Master Thesis

Czech
Technical
University
in Prague

F2

Faculty of Mechanical Engineering
Enterprise Management and Economics

Microgravity Space Printer Project - Feasibility Study

Bc. Jan Lukačevič

Supervisor: Ing. Miroslav Žilka PhD
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ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE

ZADÁNÍ DIPLOMOVÉ PRÁCE

I. OSOBNÍ A STUDIJNÍ ÚDAJE

Příjmení: **Lukačevič** Jméno: **Jan** Osobní číslo: **381523**

Fakulta/ústav: **Fakulta strojní**

Zadávající katedra/ústav: **Ústav řízení a ekonomiky podniku**

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II. ÚDAJE K DIPLOMOVÉ PRÁCI

Název diplomové práce:

Studie proveditelnosti projektu Microgravity Space Printer

Název diplomové práce anglicky:

Microgravity Space Printer Project - Feasibility Study

Pokyny pro vypracování:

1. Úvod, cíle a úkoly diplomové práce
2. Teoretická východiska práce - projektové řízení a plánování, nástroje projektového managementu, studie proveditelnosti a její struktura
3. Praktická část - technický popis projektu, věcná dekompozice cíle, personální zajištění, harmonogram, rozpočet projektu, analýza rizik
4. Závěr

Seznam doporučené literatury:

ROSENAU, Milton D. Řízení projektů. 1. vyd. Praha: Computer Press, 2000, xiv, 344 s. Business books (Computer Press). ISBN 80-7226-218-1.
SVOZILOVÁ, Alena. Projektový management. 2. aktual. a dopl. vyd. Praha: Grada Publishing, a.s. 2011, 392 s. ISBN 978-80-247-3611-2.
FOTR, Jiří, Lenka ŠVECOVÁ a kol. Manažerské rozhodování: Postupy, metody a nástroje. 2. přeprac. vyd., Praha: Ekopress, 2015, 474 s. ISBN 978-80-8692-959-0.
BURKE, Roy. Project Management: Planning and Control Techniques, 5. vyd., Viley, 2013, 448s. ISBN 978-1-118-66076-8

Jméno a pracoviště vedoucí(ho) diplomové práce:

Ing. Miroslav Žilka Ph.D., ústav řízení a ekonomiky podniku MÚ

Jméno a pracoviště druhé(ho) vedoucí(ho) nebo konzultanta(ky) diplomové práce:

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III. PŘEVZETÍ ZADÁNÍ

Diplomant bere na vědomí, že je povinen vypracovat diplomovou práci samostatně, bez cizí pomoci, s výjimkou poskytnutých konzultací.
Seznam použité literatury, jiných pramenů a jmen konzultantů je třeba uvést v diplomové práci.

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Datum převzetí zadání | Podpis studenta

Acknowledgements

I love deadlines. I love the whooshing noise they make as they go by. Thank you to my family, my supervisor and Col. Chris Hadfield for teaching me how to be a zero.

Declaration

I declare that this work is all my own work and I have cited all sources I have used in the bibliography.

In Prague, August 8 , 2017

Prohlašuji, že jsem předloženou práci vypracoval samostatně, a že jsem uvedl veškerou použitou literaturu.

V Praze, 8. srpna 2017

Abstract

"Feasibility study of the Micro Gravity Space Printer Experiment" is a thesis originally based on a real scientific experiment developed by a research team at the Czech Technical University in Prague. The experiment is being developed with the support of governmental and non-governmental institutions. The thesis introduces theoretical basis for the project, technical description as well as its planning and organisational matters in a form of a feasibility study.

Keywords: additive manufacturing, 3D printing, feasibility study, space industry

Supervisor: Ing. Miroslav Žilka PhD
Karlovo náměstí 13
121 35 Praha 2

Abstrakt

Diplomová práce "Studie proveditelnosti projektu Micro Gravity Sprinter" je založena na reálném vědeckém experimentu vyvíjeném výzkumným týmem na Českém vysokém učení technickém v Praze. Tento experiment je vyvíjen ve spolupráci s vládními i nevládními organizacemi v oblasti kosmického výzkumu. Práce předkládá teoretická východiska a termíny, které jsou aplikovány v praktické části formou studie proveditelnosti.

Klíčová slova: aditivní výroba, 3D tisk, studie proveditelnosti, kosmický výzkum

Překlad názvu: Studie proveditelnosti projektu Microgravity Space Printer

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Chapter 1

Introduction

"Feasibility study of the Micro Gravity Space Printer Experiment" is a thesis originally based on a real scientific experiment developed by a research team at the Czech Technical University in Prague. The experiment was developed along with a wide variety of experts in the respective fields from The European Space Agency (ESA), German Space Agency (DLR), German Centre for a Microgravity Research (ZARM), Swedish Space Corporation (SSC), and Swedish National Space Board (SNSB).

In order to introduce this topic the thesis presents technical terms and frameworks used in project management and its phases, along with some of the common and less common approaches and tools that are being utilised in a classic approach to project management. Additionally, it puts all of the aforementioned parts in context and extends the theory with some of the latest tools and that are being used in mechanical, as well as space engineering.

1.1 Aims

The main aim of this thesis is to draw up a feasibility study of the Micro Gravity Space Printer project. This complex task consists of multiple subtasks; in order to create such study, it is needed to compose a baseline project plan, and consider the project from various perspectives (technical, financial and organisational) as well as to present a comprehensive evaluation of the project.

To follow the main aim, the thesis presents several objectives: to introduce some of the fundamental terms that are being widely used in the area of project management; furthermore, to provide an overview of methodology and tools used to create and manage space projects and thirdly, demonstrate capabilities of these tools and methods by applying them on a specific project - The Microgravity Space Printer of which the feasibility study is presented in this thesis.

Chapter 2

Theoretical Part

2.1 Project Management & Planning

2.1.1 Project

Today, the term 'a project' tends to be overused, encompassing activities ranging from social to entrepreneurial in nature without awareness of the true meaning of what a project is. The term itself is very specifically defined as demonstrated by Robert K. Wysocki in his book[1], Effective Project Management:

"A project is a sequence of unique, complex, and connected activities that have one goal or purpose and that must be completed by a specific time, within budget, and according to specification."

According to project management experts and theorists, this particular definition may differ as the interpretation of the term is approached from various viewpoints. However, it is important to mention that even though two or more projects may appear to be identical, each project is, from the definition, unique as the circumstances and requirements change over time. To put this into context of space research and the space industry in relation to space projects, specification of the project goes one step further as the objectives and an overall purpose of the project are defined by the project initiator in the so-called *mission statement*. This statement relates to a specific mission or a project and contains technical and programmatic constraints, as well as key performance parameters that are to be applied to the project. Moreover, another important aspect of a project is its "temporariness". Should a project lack a limited and defined time period, it may turn into a complex process. The temporariness and uniqueness are mostly characterised in a project by:

- A starting and closing date (or a date when it is determined that the project cannot be completed in accordance with the initial goals);
- Specific requirements and aims that are a purpose of the project;

- Particular composition of a team (and their then-skillset) that is assigned to complete the project.

Another substantial part of a project that defines its scope and suggests the probability of a successful completion of its goals is a range and availability of resources. It is certain that completely different outcomes can be achieved depending on the way the resources are being allocated. This can be described using "The Project Management Triangle", sometimes referred as "Triple Constraint". The diagram basically builds on the following three premises:

1. There is a limited amount of resources: the quality of the outcomes is determined by the deadlines, budget constrains and desired features;

2. Person responsible for the project can only trade between these constrained variables;

3. Changes in one constraint require necessary changes in remaining constrains in order to compensate, otherwise the quality of outcomes will suffer.

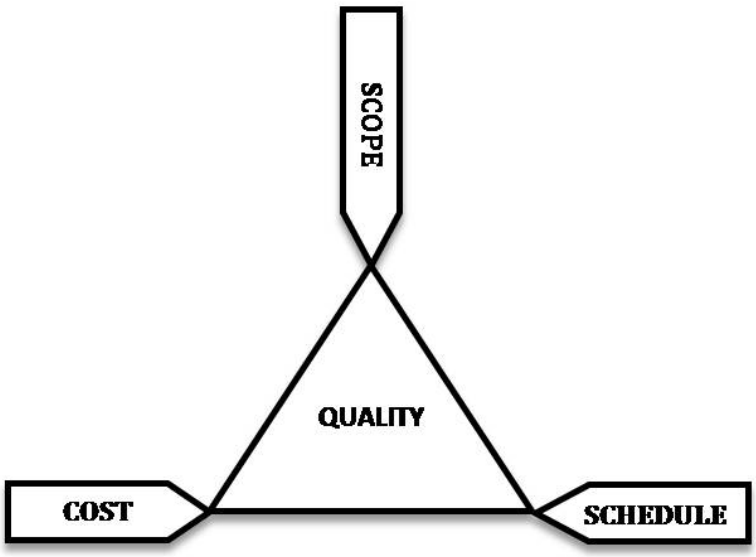

Figure 2.1: The Project Management Triangle

2.1.2 Project Management

Every project needs a certain level of governance in order to be successful. This can be rather difficult; therefore an entire discipline has been created and keeps on evolving to make the management of projects as effective as possible. For the purpose of this thesis, the following definition can be used:

"Project management is the planning, organizing, directing and controlling of company resources for a relatively short-term objective that has been established to complete specific goals and objectives."

This being said, project management can be understood as a way of applying knowledge, skills, tools, and technologies to accomplish goals set for the project [2]. It is a complex effort which encompasses a diverse portfolio of activities such as defining the requirements, gathering resources, governance of people, controlling, monitoring, and evaluating of ongoing and finished processes.

2.1.3 Life cycle of a project

Each project can be divided into several phases that focus on different aspects of the project. The reason to divide them into certain logical order is to improve the conditions for the monitoring and auditing of activities that are contained in each phase. Furthermore, this is meant to ease the orientation within the project to all stakeholders involved, and to increase the probability of the overall project success. Typically, each phase defines which types of activities shall be carried out, what specific outcomes are required to be completed, and how they are verified and evaluated. As well, who is participating in its parts. There are several systems that divide project into phases. According to Cleland and King [3], the division is as follows:

1. **Conceptualisation** - In the initial phases, a formulation of elementary intentions and questions is necessary. This comprises the evaluation of potential merits of a project, time and budget estimation required for the project completion, and a preliminary risk analysis.
2. **Planning** - Essentially, this phase focuses on elaboration of previous outcomes of the extent of frameworks used for the project. a more formalized set of plans to accomplish the initially developed goals are established, and therefore preparation of tools and methods, resources identification, a realistic time line, more precise budget calculations, and proper definition of potential risks and suggestion of mitigation strategies; a preparation of detailed plans required for a realisation of the project take a place.
3. **Execution** - During the execution phase, most of the work related activities are performed. Previously prepared resources and tools are being utilised in order to complete the goals set for the project. Throughout this phase, various performance tests take place and the project is being thoroughly examined to ensure successful completion.
4. **Termination** - Sometimes this phase is called "Closing". At this stage, the project is terminated, and remaining resources are reallocated to other projects. The project goes through an in-depth analysis and evaluation to gather inputs that might be used for a better project management of future projects.

Another system used in project management is the Project Management Life Cycle Model that consist of five process groups: Scoping, Planning, Launching, Monitoring and Controlling, and Closing. While these groups are often used, the most fitting for the Microgravity Space Printer Project is a framework developed by The European Cooperation for Space Standardization. In the ECSS-M-ST-10C standard that describes planning of space projects [6], these following seven phases are used:

- Phase 0 - Mission analysis/needs identification
- Phase A - Feasibility
- Phase B - Preliminary Definition
- Phase C - Detailed Definition
- Phase D - Qualification and Production
- Phase E - Utilization
- Phase F – Disposal

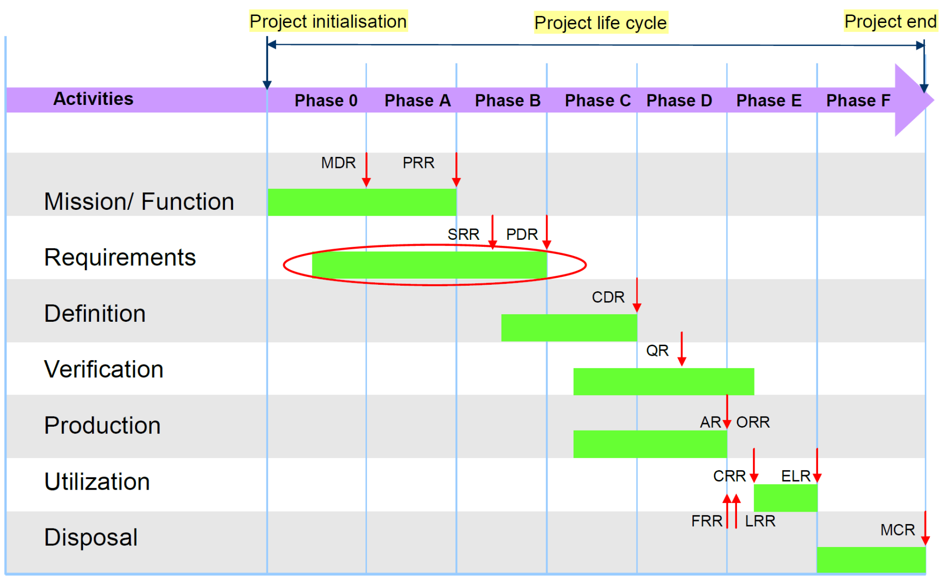

Figure 2.2: Typical Life Cycle of a Space Project.

