every progress during an iterative process is not a justified effort in a resource-constrained team and in essence a CDR should consist of the finalised calculations, simulations and drawings of the system. However, for this SLC suggests that SE designs the structure of review documentation while the subsystem teams add the content of the predefined sections. This is in order to avoid repetition or neglect of points as mentioned during the interviews.

The temporal frame of this SLC is in contrast to traditional SLCs by the NASA or ESA in the sense that not only is the mission lifetime reduced but also the development process itself. Thus, this SLC emphasises on the validation process more as it is more susceptible to neglect in a time and resource-constrained development process.

Additionally, traditional SLCs were designed to guide through the development of a single novel satellite system for a specific mission. As revealed during the interviews, private companies that build SmallSats for costumers are not developing a completely novel system each time but are rather reconfiguring modular subsystems for a specific payload and mission. In the case of a mission requiring a satellite constellations, multiple satellite systems are designed and manufactured.

Further, a novel private company or a university project attempting to build a New Space system would rely on COTS products and would not develop every component of every subsystem themselves from scratch.

Based on both those facts, the proposed SLC's emphasis is on the validation of the system rather than on the detailed design process which is in accordance with the internal standards developed by the interviewed private companies. Therefore, PhaseD is divided into four sub-phases that when implemented are likely to be partially paralleled but nevertheless have their designated tasks and reviews to finalise them and validate the system.

The purpose of distinguishing a Sub-Phase D1 ”Manufacturing Preparation” is to insure that a manufacturing plan is set that enables repetitive lean manufacturing. As prior to that the focus was on what should be produced and not how it should be produced. This is mainly relevant for missions that require multiple satellite systems to be manufactured and flown. In that case the philosophy of Economies of Scale can be applied and through setting an optimised manufacturing plan, costs can be reduced severely and the integration and testing of the systems can be further guaranteed success because of the similarity grade achieved by the manufacturing accuracy. Further, the acquisition and preparation of the manufacturing facilities is planned and conducted in the case of a novel space company.

In the case of one single space system being built and manufacturing facilities already existing D1 can be merged with Phase C and the MRR can be integrated into the CDR.

A further example of the tailoring of this SLC can be shown for Sub-Phase D4. D4 is designed to ensure the successful completion of all tasks that are not part of the satellite system design but are necessary for flight readiness. If the company is planning to use existing and calibrated ground stations, operators, operating procedures and has templates for documentation for the launch provider, then D4 can be skipped and the SAR merged with the FRR.

Subsequently, the IOCR is conducted as an external review because depending on the contract with the costumer it could mean the end of the development process and in most cases a payment will be linked to the commissioning of the satellite in orbit.

Aside from the phases and their reviews, the SLC integrates a prototyping methodology in accordance with the Bread-Brass-Silver-Gold approach (See section 6.3). During the agile iterations in Phase C the testing and validation on component level is depicted. The testing and validation of the components themselves and testing of partially integrated states up to the maturity grade of a complete prototype resembles the afore mentioned methodology up to the Silver Model. This holds true for both internally developed components and procured COTS products. In both cases component testing and validation is conducted as early as possible up to a complete prototype at CDR maturity.

However, a Version 0 (V0) EM is released at the MRR after the finalisation of the manufacturing plan. The reason behind doing so is to have a model that can be the bases for further integration validation and test preparation while being in the final flight configuration achieved after the replicable manufacturing procedure. Thus, testing and integration procedures can be finalised using the V0 EM and are insured to be replicable for the FM or FMs. This resembles a Gold Model in final flight configuration according to the afore mentioned methodology.

Additionally, the EM-FM methodology (See section 6.3) is applied in order to ensure that rigorous testing of the model itself as well as the testing of integration and test procedures is conducted. This insures a V0 integration and test run in final flight configuration that can be directly replicated for the FM.

Lastly, this proposed SLC aims at covering the development process of all the interviewed configurations. To do so it is also required to cover scenarios in which the ESA is a stakeholder. This is an additional reason for the definition of the deliverables of this SLC through ESA's TEC-SY/127/2013/DRD/RW document [74]. As illustrated by the interviews, scenarios in which the ESA was a stakeholder but did not force complete ECSS compliance on a resource-constrained team have been observed. As this SLC reaches the same deliverables as defined by the ESA for IOD CubeSat missions, an argument can be made towards its application in missions in which the ESA is a stakeholder.

Examples of the application of the proposed SLC in missions in which the ESA is not a stakeholder are presented in the next section.

7.4 Case Study: Applying the Proposed System Life Cycle at the SmallSat Startup Orora Tech

This section presents the application of the proposed SLC for the case of the novel SmallSat startup Orora Tech. It does so in two distinct ways. First, it presents a suggestion of the complete SLC application based on the application parameters of Orora Tech. Secondly, it presents the insights gathered during the initial discussions of SLC application for a scenario in which Orora Tech is given the chance to conduct part of the development of a SmallSat system.

This is due to the fact that the newly founded company is not at a maturity of developing the complete satellite system during the temporal frame of this thesis. Thus, a suggestion for future application is given. However, the payload could be launched on a satellite bus developed by Clyde Space and I was granted the opportunity to conduct the initial discussions on how to apply a SLC for that case in cooperation with Clyde Space. Hence, insights gathered during those discussions are presented in this section.

Regarding the company itself, Orora Tech is a spin-off from the MOVE-II CubeSat project at the TUM that is developing a satellite constellation that intends to capture thermal images and perform on-orbit processing to directly alert first responders in the event of wildfire within their region of interest.

7.4.1 The Proposed Application of the Complete System Life Cycle

To understand the application of the SLC onto Orora Tech's SmallSat development, one has to clarify the application parameters and goal of the company.

First, the goal is to develop a fleet of satellites making up a satellite constellation and launch them into formation on multiple orbits in order to achieve the required coverage necessary to alert first responders in time. The attempt of doing so alone underlines the afore mentioned opportunities presented by the New Space era. However, founding a space company is not comparable to the effort required to found a company with retail or digital solutions as their product. The required funding to build and launch a satellite fleet, although minuscule in comparison with traditional space, is nevertheless substantial. Thus, a lot of effort and resources are allocated towards investment rounds and business development although the mission definition is set and the mission analysis and feasibility are conducted, since they are the motivator for the founding of the company. Thus, engineering activities described in the SLC are conducted before the SLC of the complete SmallSat system is initiated.

Second, the chance to launch the optical payload on a satellite bus developed by Clyde Space influences the development process in the sense that it allows for the development and validation of the most critical subsystem before the development of the complete desired SmallSat system. This allows for valuable experiences and insights predating the complete engineering efforts required for a SLC of the desired SmallSat system.

Third, although Orora Tech is a novel startup the human resources available are not new to SmallSat development. As the company is a spin-off of the MOVE projects, the recruited talent has been part of up to three SmallSat missions. Hence, a familiarity with development methodology, space requirements, launch requirements, review conduction and deliverables is preexisting. This further means that the desired goal of minimising the development and launch time is achievable and is to be reflected by the application of the SLC.

