Project Management Incorporation in Space Systems Engineering Projects

by

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A thesis
presented to the University of Manitoba
in fulfilment of the
thesis requirement for the degree of
Master of Science
in
Mechanical Engineering

Winnipeg, Manitoba, Canada 2020

Abstract

This study presents a highly adaptive project management approach that acts as an alternative to traditional project management. The current method of managing projects is rooted in the developments from the space race, and have influenced the way complex projects of many industries are managed. The traditional rigid system allows for effective organization and planning but has difficulty adapting to changes that are required or unexpected.

There are tools found in other industries that have been successful in their respective environment. A review of Agile Philosophy, Lean Manufacturing, Concurrent Engineering, and Theory of Constraints is provided. These tools are applied to an ongoing student led nanosatellite project that is receiving guidance and support from the Canadian Space Agency. The project progress is monitored through requirements and verification as an alternative to traditional Earned Value Management to demonstrate task completion.

Data provided by a complex industry satellite project provides insight into how a traditional managed project evolves from design to manufacturing. Data reviewed includes the labour hours and amount of active tasks. As verification activities show how the satellite complies with requirements, the verification state was reviewed as manufacturing and testing progressed.

Findings show that the ManitobaSat-1 was able to allocate more labour hours to the technical design of the project compared to the industry project. The project has been able to meet the accelerated Canadian CubeSat Project schedule, providing deliverables in time for review deadlines. The research provides and analyses ManitobaSat-1 project health data as to demonstrate the impact of non-traditional approaches.

Acknowledgements

I would like to thank Dr. Philip Ferguson for all the guidance and information he has provided from the very beginning. I have greatly appreciated his patience and always valued his informative insight into the space sector and the academic process. He has shared with me demanding tasks, satisfying successes, and valuable experiences that have promoted my growth in the engineering discipline.

I would like to thank Magellan Aerospace and the Canadian Space Agency for providing funding to this research. The expert opinions they have made accessible has ensured a thorough understanding of how the space sector plans and develops complex space systems.

I would also like to thank Kathryn Atamanchuk for teaching me the project management methods, and providing guidance in the Project Management Body of Knowledge. It has provided me with valuable skills and provided the groundwork for this study and the ManitobaSat-1 project. And to my committee members, Dr. Sean O'Brien, and Dr. Karen Dow, for providing me their time to review and provide feedback for this study.

And I would also like to thank Accuer has provided valuable guidance in how to apply lean agile tools into a complex project. They provided important training and ensured we understood the core principles and philosophies. They have been very supportive whenever the ManitobaSat-1 team or I have any questions.

And to the STARLab, who have been my support group and solidarity in a complex satellite project. I greatly appreciate your friendship in the easy times and your patience, knowledge, and insight in the hard times.

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Nomenclature

Acronyms/Abbreviations

AC	Actual Cost
ADCS	Attitude Determination and Control System
AIT	Assembly, Integration, and Test
CAD	Computer Aided Design
CADM	Communication and Data Management
CCP	Canadian CubeSat Project
CDH	Command and Data Handling
CDR	Critical Design Review
ConOps	Concept of Operations
COTS	Commercial off the Shelf
CSA	Canadian Space Agency
C-TAPE	Centre for Terrestrial and Planetary Exploration
ECR	Engineering Change Request
EGSE	Electrical Ground Support Equipment
ESA	European Space Agency
EVM	Earned Value Management
FBC	Faster, Better, Cheaper

FM	Flight Model
FRR	Flight Readiness Review
FSW	Flight Software
HQP	Highly Qualified Personnel
ICD	Interface Control Document/Drawing
ID	Identification
ISS	International Space Station
IT	Information Technology
JIT	Just-in-Time (Manufacturing)
JWST	James Webb Space Telescope
MCR	Mission Concept Review
ME	Manufacturing Engineering
MGSE	Mechanical Ground Support Equipment
NASA	National Aeronautics and Space Administration
OPS	Operations
PCU	Power Control Unit
PDR	Preliminary Design Review
PM	Project Manager/Management
PMBOK	Project Management Body of Knowledge
PMP	Project Management Plan
PFM	Proto-Flight Model
PRR	Production Readiness Review
PV	Planned Value
RSSSA	Remote Sensing Space Systems Act
RVCM	Requirements Verification Compliance Matrix
SDR	System Definition Review
SE	Systems Engineering

SEMP	Systems Engineering Management Plan
SIR	System Integration Review
SMAD	Space Mission and Analysis Design
SOW	Statement of Work
SRR	System Requirements Review
STARLab	Space Technology and Advanced Research Laboratory
TOC	Theory of Constraints
TRL	Technology Readiness Level
WBS	Work Breakdown Structures

Chapter 1

Introduction

1.1 Motivation

One common belief is that the cost of technology is the main budget driver of modern missions, but Richards [1] argues that tradition has had a higher impact on costs. Richards notes that one of the key factors that drive the project cost is the traditional process that demands first time perfection. Emphasis is placed for project managers to create a well defined and detailed project to ensure cost stability during testing and manufacturing [2] [3]. Change implementation has an exponentially increasing cost as the project matures [4], to the point that the Space Mission and Analysis Design (SMAD) textbook [5] states that "hardware manufacture and test heavily influence the program's cost and schedule." The best case scenario has changes occur early when change incorporation is at a low cost, but Ward *et al.* [6] conducted a study that found that change requests increase as projects mature. Ward *et al.* note that project complexity impacts change propagation, as complex space projects are a collaboration of interlinked subsystems and teams. Changes implemented in one subsystem causes a cascading effect on other subsystems and teams to accommodate requested changes.

There have been different approaches that allow for processes or projects to be able to quickly adapt to demands at different times with minimal cost impact. One modern example is Industry 4.0 [7], the fourth industrial revolution promoting short development periods, mass customization, flexibility, and resource efficiency. Industry 4.0 accomplishes these focuses by incorporating existing technology to push development in accordance with customer demands. The technology push can range from logistic planning [8] to fabrication using additive manufacturing [9].

Although these options are available, the space industry has been slow to adopt new technologies as a method to mitigate risks [10]. This is present in the Technology Readiness Level (TRL) used to identify technology that is safe to use, but qualification can be longer than the technology is relevant. However, there are many instances where new technology infusion has benefited the space sector as a whole, from students creating working nanosatellites as a learning tool [11] [12] [13] to future plans for space tourism [14].

As space becomes more accessible to everyone, the rigidity of traditional project management [2] and system engineering methods [4] are increasingly inadequate for today's space mission environment, but can be improved by incorporation of methods found in other industries. My research theorizes that changing the management method of a space project to a more adaptive approach shall reduce cost and schedule. I hypothesize that a satellite project can inherit adaptive behaviour by incorporation of non-traditional tools from Agile philosophy, concurrent engineering, lean manufacturing, and theory of constraints. Through study of how an industry space project evolved as it matured from design to manufacturing and testing, I identified opportunities where implementation of tools would be effective, and the tools will be outlined in detail in Section 2.4.

The following subsections discuss how the risk management impacts the space sector as a whole. I will then summarize the goals and hypothesis of my research. A literature review of existing project management approaches will be presented, reviewing how it addresses common causes of project delays. An overview of the research contributions to industry and an outline of the following chapters will be provided at the end of this chapter.

1.1.1 Risk Management Approach Impact

Zee [15] described the concept of the vicious cycle, shown in Figure 1.1, where the fear of mission failure can have negative impacts. The large resource investment in a complex space project causes fear of mission failure in the sponsor and stakeholder to demand for tests to demonstrate mission success. As noted in the SMAD [5], testing can heavily influence the cost and schedule of the project, and adding more test increases the baseline cost of a space mission. This increase in mission costs limits the number of sponsors that can bear the financial burden, limiting funding only to very wealthy entities. With only a few available sources of funding, this limits the quantity and variety of space projects, which reduces our ability to undertake science experiments of space exploration. As fewer mission becoming available, the fear of mission failure intensifies, and the cycle continues.