All mentioned phases are closely connected to activities on a system and product level. The scheme may vary as certain activities can overlap project phases depending on the current circumstances of a project and the risks that may occur.

The first three phases (0,A and B) focus primarily on requirements. The goal is to further elaborate on system functional and technical requirements, as well as to identify major system concepts to adhere to the previously set mission statement. At the same time, taking into account the technical and programmatic limitations identified by the project initiator. Moreover, it is substantial to identify all resources and activities required develop the space and ground segments of the project. These three phases also include some of the the initial assessments of technical and programmatic risk and initiation of pre-development activities (as it will be elaborated further in a detailed description of these phases). The following two phases (C and D) are the core of the ground preparation of the actual space product. These phases consist of all processes required to design and produce the space and ground segments, and their products. Actions required to launch, command, fully make use of as well as to maintain the orbital elements of the space segment belong to the phase E. All the actions and activities in this phase also apply for all the segments on ground. Finally in the Phase F activities are leading to safely dispose all products launched into space as well as ground segment and to evaluate the mission success and to gather major findings and lessons learnt for future projects.

As seen in the Figure 2.2, development of a space project is a continuous sequence of activities that are being recorded using a project documentation. To achieve the most effective spending o resources and desired quality of the outcomes within the scope of the project, each of the phases ends with a milestone that comes in as a review of the phase. During the review, project documentation is carefully examined and progress on the experiment is presented to the relevant stakeholder. The outcomes of the review then decide on the readiness of the project to move to the following phase or to rework some of the outputs and products.

As this particular Project Life Cycle perfectly fits the scope of this thesis and the project, for better understanding of the task division and establishing of the work breakdown structure as well time line of the project in the practical part of the thesis, further explanation of each of the project phases is necessary. These phases are also closely related to reviews that in the space project management play an important role as they serve as milestones.

- **Phase 0 (Mission analysis/needs identification)**

  In the Phase 0, some of the major tasks include the elaboration of the mission statement in terms of identification and characterization of the mission needs, expected performance, dependability and safety goals and mission operating constraints with respect to the physical and operational environment. Furthermore, in the Phase 0 begins the process of specifying functional, operational and requirements of the project and an elementary risk analysis is conducted. This phase ends with The Mission Definition Review (MDR) which ideally results in continuation of the project in the Phase A.

- **Phase A (Feasibility)**

  Is the most relevant phase for the scope of this thesis, normally comprise tasks related to planning and discovering feasibility of the project. In this phase, it is needed to establish a series of plans, such as a preliminary management plan, system engineering plan and product assurance plan for the project. Comparison of previously identified needs and system concepts is used to estimate levels of uncertainty and risks. Proposition of elementary design, technical solutions and completion of requirements management that started in the Phase 0 and further elaboration of the risk assessment is also conducted. In the Preliminary Requirements Review that is associated with this phase it is determined which technical and operational solutions will be used and it must be ensured that management, engineering and product assurance plans are released.

- **Phase B (Preliminary definition)**

  Yet another of the preparation phases of the project. In this phase the main focus is on finalising the project management, engineering and product assurance plans and as a follow-up, the baseline time schedule and baseline cost at completion calculation is performed. Some of the managerial tasks are conducted, such as a creation of the preliminary organisational breakdown structure (OBS) and the work breakdown structure. However, more detailed engineering designs (such as deciding on preferred technical and system solutions) are specified. Unlike in the Phase 0 and Phase A, there are two reviews associated with the Phase B. Throughout the entire phase The System Requirements Review (SRR) is held and at the end of the Phase, The Preliminary Design Review (PDR) takes place. e. Within the scope of SRR is to release specification for up-to-date technical requirements, to assess the definition of the preliminary design and to assess the preliminary program focusing on verification of the processes within the project. For the PDR, as the name suggests, it is necessary to verify preliminary design of the concepts selected in previous phases and to release the final engineering, product assurance and management plans.

- **Phase C (Detailed definition)**

  May dramatically vary from one project to another. This vastly depends on previously chosen model philosophy and the verification approach. In the Phase C, selected critical components are tested in development and produced, this also applies to engineering models. As the project proceeds, risk assessment is updated and interfaces (both external and internal) are defined in detail. Upon the end of the Phase C, The Critical Design Review is held. The major outcome is utilised to decide on the readiness of the project and possibility to move to the Phase D. This is done by assessing the final design (that has to by released in Phase C) as well as the assembly, integration and experiment test planning. Flight hardware manufacturing plans and the test plans are also evaluated. Based on the PDR, the user manual is released.

- **Phase D (Qualification and production)** This phase focuses mostly on completion of various elements. Activities related to qualification testing and verification needs to completed. Phase D can extend to rather long period as all of the manufacturing, assembly and testing of the flight software and hardware must be completed within this phase. As the project proceeds, it requires more in-depth reviewing. For that reason, three different reviews are conducted. The Qualification Review (QR) concurrently with the activities within the phase, then The Acceptance Review (AR) and The Operational Readiness Review (ORR) that conclude this project phase. Each of the reviews has a different scope. The QR aims at confirming that the verification process displays that the selected design meets previously set requirements. The AR then aims at demonstration of a function of the verification process. In short, the objective is to verify if all the deliverable products and systems are available in accordance with the previously approved product deliverable list and to determine the acceptability of various waivers and changes in the original plan proposed by the production and project team. For the most part, the AR provides the project with the acceptance certificate in order to proceed to final stages of the project. During the ORR, all other accompanying activities are verified as well as the readiness of the operations team that is responsible for the actual operation and maintenance of the project during the launch and flight. That relates to the procedures developed for the flight and their compatibility with all systems involved in.

- **Phase E (Operations/utilization)** As in the Phase C, processes and actions in this phase usually vary, since the objectives and goals for each project differ. This complicates giving a comprehensive overview of tasks that are usually accomplished during Phase E. Generally speaking, it is the phase which is often the one seen as the project itself. For space project, it is the launch and operation activities during the flight mission, thus activities such as performing all on-orbit operations to accomplish the mission aims and objectives and mission support related tasks are conducted. This phase is associated with 4 project reviews. Prior to launch, The Flight Readiness Review (FRR) is held and The Launch Readiness Review (LRR) immediate prior to launch. This is followed by the Commissioning Results Review (CRR) that is conducted after commissioning activities and lastly, The End-Of-Life Review (ELR) is held at the designated completion of the mission. Name of each of the reviews speaks for itself. The main review objectives are closely related to final checks prior to launch, respectively during and at the end of flight. The ELR serves as a bridge to the last phase of the project and in order to pass the ELR, it is important to verify that the mission has completed the objectives, considering the circumstances.

- **Phase F (Disposal)** In the final phase, the disposal plan implementation must be ensured. The disposal plan consists of activities that are safely terminating the mission. At the end of this phase, The Mission Close-Out Review (MCR) is held, following the objective that all of the disposal activities are sufficiently completed.

2.2 Approaches to Project Management

As various approaches to understanding the project management have been introduced, it is equally important to introduce several approaches to project management. They differ from each other by their way of handling the project life cycle and their rate of interaction with the customer and other relevant stakeholders. Another key factor is the goal and solution clarity. These two variables can switch between the values of "clear" and "not clear" and any given project can show various degrees of clarity[1].

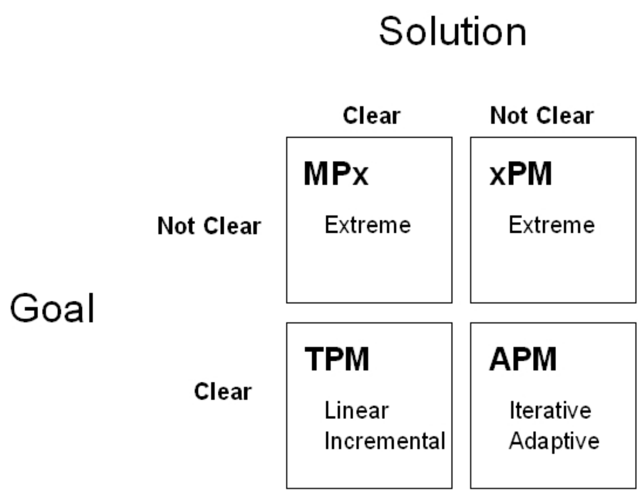

Figure 2.3: Four Quadrants of the project landscape

Depending on a combination of the aforementioned variables, every project can be placed to one of the four quadrants. This particular diagram serves as a useful tool to decide upon the best fitting approach. For the purpose of this thesis we will choose Quadrant 1 and Quadrant 2, where the Traditional Project Management and Agile Project Management can be found. These are two of the dominant approaches in project management, however the variety of approaches used in contemporary project management is very rich. Just to name few, companies all around the world also use Lean Management, Six Sigma Method, Even Chain Management or Extreme Project Approach[4].

It is necessary to say that every approach and method has its advantages and disadvantages and it is often possible to combine multiple approaches in order to successfully lead project. To give a complex overview of a situation in the space industry, apart from the Traditional Project Management and Agile Management, relatively new method, "Concurrent Engineering" is added.

2.2.1 Traditional Project Management

As the Traditional Project Management (TPM) lies within the first Quadrant, it means that we have the maximum clarity attainable. Sometimes this method is being called "Waterfall" as one phase of the project follows another. Projects that are being managed using TPM have a clearly defined goals and solutions. Yet this situation occurs more and more rarely, as only 20 % of projects completely fulfil these premises. It is typical for the projects within this category that they require very little or no change throughout the project. It is fitting for projects that have a similar predecessors and require only minor adjustments. TPM projects are often plan driven and their rate of success is determined by the strictness of compliance to the said plan.

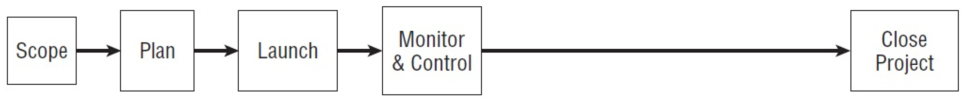

Figure 2.4: Linear Project Management Life Cycle Model

Another characteristic feature for TPM projects is the linearity. As the Waterfall name suggests, all process groups are aligned and executed one after another. This particular setting of processes has both positive and negative sides. On one hand, it offers very well arranged, uncluttered and transparent structure which is relatively easy to follow for all relevant stakeholders. Monitoring of the TPM projects is easier in comparison to other systems and depending on the complexity of the project, it is also the shortest way to a successful completion of a project. On the other hand side, Linear PMLC projects are change intolerant. This means that as soon as the projects is commenced, little or no change can be done. This negatively affects the scope of the projects (as it might be required to re-scope the project on the fly) and basically prevents any learning from the experience gained in any of the previous processes that could potentially positively influence the outcomes of the project. Due to the strict linearity it is not possible to improve deliverables of each phase. For these reasons, Linear PMLC model is not appropriate for long term projects as the environment and circumstances tend to change a lot and this makes the project more expensive if not completely unachievable. Still, Traditional Project Management is a method widely used, space industry included.

2.2.2 Agile Management

Agile Management is a large family of methods that are growing in importance as they effectively deal with rigidity of the TPM. For Agile Management models is typical that the goal has a high degree of clarity but the solution used for achieving the goal remains unclear. In comparison to TPM, in Agile Management is the contact with the customer and other stakeholders more frequent.

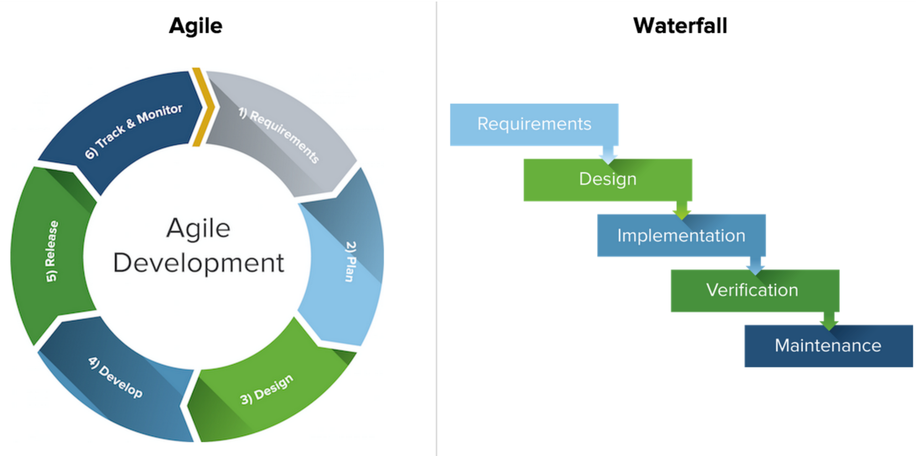

Figure 2.5: Comparison of the Agile and Waterfall Models[7]

As seen in the figure above, the Agile Management models tackle the lack of flexibility of TPM using incremental change and keeping all the processes in the loop. In essence, this method comprise continuous, cyclical processes and stimulate experimentation and adaptability. All six phases of Agile (requirements, plan, design, develop, release, and track and monitor) may overlap as it is characteristic for them that they are flexible and evolving throughout the cycle. This, as well as work in rather small and dynamic teams is in sharp contrast to the TPM.