This leaves the main parameters, distinguishable before the commence of SLC application, to be:

- The constraints of a startup due to required financial resources
- A preexisting mission definition with conducted mission analysis and feasibility
- The development of the optical payload predating the development of the complete satellite system
- A company character of an experienced SmallSat company due to the recruited talent

As for Phase A ”Mission Analysis and Feasibility”, there are two ways one can look at it. The first, is that Phase A is skipped as the satellite system is not developed for a costumer and thus mission analysis and feasibility are not conducted and presented for review in form of a SDR and thus the SLC commences at Phase B when the development of the complete satellite system commences. The second, is that the engineering activities conducted at the moment - including the development and launch of the optical payload - are part of the engineering activities in a prolonged Phase A in order to finalise the feasibility and set the requirements for the complete mission.

As for the application of the rest of the phases:

- **Phase B** ”Preliminary Solution Definition”: can be conducted as per the description in the proposed SLC
- **Phase C** ”Detailed Solution Definition”: can be conducted as per the description in the proposed SLC
- **Sub-Phase D1** ”Manufacturing Preparation”: can be conducted as per the description in the proposed SLC and is crucial for the development of a fleet system with resource constraints
- **Sub-Phase D2** ”Integration & Test Preparation”: can be conducted as per the description in the proposed SLC
- **Sub-Phase D3** ”Testing & Validation”: can be conducted as per the description in the proposed SLC
- **Sub-Phase D4** ”Final Launch Preparations”: can be conducted as per the description in the proposed SLC or be merged and paralleled to D3 if recruited talent is previously trained, the launch requirements are met beforehand and existing ground stations are used
- **Sub-Phase E1** ”Launch & Commissioning”: can be conducted as per the description in the proposed SLC even if the IOCR is merely internal it would benefit as a milestone
- **Sub-Phase E2** ”Service & Maintenance”: can be conducted as per the description in the proposed SLC with a variety of further development with regard to software

The afore mentioned conduction of a SDR as well as the conduction of all reviews is dependant on the stakeholder makeup of Orora Tech for which no direct description can be given. However, the outlines of the makeup can be discussed as Orora Tech is developing the SmallSat system for their own profit generation and not selling it as a product within the wildfire constellation. If the company would find itself in a scenario where the company stakeholders are not interested in the development progress itself but merely interested in the end product and the profit it generates, then Orora Tech could have the freedom to design the reviewing board at its discretion. As a spin-off of the MOVE-II project the expert pool available can comprise the reviewing board which would give the application of the SLC a unique characteristic because in that case the argumentation of conducting any review internally would be invalid. This is due to the fact that no flexibility is lost in review conduction if the flexibility to makeup the reviewing board exists.

This further means that the deliverables in terms of the SLC for satellite development are merely the required documents of the launch provider as previously discussed. All other deliverables are at the companies discretion although their benefit is logical especially when developing a fleet of SmallSats.

Lastly, the iteration, validation and prototyping methodologies of the proposed SLC can be applied because of the simple fact that the recruited talent is familiar with them and has previously applied them to satellite development.

7.4.2 Insights from the Initial Partial Application

This subsection aims at depicting insights from the application during the second scenario as much as is possible under the existing Nondisclosure Agreements.

The second scenario of the application of the proposed SLC is the development of the SmallSat carrying the optical payload. This scenario is made possible by the Satellite Applications Catapult which is an innovative company aiming to accelerate the growth of satellite applications and the the commercialisation of research [78]. Among other tools to achieve that, they had a competition for a IOD mission which Orora Tech has won with the goal to test their optical payload. Thus, this scenario has an innovation accelerator financing an IOD mission comprised of an optical payload developed by Orora Tech flying on a satellite bus developed by Clyde space.

Before the commence of the joint development and SLC application an agreement had to be reached on the following parameters:

- Who of the two parties is responsible for which deliverable documentation
- When which documentation is expected to be at a certain maturity grade
- How the reviews are going to be conducted
- How the makeup of the reviewing board will be

As Clyde Space was one of the interview partners and insights from their SLC implementation have influenced the proposed SLC, the proposed SLC did not differ greatly from their internal company standards. The main differences were:

- The SAR is called a Test Review Board (TRB) but fulfils the same purpose
- All reviews are conducted externally
- Clyde's SLC for IOD missions ends at the FRR
- The DIL includes less documents

The difference in documentation is due to the fact that the proposed SLC aims on covering all documentation that would be necessary to satisfy document requirements set for a mission in which the ESA is a stakeholder. This shows that in private companies the DIL differs significantly from old standards and that companies have adapted their DILs to suit their costumer requirements, as was elaborated upon during the interviews.

The fact that Clyde's SLC for IOD missions ends at the FRR can be taken to underline the point that different costumer agreements exist for operations and thus the company internal standard deals with the development process until flight readiness maturity. However, afterwards activities are conducted based on the agreement with the costumer and thus are not standardised.

Further, the conduction of all reviews in Phase D externally is a discussed possibility in the proposed SLC. The benefit of conducting them internally is to allow for flexibility, reserve resources and not halt the complete team. However, for this three party constellation and joint review conduction the previously made argument is invalid. In any case the effort made by one developing team to communicate their progress to the other, and vice versa constitute the effort necessary for external review conduction. In addition, it would be in the interest of the stakeholder to require these external reviews for such a constellation to ensure that the joint development is progressing to his satisfaction. However, no proof of this argument can be provided because Catapult has not commented on it.

The form of review conduction would be as in the proposed SLC in addition to the division of responsibilities. The same process of reviewed documentation, a presentation in front of a reviewing board and RIDs is to be solved. The reviews will be conducted in front of a reviewing board made up at Catapult's discretion as they are the main stakeholder. Additionally, representatives of Clyde's management will make up the reviewing board. During the reviews both developing teams will present their respective progress defined by their deliverables.

All deliverables except the following are Clyde's responsibility:

- A Concept of Operations (CONOPS): Orora Tech's responsibility
- Mission requirements and requirements tracker: joint responsibility
- Platform and Payload Interface Control Document (P&PICD): joint responsibility

The required maturity of the deliverables as per review is the same as in the proposed SLC, to the extent of the release of the hardware models as per the EM-FM approach. However, comparing Clyde's standard's terminology to the deliverables of the proposed

SLC as per TEC-SY/127/2013/DRD/RW one realises that the terminology is not the same as the contents of the CONOPS are covered by the MRD in the proposed SLC [6, 74]. In addition, no document templates for the deliverables of this development process exist on both ends.

7.4.3 Conclusion of the Application

For both application scenarios the coverage of them by the proposed SLC was presented. It was shown how the SLC can be applied in different scenarios based on the mission characteristics and objectives. Further, it was shown how arguments made during the development of the SLC reflected on the application.

Lastly, the discrepancy in deliverables terminology, the lack of document templates and the effort made to define the SLC application in the second scenario would not exist or be necessary if a new standard for SE applications in SmallSat missions was to be developed. Resource-constrained SmallSat teams could focus their resources on the direct development of a SmallSat system without needing to concern themselves with these tasks which would accelerate the complete development process.