Richards [1] argues that tradition has a higher impact on cost in the space sector, noting that traditionally created plans attempt to predict every task and event to secure mission success. The effort needed by the supervisor team to monitor negatively impacts the schedule, demanding valuable time and focus to re-plan, re-analyze, and re-organize work. The labour needed to sustain this highly rigid planning methods has a cost associated as skilled labour, further increasing costs at all parts of the project, continuing the vicious cycle.

Figure 1.1: The Vicious Cycle

The vicious cycle is the idea where the fear of failure leads to more tests to show compliance. This also increases the cost of the space project that ultimately makes space projects increasingly inaccessible.

One method to reduce the cost of space missions is to begin what Zee [15] calls the virtuous cycle, shown in Figure 1.2, where coming to terms with the possibility of mission failure will benefit the space sector as a whole. Accepting the possibility of mission failure relaxes the strict risk management approach that demands the project leaders to create rigid and detailed plans that demonstrate mission success, providing the flexibility to be able to quickly adapt to changes. Project managers will then be able to focus their attention to high severity risks that have a more profound effect on the mission success, and guiding the team into effective corrective actions that can lead to innovative solutions to challenges. Innovative solutions can lead to lower project cost and have a lower financial impact of mission failure on stakeholders and sponsors. The lower impact makes space missions more accessible to more sponsors, allowing for more support to be available to more diverse space missions. More and varied space missions allows for us to expand our knowledge and benefit the science community.

Figure 1.2: The Virtuous Cycle

The virtuous cycle the idea that the ability to accept risks can reduce the cost of entry for space missions and provide diversity into the science experiments.

There are contemporary management philosophies that aim to reduce development cycle times and costs, known as Agile Philosophy, Lean Manufacturing, Theory of Constraints, and Concurrent Engineering, that will be further detailed in Section 2.4. These philosophies focus on effectively using available resources, promoting team dynamics, and reducing waste that facilitate creating new solutions to common problems. These philosophies can be combined to create an adaptive project management system that is able to take on more risks without sacrificing the scope or schedule of the project.

There is academic interest in reducing the overall cost of space projects through new technology adoption [16], but as Richards [1] states, tradition has a higher impact on project cost. The space sector needs to change how it views and handles risk to reach the full potential of available resources. Beginning by accepting the possibility of mission failure, the first step in the virtuous cycle, opportunities to try methods for quicker and lower cost projects become available.

1.2 Goals and Hypotheses

Modern space projects use a traditional waterfall approach that remains largely unchanged since the age of the space race [4], [17], [18]. Although this is a reliable approach, there have been new and innovative systems management developments in other industries, such as consumer-goods and the production process industries, with proven success[19], [20]. This research investigates the applicability of non-traditional project management and system engineering methods that have been applied to a space systems project.

Early in the space race, traditional project management methods were acceptable as space demanded new and unproven technology going into a mostly unknown environment. Pate-Cornell and Dillion [21] studied how as the space programs matured and technology became more elegant, the space industry began searching for management methods that were "Faster-Better-Cheaper." Pate-Cornell and Dillion reviewed the National Aeronautics and Space Administration (NASA) efforts to transition from the large "flagship" projects, such as the Cassini mission, to new faster-better-cheaper projects, such as the New Millennium Program. Key lessons learned include: team collocation, concurrent engineering practices, commercial-off-the-shelf (COTS) components, earlier testing, and improved communication within the team, among others.

Although there is this wealth of lessons learned, the space sector is continually challenged by the inflexibility in the traditional approach. Modern examples include the James Webb Space Telescope (JWST) [22], that saw a schedule, scope, and cost increase. Bitten *et al.* [23] notes that work began in the mid 1990's, and had an original budget less than 600 million USD, but has increased to 6.8 billion USD in 2015. Gardner *et al.* [22] noted in 2006 that the JWST was planned to launch in the early 2010's, but recent news in the first half of 2020 note that JWST will miss the current planned date of 2021 [24]. An independent review in 2010 [25] found that the delays were rooted in the management, and not due to technical development of technology.

My research is focused on identifying the best method to improve how complex space projects are managed by improving the adaptability for satellite projects. The benefits and contributions I propose is the framework for satellite development projects that are adaptive to change, even late in the project. This is supplemented by an analysis of the allocation of labour in an industry space project, with considerations for tasks and verification activities. Through thorough analysis of a traditionally managed project, this research can provide a systematic understanding on implementing adaptive programmatic changes.

My research evaluates three hypothesis:

1. I hypothesize that a two year spacecraft project schedule can be shortened by two months by applying the agile philosophy to certain aspects to the project.

2. I hypothesize that a complex space system is able to quickly adapt to external project changes using Agile Philosophy.

3. I hypothesize that communication services that use Kanban and Scrum information structures, along with additive manufacturing for rapid prototyping will decrease schedule without affecting the quality work completed.

To test the hypotheses, my thesis compares and contrasts data generated by two projects. The first data set used is from an industry project that primarily used a traditional waterfall management approach to control and direct work and requirements. The second data set is from an ongoing Nanosatellite project being undertaken by the University of Manitoba, where modern and more-flexible project management practices have been employed.

I am the project manager for the ManitobaSat-1 project, a Nanosatellite project that is part of the Canadian CubeSat Project (CCP). The CCP is a initiative by the Canadian Space Agency (CSA) aiming to promote space systems engineering to post-secondary students. The ManitobaSat-1 project is the University of Manitoba's CCP entry, with a science mission to observe the optical effects of space weathering on geological samples. As the manager, I have been able to implement management tools and provide support to the technical leads. This enables me to review and analyze the progress of the project.

1.3 Research Contributions

This thesis demonstrates how my research developed and evaluated versatile project management and systems engineering methods for an ongoing nanosatellite project and provided a project management outline for future nanosatellite teams to be able to readily manage and control their work. My research also provided a case study into an innovative and well documented nanosatellite project that incorporates many non-traditional management tools.

My research also provided an analysis of a large project management data set provided by a space industry company for design, manufacturing, and testing tasks to identify areas to address hypothesis two, that a complex space system is able to quickly adapt to external project changes using Agile Philosophy. Task duration data for critical design and manufacturing activities was analyzed to establish the project's resource loading. Labour hours for preliminary design, critical design, and manufacturing activities were received to study the labour distribution for a traditional project management system. This data provided insight into how a complex space systems project evolves as the schedule progresses. My research also used this data to make recommendations on how Agile activities could positively impact the schedule and scope. The analyzed industry data acts as a control case for comparison with the ManitobaSat-1 project as evidence for hypothesis two and three. Hypotheses one is proved through comparison between the ManitobaSat-1 project schedule and the CCP planned schedule.

I have provided a detailed study into the impact of non-traditional project management and systems engineering tools applied to the space sector. This thesis provides a detailed description of a highly adaptive CubeSat project that incorporates methods from Agile Philosophy, Lean Manufacturing, and Theory of Constraints. The ManitobaSat-1 project used labour hours and project requirements as project health data to provide further insight into how a project evolves through design and manufacturing efforts.

1.4 Thesis Summary

Chapter 1 provided a demonstration, goals and hypothesis, and research contributions.

Chapter 2 outlines the traditional and non-traditional project management approaches that are commonly implemented in modern projects. This chapter details how managers mitigate risks through detailed planning, incremental progress, and stakeholder reviews.

Chapter 3 presents industry management data of a recently completed satellite project, providing insight into labour hours and verification activity status as the project matured. The industry data is presented and analyzed to provide a reference case for the ManitobaSat-1 project analysis.