Within the Agile family we distinguish following major methods:

- **Scrum**

  As in the general approach, Scrum also values collaboration and experimentation, but out of all Agile methods, Scrum is more structured. Usually there are iterations with fixed length, during which the work is completed. These periods are called Sprints and depending on the size and scope of the project, they usually lasts from two to four weeks and focus on completing an individual task initially assigned. These tasks are assigned to a single member of a team whose sole responsibility is a completion of this task. Such task aims at development of a single product or piece of software. For this reason, this method is widely used in software development companies and IT departments and teams of larger corporation.

- **Kanban**

  Kanban is a less formally managed system. It is inspired by a Japanese method used in industrial and production engineering. In comparison to Scrum, Kanban avoids using the system of specific roles or responsibilities and the schedule is also more fluid as there are not set any time limits related to a completion of partial goals during the project. To establish certain time frame, work in progress (WIP) at any given time is measured and limited. Instead of products and materials as in the industrial engineering method of the same name, team members simply pull work (like Kanban papers) from the pool of available tasks into the WIP category. This method allows a continuous work with minimise risk of creation of bottlenecks.

Both of the introduced methods suggest that they are ideally used in software development, and that is actually the most common way they are being employed nowaydays. Agile Methods may not be optimal for the management of the entire space projects, but can serve very well in the development of various subsystems and independent parts of the project. A great example could be a components design for the Pressure Difference Dependency on Altitude Verificator Experiment [8] (PREDATOR) supported by the European Space Agency and developed by a team consisting of students from several faculties of Czech Technical University in Prague. Agile Method has been used in a combination with 3D printing which allowed fast and flexible adjustment of an enclosure developed to protect pressure sensors used for the experiment. Products of every iteration corresponded to functional and operational requirements of the experiment.

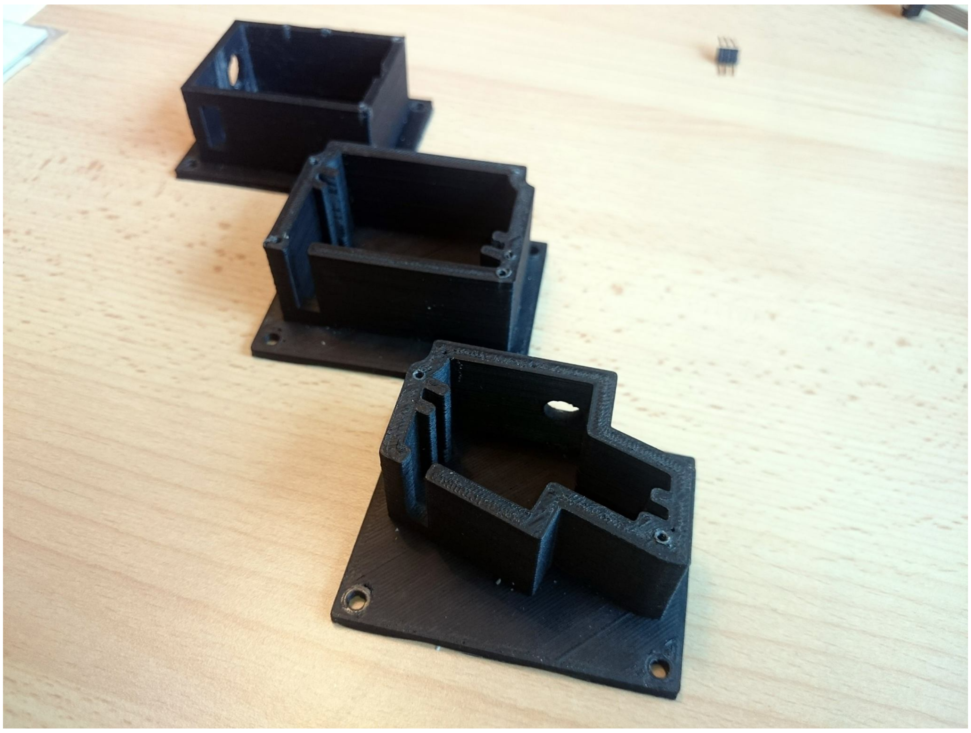

Figure 2.6: Evolution of Enclosures developed using Agile Method

2.2.3 Concurrent Engineering

"Concurrent Engineering (CE) is a systematic approach to integrated product development that emphasizes the response to customer expectations. It embodies team values of co-operation, trust and sharing in such a manner that

decision making is by consensus, involving all perspectives in parallel, from the beginning of the product life cycle."[1]

Another project work methodology of designing and developing products is called Concurrent Engineering. While the Traditional Project Management and other similar design methods on the same bases continue linearly, in this particular methodology all subsystems are designed concurrently (hence the name). Experts of all disciplines and subsystems that are part of the project cooperate using working-in-joint sessions. This method is used by the most progressive teams in the space industry, such as NASA Team X, CNES (French Space Agency), Thales Alenia Space or German Aerospace Center (DLR). European Space Agency is using this methodology to perform feasibility studies at specially dedicated facility named Concurrent Design Facility (CDF). In initial stages, establishing a working structure for concurrent engineering is a more complicated process than with other methods, and needs to be learnt and accepted by all team members. Use of this system requires constant communication with other teams developing other subsystems nonetheless this feature enables to identify mistakes in much earlier stages. This results in higher efficiency and reduction of the design time.

2.3 Feasibility Study

A feasibility study is a document which serves as comprehensive report of all known aspects and relevant information describing a project that is up for an assessment and potential realisation. The purpose is to present all the realisation alternatives and evaluate (as the name suggests) feasibility of a project. Mostly we create feasibility studies for investment projects or construction projects but this document can be also used as a relevant supportive material for space projects. It should give an overview of the project with its advantages, disadvantages and specifics which may influence its milieu. In other words, it analyses how successful a project can be, taking in account for aspects that affect it.

In order to maintain certain level of clarity, feasibility studies are usually using a general template and follow a similar structure. This ensures that all factors are taken into account and feasibility studies can be compared and evaluated in case of multiple projects are available. According to the Czech Ministry of Regional Development methodology[9], the general structure of a feasibility study consists of following topics:

1. **Content of the feasibility study** - mainly introduces the range of the feasibility study, presents its structure and serves as an orientation within the document.

2. **Introduction** - includes formal information: purpose of the feasibility study, project initiator credentials and the date when the study has been

[1] This is an official definition of Concurrent Engineering by the European Space Agency's Concurrent Design Facility

created.

3. **Brief evaluation of a project** - in about 1 or 2 pages, a brief summary of the key points elements of the feasibility study is presented. Usually using a table, an overview of cash flow as well as the risk analysis outcomes are visually represented for easier understanding. Financial effectiveness, chances to realise the project from all different aspects and results of the risk analysis are all summed up there.

4. **Brief description of the project and its phases** - includes a complex description of key project characteristics and its phases. It answers fundamental questions regarding the project such as what is the motivation and purpose of the project; what services or products are deliverables of the project and how they solve the initial problem; who is an owner or an investor of the project; what is a capacity and location of the project, what are the project phases and what are their specific characteristics as well as what are the other project specifics.

5. **Market Analysis, Marketing Strategy and Marketing Mix** - includes a description of all marketing aspects of the project. This answers questions regarding the customer's needs, competitiveness of the project. It is based on analysis of the situation and proceeds towards strategy and implementation. Specifically, it includes:

   a. Market analysis and demand estimation
   b. Marketing strategy
   c. Marketing mix

6. **Project Management** - includes the plan and layout of the project which corresponds to realisation of the project. This comprise all of the project planning, organisational matters, controlling, monitoring, and audit of all processes, organisational units and human resources.

7. **Technical and technological solutions for the project** - sums up technical and technological aspects of the project such as parameters of the technology and machines used in the project; also, operational, functional and other requirements that need to be met to enable a full functionality. Furthermore, a plan that includes material and energy flows and information regarding durability and lifetime period of used technology.

8. **Environmental aspects of the project** - description of all positive and negative aspects originating from the project.

9. **Investment strategy** - definition of the investments structure and its stratification. Investment amount estimation and amortisation scheme.

10. **Current assets controlling strategy** - definition of the current assets structure, including material, unfinished production and products;

furthermore, a required liquidity estimation scheme, control of the short-term offer and demand.

11. **Financial plan and analysis of the project** - a complex overview of financial aspects of the project which is structured in following points:

    - Basic calculation & Break-even point analysis
    - Financial plan including:
        a. Costs and revenues estimation plan
        b. Planned condition of assets
        c. Cash flow progression plan

12. **Effectiveness & sustainability of the project** - project assessment utilising basic viable criteria, such as Net Present Value, Internal Rate of Return, Payback Time and Profitability Index

13. **Risk analysis** - substantial tasks comprise an identification, definition and specification of project risks; their categorisation and suggested mitigation strategies, evaluation of the risk analysis.

14. **Time line of the project** - as the name suggest, this chapter includes a time line and expected schedule of the project. It is beneficial to create a plan with sufficient clarity which marks beginning and ends of key tasks of the project as well as allows to identify potential overlaps.

15. **Final evaluation of the project** - the final chapter of the feasibility study includes complex and in-depth evaluation of the project, presenting the final decision regarding the realisation of the project. It uses all baseline aspects mentioned before in previous chapters and it can also suggest recommendations to increase a chance to realise the project.

For the purpose of this thesis, it is substantial to understand that some major modifications need to be done. The presented general structure fits majority of the investment projects but since Micro Gravity Space Printer does not fall into the category, certain measures need to be taken. The primary purpose of the feasibility study remains to be an overview allowing to understand the project in its complexity. As some of the aspects of projects are rarely present in space research, chapters such as Investment Strategy, Current assets Controlling Strategy or Market analysis are to be left out; the others are arranged in an order which follows a logical sequence and ensures high clarity of the document.

2.4 Creation of a Project Budget

An integral part of a project plan is a project budget. The project budget includes the plan of utilisation of financial resources throughout the project and serves as a key characteristic of the project itself. It is a necessary tool which is used as a source for other plans within the project and has a decisive character in terms of resources allocation, the project scope and the quality of project outcomes.

The budget is usually created upon two occasions:

- In the conceptual phase of the project, such as the feasibility study preparation. At that stage, it is used as a baseline for cooperation, partnership and investment meetings, therefore the amount of disclosed information is limited.
- In the planning phase of the project: at that stage it is an inseparable part of the project plan and it is desirable to achieve as high accuracy as possible given all other uncertainties during the planning stage of the project.

2.4.1 Standard items in a project budget

Every project budget consists of a wide variety of estimated costs. It is beneficial to divide them into several categories as each type might be sourced from a different kind of funding and these costs also have different level of priority. We distinguish following categories:

- **Direct costs**

  Direct costs include all articles that are directly related to the project budget and can account for specific items, tasks and processes. As direct costs we usually consider: work; material; purchase or rental of used technology; travel expenses; licenses and insurance of the project.

- **Indirect costs**

  As indirect costs we usually consider items that do not directly account to specific items but it has been decided by the project manager or economic department using calculated coefficients to include them. These can be: personal costs (such as salaries of the management and employees in supportive roles); costs related to marketing and external services; building and technology maintenance costs; taxes and other fees.

- **Other costs**

  Are a special category. This category includes costs that could not be directly linked to any of the previous categories and they are estimated using various analyses. These can include: risk reserves (in case of a project failure or an occurrence of any major risks endangering the success of the project) and bonuses or benefits paid to the sales department.

2.4.2 Methodology in a budget estimation

As the project budget is being prepared beforehand of the actual realisation, it is necessary to conduct a budget estimation. There is a wide range of possible techniques and methods. Some of which are:

- **Company methodologies and standards** - major companies that are using project management have detailed frameworks to estimate budgets, these are usually based on calculations and internal policies.
- **Expert estimations** - a project manager conducts an analysis of potential costs alongside with the project team members using a detailed work package overview and projection of indirect and other costs.
- **Statistical methods** - budget estimation is based on statistical calculations and mathematical models that count with the circumstances and future conditions for the project.
- **Historical information** - using information gathered during previous projects, a new project budget estimation is prepared by modifying and adjusting the previous budget to new circumstances.

The budget estimation is usually conducted in a series of subsequent steps. These steps are gradually adding more layers to the budget plan and eventually make it a very complex document. The steps go as follows:

1. Linking direct costs to specific items related to them - as it was mentioned in section 2.4.1, this can be achieved by giving a detailed description of particular work tasks and processes and breaking them down into time schedule. Based upon that, specific tariffs are applied.
2. Evaluation and time distribution of costs - linking material costs, purchase and rental of the technology and licences is not considered as complicated.
3. Assessment of the project member needs - to satisfy the needs within the team, such as travel expenses.
4. Consideration of indirect project costs.
5. Qualitative and quantitative analysis of project risks - calculation of reserves and costs related to mitigation strategies.
6. Cash flow assessment - calculating costs related to the cash flow maintenance and including them in the budget plan.
7. Final assessment - assessing the acceptability of the budget in relation to the project scope and quality and certain level and considering modifications and adjustments to meet the expectations and objectives of the projects.