Further, the presented example elaborates the freedom a New Space company has during the development of a SmallSat system. This further supports the development of a new standard not only for the acceleration and advancement of the development process but also for ensuring a minimum amount of quality assurance not through restriction but through applicable guidance.

8 Discussion of the Applied Research Methodology

The purpose of this chapter is to reflect on the methodology implemented during the course of this thesis (See chapter 4).

The literature research methodology was stated to be plainly simple because of the fact that SLC implementation was standardised by governmental agencies and thus can be considered the basis for any literature on that manner. This hypothesis was proven true during the interviews as interviewed missions referred to the cited literature, if at all. The ones that did define the implementation of SLCs for their project based it on the cited literature if they did not base it solely on lessons learned. The interviewees further stated that they combined the different sources as was the done during the course of this thesis.

As for the interview methodology, the general approach of a semi-standerdised survey covering all aspects of SLC implementation did allow for the obtainment of a wide variety of insights. Those insights further allowed the interviews to be tailored uniquely to suit the interviewee and obtain a deeper understanding of the points that they wanted to address and deemed relevant.

This approach may have been the correct method in order to obtain as much insight as possible of this broad subject matter but it makes the effort of presenting the collected data a difficult process which leaves a narrow disputable margin. Further, having a semi-standardised approach on a wide subject matter increases the amount of different answers and thus decreases the value of the data in terms applicability of statistical methods.

If the research conducted in this thesis were to be continued or replicated, then future surveys would be advised to narrow down on specific components of the SLC that have been highlighted as interesting by the research conducted during the course of this thesis. In addition, standardised answers could result in statistically more valuable data. In that case the researcher would have to rely on his creativity and the previous research to extract insights not covered by the questions.

In summary, the approach of a semi-standardised survey followed by a tailored interview was a method that allowed for the initial coverage of a broad subject matter while giving interviewees the freedom to highlight relevant points that were further investigated in depth. The interviewees remarked themselves the effectiveness of the method during the interviews. However, in the case of continuing or replicating this research a standardised approach with a narrower subject matter is advised and could yield interesting results for less effort.

9 Results of the Thesis

This chapter aims at comparing the results of the thesis with the set goals of the thesis in chapter 3 before the conclusion is presented in the next chapter.

The analysis of System Life Cycle (SLC) implementation in both university projects and private companies was conducted through the digital survey and the subsequent interviews. The results thereof are presented in chapter 5 and further discussed in chapter 6. Both the collected data and additional points raised by the interviewees are summarised and discussed in order to prepare their content's integration into the proposed SLC.

An analysis of compliance with European Cooperation for Space Standardisation (ECSS) standards was conducted during the interviews. Further, the ESA-proposed tailored standards for IOD CubeSats were analysed to the detailed degree of document templates with regard to the applicability in resource constrained teams. In addition, shared company internal standards were compared to each other and to the ECSS standards and the results thereof were presented and further implemented in the SLC. Afterwards, a SLC is proposed that encompasses:

- **Phases** and their defined objectives in addition to a discussion of their applicability for New Space SmallSat development and the different cases thereof
- Positioned internal and external **reviews** with **Key Decision Points** and **deliverables**. In addition to an elaboration on their placement, purpose and type
- A mixture of **methodical approaches** of going through the complete SLC as well as going through specific phases and the holistic use of prototyping methods. As well as an elaboration on the reason and benefit of their usage to the complete development process
- An argumentation towards **ECSS compliance** of the proposed SLC was conducted in the form of arguing why it should not attempt at complying based on the collected insights from the interviewees.

Further, an example of the application of the SLC based on the case of the SmallSat startup Orora Tech was presented for the complete development process as well as for the current development process of the optical payload and launch thereof. In addition the insights gathered from the application are discussed with respect to the standardisation of SmallSat development in the New Space era.

Moreover, a critical discussion on the applied research methodology is offered in order to ensure both an improved replicability and continuation of the research of the subject matter. Lastly, the resources of BERNS Engineers GmbH were used in order to compare the creation of standards to other industries and propose a novel approach to be implemented in the emerging SmallSat industry.

10 Conclusion

During the course of this thesis the implementation of SLCs in SmallSat missions has been researched. The collected data from the survey and the insights from the interviews have shown that the novel development parameters for satellite missions in the New Space era have rendered existing standards inapplicable. This holds true for the parameters presented in the state of the art, in respect to the accelerated development of a responsive satellite system with innovative process methodology.

It was shown that existing standards are not implemented by SmallSat developers in resource constrained missions. In some cases this even holds true for missions in which governmental agencies are stakeholders. Furthermore, the interviewees expressed that existing standards do not necessarily cover aspects leading to mission failure in SmallSat missions. The sole requirement that is upheld for missions in which governmental agencies are not a stakeholder, are the requirements set by the launch provider. These requirements themselves only comply with standards if governmental agencies are involved on either end of them. Other than that, they are derived from the requirements of the launch vehicle operator which are set at his respective discretion. Furthermore, the necessity of developing new standards for SmallSat development was proven through the revelation of the fact that companies already have established reduced internal standards for their respective development processes.

Based on those results a SLC was designed and proposed which reduces conventional standards found in literature to an applicable scope of SmallSat development. The scope was defined based on the gathered insights during the interviews and the contents of internal company standards. In addition, the SLC guides on the implementation of process, validation and prototyping methodology during the development of a SmallSat system. Furthermore, it addresses communication with stakeholders and requirements management with respect to their direct influence on the development process, as was illustrated by the interviewees.

Additionally, two scenarios for the application of the proposed SLC during the development of Orora Tech's SmallSat system are presented and discussed in order to to validate applicability and underline the coverage of both development processes in their respective configuration by the SLC.

Because the SLC is designed based on both literature and the current reality of implementation, it can be taken as a basis for discussion on standardisation of systems engineering application in SmallSat missions. Which in turn could initiate the standardisation of further disciplines, leading to the acceleration and improvement of responsive SmallSat systems and an increase in their benefit to the space industry as a whole.

11 Outlook

This final chapter of the thesis aims at providing suggestions for the continuation of the research and work conducted during the course of this thesis.

As previously addressed, the repetition of the interview process with the focus on the points deemed relevant based on the current research, could provide additional insights on the subject matter. Narrowing down the subject matter that is to be researched and implementing a standardised approach will allow the repetition to be conducted with less effort and therefore allow for a faster and greater coverage of the target group. Further, a standardised approach will output data that can be statistically processed and thus implemented in a SLC through different methodologies.

Additionally, the observation of the implementation of the proposed SLC at both startups and established companies can yield valuable insights regarding its applicability. In the case of established companies the implementation of the proposed SLC can be compared to the implementation of existing internal standards. As it is a merger between multiple internal standards, insights from companies and university projects and existing literature, this comparison could lead to the highlighting of existing internal best practices that were not previously noticed or documented.