Chapter 4 provides background information and data collected throughout the ManitobaSat-1 project. This chapter discusses the methods used to direct work, manage information distribution, and decision making procedures. Data collection methods and tools are discussed and presented. ManitobaSat-1 project data is analyzed to identify the impact of the applied tools.

Chapter 5 provides a closing remarks and conclusion for this research, and areas for further study.

Chapter 2

Project Management Literature Review

This chapter provides a study in the traditional project management approach that is commonly adopted by the space sector. Background research for traditional project management advantages and disadvantages are provided followed by a discussion of opportunities to improve the current approach. To understand how to best change the traditional approach, an overview of the roots of project management and how it has changed since its introduction is presented. An overview of non-traditional approached developed in other industries is presented and how they mitigate common sources of delays.

2.1 The Beginning of Space Project Management

The Apollo program set the groundwork for the modern space sector, providing a proven blueprint in how work is organized and executed. Bowman and Tomlin [18] discussed the historical background of the Apollo program and analyzed the management method through a modern Project Management Body of Knowledge (PMBOK) [35] perspective. The Apollo program management approach was created to meet the challenge issued by the then president of the United States of America, John F. Kennedy, to place a human on the moon by the end of the 1960's. This provided more resources to the newly formed National Aeronautics and Space Administration (NASA), but it also created the problem of a large project scope with a tight deadline.

Seamans [17] provided a detailed history of the Apollo program, noting that although space exploration was a civilian endeavour, the newly formed space sector had abundant experience from the military to draw upon. The hierarchical organization and discipline of the defence sector can still be observed in the traditional methods' focus on work breakdown structures (WBS), team organization, and risk management architecture [4] [55]. Seamans provided insight into how the program developed an incremental progress system that ensured the product conformed to requirements. He provides the **Apollo Phases** as:

- **Definition Phase**

  Defines the mission concept and requirements, completed at the Preliminary Design Review.

- **Design Phase**

  Designs and develops technology to be used in the mission, completed at the Critical Design Review.

- **Manufacturing Phase**

  Manufacturers and assembles subsystems and integrates the spacecraft, completed at the First Article Configuration Inspection.

- **Operations Phase**

  This phase encompasses operations tests, Flight Readiness Review, launch, and mission operations.

Each phase has a review with stakeholders that provides a control decision point to ensure a requirement conforming spacecraft and a resource safe path forward. The Apollo program overcame the Kennedy challenge with the Apollo 11 lunar landing in 1969 and the safe return of the mission's crew, showing the benefits of careful study and detailed planning. The frame developed by the Apollo management system that has evolved into the traditional management method used today and detailed in the NASA Systems Engineering Handbook [4], and will be further detailed in Section 2.2. The **Traditional Phases** are defined below:

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

The Apollo management approach has impacted how work is organized and conducted beyond the space sector. Gauthier and Ika [56] discuss the foundations of project management research through establishing management knowledge and perspectives in different eras. They note that the modern view of project management can be traced back to the 1950's and 1960's, highlighting the impact of the Manhattan project and the Apollo missions. The PMBOK [35] provides education and guidance in a commonly accepted management style echoing the Apollo method.

The PMBOK [35] provides guidance in five **PMBOK Process Groups**: Initialization, Planning, Executing, Monitoring and Controlling, and Closing. The initialization group developed the project charter, establishing success and fail criteria of the project. The planning process is when the project manager develops all management plans that will define the operations of the project and details scope, schedule, and budget. The executing phase is where the planned work is being undertaken, and it occurs in parallel with monitoring and controlling process group. This allows projects to undertake work while being able to take corrective actions to ensure that the project charter and project plan is met. The closing process group contains the final steps of a project, including final documentation and delivering the product to the sponsor.

The five PMBOK process groups parallel the project phases in the Apollo era phases [17] and the modern space project phases [4]. The phase overlaps between all three frameworks are compared in Table 2.1.

<table>
<tr><th>Apollo Phases</th><th>Traditional Phases</th><th>PMBOK Process Group</th></tr>
<tr><td rowspan="2">Definition</td><td>Pre-Phase A</td><td>Initiating</td></tr>
<tr><td>Phase A</td><td>Planning</td></tr>
<tr><td rowspan="2">Design</td><td>Phase B</td><td rowspan="5">Executing
Monitoring and Controlling</td></tr>
<tr><td>Phase C</td></tr>
<tr><td>Manufacturing</td><td rowspan="2">Phase D</td></tr>
<tr><td rowspan="3">Operations</td></tr>
<tr><td>Phase E</td></tr>
<tr><td>Phase F</td><td>Closing</td></tr>
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Table 2.1: Project Management Phase Comparisons

The phases used by each management method provide structure for organizing work in any complex project, but a review of the methods allows us to better understand the impact of administrative change. Development progresses incrementally from the concept of a mission to testing the spacecraft, allowing for systems engineers and manager to identify non-conformances. Because of the difference in work types between phases, how the work progresses also changes. To identify areas where the application of tools discussed in Section 2.4 can positively impact the space sector, understanding the accepted NASA phase expectations and milestones is important. The following section will detail the traditional phase approach, risk mitigation, and requirements verification.

2.2 Traditional Management in the Space Sector

Traditional management has an abundance of details that managers need to know to improve the probability of a successful mission. During the space race, the traditional method quickly developed and implemented new technology under great political pressure for an ideological victory. The pressure in modern times comes from sponsors' need for a successful mission by risk mitigation that demands a highly detailed and thoroughly documented approach for managers to make informed decisions. The approaches that are presented were designed to control risks through careful planning, studying, testing, and reviewing. The approaches that mitigate technical risks in the space sector are detailed in the following subsections.

2.2.1 Project Phase Descriptions

NASA [4] organizes work by the task category that needs to be completed, traditionally in the order of design, build, and test. To ensure that the manufacturing does not begin before the design is accepted, each phase is reviewed by stakeholders prior to the next task sequence. The reviews also provide control over the technical progress to administration, experts, and other stakeholders. The NASA Program Management Handbook [2] and the Systems Engineering Handbook [4] provide the full traditional process summarized below.

Pre-Phase A has the project team do initial concept studies to complete a goal and provide different options for a product concept that can be realistically achieved with the allocated resources. This phase also has the project leads develop a project charter that outlines the goals, mission requirements, project milestone schedule, Concept of Operations (ConOps), and key stakeholders [35]. The key decision point in this phase is the Mission Concept Review (MCR) where stakeholders analyze the developed concepts to complete the mission. If a presented concept is found to be feasible at the end of the review, it is further developed in Phase A.

Phase A expands on the accepted concepts from Pre-Phase A by developing them into systems that meet goals and expectations. Systems engineering becomes a critical element in this phase for converting stakeholder goals into mission and system requirements. Major technical efforts are devoted to establishing product element functions through trade-off analyses and functional baselines. Major administrative efforts expand on the project charter by developing management plans, verification plans, WBS and statements of work (SOW) [4].

The end of this phase has two decision points: System Requirements Review (SRR) and the Mission Definition Review (MDR). The SRR focuses on the developed requirements and ensures that they are within the scope of the project and in accordance with stakeholder objectives. The MDR analyzes if a project meets stakeholder needs, contains adequately planned tasks, mitigates risks, and can operate within allocated scope, budget, and schedule. If the project requirements and architecture are accepted by both reviews, the project progresses to Phase B.

Phase B develops a preliminary design of the accepted mission concepts to meet stakeholder goals, providing the basic structure of the space product. The product design if further developed and analyzed to identify the best design for the mission concept. Requirements are initially verified in this phase through review of design and analysis to demonstrate compliance with mission needs. Verification results are documented to provide necessary information for project decision making and corrective actions.