2.5 Project Management Tools

2.5.1 Breakdown Structures

In project management, Work Breakdown Structure is the most known tool to clearly mark the hierarchical structure of all work required to complete a project. However, it is closely related to other Breakdown Structures which it is using as a source of information and further elaborate on them. In order to understand the WBS, other break down structures that are usually utilised need to be mentioned:

- **Resource Breakdown Structure (RBS)**

  To start with, in a project we need to enlist our resources. The Resource Breakdown Structure lists all the human resources in relation to their function and arrange them in a hierarchical structure. This improves the facilitation of a project management and control.

- **Organisation Breakdown Structure (OBS)**

  In order to define mutual or interdependent and other relationships within the project, the Organisation Breakdown Structure is used. It aids to define the organisational relationships and is used as the framework for assigning work responsibilities. There is an intersection of the OBS and WBS which identifies points of management accountability for the work that is being referred to as Control Accounts.

- **Risk Break Down Structure (RBS)**

  Similarly to the Risk Analysis later utilised in the practical part of this thesis, the risk breakdown structure identifies and arranges project risks by their category. However, the difference is that the risks in RBS are placed into the hierarchical structure as they are identified, and the structure is organised by origin of the risk so that the overall risk exposure of the project provides with higher visual clarity. Despite its visual appeal, this structure is not suitable for very complex projects.

- **Work Break Down Structure (WBS)**

  The actual Work Breakdown Structure usually combines the aforementioned breakdown structures. As an example, the WBS explains what kind of work has to be done to satisfy the needs of RBS. This is done from the baseline structures included in the RBS and the elementary level of decomposition in there. Items and deliverables are hierarchically decomposed to allow a better identification of success criteria (meaning what needs to be done in order to complete each of the work tasks).

  To decompose the tasks, multiple approaches can be taken. They are usually divided between organisational approaches, verb-type approaches and noun-type approaches. Noun-type approaches tend to define the project work deliverables (as the name suggests) in terms of the components; verb-type approaches, that are used the most in space project management describe the deliverable of the project verb as actions and activities that need to be carried out to deliver these products. Lastly, the organisational approaches describe the deliverable project work in relation to the specific organisation units responsible for the specific part of the projects. Within these, the choice or structuring the work relates to the organisational characteristics, such as location of the project (in case of geographically complex projects), department/division structure or process-wise.

2.5.2 Gantt Chart

Gantt chart is one of the graphic methods used during the planning and monitoring phase of the project. It serves as a tool that allows us to organise and arrange tasks which belong to the project in a series of logical subsequent sequences as well as to define key moments (milestones) of a project. This allow us to clearly determine optimal moment to begin for each activity the way that the project is completed according to an intended schedule.

This method has been in use for more than 100 years as it has been developed by Henry L. Gantt during the Wold War I. For its clarity and easy way of creation, it has been incorporated into modern software tools such as MS Project or GanttProject. However, in its original shape, Gantt charts also do have certain disadvatantages:

- Gantt Charts do not reflect on dependencies between individual tasks - If there is other than a time dependence or a priority of a particular task, Gantt chart can not effectively sort out this issue.
- They are dependent on well defined and detailed Work Breakdown Structure - In case there is any important task or a milestone missing, it is not obvious from the first sight. This can cause severe issues and result in great delays or a potential failure of a project.
- They are not appropriate for very complex projects - The main advantage of a Gantt Chart is how easy and clear is to read and get oriented in them. This functionality is lost in case of large scale projects.

Despite the aforementioned weaknesses, Gantt charts are a popular tool, space industry including. They are a mandatory part of a project documentation for small scale projects such as projects within the REXUS/BEXUS campaign underneath which the Micro Gravity Space Printer is supposed to be primarily realised.

2.5.3 Modern Tools in Project Management

Aside of the traditional tools and methods, modern ways of managing projects more effectively are appearing. These tools are not only used in small teams of enthusiastic evangelists and innovators. They are utilised by governmental and non-governmental agencies, research institutions, university research teams, start ups, real businesses and other involved in project management. These tools aid to lead and manage projects and teams more effectively, assist project managers and improve communication within teams. Knowing that software is ever changing and the progress never stops, it is obvious that these applications and programmes will become outdated in future. To give this

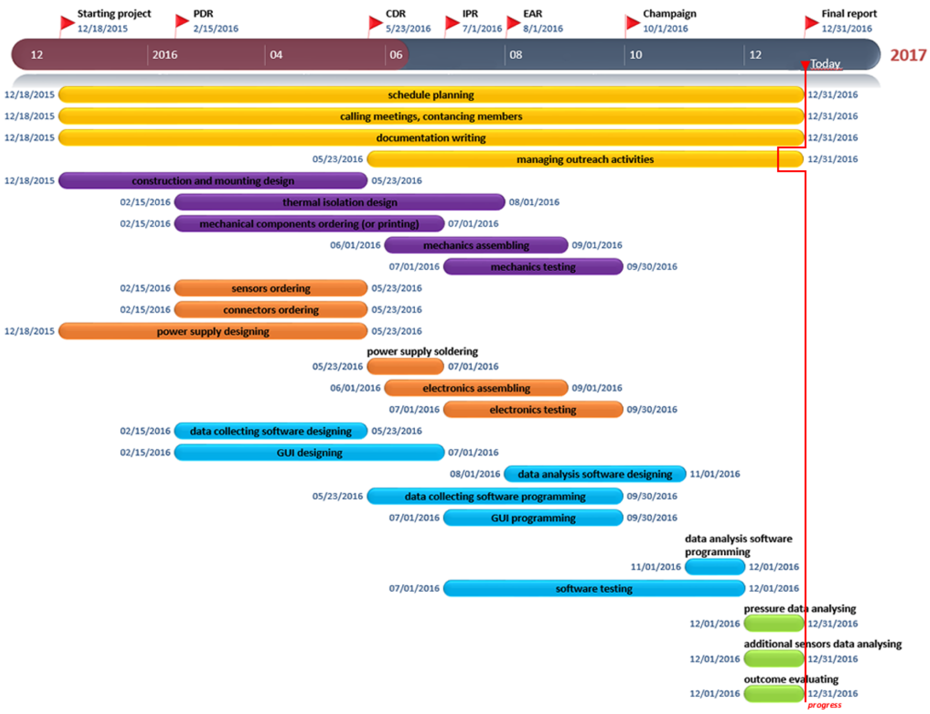

Figure 2.7: Gantt Chart of The PREDATOR Experiment project

thesis a contemporary context, some of the apps commonly utilised in space industry are worthy of mentioning:

- **Trello**

  Trello is a software tool that does not handle project management per se, but cna very well support its processes. It works as a virtual board, to which various cards can be pinned and moved around. These cards usually represent individual tasks to which either one or multiple team members can be assigned. Trello is mostly used in Agile approach, however, the tool is very versatile and categorisation can be individualised. An example of a product development board for Agile approach can be seen in Figure 2.8.

- **Slack**

  Is a tool dedicated to a team communication. It is based on real-time messaging, however all conversation remain stored in the app and using hashtags they can be categorised. This helps teams to organise their communication and potentially increases throughput. This application also allows file sharing, therefore the teams are not limited to written communication only.

- **Cloud tools**

  Nowadays, global organisations are using cloud services to be able to operate within greater distances and in real time. Cloud services is a

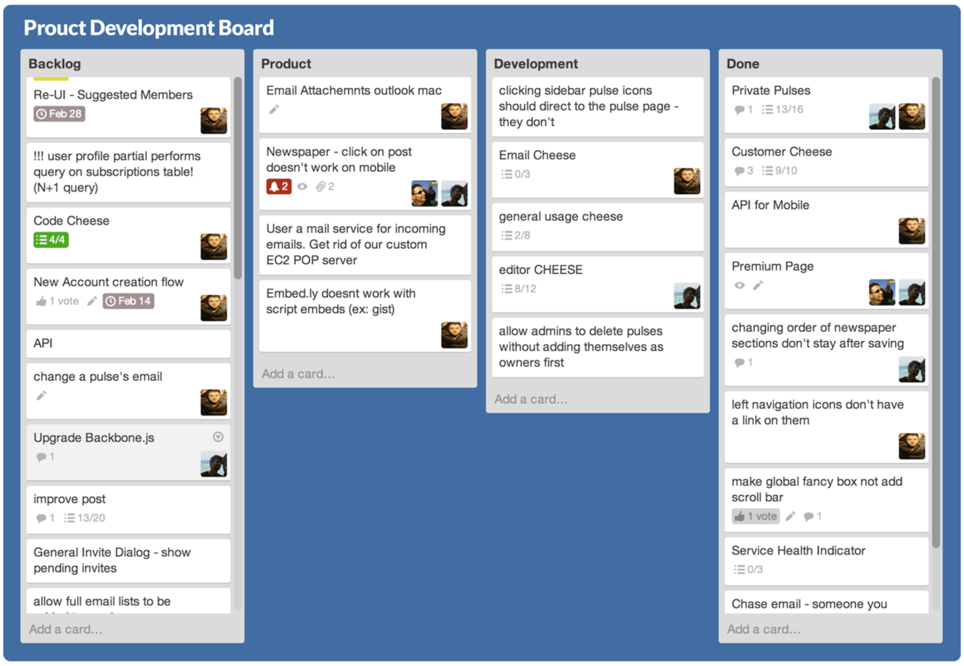

Figure 2.8: Product Development Board visualised in Trello

broad category of tools which operate via internet. It can be either a platform as a service, an infrastructure as a service or software as a service. Organisations in space industry are using all three. For an end user, such as individual scientists or project managers, is software as a service the most common one. Aside from Trello, Slack, Asana and other tools, the most utilised is G Suite, formerly known as Google Documents.

2.6 Risk Management

Real threat to project success are various risks. They often impose additional challenges to management and negatively project in cost, schedule as well as the actual technical performance Risk management is an appropriate answer to control them and it well performed risk analysis can save costs and positively impact the project in general.

Project risk management follows various objectives, which range from identification and assessment of a space project, through the risk reduction (or mitigation) and effective control of those risks that cannot be completely removed. This is achieved in systematic manner and requires educated and proactive approach. Within a project, risk management is an evolving process, and as the project advances, so does the identification, definition and potential mitigation of risks.

Space project risk management operates with various methods, starting with system and engineering analyses, safety analyses, process and components dependability and cost analysis. Major objective for risk management is a proper categorisation and ranking of risks per their criticality for project success. This enables to focus and manage fundamental issues.

At the beginning, certain project's risk management policy needs to be established. In accordance with this policy, processes of risk management are carried out, considering optimisation of available resources. Per se, risk management helps engineers and team managers by incorporating risk aspects in management and engineering activities and judgements during the whole of the project life cycle, including the preparation of project requirements documentation. This is done using an integrated, holistic approach. Such approach is generally beneficial for activities in areas such as:

- management, cost, and schedule;
- control over risk consequences;
- development, production, testing, operation, maintenance, and disposal, all together with their interfaces.

2.6.1 Process of risk management

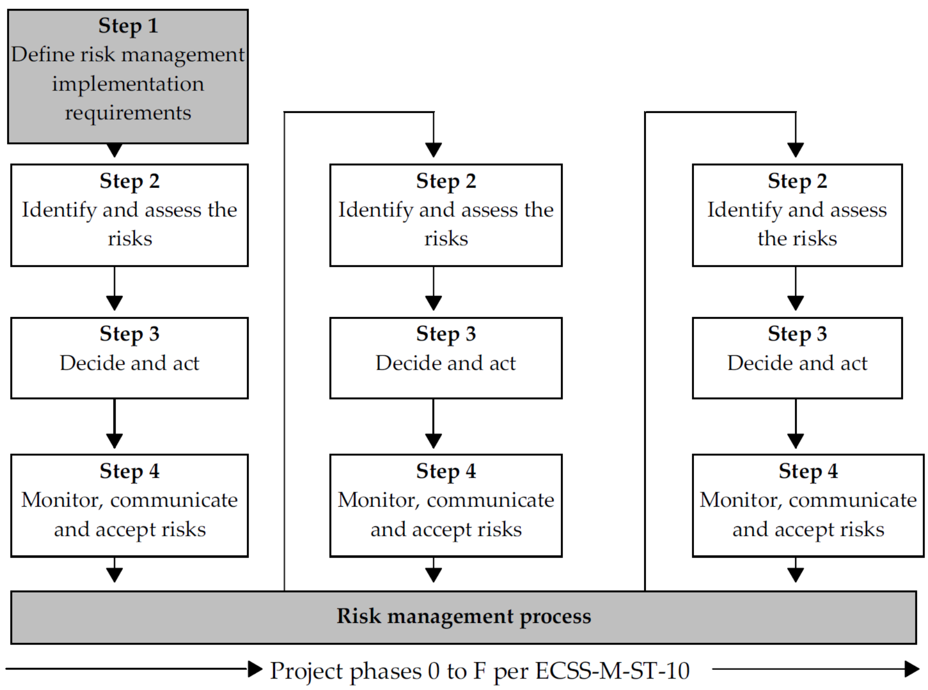

Figure 2.9: Risk Management Process Steps

In Step 1, the aforementioned project's risk management needs to be establish. Another important foundation for the whole process is a creation of risk management plan, however this has to be done in cooperation with other areas, mainly consisting of system and operation engineering and product assurance. The risk management process requires full cooperation and information coordination between the disciplines of the project.

In Step 2, the goal is to define and project risk scenarios and using the policy and plan from the previous step calculate the PxS ratio and rank them according to their potential impact afterwards.