For the case of startups, the observation of the implementation can lead to insights regarding the resource efficiency of the SLC, the applicability in an environment demanding agility and if it truly aids in increasing and easing the cooperation with suppliers and stakeholders. As will be continued for the case of the implementation at Orora Tech.

Furthermore, the research scope could be broadened beyond Europe to encompass world wide SLC implementation in SmallSat missions. This could aid as a step towards standardising the complete SmallSat industry and increasing international cooperation which will further support the increased output of novel technologies emerging from SmallSat development. If an international standard is developed to encompass the requirements set by launch vehicle operators and thus the requirements of launch providers, then collective launch contracts or end of life agreements might not be too far in the future.

As is advised in this thesis, the SmallSat industry should not wait for governmental agencies to develop novel standards but rather the private sector should come together to develop novel standards based on its existing internal standards and lessons learned, similar to established standards in other industries. An interest in this was shown by the interviewees and the framework for it is being set up by BERNS Engineers and Orora Tech. This will be in the form of a conference for SmallSat developers with the goal of cooperation towards standardisation.

Bibliography

[1] E. S. A. TEB, "Tailored ecss engineering standards for in-orbit demonstration cubesat projects," 2016, [TEC-SY/128/2013/SPD/RW].

[2] J. L. Bromberg, *NASA and the Space Industry*. JHU Press, 2000.

[3] J. J. Taylor and J. Matthews, "Advancing socially disruptive aerospace technologies through venture capital investment," in *54th AIAA Aerospace Sciences Meeting*, 2016, p. 1896.

[4] O. Brown and P. Eremenko, "Fractionated space architectures: A vision for responsive space," DEFENSE ADVANCED RESEARCH PROJECTS AGENCY ARLINGTON VA, Tech. Rep., 2006.

[5] T. D. Rivers, "Small satellites–evolving innovation for the entire market," in *31st Space Symposium, Colorado Springs, Colorado, USA*, 2015.

[6] S. J. Kapurch, *NASA systems engineering handbook*. Diane Publishing, 2010.

[7] C. Haskins, K. Forsberg, M. Krueger, D. Walden, and D. Hamelin, "Systems engineering handbook," in *INCOSE,*, 2006.

[8] A. T. Hensel, "Der wettlauf zum mond," in *Geschichte der Raumfahrt bis 1970*. Springer, 2019, pp. 143–191.

[9] M. Macdonald and V. Badescu, *The international handbook of space technology*. Springer, 2014.

[10] B. Canis, "Commercial space industry launches a new phase," https://fas.org/sgp/crs/space/R44708.pdf, 2016.

[11] G. S. Parnell, P. J. Driscoll, and D. L. Henderson, *Decision making in systems engineering and management*. Wiley Online Library, 2011, vol. 81.

[12] J. T. Alessandro de Concini, "The future of the european space sector," https://www.eib.org/attachments/thematic/future_of_european_space_sector_en.pdf, May 2019.

[13] R. Meurer and P. H. Seah, "Global commerce in small satellites trends and new business models," 2014.

[14] K. Woellert, P. Ehrenfreund, A. J. Ricco, and H. Hertzfeld, "Cubesats: Cost-effective science and technology platforms for emerging and developing nations," *Advances in Space Research*, vol. 47, no. 4, pp. 663–684, 2011.

[15] S. Müncheberg, M. Krischke, and N. Lemke, "Nanosatellites and micro systems technology—capabilities, limitations and applications," *Acta Astronautica*, vol. 39, no. 9-12, pp. 799–808, 1996.

[16] C. B. Christensen, K. Armstrong, R. G. Perrino, and M. Hill, "Start-up space: Interim results," in *AIAA SPACE 2015 Conference and Exposition*, 2015, p. 4405.

[17] J. N. Pelton, “Trends and future of satellite communications,” *Handbook of Satellite Applications*, pp. 533–557, 2013.

[18] P. Platzer, C. Wake, and L. Gould, “Smaller satellites, smarter forecasts: Gps-ro goes mainstream,” 2015.

[19] R. Sandau, K. Brieß, and M. D’Errico, “Small satellites for global coverage: Potential and limits,” *ISPRS Journal of photogrammetry and Remote Sensing*, vol. 65, no. 6, pp. 492–504, 2010.

[20] E. Pawlikowski, D. Loverro, and T. Cristler, “Space: disruptive challenges, new opportunities, and new strategies,” *Strategic Studies Quarterly*, vol. 6, no. 1, pp. 27–54, 2012.

[21] K. Bozdogan, J. Deyst, D. Hoult, and M. Lucas, “Architectural innovation in product development through early supplier integration,” *R&D Management*, vol. 28, no. 3, pp. 163–173, 1998.

[22] D. J. Smith and D. Tranfield, “Talented suppliers? strategic change and innovation in the uk aerospace industry,” *R&D Management*, vol. 35, no. 1, pp. 37–49, 2005.

[23] P. Fortescue, G. Swinerd, and J. Stark, *Spacecraft systems engineering*. John Wiley & Sons, 2011.

[24] Köchel, “New space: Impacts of future concepts in satellite development on the space industry,” May 2017, [RT-SA 2017/21, Chair of of Astronautics, Technical University of Munich].

[25] W. Ley, K. Wittmann, and W. Hallmann, *Handbuch der Raumfahrttechnik*. Carl Hanser Verlag GmbH Co KG, 2019.

[26] S. C. Spangelo, J. Cutler, L. Anderson, E. Fosse, L. Cheng, R. Yntema, M. Bajaj, C. Delp, B. Cole, G. Soremekum *et al.*, “Model based systems engineering (mbse) applied to radio aurora explorer (rax) cubesat mission operational scenarios,” in *Aerospace Conference, 2013 IEEE*. IEEE, 2013, pp. 1–18.

[27] M. Langer, F. Schummer, A. Lill, D. Meßmann, N. Appel, and B. Rückerl, “MOVE-II System Documentation,” Technical University of Munich, Department of Aeronautics, Tech. Rep., 17 2017.

[28] D. Jenkins, Robert, “Nps-scat : Systems engineering and payload subsystem design, integration, and testing of nps’ first cubesat,” 2010. [Online]. Available: https://calhoun.nps.edu/handle/10945/5283

[29] J. Collins and M. T. Hansen, *Great by Choice: Uncertainty, Chaos and Luck-Why some thrive despite them all*. Random House, 2011.

[30] J. Hampton, “Space technology trends and implications for national security,” *Kennedy School Review*, vol. 15, pp. 12–17, 2015.

[31] J. Bouwmeester and J. Guo, "Survey of worldwide pico-and nanosatellite missions, distributions and subsystem technology," *Acta Astronautica*, vol. 67, no. 7-8, pp. 854–862, 2010.

[32] M. Hurley and B. Purdy, "Designing and managing for a reliability of zero," in *ESA 4S Symposium, Funchal, Portugal, Paper*, no. 1885505, 2010.

[33] D. Selva and D. Krejci, "A survey and assessment of the capabilities of cubesats for earth observation," *Acta Astronautica*, vol. 74, pp. 50–68, 2012.