This phase also has the project leads develop and update plans to meet stakeholder expectations. Systems engineers create technical plans based on the ConOps, including decommission and disposal plans to demonstrate compliance with governing agency requirements. Project leads continuously update plans created in Phase A as information from analyses identify requirements incompatible with either project goals or available resources. These updates can also impact the established ConOps and the derived work.

The Preliminary Design Review (PDR) marks the end of this phase and provides stakeholders an important decision point. The PDR focuses on the consistency between requirements and product design to ensure that design decisions reflect stakeholder needs. The PDR decision point often consists of a series of subsystem PDRs to ensure that subsystem designs both meet the requirements and are in accordance with the system design.

Phase C fully details the product design in accordance with requirements in preparation for manufacturing and testing activities. Major technical work includes developing product baselines, that outline subsystem interfaces, configuration, and assembly plans. This phase also needs project leads to develop subsystem manufacturing plans and consideration of final space product assembly and verification testing. Plans developed in past phases are continuously updated as new analyses and engineering test models reveal new information.

Product configuration is continuously monitored and updated as the design is detailed and analyzed. Phase C has an incremental evolution from preliminary design to a fully detailed product that is ready for manufacturing. Systems engineers also develop a final post-launch space product activation plan based on the ConOps to demonstrate mission functionality.

There are three decision points in this phase: the Critical Design Review (CDR), the Production Readiness Review (PRR), and the System Integration Review (SIR). The CDR evaluates if the product design is mature enough to go into manufacturing. Similar to the PDR, it can be a series of reviews that ensure consistency between the subsystems and the system. The PRR focuses on facilities, tools, personnel, and production plans to confirm that resources are ready to undertake manufacturing activities. The final decision point is the SIR that analyzes if the project and infrastructure is ready to begin manufacturing the detailed design.

The three reviews act as a final check before flight hardware manufacturing begins. These are arguably the most critical part in a project as it is the final point that corrective actions can be undertaken before the impact of change on cost and schedule increases dramatically. If all reviews are completed and corrective actions are addressed, Phase D starts manufacturing activities.

Phase D is also known as Assembly, Integration, and Test (AIT), where hardware is created and tested to demonstrate compliance with requirements. Subsystem fabrication and functional testing takes place before being integrated into the whole subsystem. Verification activities are completed incrementally to mitigate risk and demonstrate that each requirements is met. System level tests ensure that the operations and system requirements are met.

At the end of AIT activities, a Flight Readiness Review (FRR) oversees the state of the system to ensure it is ready for the mission. Major activities follow plans developed in the preceding phases, where subsystems are built, tested, and then integrated into the final space product. After integration, testing in representative environments is undertaken to demonstrate functional capabilities for the mission. Once verification activities are completed, attention then shifts to pre-launch integration, ensuring that the product survives launch to space.

There are four decision points for this phase: Test Readiness Reviews (TRR), System Acceptance Review (SAR), Operational Readiness Review (ORR), and the Flight Readiness Review (FRR). TRRs are used to ensure that tests, including articles, facilities, and personnel, are ready to begin testing. The SAR compares the status of the flight article to the expected design status and requirements, ensuring that an acceptable system is ready for submission to the stakeholders. The ORR is used to ensure that the system is operationally ready for the mission, supported by thorough documentation of characteristics, hardware, software, and procedures. The

FRR is the last review before integration to the launch vehicle, investigating all tests, demonstrations, and analyses to ensure that the product is ready for flight. Phase D is considered closed upon launch, with the space mission beginning in the following phase.

Phase E is the post-launch operations for a spacecraft, when the intended mission is executed. This phase requires constant monitoring, review, and updating by the operators with supporting activities by the satellite development team. This part of the project will have a reduced project team effort, with the majority of the responsibility with the mission operators. This phase has some stakeholder reviews to monitor mission state and occur based on the nature of the mission.

Phase F is the conclusion of the mission and decommissioning of the spacecraft. The systems engineers document all technical and system information, ensuring that all issues are properly identified and archived. When the conclusion of the mission occurs depends on different factors, such as the type of mission, in flight events, or even stakeholder decisions. A major technical concern in this phase is to control space debris generated by the spacecraft by following the decommissioning plan established in earlier phases.

This subsection presented the project phases as work evolves from invisible design to visible hardware manufacturing and testing, with the main focus of ensuring the product meets requirements. I have discussed how requirements are created from stakeholder wants, needs, and goals, but we also need to understand how the traditional method demonstrates that the design conforms to requirements. The following subsection discusses the traditional method of requirement verification.

2.2.2 Requirements and Verification

The PMBOK [35] defines a requirement as "A condition or capability that is necessary to be present in a product, service, or result to satisfy a business need." Requirements are a constant focus throughout a space project's phases; they are critical to success since they define the necessary technology capabilities, environmental conditions, project goals, wants, and needs. NASA [4] recommends defining mission requirements in Pre-Phase A and Phase A, providing the foundation for project definition and scope. When a subsystem requirement is created from the mission requirement, it is known as a child of that requirement, that provides an important link between mission definition and design. Child requirements provide guidance to the design philosophy and the verification milestones necessary to advance the project.

The verification process shows that the design and product conform to requirements, and presents evidence that the product will function as intended [4]. Developing a meaningful verification activity requires four inputs: the article or product, design documentation, requirements to be verified, and support equipment. Verification results can be compliance, partial compliance, or non-compliance with requirements, and are submitted to the project sponsor for approval or corrective action. The product is not considered fully verified until all verification activity results are accepted by the sponsor. NASA describes four verification methods:

- **Analysis**

  The project team analyses the capability of the product through calculations or simulations to ensure it meets required capabilities or performance. These are undertaken throughout the project.

- **Demonstration**

  This verification method demonstrates functionality of the final product. This is different from testing by the lack of data gathering and can occur at any phase with representative test models or the final model.

- **Inspection**

  The project team visually inspects the product hardware to ensure that features meet specifications. Inspection activities are completed during or after manufacturing.

- **Test**

  The project team undertakes tests to ensure that the product performs as required. Tests can be completed with engineering test models or final product.

Verification activities need to be clear in how they demonstrate requirement compliance through details, such as test environment and pass/fail criteria. Depending on the complexity of the project, requirements often need more than one verification activity over the lifetime of the mission.

Ensuring that the product is fully compliant with requirements ensures that mission goals are met, but selecting low risk technology that conforms to requirements improves success. As Richards [1] mentions, there is a demand for first time perfection, and systems engineers need to select technology with the lowest risk in any space mission. The method used by the space sector to select safe technologies is described in the next section.

2.2.3 Technology Readiness Level (TRL)

NASA [4] uses the TRL to ensure that projects use safe and proven technology that survives in the space environment. NASA notes that uncertainty in technology maturity in the beginning of a space project is a major factor that results in delays and cost overruns. This uncertainty can be drastically reduced through understanding of requirements, candidate technology maturity, and needed technology development to meet goals. TRL is divided into 9 levels detailed in Table 2.2.

Level	**Level Definition**
1	Basic principles observed and reported
2	Technology concept and/or application formulated
3	Analytical and experimental critical function and/or characteristic proof-of-concept
4	Component and/or breadboard validations in laboratory environment
5	Component and/or breadboard validation in relevant environment
6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
7	System prototype demonstration in a target/space environment
8	Actual system completed and “flight qualified” through test and demonstration (ground or flight)
9	Actual system “flight proven” through successful mission operations

Table 2.2: TRL Definitions

Shapiro [10] notes that ideal technology is TRL 9, which has demonstrated reliability in flight missions. Because of this, preference is given to technology inherited from previous space missions since new technology increases risk through perceived uncertainty. Dubos *et al.* [57] undertook a study on the impact of different TRLs at the beginning at the start of space projects, finding that schedules had higher slippages with decreasing TRL.