In Step 3, the main objective is to carefully analyse to what extent are the previously listed risk scenarios acceptable. Based on this analyses, using available resources determine suitable risk mitigation strategies.

In Step 4, all tasks are related to monitoring, continuous updating and communicating the risks with stakeholders responsible for work in affected areas. All four steps are repeated in cycles during the entire duration of the project as the circumstances and amount of resources change over time. It is important to understand that a complex set of internal and external factors can change the situation within the project immediately and unforeseen risks in the initial phase of establishing policies and plans may have a critical impact on successful completion of the project.

2.6.2 Risk Categorisation

To properly list all the risk and prepare sufficient mitigation strategies, certain system of categorisation needs to be put in order. In space project management and risk management of space projects, following categories of risks are commonly used:

Risk ID:

- TC – technical/implementation
- MS – mission (operational performance)
- SF – safety
- VE – vehicle
- PE – personnel
- EN – environmental

In space project risk management, risks are evaluated using two dominant factors: Probability and Severity. For both of them, there exist standardised scales in accordance with ECSS-M-ST-80C that are in use and every considered risk can be assessed on the respective scale.

Probability (P)

- A. Minimum – Almost impossible to occur
- B. Low – Small chance to occur
- C. Medium – Reasonable chance to occur
- D. High – Quite likely to occur
- E. Maximum – Certain to occur, maybe more than once

Severity (S)

1. Negligible – Minimal or no impact
2. Significant – Leads to reduced experiment performance
3. Major – Leads to failure of subsystem or loss of flight data
4. Critical – Leads to experiment failure or creates minor health hazards
5. Catastrophic – Leads to termination of the REXUS and/or BEXUS programme, damage to the vehicle or injury to personnel

2.6.3 Risk Register

The purpose of a risk register is to clearly present project risks which have an impact on the quality of project outcomes. It uses a simple structure which contains the risk identification number, a brief description of the risk and ten it rates it using the aforementioned framework from the section 2.5.2.

2.6.4 Mitigation strategies

Another important part of a risk analysis is a list of mitigation strategies. These are procedures and processes aiming at reduction or a complete elimination of risks posed on the project. Mitigation strategies are a good reference for project planning as they often discover a need for an extension of a duration of a task or they may require an increase of costs per specific items. This may be unintuitive, however occasionally a small spending can protect the project from a failure on a large scale.

Chapter 3

Practical Part

Taking into consideration all the specifics of the scientific experiments and projects, it is necessary to modify the structure of the feasibility study. This mostly affects chapters regarding Market Analysis, Marketing Strategy, Current assets controlling strategy and Investment strategy as they are not relevant for this particular scientific feasibility study. For that reason, these chapters are absent.

3.1 Technical Description of the Experiment

3.1.1 Introduction

3D printing is a technology that is growing in important across all the technical industries. It has already taken an important role in mechanical engineering and aerospace engineering and automotive industry as a way of speeding up the design and development of new products. This technology, still often branded as “rapid prototyping” is slowly finding its way to the space industry.

As other technologies advance, it is becoming more and more apparent that long term deep missions will soon become a reality. This imposes major challenges related to a degradation of materials and components of a spacecraft. Such issue can be addressed by developing a technology that will be more sustainable and able to reuse available resources. Reflecting on current development in space exploration, printing in space seems like a viable and sustainable option for production of spare parts and later even biological tissue replacements. 3D printers can become a substantial tool for deep space exploration and long-term human space flight as they can reduce the mass that needs to be transported to Earth’s orbit due to the fact that instead of complete (and often eventually useless) components and spare parts, only the printing material would be carried and utilised for printing whatever is needed. Furthermore, in the future, there might be more options as mining and other ways of obtaining resources are being explored. Currently, only a limited research is being conducted in this field (and using this project would enable to create foundations for further research and ultimate advancement of this technology.

So called In Space Manufacturing contains work in many development areas that are key to reducing reliance on Earth-based platforms and enabling sustainable, safe exploration. These include:

- **3D printing from multiple materials** One of the desirable manufacturing metallic parts in space is a desirable capability for large structures, components with high strength requirements, and repairs. NASA is evaluating various additive manufacturing metal processes for use in the space environment.

- **External structures and repairs**

  As it has been mentioned before the lifetime of space structures is limited, and astronauts will need to perform repairs on tools, components, and structures in space. 3D printing could be potentially used to perform repairs.

- **Printed electronics**

  Ultimately, after mastering multi-material printing, components, sensors, and circuits that make up electronics used in spacecraft can be manufactured in space.

- **Printable satellites**

  As soon as the multiple material printing and assembling is mastered, this enables the on-orbit capability to create small scale satellites 'on demand.'

- **External structures and repairs**

  As it has been mentioned before the lifetime of space structures is limited, and astronauts will need to perform repairs on tools, components, and structures in space. 3D printing could be potentially used to perform repairs.

- **Additive construction**

  Developing an ability to manufacture structures on planetary bodies or asteroids using available resources, such as base camps and stations. As it has been reported, ESA is planning to use such technology for a construction of the so-called Moon Village.

- **Printing from organic materials**

  In long term, mastering this technology would enable not only maintenance and operation of technical components and systems of the mission, but also serve as a solution for a crew on board of manned missions. Certain advances have been already made, as researchers at University of Carlos III in Madrid successfully printed a fully functioning human skin tissue.

3.1.2 Objectives of the project

The project follows multiple objectives on different priority and importance level. This needs to be taken into consideration while evaluating the overall success of the projects.

- To design and build a printing device capable of printing in reduced gravity environment with low operational requirements.
- To research on material of samples printed in microgravity in comparison with normal Earth environment. It is expected that components printed in the microgravity conditions will have different material characteristics from the ones printed on Earth which negatively effects their durability and potential use as spare parts.
- To develop a printing material composed of thermally-resilient plastic and ferromagnetic dust which are melted together. This material is exposed to a magnetic field underneath the printer's bed and therefore it attracts the printed material and thus compensating the lack of gravity that is naturally present on Earth but missing during long term space missions.
- To develop a pressurised vessel inside of which will be the printing device situated. This will ensure stable conditions throughout the flight.
- To provide greater statistical sampling for mechanical property data of specimen printed in space.
- To isolate the effect of microgravity on the FDM process and study this phenomenon more in-depth.

3.1.3 Scientific Background

As this thesis mostly focuses on comprehensive overview and evaluation of the project from the managerial perspective, it is pointless to use detailed and thorough descriptions of the scientific phenomenons that the experiment is built upon. However, some of the critical ones need to be mentioned as they play major role in definition of requirements, selection of particular solutions for technical systems and helps us understand costs of particular components the discussed experiment consists of.

- **Effects of reduced gravity**

  In space, further away from the planet Earth, the effects of its gravitational field decrease. For most of the solid or stationary machines and systems this does not impose any major risks or negatively effects their operation. At this moment, this reality affects mostly astronauts as a life in gravity reduced environment causes loss of muscular tissue and confusion of vestibular system. A situation changes when it comes to mobile systems and technologies of 3D printing. As most of the methods used for 3D printing involve movable parts (liquids, dust or a solid material) they need to be fixated both prior and during the printing. For some methods, this is practically impossible, therefore it narrows down the amount of options regarding the method used.

As it can be found in the NASA Report released after first series of tests during the Zero-G Technology Demonstration Mission at the International Space Station, in general, the flight samples are mostly denser, strong and stiffer compared to the ground samples, however, certain material characteristics range widely and and there are variations in density throughout many of the samples. This can be caused by the reduced gravity environment as there is no constant force pulling down the unstable printing material which then only relies on the adhesive forces within the liquefied material. It is arguable how positively or negatively aforementioned characteristics affect the function and operational use of the components so a further investigation is required. At this stage, 3D printed components are not used as critical system components and they are being further examined and tested which reduces their rate of utilisation in real-life systems.

- **Homogeneous magnetic field**

In terms of liquefied materials and dust, there is a possibility to counter the effects of the reduced gravity environment. One of a ways is replace the missing gravitational force with artificially induced electromagnetic field. However, this would not be of any use as a regular electromagnetic field has a very irregular shape, as the magnetic field lines follow the direct from one pole to another. This can not effectively replace the gravitational force which works on much larger scale and therefore creates more homogeneous field in which objects are usually printed on ground.

A sufficient replacement would be a homogeneous magnetic field. Homogeneity refers to the uniformity of a magnetic field, meaning how uniform is the magnetic flux between the poles.

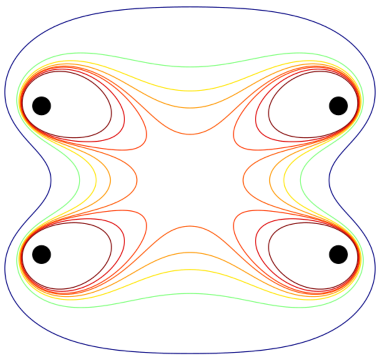

Figure 3.1: Homogeneous Magnetic Field

To generate such magnetic field, a special configuration of electromagnetic coils needs to be set up. The device is called Helmholtz Coil. In principle, Helmholtz Coil is able to generate an area of a nearly uniform magnetic field. This is achieved by using two solenoid electromagnets on the same axis. The device, consisting of two circular coils that are situated symmetrically on a common axis, is a widespread scientific instrument that is also used to cancel out Earth's magnetic field. There is also a possibility to improve the uniformity of the magnetic field by configuring two or more Helmholtz pairs with their axes perpendicular to each other.

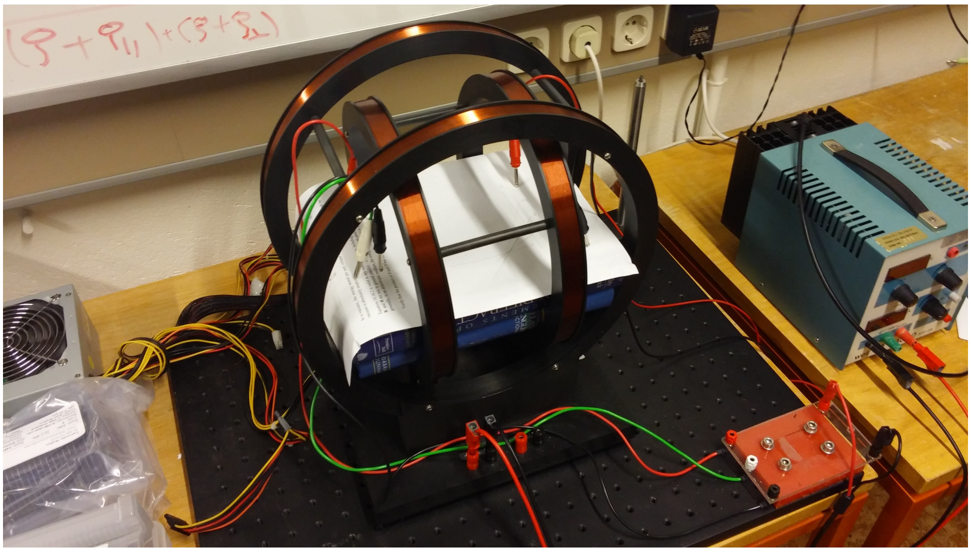

Figure 3.2: Helmholtz Coils at the University of Iceland Laboratory

As it is not in scope of this thesis, detailed calculations of the desired characteristics for the homogeneous magnetic field are not included, in order to determine the size of the device, following mathematical apparatus is used [12].

$$B = (\frac{4}{5})^{\frac{3}{2}} \frac{\mu_0 n I}{R}$$

Where B is the magnetic field B at the midpoint between the coils and μ_0 is the permeability of free space. Then the basic formula defines the magnetic B for a single loop with this formula:

$$B_1(x) = \frac{\mu_0 I R^2}{2(R^2 + x^2)^{3/2}}$$

In order to set up different variables for the magnetic field, Helmholtz coil is using n-loops, this propagate into the equation to calculate a coil with n-loops:

$$B_1(x) = \frac{\mu_0 n I R^2}{2(R^2 + x^2)^{3/2}}$$

And finally, a point halfway between the two loops has an x value equal to R/2, so calculate the field strength at that point:

$$B_1\left(\frac{R}{2}\right) = \frac{\mu_0 n I R^2}{2(R^2 + (R/2)^2)^{3/2}}.$$

Where
μ_0 = the permeability constant
$\mu_0 = 4\pi \times 10^{-7}$ T · m/A = 1.257×10^{-6} T · m/A,
I = coil current, in amperes,
R = coil radius, in meters,
x = coil distance, on axis, to point, in meters.

- **Materials**

  In order to make the homogeneous magnetic field an effective replacement of the missing gravitational force, it is required to use a material that is affected by the magnetic field. Typically, these are ferromagnetic materials, such as metals. Metals are not widely used for 3D printing as they require very high temperatures for melting and manipulation and creation of a desired component as well as very particular conditions and controlled environment throughout the cooling process. The cooling process greatly affects the final material characteristics of a metal component and currently developed methods are unable to achieve so. Therefore the current 3D printing technology nowadays uses plastic materials.

  To cope with that, a new composite material needs to be developed in order to make a method proposed for this project functioning. One of the options is to create a composite material that combines both of the desired qualities. It is ferromagnetic, therefore manipulable by a homogeneous magnetic field, and at the same time exhibit all the qualities of plastic materials: low melting temperature, easy manipulation, acceptable material characteristics. Considered source for the plastic basis would be Teflon or ABS, while the ferromagnetic dust could be some of the iron oxides.