[34] A. Shao, J. R. Wertz, and E. A. Koltz, "Quantifying the cost reduction potential for earth observation satellites," in *Proceedings of the 12th Reinventing Space Conference*. Springer, 2017, pp. 199–210.

[35] D. Werner, "Smallsat builders admit a little bigger might be a little better," https://spacenews.com/smallsat-builders-admit-a-little-bigger-might-be-better/, 2017, [Online; accessed 8 December 2019].

[36] A. Mehrparvar, D. Pignatelli, J. Carnahan, R. Munakat, W. Lan, A. Toorian, A. Hutputanasin, and S. Lee, "Cubesat design specification rev. 13," *The CubeSat Program, Cal Poly San Luis Obispo, US*, vol. 1, no. 2, 2014.

[37] "Spaceflight website," http://spaceflight.com/sso-a/, [Online; accessed 15 January 2019].

[38] "Rocketlab Website," https://www.rocketlabusa.com/, [Online; accessed 5 November 2019].

[39] W. Ley, K. Wittmann, and W. Hallmann, *Handbuch der Raumfahrttechnik*. Carl Hanser Verlag GmbH Co KG, 2019.

[40] B. Doncaster, C. Williams, and J. Shulman, "2016 nano/microsatellite market forecast," *SpaceWorks Enterprises, Inc*, vol. 1, 2017.

[41] J. H. Saleh, J.-P. Torres-Padilla, D. E. Hastings, and D. J. Newman, "To reduce or to extend a spacecraft design lifetime?" *Journal of Spacecraft and Rockets*, vol. 43, no. 1, pp. 207–217, 2006.

[42] P. P. h.c. Dr. Dr. h.c. U. Walter, "Systems engineering lecture," 2017.

[43] E. C. for Space Standardization, "System engineering general requirements," https://ecss.nl, 2017, [ECSS-E-ST-10C Rev.1;Obtained; accessed 29 December 2019].

[44] J. Ponn and U. Lindemann, *Konzeptentwicklung und Gestaltung technischer Produkte: systematisch von Anforderungen zu Konzepten und Gestaltlösungen*. Springer-Verlag, 2011.

[45] B. W. Boehm, "A spiral model of software development and enhancement," *Computer*, no. 5, pp. 61–72, 1988.

[46] K. Schwaber and M. Beedle, *Agile software development with Scrum*. Prentice Hall Upper Saddle River, 2002, vol. 1.

[47] E. C. for Space Standardization, “Tailoring of space standards,” https://ecss.nl, 2000, [ECSS-M-00-02A;Obtained; accessed 29 December 2019].

[48] ——, “Verification,” https://ecss.nl, 2009, [ECSS-E-ST-10-02C;Obtained; accessed 29 December 2019].

[49] ——, “Testing,” https://ecss.nl, 2012, [ECSS-E-ST-10-03C;Obtained; accessed 29 December 2019].

[50] ——, “Space enviroment,” https://ecss.nl, 2012, [ECSS-E-ST-10-04C;Obtained; accessed 29 December 2019].

[51] ——, “Electrical and electronic,” https://ecss.nl, 2008, [ECSS-E-ST-20C;Obtained; accessed 29 December 2019].

[52] ——, “Photovoltaic assemblies and components,” https://ecss.nl, 2008, [ECSS-E-ST-20-08C;Obtained; accessed 29 December 2019].

[53] ——, “Thermal control general requirements,” https://ecss.nl, 2008, [ECSS-E-ST-31C;Obtained; accessed 29 December 2019].

[54] ——, “Structural general requirements,” https://ecss.nl, 2008, [ECSS-E-ST-32C Rev.1;Obtained; accessed 29 December 2019].

[55] ——, “Fracture control,” https://ecss.nl, 2009, [ECSS-E-ST-32-01C Rev.1;Obtained; accessed 29 December 2019].

[56] ——, “Structural design and verification of pressurized hardware,” https://ecss.nl, 2008, [ECSS-E-ST-32-02C Rev.1;Obtained; accessed 29 December 2019].

[57] ——, “Materials,” https://ecss.nl, 2014, [ECSS-E-ST-32-08C;Obtained; accessed 29 December 2019].

[58] ——, “Mechanisms,” https://ecss.nl, 2009, [ECSS-E-ST-33-01C;Obtained; accessed 29 December 2019].

[59] ——, “Liquid and electric propulsion for spacecraft,” https://ecss.nl, 2008, [ECSS-E-ST-35-01C;Obtained; accessed 29 December 2019].

[60] ——, “Communications,” https://ecss.nl, 2008, [ECSS-E-ST-50C;Obtained; accessed 29 December 2019].

[61] ——, “Radio frequency and modulation,” https://ecss.nl, 2011, [ECSS-E-ST-50-05C Rev.2;Obtained; accessed 29 December 2019].

[62] ——, “Satellite attitude and orbit control system (aocs) require- ments,” https://ecss.nl, 2013, [ECSS-E-ST-60-30C;Obtained; accessed 29 December 2019].

[63] “Automotive spice,” http://www.automotivespice.com/about/, [Online; accessed 8 December 2019].

[64] “What is automotive spice?” https://www.plays-in-business.com/automotivespice/, [Online; accessed 8 December 2019].

[65] L. Qiao, C. Rizos, and A. G. Dempster, "Analysis and comparison of cubesat lifetime," in *Proceedings of the 12th Australian Space Conference*. Citeseer, 2013, pp. 249–260.

[66] S. Balaji and M. S. Murugaiyan, "Waterfall vs. v-model vs. agile: A comparative study on sdlc," *International Journal of Information Technology and Business Management*, vol. 2, no. 1, pp. 26–30, 2012.

[67] A. Lill, T. Zwickl, C. Costescu, L. Patzwahl, C. Soare, and M. Langer, "Agile mission operations in the cubesat project move-ii," in *2018 SpaceOps Conference*, 2018, p. 2635.

[68] J. Emison, K. Yoshino, S. Straits, and H. D. Voss, "Satellite design for undergraduate senior capstone," in *2014 ASEE Annual Conference*, 2014.

[69] D. Voss, K. Alexander, M. Ford, C. Handy, S. Lucero, and A. Pietruszewski, "Educational programs: Investment with a large return," 2012.

[70] M. Weisgerber, M. Langer, F. Schummer, and K. Steinkirchner, "Risk reduction and process acceleration for small spacecraft assembly and testing by rapid prototyping," in *Proceedings of the German Aerospace Congress, Munich, Germany*, 2017, pp. 5–7.

[71] M. Langer, F. Schummer, N. Appel, T. Gruebler, K. Janzer, J. Kiesbye, L. Krempel, A. Lill, D. Messmann, S. Rueckerl *et al.*, "Move-ii-the munich orbital verification experiment ii," in *Proceedings of the 4th IAA Conference on University Satellite Missions & CubeSat Workshop, IAA-AAS-CU-17-06*, vol. 5, 2017.

[72] M. Langer, "Reliability assessment and reliability prediction of cubesats through system level testing and reliability growth modelling," Ph.D. dissertation, Technische Universität München, 2018.