The traditional management method controls many aspects of a project, including technology used in the product (typically via TRL management), but it also needs to monitor and control progress. Project definitions set in Pre-Phase A and Phase A provide metrics that managers can use to determine the project health, providing insight into the need for corrective actions, and is detailed in the following subsection.

2.2.4 Progress Management

Hill [58] argues that progress management is comparing the current state of the project to the planned completed state, enabling the team to identify and undertake corrective actions to ensure the project remains on schedule. Hill discusses three metrics to be able to understand project progress: where you are, where you need to be, and where you are going. One common approach used in complex projects is to implement Earned Value Management (EVM). Cabri and Griffiths [59] describe EVM as a method of measuring progress by comparing three main metrics: planned value (PV), earned value (EV), and actual cost (AC). The PMBOK [35] defines the three main metrics below:

- **Planned Value (PV)**
  Authorized budget assigned to scheduled work.
- **Earned Value (EV)**
  The measure of work performed expressed in terms of the budget authorized for that work.
- **Actual Cost (AC)**
  The realized cost incurred for the work performed on an activity during a specific time period.

These metrics are the basic measurable elements in a project that can be used to derive other values that indicate the project health based on definitions established in Pre-Phase A and Phase A. EVM provides managers and sponsors a meaningful progress overview when compared to the established detailed plan. However, the baseline needs to be clearly defined and highly detailed to implement EVM. Cabri and Griffiths [59] explain the EVM assumptions:

- Project scope is through the work breakdown structure.
- Each task has an assigned responsible person.
- Key project milestones are identified.
- Master detailed schedule and budget is established.
- Detailed schedules and budgets are established.
- Master and detailed schedules and budgets are integrated.

EVM implements burn graphs as a method to visualize how the project is progressing relative to the plan. PMBOK [35] defines burn graphs as a chart that "tracks the work that remains to be completed in the iteration backlog." A sample burn chart is shown in Figure 2.1, and provides a visual guide for the common elements. As mentioned in the PMBOK, burn graphs are an iterative tool that are updated when a milestone is reached or a work package is closed.

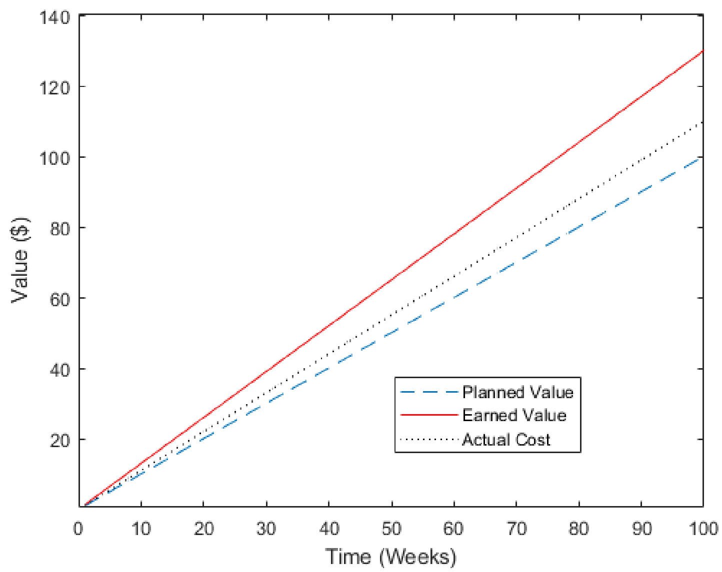


Figure 2.1: Sample Burn Chart

This is a highly idealized burn-up chart, where the value and costs happen in a linear fashion. This is not representative of a real project, but instead a visual representation of burn chart elements.

This section has provided an introduction to the traditional project management approach for the space structure, establishing the foundation needed to understand the advantages and disadvantages. Although the traditional management method stresses constant planning and rigid organization, it requires more effort than undertaking the work. The following section provides analyses of project data and presents recommendations for a more adaptive management approach.

2.3 Traditional Project Management Approach Analysis - Advantages and Disadvantages

Traditional project management is rooted in a rigid framework developed in the defence sectors [56] and provides a useful formula to control and monitor project tasks. The traditional approach is useful for allowing managers to be in control of the internal aspect of a project through detailed planning and organization. However, there are examples of modern projects requiring change not accounted for in the plan, manifesting as a schedule slip or budget overrun to external observers [60] [6] [24]. The following subsections describes the advantages and disadvantages of the traditional method with a discussion on opportunities to improve how the space sector manages projects.

2.3.1 Advantages of the Traditional Management Approach

The traditional project management approach provides an effective method to organize stakeholders, their expectations, and required work. NASA [2] expresses that the goal of their management approach "is to ensure programs and projects are developed and successfully executed in the most cost-effective and efficient manner possible." Webster [3] discusses recent changes to the NASA management approach, stresses the importance of early planning and definition of the space mission and how it stabilizes costs at the end of the project. Low cost variability creates a reliable plan that allows teams to better understand and prepare future space missions.

The cornerstone of the traditional project management approach in the space sector is systems engineering. NASA [4] defines the systems engineering as a methodical approach to design and manage the technical elements of the product, including requirements, fabrication, operations, and retirement. The systems engineering role is a central interface for all aspects of the project and demands training in the different technical aspects of the product. One area where the systems engineering input is critical is balancing administrative and technical constraints to create an optimized final product. Smartt and Ferreira [61] suggest that systems engineering ability to understand the business and technical elements of a project provides an engineering strategy that improves the organization's competitive advantage.

NASA [4] views systems engineering as a valuable discipline for any complex space project, with responsibilities including requirements management. As described in Section 2.2.2, requirements are the blueprints to create the project product that capture the stakeholder wants, needs, and goals. Nagano [62] studied how requirements are managed and verified, arguing that considerable effort is needed to properly develop requirements and highlighted the need for systems engineers. Carson [43] notes that the system engineering approach uses periodic technical reviews to ensure that the final delivered system conforms to requirements.

Carson [43] argues that to ensure that the product conforms to requirements, systems engineering incrementally develops the product as a whole, which allows stakeholders an opportunity to verify the product piece-wise. The incremental design provides a method to mitigate risks by ensuring that emergent system behaviour is well understood through methodical subsystem element verification. Carson suggests that the real strength in the traditional systems engineering approach is the ability to slowly discover the emergent system behaviour and to thoroughly record new information. Slowly documenting new information is not exclusive for systems engineering, but also for project management in the space sector. The NASA Space Flight Program and Project Management Handbook [2] also stresses the importance of understanding and thoroughly documenting the project, noting the need to accurately characterize the complexity of a program or project.

As systems engineers ensure that the product conforms to requirements, they are also responsible for mitigating risks, and this can be shown by the concept of TRL as described in Section 2.2.3. The need for first time perfection as described by Richards [1] demands that the selected technology is highly reliable. Dubos *et al.* [57] studied the relationship between schedule and cost increase with different TRLs, noting that a low TRL is viewed as a project risk for creating an acceptable design since relative schedule slippage correlates with low TRL at the beginning of the project. Dubous *et al.* states that projects responsible for TRL increase are at the highest risk of schedule and cost increase. The technical maturity of all elements of the project, including technology considered to be integrated into the final product, is closely studied by systems engineering and project managers to mitigate the risk of failure.

In summary, the traditional approach provides valuable structure that allows for organization of work, stakeholders, requirements, and risk. This structure is a critical factor in the success of a mission, especially as the spacecraft becomes more complex. Technical and administrative communication is facilitated by a project's systems engineering team, with experience in both the business and the engineering disciplines. They manage requirements and the verification activities undertaken to demonstrate compliance with the sponsor needs. This structure has taken humanity from earth to the moon, but the traditional method has disadvantages that need to be considered.