3.1.4 Design of the experiment

The Design of the experiment is very complex as it comprise technical designs (mechanical, electronics, thermal and software) as well as a particular series of stages in which the experiment is carried out. For a better clarity, the overall design will be explained in following categories

- **Technical design of the experiment** Technical design of the experiment vastly depends on requirements and constrains set by the parameters of the space flight. In the original scenario, it is considered to use rockets provided by the REXUS programme. This programme enables students from universities and higher education colleges from all around Europe to conduct scientific and technological experiments on sounding rockets.

Within the REXUS programme, for a payload delivery is normally used a single-stage rocket using an improved Orion motor. This determines maximum dimensions for the considered payload. The baseline for the mechanical design is the outer structure with 14 inch diameter and various sizes of aluminium shells. The experimental device must fit inside of such container in order to maintain structural integrity of a vehicle.

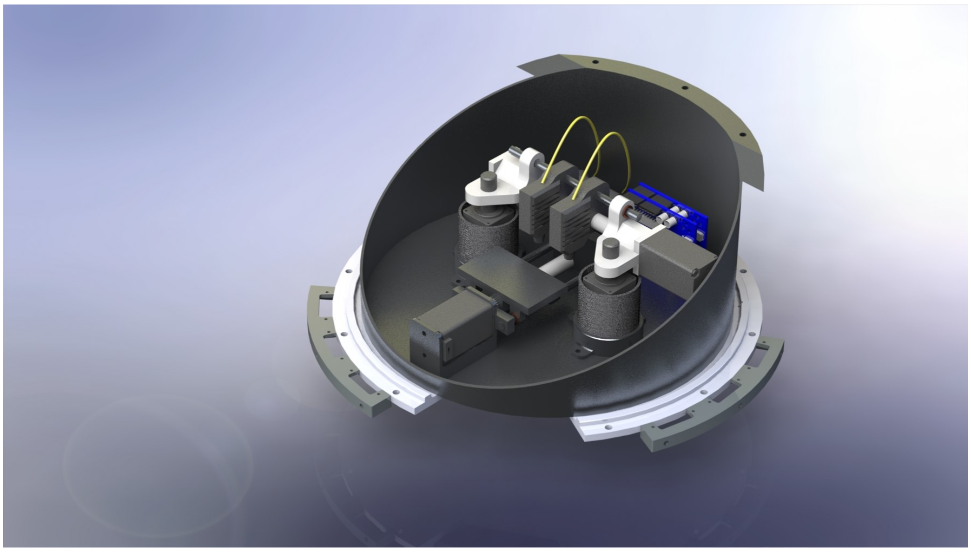

Figure 3.3: 3D Rendering of the Preliminary Mechanical Design

Experimental device is using components from Prusa i3 Mk2S printer with major modifications to its structure. As seen in the 3D rendering, a pair of heated printing nozzles is placed on a bridge between legs that serve as a support. It has been decided that with the limited time spent in the microgravity conditions, it is better to optimise space within the payload container and use multiple nozzles. This allows a simultaneous printing process and increases the amount of samples that can be used for later examination. Apart from the nozzles, the device has a movable printer bed, feeder which moves the printing material through the nozzle, set of legs based on threaded rods and set of motors allowing the nozzle movement in horizontal and vertical direction. This movement is ensured by a set of small step motors. One motor is powering the feeder, two motors are responsible for horizontal and vertical movement. Underneath the printing bed there is an Arduino unit responsible for the control of experiment as well as the heating systems. All components are in a very compact set-up to ensure that construction is sturdy enough to survive the acceleration during the start of the rocket.

For a successful measurement, it is substantial to understand the flight

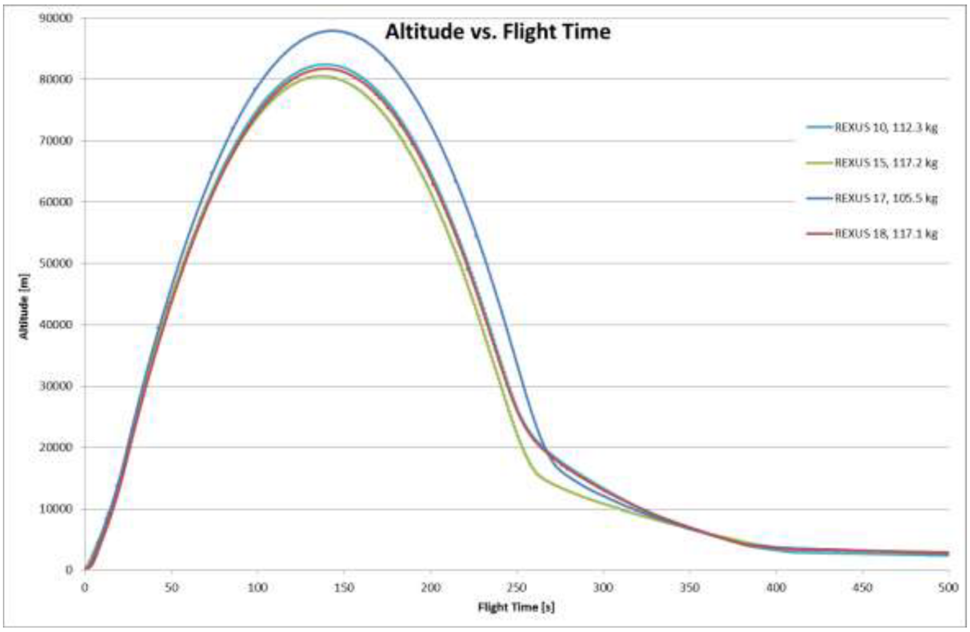

Figure 3.4: Altitude vs Flight Time

conditions provided by a launching vehicle. It is estimated, depending on the payload mass, that approximately 90 to 120 seconds of effective reduced micro gravity state can be utilised[13]. As seen in the the figure 3.4, the vehicle quickly reaches high altitude and operates in near-space environment. In such environment, extreme conditions are present. Since the rocket has no particular atmospheric protection, major pressure drop occurs which results in an actual vacuum. Apart from that, friction, as well as the the motor, heat up the rocket surface and inside environment. For the MG Sprinter experiment is important to maintain environment with stable temperature and pressure conditions. This can be achieved by developing an independent lightweight pressurised vessel which will protect the experimental device. A preliminary design of such device can be seen in a figure 3.5.

- **Stages of the experiment** The experiment itself is divided into three practical stages. According to the ECSS Standards, they belong to the Phase D and E, as at that moment, the project is well defined, considered as feasible and the production has commenced.These phases are partially overlapping and certain processes are conducted concurrently.

  1. Stage focuses on development of the printer as a device functional in the conditions of reduced gravity as well as other constrains related to the rocket flight (high temperatures, extreme acceleration, low pressure, dimension constrains etc.). This way the one of the main objectives of the experiment is accomplished.
  2. Stage focuses on development of specific kind of sample (shape and material wise) that would allow to conduct a comparative analysis

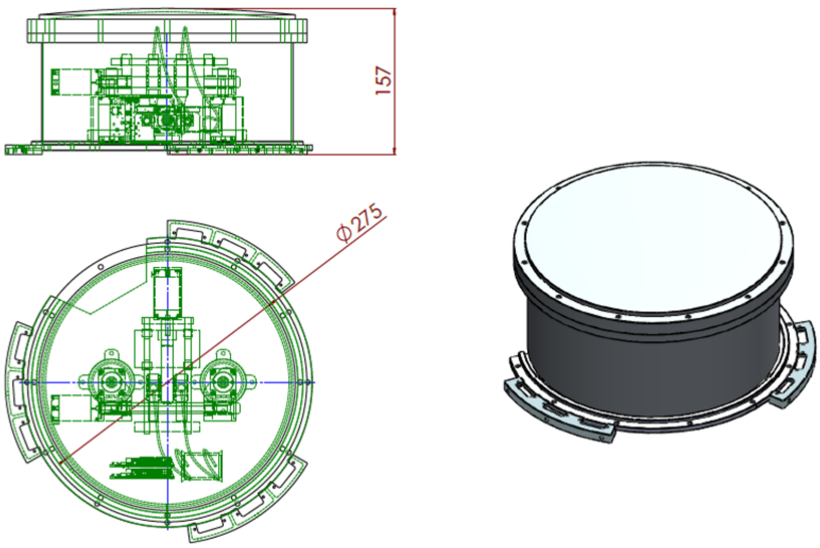

Figure 3.5: 3D Model of a suggested pressurised vessel

of flight and ground printed samples after the flight. In this stage, verification process and the measurement methodology is developed.

3. Stage focuses on development of a printing material composed of thermally-resilient plastic and ferromagnetic dust which are melted together as well as the technology to utilise it during the in-flight testing.
4. Stage focuses on the post flight ground comparative analysis and methods used to determine differences between samples printed both during flight and on ground in very similar conditions (temperature and pressure wise) in order to isolate the microgravity as the decisive factor for differences between samples.

- **Process Flow of the experimental flight**

Prior to the launch, after powering up the experiment all the sensors will start sending data to the ground station where it will be displayed and available for a fast feedback. Afterwards, the heating starts and when the the exact timing is known, the printing sequence "printing autopilot" with the exact timing will be run. During the launch further optical and temperature measurements are conducted. In the beginning of the microgravity state the nozzle is moved towards the printing bed and the printing starts. Measurements are ongoing to ensure that the printing is happening as predicted.At the end of the microgravity state, heating is switched off and nozzle moves from the printing bed again. Optionally a cooling is switched on (implementation of cooling will be decided based on thermal analysis of the experimental assembly). This concludes the flight part of the experiment. During the ground part of the experiment, printer is exposed to the same conditions that were measured during the flight (temperature and pressure development) and a new set of samples is printed out. Afterwards, the data recorded during both (flight and ground) printing sessions are evaluated to ensure that microgravity has been isolated as the main effect on printed materials. This process flow is is visualised in the diagram in Annex of the thesis.

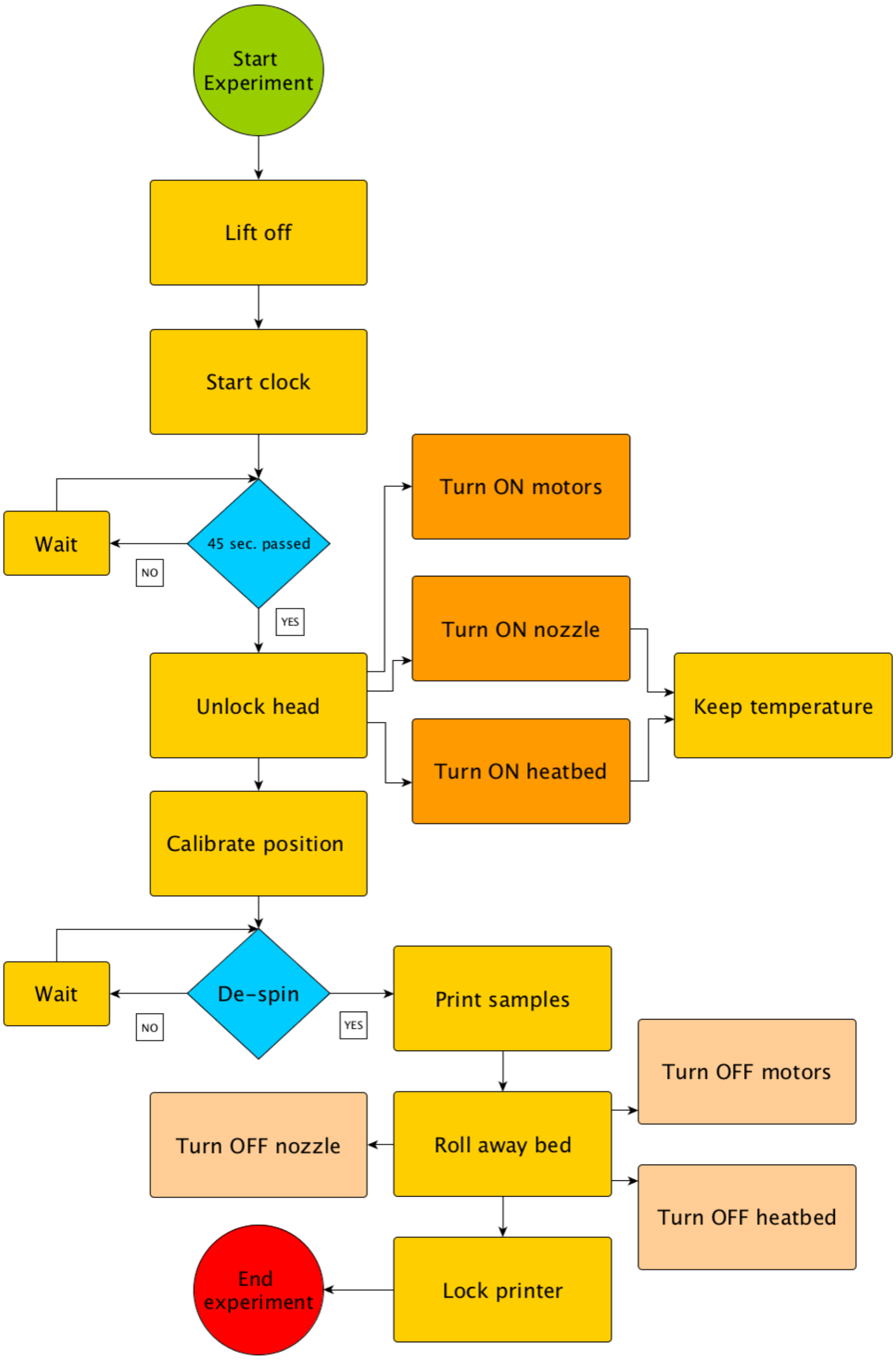

Figure 3.6: Logic Scheme describing the process flow

- **Data Analysis**

  The basic premise for an effective data evaluation is to conduct a comparative analysis using multiple invasive and non-invasive methods.