[73] Elhag, "Architecture based methodical fault identification and satellite recovery," 2018, [RT-SA 2018/17, Chair of of Astronautics, Technical University of Munich].

[74] E. S. A. TEB, "Iod cubesat document requirements definition," 2016, [TEC-SY/127/2013/DRD/RW].

[75] B. Shiotani, N. Fitz-Coy, and S. Asundi, "An end-to-end design and development life-cycle for cubesat class satellites," in *AIAA SPACE 2014 Conference and Exposition*, 2014, p. 4194.

[76] H. Helvajian and S. W. Janson, *Small satellites: past, present, and future*. Aerospace Press, 2008.

[77] T. B. Alejandro, D. V. Souza, J. S. Boles, Á. H. P. Ribeiro, and P. R. R. Monteiro, "The outcome of company and account manager relationship quality on loyalty, relationship value and performance," *Industrial Marketing Management*, vol. 40, no. 1, pp. 36–43, 2011.

[78] "Satellite applications cataput," https://sa.catapult.org.uk/, [Online; accessed 29 December 2019].

A Deliverables as per TEC-SY/127/2013/DRD/RW

This appendix includes pages 5 to 12 of the TEC-SY/127/2013/DRD/RW titled ”IOD CubeSat Document Requirements Definition” used for the definition of deliverables of the proposed SLC in chapter 7. These pages present the contents of the deliverables as required by the ESA.

2 DOCUMENT REQUIREMENTS DESCRIPTIONS

Title	Purpose	Content
Mission Requirements Document (MRD)	To specify the mission requirements and constraints, and high level payload user requirements	The MRD shall include as a minimum: • mission objectives • mission constraints (launcher, orbit, target launch date, duration, comms coverage) • science observation requirements • payload requirements, incl. operational & data • mission phases and operational modes requirements • autonomy requirements • ground segment requirements • mission data acquisition, storage and dissemination requirements
Mission Analysis Report (MAR)	To describe all of the analysis performed in support of the mission planning prior to launch	The document includes: *Mission design:* • mission profile including mission duration, phases, satellite operational modes • Orbit and pointing profiles during the phases/modes • Available ground segment resources, including ground stations • degree of ground segment automation and satellite on-board autonomy • mission operations concept *Mission analysis:* • launch/operational orbit trade-offs and selection • orbit/trajectory predictions throughout the mission • payload operations planning and analysis (e.g. imaging revisit analysis) • ground track and ground station visibility analysis • solar eclipse analysis • contingency analysis with respect to mission recovery in cases of failures during critical periods
System Requirements Document (SRD)	To specify the system requirements relating to the spacecraft, payload and ground segment	The SRD shall include as a minimum: • system functional, performance and interface requirements • requirements for environment, cleanliness and ground handling, AIV, EMC, interfaces, modes and on-board autonomy/FDIR • ground segment requirements for ground stations, flight dynamics and simulation support, ground systems automation • programmatics requirements (project cost and schedule)

System Design Report (SDR)	To provide a summary technical description of the overall baseline mission, spacecraft system and ground segment, including external interfaces and system budgets.	Technical description, to include: • introduction, • mission phases, performances and operations overview • launch, LEOP and on-orbit configurations • satellite operational modes • spacecraft design concepts & trade-offs, including electrical, thermal and mechanical architecture • data processing hierarchy / software architecture • baseline spacecraft description • system budgets (mass, power, link, data) • For each subsystem, including Primary Payload, and for GSE: ➢ functional block diagram / schematic ➢ description of key design features, performances and interfaces • external interfaces (Launcher, GSE, Ground Segment) • ground segment architecture
Environmental Design Specification (EDS)	To define the launch and space environments that the satellite is expected to be encountered by the spacecraft throughout the mission, and to form an Environment requirements specification for application to the system and subsystem design.	The document shall specify the launch environment considering compatibility with all specified launch vehicles. The specification shall consist of (at both qualification and acceptance levels) the following environments: • quasi-static loads • sine and random vibration • shock • acoustic • pressure • temperature and humidity under fairing on launch pad The document shall specify the following space environments (based upon analysis results): • energetic particle fluxes and fluences (protons, electrons, cosmic-rays) The document shall also specify the following effects of these environments on the spacecraft: • total ionizing radiation dose • single event effects • materials outgassing due to vacuum
Space Debris Mitigation Document	To define how the project plans to fulfil the ESA space debris mitigation requirements, and report on analysis results demonstrating compliance	As per ESA/ADMIN/IPOL(2008)2 - Space Debris Mitigation for Agency Projects.

Product Assurance Plan (PAP)	Ensure that the organization, requirements, methods, tools, resources and responsibilities for the product assurance and safety disciplines are well defined before development and implemented at each project level.	The PA plan shall describe the resources, tasks, responsibilities, methods and procedures adopted by the Contractor for the implementation of the ESA PA&S requirements and for the achievement of the PA objectives. The PA plan shall include the following major elements: • Scope, Applicability, • PA management: Objectives, Policies, Implementation Approach, Responsibilities, Organization, Reporting, • Applicable and reference documents. • Tasks and activities to be performed for compliance with ESA PA/QA requirements • Cleanliness plan

Space-to-ground Interface Control Document (SGICD)	To define the interfaces between the spacecraft and the ground segment, including all ground stations.	The main interfaces to be addressed are at the level of command and control, Mission data and telecommunications aspects for which format, content and RF transmission need to be described.
		Spacecraft to Ground Segment I/F definition, including:
		• system overview
		• spacecraft and orbit, range definition
		• data formats and rates, coding scheme and modulation
		• encryption, authentication
		• reference profile assumptions
		• telecommunications:
		  o frequencies
		  o link budgets, indicating worst case link margins expressed in dB for meeting the bit error rate requirements expressed in the SRD.
		• data formats
		• TM/TC formats
		• ground station front-end interfaces
		• ranging interfaces
		• database interface
		• spacecraft to Ground Segment verification.

Satellite Mechanical Analysis Report	To describe the s/c mass properties, structural analysis set-up, assumptions, and analysis results in relation to the relevant requirements	*Mass Properties Analysis*
		The document shall contain (based on analysis of the satellite 3D CAD model):
		• Overview of the stowed and deployed satellite configurations
		• Satellite total mass
		• Satellite Centre of Gravity position (& uncertainties) in spacecraft coordinate system –stowed and deployed configurations
		• Satellite Moments of inertia –stowed and deployed configurations
		Structural Analysis
		The document shall contain:
		• Input loads description
		• Analysis cases
		• FEM description and underlying assumptions & approximations
		• Materials properties
		• Model cross-checks
		• Analysis tool description & outputs
		• FEA results, including Margins of Safety on structural elements
		• Conclusion with respect to requirements compliancy & areas of further work
		Mechanisms Analysis
		The document shall contain (for each mechanism):
		• Design overview and description of operation in flight for all mechanisms, including hold-down, release, deployment and actuation functions
		• Identification of worst case operational and environmental conditions
		• For new developments:
		  o Pre-load & tolerance budget analysis
		  o Actuation torque or force analysis
		  o Performance analysis
		  o Analysis of lubrication selection & sizing for the application & lifetime
		• Prediction of the number of on-ground and in-orbit cycles
		• Power demand of electrically actuated mechanisms