2.3.2 Disadvantages of the Traditional Management Approach

In the previous section, Webster [3] noted that the traditional project management approach focuses on detailed planning early in the project for a stable budget at the end, but this same benefit can create challenges. Careful planning and thorough documentation provides project managers and systems engineers detailed information to analyze the impact of changes or new information, but this can create more work than management resources have task capacity available. This subsection describes areas where the strict discipline of traditional project management creates challenges for the space sector.

In an ideal project, all changes are identified and implemented early in the project, but changes can occur at any phase. Ward *et al.* [6] studied the changes in space systems management, and documented how engineering change requests (ECR) are generated. ECRs are the primary source of technical change used in the engineering field, and are common when changes are required in system design or hardware manufacturing. These documents are created from reviews, stakeholder requests, or as a consequence from another change. The Ward *et al.* study showed that ECR creation increases as the project progresses, but have the highest creation rate around stakeholder reviews late in the project. The change request pattern presented by Ward illustrates that adapting to changes is needed in a space project, especially late in the development cycle.

In the traditional project management method, change implementation requires careful review that demands the attention of project teams, dividing their attention that can lead to delays. The PMBOK [35] stresses that approved changes can require that the project manager create new or revised cost estimates, task dates, resource requirements, and analysis of risk response alternatives. This can cost the management team valuable resources that can in turn negatively impact the duration of the project. Reinertsen [28] notes that the time work is in a queue increases exponentially around sixty percent resource capacity use. The exponential increase is due to the effect of task variability that causes delays in subsequent tasks, increasing the time in the queue. The increased queue time can result in two sources of delays mentioned in Section 2.4.1, multitasking and unavailable management resources.

Risk is defined by the PMBOK [35] as an uncertain event or condition that has an effect on the project objectives, reflecting how requested changes can be seen as a risk. The NASA Risk Management Handbook [55] outlines the traditional risk analysis and reporting hierarchy. Identified risks are analyzed on three metrics: scenario that leads to risk occurring, likelihood of the scenario, and consequence or risk being realized. Based on an established "risk threshold," concerns are reported up the chain of command to administrative leads, where thorough impact analyses are undertaken, and amended project priorities are promulgated down the chain of command. The communication architecture provides an important series of control for complex project but can demand extended decision making time based on the level of analysis needed, creating a risk for teams to work on incorrect priorities or be delayed until a decision is made.

The rigid organization of the traditional management approach can be detrimental to the space sector, and it is demonstrated in mitigating risk for new technologies. TRL is an assessment method used to mitigate risks born from new and unqualified technology, but it also prevents the space industry from incorporating new technology. Shapiro [10] claims that TRL qualification can take a minimum of two years if new technology is classified as critical to a space mission, and much longer if not. The time required for qualification often prevents the space sector from using current or cutting-edge technology due to Moore's law. Shapiro explains that Moore's law is the trend that transistors on a chip doubles every eighteen months, improving performance. Therefore the newest technology available to the space sector is already six months obsolete compared to commercially available products. The technology infusion disconnect between commercial and space sectors restricts the capabilities of modern satellites, as they use technology that is long obsolete upon launch.

Other industries, such as the automobile and software industry, have created new management approaches that mitigate and control the traditional management approach's disadvantages. Where the traditional project management approach is able to use a rigid structure to organize and control work, new approaches allow for steady workflow and an adaptive nature that captures project sponsor's goals and expectations. The following section provides a literature review of non-traditional project management approaches developed in other industries.

2.4 Literature Review of Non-Traditional Project Management Methods

The following subsections provide a literature review of existing management approaches that are currently used, and how they address common sources of delays. The methods reviewed are Lean Manufacturing, Theory of Constraints, Concurrent Engineering, and Agile Philosophy. Each of these provide useful perspectives in workflow and management structure that can positively impact the space sector. To understand the strengths of each of these, I will present common sources of delays in a project with a discussion of how they manifest in a project.

2.4.1 Sources of Delays

Organizing and managing tasks and schedules is critical for work that is not easily visible. Visible work is hardware work where progress can easily be seen, such as assembly, integration, or testing. Design and documentation is less visible, and mechanisms need to be in place to monitor a project's health. Playbook [26], a lean-agile project management resource, has identified four sources of delays:

1. Incorrect Priorities

2. Multitasking

3. Unavailable Resources

4. Technical Difficulties

Item 1 is that the project team has incorrect priorities. Projects are a complex collection of work that require some tasks to be completed before starting the next one, but missing critical task deadlines can cause the whole project to be delayed. When team members have a task backlog, they ideally chose the critical task, but without proper information, identifying high priority work can be challenging. A project is delayed by the same amount of time a critical task is left in the backlog.

Item 2 is multitasking by resources, the belief that time can be saved by undertaking two tasks simultaneously. The myth of multitasking claims that we can complete twice the amount of work in the time needed for one when we divide our attention. The reality is that workers are unable to divide their focus effectively on more than one task and instead switch their focus between the two activities. They ultimately waste time switching between their active tasks, which has them reorganizing their thoughts during switches. Their divided attention ultimately extends the time on all active tasks, and adversely affects the schedule.

Item 3 is unavailable resources when scheduled. A schedule assumes that resources will be available to complete tasks before deadlines. If a task requires a specific resource for completion but it is not available due to other work, the task will need to be delayed. A resource's availability can create a task backlog that limits productivity throughout the whole project.

Item 4 are information technology (IT) issues that will be present in every project. These difficulties can impact any part of the project, from available design software to communication tools. Beyond having a strong information technology team in place, project teams do not have the capability to mitigate these issues.

Items 1-3 can be mitigated through careful planning and project controls to ensure a constant work throughput [26]. Different approaches to address the first three items have been created through study and practice. The following subsections will each present different management approaches with special focus on the specific tools that have been incorporated into the ManitobaSat-1 project. These tools will be related to how they address one of the three manageable delay items, and how they can provide stable workflows for a satellite project.

2.4.2 Lean Manufacturing

The introduction of the Toyota Production System provided Toyota a high profit margin compared to the rest of the industry [27], and soon became a subject of study that led to the creation of Lean Manufacturing during the 1980's [28]. As Melton [29] notes, there are three principles of lean: identification of value, elimination of waste, and generation of flow. Value is in the product, and waste is generated by work-in-progress, as money is required to maintain inventory. By minimizing work-in-progress, manufacturers are able provide a steady flow of value to market, which provides the manufacturer an advantage over their competitors.

Melton [29] states that Lean can be applied to supply chains, but Reinertsen [28] guides us in applying Lean ideas to design settings. Reinertsen provides two useful tools, Kanban task loading and queue theory. These are particularly effective for invisible work, such as product design and manufacturing, as the tools can provide valuable visibility to work-in-progress.

Kanban is a flow orientated method developed by Lean Manufacturing to make invisible work visible [30] [28]. Kanban is a task management system that frames work as a flow of value by recording tasks on sticky notes to visualize all work that needs to be done from a backlog to completion. Tasks are then placed into one of three categories: backlog, in-progress, and finished. Team members only work on one task at a time (two if they were blocked), reducing the impact of multitasking. Once the task is complete, the sticky note is moved on the Kanban finished category, and the team member then pulls another task from the backlog to the in-progress category [31]. Kanban provides a way to mitigate multitasking and communicate correct priorities, ensuring that the team does not divide their efforts into non-critical tasks.

Lean manufacturing also places an importance in task queues, noting that a resource work throughput decreases as work loading increases [28]. The relative time in a queue increases exponentially around sixty percent work loading for a resource, due to work time variability and unforeseen circumstances. The decreased throughput predicted by queue theory can be seen in the different settings including traffic during rush hour. This phenomenon can also be observed in project resources, as schedule delays occur when the team members begin to take on more work than they have work capacity for. Having awareness for work loading will combat the effects of unavailable resources by ensuring that they are loaded below this sixty percent of their capacity.