  - **Mass Measurement** A measurement of the mass using a calibrated laboratory scale in the laboratories of Czech Technical University in Prague, Faculty of Mechanical Engineering. Based on these repeated measurement, density can be calculated.

- **Photographic Inspection** As an elementary visual method, photographic inspection will be conducted. Each ground sample and flight sample. Following a previously decided pattern, each of the samples is photographed from various angles in scale. This method allows the first sight detection of potential damages or anomalies at each sample. Pictures should be in high resolution, available for more in-depth analysis later.
- **Mechanical Testing** Mechanical testing follows the previously mentioned non-destructive analytical methods. At aims at discovering and documenting mechanical properties of both flight and ground samples. Measurements at the testing facility of Czech Technical University can identify the tensile strength, yield strength, elastic modulus, and fracture elongation of the printed material.
- **Optical Microscopy and Scanning Electron Microscopy** As this technology is not available at CTU, other facilities (such as test centre at the ESA European Space Research and Technology Centre in Noordwijk) need to be used. It is considered that both optical and electron microscopes will be used for a detail surface analysis of printed samples in order to detect any visible damage and structural anomalies.

3.2 Organisation of the project

In order to organise the project successfully, certain tasks must be conducted. In terms of the project planning, it is required by the European Space Agency to define the Work Breakdown Structure; a basic time line of the project; work packages, Gantt chart of the project; Budget Estimation and detailed look into financial aspects of the project such as funding and Risk Analysis, including the Risk Register and mitigation strategies. In the project proposal, these need to defined on at least elementary level and as the project progresses, further specified with more accuracy. These requirements therefore serve as a baseline for this thesis which serves as a feasibility study for such project.

3.2.1 Work Breakdown Structure

As seen in the High level Work Breakdown Structure Figure 3.6, the project requires division into thematic teams. Tasks demanding similar skill set and knowledge base are grouped together and carried out by independent teams. Since this is the high level Work Breakdown Structure each of the branches will have a more detailed WBS developed as the project gets more specific definitions and goes more in-detail regarding its constrains and requirements. In practice, the project will be divided into following sub-teams:

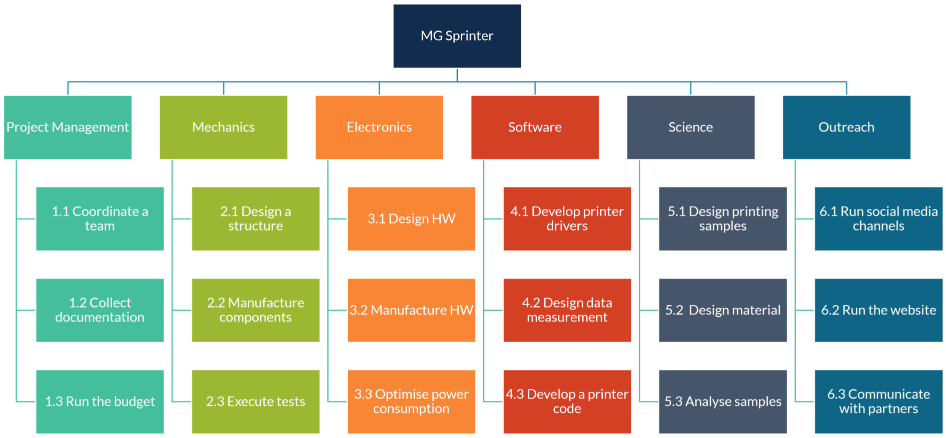

Figure 3.7: High level Work Breakdown Structure of the project

- **Mechanical & Thermal Design**

  Tasks that belong to the Mechanical and Thermal Design are related to the the structural development and mechanisms. These consist of the design of the experimental device itself and its tuning and testing, manufacturing the individual components and executing the tests that are ensuring low risk rate and dangers originating from a failure of any of the critical systems. Team members of this branch also support the science branch in the design of the composite printing material.

- **Electrical Design**

  In Electrical Design, all the electronics are put together. The aim is to either develop or find suitable hardware solutions (chips, processors, sensors, wiring); apart from that, development of hardware interfaces with other electrical components of the rocket, such as communications and power supply. Ultimately, as the power supply is limited, optimisation of power consumption is desired.

- **Software Design**

  In terms of software design, first, the logical scheme of the measurement and printer's functionality needs to be developed. This impacts the work of both Mechanical and Electrical Design, therefore in the initial stages these teams work closely together. The Software Team needs to develop drivers to effectively control the printer and data measurements sequences.

- **Science**

  Core of the work for the Science team are tasks related to material sciences. The team is required to design suitable printing samples that will allow meaningful analysis of the printed specimen. Furthermore, a crucial task is to develop and test new composite material. Aside of the actual analysis of the printed samples, team members are required to develop comprehensive methodology for the material analysis.

- **Outreach**

  Nowadays, outreach of experiments is growing in importance. It was understood that the communication with both wide public and a scientific community are beneficial for spreading the results and can provide with long term sustainable funding of future projects. In the outreach, the team will be responsible for communication on social media channels such as Facebook and Twitter, create content and maintain the project website as well as to directly communicate with public and other relevant stakeholders.

- **Project Management**

  Although each of the team is in a way self-governed and managed by its leader. This branch stands alone, as the project needs an independent leadership, control and constant monitoring. With this complexity of a project, a project manager supports other teams with the administration and documentation of the entire project. Apart from that, he runs the budget and closely cooperate with the Outreach team in regards of communicating with project initiators. It is expected that the Project Management will consist of two people, the project manager and his/her deputy.

Other than the Project Team Branch, each of the small teams will consist of at least three or four members so they could replace and help each other throughout the development if needed. As this is a student experiment team, there is a strong emphasis on learning of new team members. This way new team members would avoid unnecessary obstacles made in previous projects and they could focus on the development and gaining the learning experience.

Additionally, each team will be also responsible for its own chapter in the project documentation; coordinated from above by the project manager. This way, a smooth documentation of the whole process of the project is ensured.

3.2.2 Timeline of the project

Project such as Microgravity Space Printer is suitable for various development schemes. Of the schemes within a geopolitical region, the most suitable seem to be the REXUS (Rocket Experiments for University Students) programme.

As it is expected to realise the full scale project within the REXUS programme, workload related to creation of the project time line and planning of the schedule is reduced. REXUS projects are using the Standardised ECSS Project Life Cycle Model[6], therefore phases mentioned in the Chapter 2.1.3 are adopted. The structure is simplified and uses lower amount of reviews as milestones. For REXUS programme, the project is divided into pre-development phase prior to the application for the programme support itself, and the actual development which commences as soon as the project gets approved by the Board of Experts. It's important to mention that execution project is variable and depends on what cycle of the REXUS programme would be chosen. There is also a possibility (as it will be mentioned in the evaluation of the project) to realise the project in different programmes and development schemes, should an up-scale or down-scale alternative of the project be chosen. For the purpose and practical demonstration of the chosen project management methods, this variety of options has been narrowed down to the REXUS programme alone and its closes programme cycle.

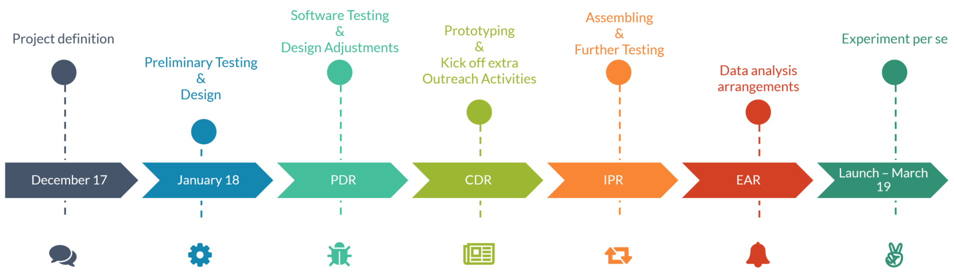

Figure 3.8: Simplified visualisation of the D phase of The MG Sprinter project

The entire duration of project is over 2 years and the development phase 1,5 starting with the Selection Workshop and approval by the Board of Experts in Q4 in year 2017, going through the entire year 2018 with a launch of the experiment in Q1 of 2019. Using the previously defined terms and specifics regarding reviews and project documentation, more specific general progress plan sets following milestones:

1. T-18 months: Call for experiment proposals
2. T-16 months: Project Proposal submission deadline
3. T-16 months: Proposal shortlisting
4. T-15.5 months: Selection workshop and presentation of proposals
5. T-15 months: Final experiment selection
6. T-13.5 months: Project Documentation v1-0 submitted
7. T-13 months: Preliminary Design Review (PDR)
8. T-9 months: Project Documentation v2-0 submitted
9. T-8.5 months: Critical Design Review (CDR)
10. T-7.5 months: Project Documentation v3-0 submitted
11. T-7 months: IPR at experimenters' organisation
12. T-5 months: Project Documentation v4-0 submitted

13. T-4.5 months: Experiment Acceptance Review

14. T-4 months: Delivery of Experiments to Integration Week (ITW)

15. T-2.5 months: Bench Test

16. T-0.5 months: Spin and Balance Test

17. T+0 months: Launch Campaign of the experiment

18. T+0.5 month: Flight Report Documentation from experimenters submitted

19. T+1 month: Distribution of the REXUS post flight Report used for flight data analysis

20. T+3 moths: Project Documentation v5-0 submitted including experiment results

21. T+4 months: Publication of Final Report/Results Seminar

3.2.3 Work Packages

To successfully create a Gantt chart for the Micro Gravity Space Printer project, work packages need to be created and defined. A work package is an elementary unit that organisational charts (such as Gantt chart) are made of. It includes description of the task as well as start and end dates for the task. Work packages are usually prepared by team members who are familiar with the peculiarities of the task they are responsible for thus they can very well estimate the duration of tasks. As this is a feasibility study, exact personal management is not known yet, therefore tasks from the High level Work Breakdown Structure are used and broken further into sub tasks and respective work packages.

3.2.4 Gantt Chart

Regarding the time schedule, The MG Sprinter Gantt chart is based on the time line outlined in the section 3.2.2.

Figure 3.9: Gantt Chart

3.3 Financial Aspects of the Project

Generally speaking, most of the scientific experiments and projects do not have a direct commercial utilisation, therefore it is barely possible to calculate the actual value of the scientific project. However, a vast portion of applied research results in development of commercially usable and profitable technologies.

3.3.1 Budget Estimation

Mechanics		Electronics		Software		Science		Miscellaneous		Total Costs	
Pressurised vessel(s)	€500	PCB Components	€250	Licences	€200	Material Development	€400	Promotional Materials	€200	Risk reserve +20 %	€2680
3D Printers	€3000	Sensors	€800	–	–	Testing Facilities Rental	€600	Social Media	€100	–	–
3D Printer Components	€300	Step motors	€280	–	–	–	–	Web Hosting	€50	–	–
Structural Components	€250	Cabling	€50	–	–	–	–	Team building	€200	–	–
Helmholtz Coil	€4000	Connectors	€100	–	–	–	–	Travel Expenses	€1500	–	–
Cooling system	€220	–	–	–	–	–	–	Shipping	€200	–	–
Production Material	€200	–	–	–	–	–	–	-		–	–
€8470		€1480		€200		€1000		€2250		**€16080**	

Figure 3.10: Preliminary Budget Estimation for the MG Sprinter Project

Following the previously set project division, the preliminary budget represents costs of each project team and major expected expenses. These mostly account for material costs, such as specific technical components, systems and materials used for construction. As the project has an international background, it is important to include travel expenses. Various tests, review presentations and the actual flight campaign take place abroad and at least part of the team (usually team members that are the most relevant for each respective review) should attend these meetings. Reasoning for the figures in each of the branches are described in its respective category:

- **Mechanics**

  Underneath this category, an array of items opens up. As it has been mentioned in the technical design of the experiment, most of the costs consists of the 3D printers (as it is required to use multiple ones - two at least - and modify them to function in a space environment and the device responsible for generation of uniform magnetic field. Figures for all the items have been chosen after careful market analysis and calculating the average price of each device. It is important to mention that the estimation is rather conservative and intentionally is using values from the upper range of the available products.

- **Electronics**

  Items in this category exceed normal prices of components available on a regular market. This is caused by a particular selection of components. As in space research, electronics must have much wider temperature operation range, reliability and sufficient radiation protection. Therefore, even basic components require space certification, which dramatically increases their price.

- **Software**

  As of software, only some computing programme licences and drivers are required and most of the solutions will be tailor made by the team members themselves. For this reason, this item is estimated as relatively low. In case of any major increases, this can be sourced from the Risk reserve.