Satellite Thermal Analysis Report	To describe the thermal analysis set-up, assumptions, and analysis results in relation to the relevant requirements	The document shall contain: • Input parameters and assumptions • Analysis cases (hot, cold, transient etc) • TMM description and underlying assumptions & approximations • Materials properties • Thermal Reference Point definitions • Model checks • Analysis tool description & outputs • Analysis results, including temperatures of satellite equipment • Conclusion with respect to requirements compliancy & areas of further work
Satellite AOCS Analysis Report	To describe the AOCS analysis set-up, assumptions, and analysis results in relation to the relevant requirements	The document shall contain: • S/C design configuration relevant to AOCS • Input parameters and assumptions (sensor/actuator noise, controller bandwidth) • Analysis cases (pointing modes, orbits/trajectories, stowed/deployed configurations) • AOCS performance model description and assumptions • AOCS performance analysis results, including pointing error budget • Conclusion with respect to requirements compliancy & areas of further work
COTS User Manuals	To describe the Commercial Off The Shelf products to be used in the satellite design baseline.	The document shall provide user manuals provided by suppliers of all the COTS products to be used in the satellite, including: • Option sheets and clear selection of options used in the satellite • Electronic circuit diagrams (if available) • Interface definitions (if available) • User instructions (if available) • Acceptance tests performed by the supplier prior to delivery (if available) If a user manual is not available for a particular COTS product, then as a minimum a product data sheet shall be provided.
System Development Plan	To define the planning for the detailed activities to be performed on new development items.	Plan shall include: • Qualification Status List of the equipment with respect to the mission/system requirements • model philosophy • hardware development plan (covering manufacturing and assembly plans) • software development plan (covering coding) • hardware/software co-engineering approach • engineering tools and facilities used to support developments (hardware and software)

Platform-Payload Interface Control Documents (ICDs)	To define the payload item interfaces with the platform.	The document shall define the payload interfaces in terms of: • mechanical interfaces • electrical interfaces • thermal interfaces • data interfaces
Declared Lists for parts, materials and processes (DLs)	To identify all types of electrical components, mechanical parts and materials needed for the current design for all system-level models.	See ECSS-Q-ST-60C Annex B, ECSS-Q-ST-70C Annexes A, B and C for example format.
Satellite AIV Plan	To define and control all assembly, integration, verification and transportation activities associated with the satellite proto-flight model	Spacecraft model assembly/integration plan • Integration sequence • Integration constraints • Use of MGSE/EGSE • Payload calibration Protoflight test programme definition in terms of: • Test philosophy • Test conditions • Hardware/software matrices • Functional and performance verification, including interface integrity verifications. • Protoflight test programme (involving functional testing at ambient, vibration and TV test limits, TV profile and EMC) • Test plan, criteria and methods
Safety Data Package	To demonstration the compliance with the launch safety requirements	Defined by the launch authority.
System Verification Control Matrix	To identify verification methods to track verification status with respect to requirements during the project lifecycle	For each system requirement: • Requirement identifier • Requirement description • Design configuration item • Verification method (review/ analysis/inspection/ demonstration/test • Verification status • Reference to supporting documentation (ie. inspection/analysis/test reports) Requirements to be verified in this matrix include: • Mission/system requirements • Space debris mitigation requirements • Environmental Design specification requirements • Applicable CubeSat design specification requirements • Launcher requirements • Safety requirements

Test Procedures	To establish the objectives, organization, set-up and constraints of verification tests. To establish the procedures/success criteria used in verification tests and the requirements to be verified.	As per ECSS-E-ST-10-03C Annex C
Test Reports	To describe the results of the verification tests at all levels against the specified requirements.	The document shall include for each test: • Test method • Test equipment and set-up description • As-ran test procedure • Pass/fail criteria • Test results including pre- and post-processed test data in the form of tables and graphs • Interpretation of the test results with respect to the criteria • Conclusion regarding test outcome and identification of any remedial measures in case of test failure
Satellite Integration Logbook	To record the actual events of the satellite integration process	The document shall contain: • Integration methods and equipment used • Ambient conditions during the integration • Cleanliness conditions, including clean room and clothing of the AIV personnel • Condition of the incoming hardware • Integration as-run procedure • Fasteners, adhesives and harness tie-downs used • Notable events during integration: o Anomalies o Discrepancies o Errors o Any corrective measures
Mission Operations Plan	To define the full plan of activities immediately preceding and during the mission operations phase, including the Mission Timeline. It shall cover all mission phases, from lift-off from the launch pad until and including the Spacecraft end of life disposal, covering nominal and contingency recovery operations.	The document shall include: • Pre-launch mission rehearsals planning • Mission timeline including all mission events and telecommand/telemetry flows • Mission planning activities & work flow (including flight dynamics and simulator activities) • Payload operations planning & work flow • Operations personnel, operator responsibilities & lines of authority • Operations work schedule & flow • Support services and emergency contact points in case of ground systems failure

Mission Operations Status Reports	To regularly report on the health status of the platform and payload in orbit and the progress with respect to the Mission Operations Plan	The document shall include: • Platform health status and major operations performed • Payload operation status • Communications link sessions and data uplinked/downlinked • Major/minor in-orbit anomalies and associated cause • Recovery actions with respect to the anomalies (if any)
Non-Conformance Reports (NCRs)	To record non-conformances of the system product with respect to requirements in terms of nature, root cause, and corrective actions.	As per ECSS-Q-ST-10-09C, Annex C.
Request For Deviations (RFDs)	Request departures from an approved configuration baseline	As per ECSS-M-ST-40C Annex I
Request For Waivers (RFWs)	Request waivers for established requirements.	As per ECSS-M-ST-40C Annex J

Post-flight Analysis Report	To summarise the main results of the mission based on the data acquired, and describe the lessons learned	The document shall include:
		• Overview of the actual mission as performed, including the payload operations and any interruption in the mission due to in-orbit anomalies/failures (if any)
		• Overview of the operations data post-processing
		• Post-processed results of the mission operational data (including any failure analysis if failures occurred)
		• Outcome and achievements of the in-orbit demonstration mission with respect to the mission objectives
		• Lessons learned from the mission operations for:
		    ○ application of the demonstrated technology to future missions
		    ○ future missions using CubeSat platforms

B Requirements Checklist as per NASA Systems Engineering Handbook

This appendix includes the Appendix C of the NASA System Engineering Handbook titled ”How to Write good Requirements- Checklist” wich is referenced in the proposed SLC in chapter 7 as a template for requirements definition.

Appendix C: How to Write a Good Requirement—Checklist

C.1 Use of Correct Terms

- ☐ Shall = requirement
- ☐ Will = facts or declaration of purpose
- ☐ Should = goal

C.2 Editorial Checklist

Personnel Requirement

- ☐ The requirement is in the form "responsible party shall perform such and such." In other words, use the active, rather than the passive voice. A requirement should state who shall (do, perform, provide, weigh, or other verb) followed by a description of what should be performed.