Kanban and queue theory has been implemented into the ManitobaSat-1 project management plan to provide visibility to design activities as described in chapter 4. These two tools provide visibility into design and documentation work in progress, increasing the work throughput of the project. The visibility helps teams recognize critical work, ensuring correct priorities. When combined with queue theory, this presents the team with everyone's capacity loading, allowing for quick identification of member availability if help is required. If changes are needed, this visibility allows the team to have priority impact and available resources able to act immediately.

2.4.3 Theory of Constraints

Theory of Constraints (TOC) is a planning method that was inspired by Lean Manufacturing and focuses on production bottlenecks. It was first developed by Goldratt [32] as a method to identify factory operations that limit production throughput. Goldratt had five steps to successfully apply TOC:

1. Identify the system's constraints
2. Decide how to exploit the system's constraints
3. Subordinate everything else to the above decisions
4. Elevate the system's constraints
5. If in the previous steps a constraint has been broken, go back to step 1, but do not allow inertia to cause a system constraint

The TOC steps provide a formula to analyze a factory configuration and to quickly identify the system element with the lowest productivity or throughput. While practical instinct tells us to increase capacity by adding more resources, Goldratt recommends instead finding configurations that allow the full use of the station's capacity by understanding the system. The factory configuration is then subjugated to the capacity of the restrained schedule, monitoring how the productivity is affected throughout the factory. With this model, the manager is a able to fully understand how constraints are affected with a change in configuration.

Goldratt also applied this philosophy to projects in what is known as the Critical Chain [33]. Robinson and Richards [34] discuss Critical Chain's ability to limit multi-tasking, the student syndrome, and Parkinson's law. Robinson and Richards describe the student syndrome as procrastination that arises from a distant deadline, potentially emerging as incorrect priorities. This is similar to Parkinson's law that dictates that work will take up the allocated time. Parkinson's law can also be a cause for early completions not being reported because unused allocated time may have negative connotations for the project team.

Critical Chain creates a schedule with with a focus on resource work capacity, similar to how TOC focuses on the production capacity. Critical Chain expands on the idea of a critical path, which is defined by the Project Management Body of Knowledge (PMBOK) [35] as the string of connected and related tasks that have no spare time from start to finish. This is an important concept in traditional management, since the critical path dictates the shortest project duration. If any task in the critical path is delayed, the project as a whole is delayed. Robinson and Richards [34] explain that the critical chain differs from the critical path by also taking into consideration resource task loading. The critical chain approach creates a schedule that reflects task duration and the available resources throughout the project duration. The schedule created from this method ensures that resources are focusing on their given task without being overloaded by other work, mitigating delay items two and three.

The critical chain method is applied to the ManitobaSat-1 project, providing a schedule that reflects the availability of the team. Combined with Lean tools discussed in Section 2.4.2, it provides a schedule that is able to be quickly analyzed to determine the impact on the schedule, highlighting the availability of the team.

2.4.4 Concurrent Engineering

Concurrent engineering is an approach that has been incorporated by some members of the space community, notably promoted by the European Space Agency (ESA) [36] [37]. Concurrent Engineering is best described as:

> Concurrent engineering is a system design practice that encourages immediate collaboration between groups working on interrelated subsystems, so that the whole system can be integrated seamlessly and quickly. [38]

Jian and Oriet [39] describe concurrent engineering as a method that provides considerations of all elements of the product life cycle, involving all team members from the beginning. This is contrasted with the traditional waterfall approach that involves manufacturing team once the design is complete, but can find that design fabrication is impossible without changes. Concurrent engineering involves the manufacturing team from the beginning to ensure that the product is designed to be manufactured with the available tools and methods. In turn, the manufacturing team understand the progress of the design and are able to allocate necessary equipment in accordance with the schedule. As Doerksen *et al.* [38] explain, concurrent engineering promotes greater communication within the team to better build the system as a whole, giving individual subsystem teams the freedom to concurrently execute design, build and test cycles. The necessary transfer of knowledge is facilitated by the available engineering technology such as Computer Aided Design (CAD), Product Data Management systems, and IT systems.

Franchi *et al.* [40] documented lessons learned by small student-led teams in an academic concurrent engineering project. They noted that concurrent engineering was a useful method of project management that used available technology to create a centralized database that facilitated knowledge transfer. Franchi *et al.* also discussed the benefits of a multi-disciplinary team, providing students with exposure to different parts of the project that improved decision making in difficult situations. The centralized information approach allowed for each individual to understand the state of the project and possible impacts to design changes.

As Parkinson and Short [41] discussed, having new team members master concurrent engineering is best done through interaction, guided by an expert within the team. They note that there are obstacles in teaching concurrent engineering, as training available to product designers may be geared to the traditional waterfall approach. Since concurrent engineering is based on interpersonal communication, mentors and experts are critical elements within concurrent engineering projects to create an effective team system. Mentors provide important training in changing the perspectives of new members, allowing for the whole project team to act as a dynamic whole.

Concurrent engineering has been implemented in the ManitobaSat-1 project as a method to improve team communication. The ability to involve and consider all aspects of a project at the beginning provides the team the ability to have a better understanding of the impacts of change. The understanding provides a useful method to assess the cascading effect of the change, to better understand how to correctly identify priorities.

2.4.5 Agile Philosophy

In the early 2000's, the Agile Manifesto was promulgated, promoting the idea of highly adaptive project management methods for software development [42]. Agile philosophy is sometimes viewed as a foil to traditional management ideologies, disregarding requirements to focus on the customer's wants [43]. The goals of traditional management and Agile philosophies are not mutually exclusive; where they overlap is a field that is rich with opportunity. Space systems engineering can benefit from this overlap and decrease project schedule and cost by incorporating Agile elements and tools.

The Agile Manifesto [42] is composed of four values that are supplemented by twelve principles. The core four values of Agile philosophy are:

1. Individuals and interactions over processes and tools

2. Working software over comprehensive documentation
3. Customer collaboration over contract negotiation
4. Responding to change over following a plan

The Agile manifesto clarifies that in each value "the first segment indicates a preference, while the latter segment describes an item that, though important, is of lesser priority" [42]. In other words, when a choice between the two needs to be made, preference will be given to the first segment. When teams remember these values, they remind themselves that it is the team and the customer that undertake the work, where processes, tools, documentation, and contract can only provide support and guidance. The plan is valuable to every project, but can be detrimental if the plan is incapable of responding and adapting to changes. The Agile values are further detailed through the twelve agile principles in the manifesto:

1. Our highest priority is to satisfy the customer through early and continuous delivery of valuable software.
2. Welcome changing requirements, even late in development. Agile processes harness change for the customer's competitive advantage.
3. Deliver working software frequently, from a couple of weeks to a couple of months, with a preference to the shorter timescale.
4. Business people and developers must work together daily throughout the project.
5. Build projects around motivated individuals. Give them the environment and support they need, and trust them to get the job done.
6. The most efficient and effective method of conveying information to and within a development team is face-to-face conversation.

7. Working software is the primary measure of progress.

8. Agile processes promote sustainable development. The sponsors, developers, and users should be able to maintain a constant pace indefinitely.

9. Continuous attention to technical excellence and good design enhances agility.

10. Simplicity, the art of maximizing the amount of work not done, is essential.

11. The best architectures, requirements, and designs emerge from self-organizing teams.

12. At regular intervals, the team reflects on how to become more effective, then tunes and adjusts its behaviour accordingly.

For a project to have agility, it must be able to accept change without completely discarding processes and tools, comprehensive documentation, contract negotiation, and a plan. The following subsections will cover interpretation of the Agile values.