- **Science**

  The highest cost in terms of the science team will be the new composite material development, however, thermal-resilient plastic is available on market for relatively cheap price if it is purchased in large quantities. Therefore, the estimated costs are derived from the price lists of wholesale stores. Additionally, it has no meaning to buy all of the measurements devices such as optical and electron microscopes. Purchase of these devices would undoubtedly multiplied the entire project budget.

- **Miscellaneous**

  In this category, all the other expenses are covered. Since the team of approximately 15 to 20 people will spend working for nearly two years together, it is important to invest into building an efficient team and develop functioning group dynamics. Furthermore, including expenses on social media (such as sponsored posts on Facebook or Instagram) can not be omitted. As it has been mentioned in the introduction of this section, the budget estimation also covers travel expenses that exceeds the maximum amount guaranteed by the REXUS programme organisers.

3.3.2 Financial resources

In project planning, it is crucial to not only identify potential costs, but also determine ways of sustaining the budget and funding each of the respective items on the list. There is a need to diversify the funding and ways of covering expenses. If there is a way how to decrease costs without imminent decrease of quality and deteriorating from the objectives, it increases the chance of realising the project. In the estimated budget, there are several major items. For some of them, such as the printers, certain savings can be achieved by cooperating with 3D printer producers, such as Prusa Research. Donation or a partnership would be an option.

Other than that, facilities, such as workshops used for manufacturing and assembly, testing rooms and devices used for the analysis of printed samples can be provided the Czech Technical University in Prague - Alma mater of the project team - or affiliated institutions. This can save up a lot of costs and it has proven as a sufficient solution in the past with The PREDATOR Experiment team.

The PREDATOR Experiment was supported by the research program no. SGS15/212/OHK3/3T/13, “Safe and Safety Elements in Aerospace and Space Technology II”, of the Czech Technical University in Prague. It is also expected to use similar ways of funding the remaining expenses.

Another great advantage of taking part in the REXUS programme is wide financial support. Participating organisations are committed to cover the rocket launch itself (which would be otherwise extraordinarily expensive) as well as to support teams financially. All project teams selected for the programme has a privilege of sending two fully covered team members to every review.

Lastly, in regular teams, one of the major items would be salary-related costs of the team members. This is a huge advantage of a student project, as all the team members are required to be full time university students and therefore work on the project is a learning experience and not an actual job per se. Optionally, university scholarships can be used an incentive.

3.4 Environmental Aspects of the Project

Every regular feasibility study includes environmental aspects of the project, assess potential health risks and evaluates impact on the environment. This is usually listed in Environmental Risk Register and its subsequent analysis. The situation with space project usually differs as they are designated to function in outer space, outside of the environment that is commonly affected by terrestrial construction or investment projects. For this reason, the list of risks would not be sufficient for a complete analysis, all potential risks - at least remotely related to the damage of a natural environment or imposing threats to human health - are included in an extensive Risk Analysis in chapter 3.5.3.

3.5 Risk Management of the project

As in every project, there is a threat of a complete or partial failure of the project due to project risks. Due to a complexity of the MG Sprinter Project, a variety of risk has been identified. Risks with greater magnitude are not mentioned as they exceed the acceptable levels. In a following section the project Risk Register can be found.

3.5.1 Risk Register

In the following Risk Register, relevant risks are listed. To understand the structure, each category of risks has been explained. Only risks that have the PxS product of a value "low" and "very low" are listed. Medium, High and Very High Risks are not acceptable in space project risk management. Should any risk of this magnitude occur, a new team process needs to be implemented or a new baseline (in the risk management plan) needs to be established.

ID	Risk	P	S	PxS	Mitigation
MS00	Nozzle gets clogged	B	4	low	Mit. Strategy 1
MS10	Measurement data does not get saved in memory	A	1	very low	Mit. Strategy 2
MS20	Material of mechanical structure might degrade in higher temperatures	A	4	very low	Mit. Strategy 3
MS30	Uniform magnetic field can influence other electronics	B	3	low	Mit. Strategy 4
MS40	Temperature outside operating range of components	B	3	low	Mit. Strategy 5
MS50	Pressurised vessel failure in low pressure	B	4	low	Mit. Strategy 6
MS60	Electrostatic discharge might cause failure to components	B	3	low	Mit. Strategy 7
MS70	Software program in micro controller fails during flight	C	3	low	Mit. Strategy 8
MS71	(Residual of MS70)	B	1	very low	Mit. Strategy 9
MS80	Flight vibration destabilise the printer calibration	B	2	very low	Mit. Strategy 10
MS90	G-force during the start destabilise the printer calibration	B	2	very low	Mit. Strategy 11
MS100	Printing Material may degrade before the flight	C	3	low	Mit. Strategy 12
MS101	(Residual of MS100)	A	1	very low	Mit. Strategy 13
MS110	Autopilot memory fails	B	1	very low	Mit. Strategy 14
MS120	Experiment not delivered on time at ESRANGE	B	4	low	Mit. Strategy 15
MS130	Experiment is influenced by emission of other experiments	B	3	low	Mit. Strategy 16

Table 3.1: Risk Register, part 1

3.5.2 Mitigation Strategies

In the section 3.5.3, 25 potential risks are listed. Although they are all rated with "low" or "very low" magnitude, it is important to develop and formulate mitigation strategies in order to cause minimal damage, deviation for the project scope and limit potential financial expenses. Mitigation strategies can be grouped together, as some of the risks belong to the same category and the way to reduce the risk or completely mitigate it is similar.

- Mitigation strategies 1, 3, 6, 10, 11, 19 are of a similar nature: Risks are

ID	Risk	P	S	PxS	Mitigation
SF10	Injury by high temperature components post flight	A	5	low	Mit. Strategy 17
SF20	Injury by high temperature components during integration	A	5	low	Mit. Strategy 18
SF30	Pressurised vessel explodes in case of crash landing	C	1	very low	Mit. Strategy 19
SF40	Pressurised vessel may cause cuts upon retrieval of the experiment	A	5	low	Mit. Strategy 20
EN10	Potential environmental damage caused by the materials used	A	3	very low	Mit. Strategy 21
EN20	Printing material may cause pollution if dispersed in environment	B	3	low	Mit. Strategy 22
TC10	Parts do not arrive on time during development	C	3	low	Mit. Strategy 23
TC20	Critical component is destroyed during testing	B	3	low	Mit. Strategy 24
PE10	Low availability of experts during summer holiday creates delays in design	C	2	low	Mit. Strategy 25

Table 3.2: Risk Register, part 2

caused mostly by mechanical errors that are usually caused by insufficient design and lack of precision in calculations. It is suggested to extend tasks related to verification and testing (such as vibration test) and reconsider the choice of materials.

- Mitigation strategies 2, 8, 9 and 14 are closely related to the software team tasks. In order to reduce risks for MS10, MS70, MS71 and MS110, it is suggested to double the system hardware, therefore in case of failure there is a back-up system that can functionally replace the original. Additionally, all software solutions needs to be run through software inspections and virtually conduct the experiment in a modelling software.
- Mitigation strategies 4, 5, 7 and 16 are related to risks that are caused by electronics hardware failure. These can be tackled by a careful choice of components. It is up for a careful consideration if a slight investment into more expensive hardware would not be beneficial for an overall success of the project.

- Mitigation strategies 12, 13, 21 and 22 is related to the risk that is caused by a potentially imperfect process of a material development. It is suggested to prolong the development and include more testing focusing on a long term degradation and relaxation of the printing material.
- Mitigation strategies 15, 23, 24 and 25 are related to logistics. This means that for logistical tasks there needs to be more time allocated and greater time reserves created.
- Mitigation strategies 17, 18 and 20 mitigate health risks. In order to cope with these, user manuals for manipulation need to be created and work safety policies must be enforced.

3.6 Evaluation of the project

The Microgravity Space Printer is a very complex project with fields of interest that span from research, development of a new technology with a considerable societal and environmental impact (in a positive manner). Following evaluation is divided into several categories and takes into consideration very peculiar nature of the project as well as its specifics:

- **Evaluation of environmental impacts**

  This touches the environmental aspects of the project: the MG Sprinter project itself imposes very little risks to human and natural environment. Risks are mostly related environmental pollution, however, it can be said that there are any materials which would pose any health risk or cause an environmental damage.

  In long term, the project and projects subsequent to this one can actually have positive impact as the technology presented in the MG Sprinter research is theoretically more efficient and decreases material costs, which is a beneficial factor for natural environment.

- **Financial evaluation of the project**

  Regarding the financial aspects of the project, the project can be considered as relatively inexpensive. In comparison with experiments of a similar scope, costs are lower. To give an example, Upgraded Pulsating Heat pipe Only for Space (U-Phos), another REXUS project, had an overall budget of 47,700 Euro. Therefore, 16,080 Euro for the MG Sprinter project appears to be a reasonable budget estimation. Funding opportunities presented for this project seem to be realistic and very promising. It might be interesting to focus on establishing partnerships with subjects with a particular interest which could push the costs even lower. The entire project is widely affected by available funding opportunities provided by the university, nevertheless, from the financial perspective, the project definitely looks feasible.

- **Technical and technological solution of the project**

  Regarding the technical solution of the project, it is an indeed interesting technological concept. However, such complex project may be difficult to keep within the defined scope. Development of the printer itself is already a challenge as well as the lightweight pressurised vessel. Newly developed composite material is yet another challenge. It is expected that the team will build upon experience of the previous REXUS/BEXUS team, therefore a knowledge transfer sessions are suggested.

- **Evaluation of the project organisation**

  In terms of organisational matters, a major advantage of the project is the fact that it closely adheres to the European Cooperation for Space Standardization norms and standards. With this particular project proposal, guidance provided by the European Space Agency is making it very strong and significantly improves the quality of the project. The time estimation, beginning with individual tasks and going through work packages and work of individual team is sober and realistic. It provides the project team with sufficient time to keep the quality of the outcomes high. On the other side, a potential risk is a time availability of the individual members. As it is a student project, some initially unforeseen motivation and commitment issues may propagate as the project progresses further and work load increases. For that reason, it is suggested to focus on the team motivation and development of healthy team dynamics and more importantly, thorough recruitment process. Over all, the project at this moment is well prepared and can be recommended for realisation.

3.6.1 Potential up-scale and down-scale alternatives

Although the original scope of the project has been well estimated to meet the requirements for sufficient scientific advancement and at the same time using all the available resources to maximum, it is important to present both up-scale and down-scale alternatives of the project. The final decision of which alternative should be realised vastly depends on circumstances, such as funding and human resources, as well as the institutional support.

- **Up-Scale Alternative**

  It may occur, that a better funding opportunity will present itself or there may be a better opportunity for the experimental rocket flight. Some of the opportunities could be a flight with MASER or MAXUS rocket, which present with better micro-gravity conditions and can improve the quality of the measurement and thus the overall quality of the outcomes. This depends on opportunities provided by space agencies and private sector. Should such up-scale happen, it is required to redefine the project and especially the funding and management of human resources. Better flight conditions presents the team with higher complexity of problems, therefore a shift from a student team towards professional researchers is the following step. Such project can be PRODEX funding.

- **Down-Scale Alternative**

  On contrary, a cut in funding may occur. Should such situation happen, certain measures must be taken. It is obvious that with limited funding, the scope of a project would have to be redefined. This would probably result in reconsidering the project objectives. As an obvious choice, the composite material development would be dropped just as the utilisation of a uniform magnetic field. A new main objective would most likely aim at developing the printing device and extend the known information of samples printed in space and behaviour of FMD technology in reduced gravity environment. Still, such project provides with enough new information that its realisation would be justified.

In conclusion, there different alternatives have been presented. Two of them are able to provide us with extraordinary scientific results which may be turned into profitable business in case of a project success. This would require a creation of a new, subsequent project that would build upon the results.

Project Microgravity Space Printer is well design and covers all sorts of aspects. It has a potential to combine a learning experience at a higher education institution, advancement of human knowledge, development of a new technology and a business opportunity. It carries a very low amount of risks and even pessimistic, down-scale alternative presents an interesting project with a very good price-to-value ratio. The Micro Gravity Space Printer project can be definitely recommended for realisation.

Chapter 4

Conclusions

The Microgravity Space Printer Project is an ambitious experiment aiming at developing an innovative technology. A great advantage is its immediate utilisation: it solves a long term issue for which there are currently not existing sufficient solution. It is therefore filling the gap and thus easy to see a potential development. This technology can be also used on Earth. With certain level of modification, it can take control of a significant part of a market. Uniform magnetic field can be generated in a way that it improves material characteristics in designated directions.

To conclude this thesis, it is appropriate to give several recommendations which may improve the quality of the project outcomes. Some of the recommendations are:

In The Micro Gravity Space Project - Feasibility Study, we have had an opportunity to learn more about project management, its traditional as well as unconventional contemporary methods and tools. We have become familiar with the project life cycle and risk management and some of the ways these are approached in space project management.

This all was required to set a baseline for the practical part of the thesis. In the practical part, we have used the theoretical knowledge to introduce the Micro Gravity Space Printer project - an effort suggested to be carried out by a student team. Scientific background, technical description, organisational and other aspects of the project: this all had to be described in order to evaluate the project and assess its chance for a successful realisation.

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