Product Requirement

- ☐ The requirement is in the form "product ABC shall XYZ." A requirement should state "The product shall" (do, perform, provide, weigh, or other verb) followed by a description of what should be done.
- ☐ The requirement uses consistent terminology to refer to the product and its lower-level entities.
- ☐ Complete with tolerances for qualitative/performance values (e.g., less than, greater than or equal to, plus or minus, 3 sigma root sum squares).
- ☐ Is the requirement free of implementation? (Requirements should state WHAT is needed, NOT HOW to provide it; i.e., state the problem not the solution. Ask, "Why do you need the requirement?" The answer may point to the real requirement.)
- ☐ Free of descriptions of operations? (Is this a need the product should satisfy or an activity involving the product? Sentences like "The operator shall…" are almost always operational statements not requirements.)

Example Product Requirements

- ☐ The system shall operate at a power level of…
- ☐ The software shall acquire data from the…
- ☐ The structure shall withstand loads of…
- ☐ The hardware shall have a mass of…

C.3 General Goodness Checklist

- ☐ The requirement is grammatically correct.
- ☐ The requirement is free of typos, misspellings, and punctuation errors.
- ☐ The requirement complies with the project's template and style rules.
- ☐ The requirement is stated positively (as opposed to negatively, i.e., "shall not").
- ☐ The use of "To Be Determined" (TBD) values should be minimized. It is better to use a best

estimate for a value and mark it "To Be Resolved" (TBR) with the rationale along with what should be done to eliminate the TBR, who is responsible for its elimination, and by when it should be eliminated.

- ☐ The requirement is accompanied by an intelligible rationale, including any assumptions. Can you validate (concur with) the assumptions? Assumptions should be confirmed before baselining.

- ☐ The requirement is located in the proper section of the document (e.g., not in an appendix).

C.4 Requirements Validation Checklist

Clarity

- ☐ Are the requirements clear and unambiguous? (Are all aspects of the requirement understandable and not subject to misinterpretation? Is the requirement free from indefinite pronouns (this, these) and ambiguous terms (e.g., "as appropriate," "etc.," "and/or," "but not limited to")?)

- ☐ Are the requirements concise and simple?

- ☐ Do the requirements express only one thought per requirement statement, a stand-alone statement as opposed to multiple requirements in a single statement, or a paragraph that contains both requirements and rationale?

- ☐ Does the requirement statement have one subject and one predicate?

Completeness

- ☐ Are requirements stated as completely as possible? Have all incomplete requirements been captured as TBDs or TBRs and a complete listing of them maintained with the requirements?

- ☐ Are any requirements missing? For example, have any of the following requirements areas been overlooked: functional, performance, interface, environment (development, manufacturing, test, transport, storage, and operations), facility (manufacturing, test, storage, and operations), transportation (among areas for manufacturing, assembling, delivery points, within storage facilities, loading), training, personnel, operability, safety, security, appearance and physical characteristics, and design.

- ☐ Have all assumptions been explicitly stated?

Compliance

- ☐ Are all requirements at the correct level (e.g., system, segment, element, subsystem)?

- ☐ Are requirements free of implementation specifics? (Requirements should state what is needed, not how to provide it.)

- ☐ Are requirements free of descriptions of operations? (Don't mix operation with requirements: update the ConOps instead.)

- ☐ Are requirements free of personnel or task assignments? (Don't mix personnel/task with product requirements: update the SOW or Task Order instead.)

Consistency

- ☐ Are the requirements stated consistently without contradicting themselves or the requirements of related systems?

- ☐ Is the terminology consistent with the user and sponsor's terminology? With the project glossary?

- ☐ Is the terminology consistently used throughout the document? Are the key terms included in the project's glossary?

Traceability

- ☐ Are all requirements needed? Is each requirement necessary to meet the parent requirement? Is each requirement a needed function or characteristic? Distinguish between needs and wants. If it is not necessary, it is not a requirement. Ask, "What is the worst that could happen if the requirement was not included?"
- ☐ Are all requirements (functions, structures, and constraints) bidirectionally traceable to higher-level requirements or mission or system-of-interest scope (i.e., need(s), goals, objectives, constraints, or concept of operations)?
- ☐ Is each requirement stated in such a manner that it can be uniquely referenced (e.g., each requirement is uniquely numbered) in subordinate documents?

Correctness

- ☐ Is each requirement correct?
- ☐ Is each stated assumption correct? Assumptions should be confirmed before the document can be baselined.
- ☐ Are the requirements technically feasible?

Functionality

- ☐ Are all described functions necessary and together sufficient to meet mission and system goals and objectives?

Performance

- ☐ Are all required performance specifications and margins listed (e.g., consider timing, throughput, storage size, latency, accuracy and precision)?
- ☐ Is each performance requirement realistic?
- ☐ Are the tolerances overly tight? Are the tolerances defendable and cost-effective? Ask, "What is the worst thing that could happen if the tolerance was doubled or tripled?"

Interfaces

- ☐ Are all external interfaces clearly defined?
- ☐ Are all internal interfaces clearly defined?
- ☐ Are all interfaces necessary, sufficient, and consistent with each other?

Maintainability

- ☐ Have the requirements for maintainability of the system been specified in a measurable, verifiable manner?
- ☐ Are requirements written so that ripple effects from changes are minimized (i.e., requirements are as weakly coupled as possible)?

Reliability

- ☐ Are clearly defined, measurable, and verifiable reliability requirements specified?
- ☐ Are there error detection, reporting, handling, and recovery requirements?
- ☐ Are undesired events (e.g., single-event upset, data loss or scrambling, operator error) considered and their required responses specified?
- ☐ Have assumptions about the intended sequence of functions been stated? Are these sequences required?
- ☐ Do these requirements adequately address the survivability after a software or hardware fault of

the system from the point of view of hardware, software, operations, personnel and procedures?

Verifiability/Testability

- ☐ Can the system be tested, demonstrated, inspected, or analyzed to show that it satisfies requirements? Can this be done at the level of the system at which the requirement is stated? Does a means exist to measure the accomplishment of the requirement and verify compliance? Can the criteria for verification be stated?

- ☐ Are the requirements stated precisely to facilitate specification of system test success criteria and requirements?

- ☐ Are the requirements free of unverifiable terms (e.g., flexible, easy, sufficient, safe, ad hoc, adequate, accommodate, user-friendly, usable, when required, if required, appropriate, fast, portable, light-weight, small, large, maximize, minimize, sufficient, robust, quickly, easily, clearly, other “ly” words, other “ize” words)?

Data Usage

- ☐ Where applicable, are “don’t care” conditions truly “don’t care”? (“Don’t care” values identify cases when the value of a condition or flag is irrelevant, even though the value may be important for other cases.) Are “don’t care” conditions values explicitly stated? (Correct identification of “don’t care” values may improve a design’s portability.)