Individuals and Interactions Over Processes and Tools

The first value points out that people and interactions in a team take precedence over processes and tools. Rakitin [44] provides one interpretation of this value as "Talking to people instead of using a process gives us the freedom to do whatever we want." Rakitin's interpretation goes against the spirit of this value, which is described by principles four through six, eight, eleven, and twelve. The team and customers are the entities that undertake the work, and effective communication is a key factor in task completion. Processes and tools can support the team, but will not complete project tasks without the team.

Highsmith [45] discusses the importance of the human factor in projects, arguing that innovation comes from a self-organizing and self disciplined environment, not from rigid management structures. In constantly changing projects, creative solutions that address needed changes are choked by the traditional management method's obsession to complete tasks. The first value challenges this approach by encouraging leaders to act as guidance for the team instead of as managers. Agile leaders provide information, counsel, and knowledge for the teams to find the best solutions to problems.

Highsmith argues that self-organization ensures that the best product is achieved in the face of constant changes. The team needs to act as a cohesive whole to achieve their potential, and the environment needs to promote collaboration between all team members. Communication is the main vehicle for collaboration, making methods for communication the most important aspect of teamwork. Processes and tools should be geared to streamlining interactions, as opposed to replacing them [26].

Working Software Over Comprehensive Documents

Although this value is rooted in software development, it is applicable to hardware because delivering a working product is the goal of industry. The essence of this value is described in principles one, three, seven, and ten. The best method to demonstrate progress to stakeholders is to present working product.

Working product is more valuable to sponsors and stakeholders compared to documentation, demonstrating a tangible metric for progress. Highsmith [45] describes the ability to provide continuous value as a method of fault or non-conformance detection, giving the development team opportunities to incrementally improve the product as opposed to corrective actions at the end of the project. Highsmith summarizes this thought as "deliver today, adapt tomorrow."

Rakitin [44], provides one interpretation for this value as "We want to spend all our time coding. Remember, real programmers don't write documentation," but the value still places importance in documentation. In the space industry, a working spacecraft is the main measure of success of a mission, since a non-functioning satellite in space is considered a mission failure even if all documentation is completed. Documentation is important for hardware since it is the main method for hardware designers to demonstrate and express their design to manufacturers [26]. For manufacturers to understand how to build a product, the designers need to communicate their designs in a clear and understandable method.

Customer Collaboration Over Contract Negotiation

This value calls for sponsor involvement instead of the project team interpreting sponsor goals through contract terms. This value is further detailed in principles one, four, six, eight, and ten, highlighting the importance of communication. Projects are a team effort to meet needs and goals of all stakeholders, including the sponsors. The involvement of sponsors within the project team allows for better understanding of the expectations, goals, wants, and needs.

Rakitin [44] interprets this value as "Haggling over the details is merely a distraction from the real work of coding. We'll work out the details once we deliver something," but Agile philosophy stresses that collaboration creates the best product. This is the main message of the fourth principle, where sponsors and stakeholders need to work together to fully realize the product. Although the understanding of a sponsor's needs may be originally misinterpreted, effective communication and collaboration can provide a satisfying path forward. A constant flow of feedback from the customer will continuously ensure the product aligns with their needs at throughout the project duration.

Responding to Change Over Following a Plan

This value highlights the importance of incorporating changes instead of working to meet the original plan. This value is detailed in principles two, ten, and twelve, highlighting that change can be a powerful tool to provide a business advantage to the stakeholders if incorporated correctly. Principle twelve notes that it is the team that needs to understand how they can be more effective and to be able to adapt their behaviour to meet needed changes.

Rakitin [44] interprets this value as "following a plan implies we have to think about the problem and how we might actually solve it. Why would we want to do that when we could be coding?" However, adapting to changes require teams to have strong problem solving abilities, as the PMBOK [35] stresses that managers need to carefully analyze changes and revise existing plans. Responding to change builds on the team and collaboration called upon by the first three values, as creative solutions to new challenges emerge from teamwork.

Carson [43] also argues that hardware projects cannot incorporate Agile philosophy of adapting to change since requirements dictate the project at the beginning, but Ward *et al* [6] found that requirements receive the second most requests for change, even late in the project. Ward *et al.* observed that most engineering changes occur during design reviews and/or sponsor interactions, highlighting that requirements can be crated from initial misinterpretations in accordance with value three and corrective changes can occur at any point in the project.

The values and principles provide a perspective for teams to consider when planning and completing work. Agile philosophy focuses on creating the best product to meet stakeholders goals and provide an advantage even in changing situations. This has led to the creation of different approaches to implement Agile philosophy in hardware industries. Common tools and approaches will be discussed in the following subsection.

2.4.6 Adaptive Applications for Hardware Development

Although Agile philosophy began in software development, it has been studied to find the best methods to incorporate into other industries [45]. Playbook [26] provides agility to hardware projects using many tools, such as Kanban from lean manufacturing and Scrum from Agile philosophy applications. These approaches are used to mitigate the risk of workers multitasking and ensure that they focus on critical tasks. The combination of Agile philosophy and lean manufacturing improves team communication to ensure that the team has situational awareness to easily identify high priority work.

Scrum is a popular Agile management method that monitors progress over a small period of time, adjusting the overall plan based on team and customer feedback [30]. Scrum has teams focus their efforts to complete a software feature by the end of a time period. Teams will have short daily meetings to ensure the correct priorities are worked on, monitor resource availability, and to ensure task accountability. The Scrum method has already seen implementation in the aerospace industry to monitor the project work completed [46].

Carson [43] also claims that traditional systems engineering focuses on managing risks and requirements to minimize future rework, but Agile management relies on discovery through testing. He voices skepticism about a hardware manufacturer's ability to be agile, arguing that there is a fundamental difference between hardware and software. Software is easier to incorporate design changes compared to hardware, noting that the one software developer is both the designer and fabricator. Hardware development requires different disciplines to create a part, requiring the designer to document the change, and the manufacturer to implement. However, this gap between hardware designer and manufacturer is decreasing with the introduction of additive manufacturing [9] [47], allowing for the designer to build an inexpensive hardware from their CAD model. Additive manufacturing for rapid prototyping makes the hardware designer and fabricator the same person, allowing for quick hardware changes as needed.

The ability to create early and inexpensive prototypes give space projects the ability to discover faults early, and has been a request from existing lessons learned in the space sector [21]. Reinertsen [28] supports the idea of early testing, noting that iterative testing allows us to better control the quantity of non-conformances in a part. Prototyping early will find defects and reduce the amount of rework needed late in the project and control the impact of change during manufacturing.

Although the benefits of using Agile philosophy are clear, there is always an inherent challenge of cultural dissonance between the team and the parent organization. Cunningham [48] provided their experience leading an Agile team within a traditionally managed organization, documenting their challenges in the interactions between his team and the company. Although their Agile team provided products with less defects compared to non-Agile teams, role expectations can lead to misunderstandings with the rest of the organization. Cunningham reported that compliance with the standard organizational procedures called for non-essential documents, taking valuable effort away from improving the deliverable product. Furthermore, meetings to review instances of non-compliance added time that was not devoted to mitigation and resolving the issues.

Wells *et al.* [49] notes that the methods for implementing Agile philosophies will have a big impact on the benefits. Misalignment between existing systems and the Agile methods may cause delays and frustrations. This can be attributed as a miscommunication between teams, acting against the first Agile value of people and interactions over processes and tools. Tian *et al.* [50] recommends that businesses should carry out agile methods on the aspects of people, organization and communication to increase the speed of response and business performance.

In industry, it has been shown that Agile manufacturing adapts to current market trends in terms of product volume flexibility, time to market, and delivery speed [51]. Comparing lessons learned from Agile hardware projects [52] and lessons learned from traditional space sector projects [21], highlights the similar methods those researchers used, namely external help, team co-location, interactive design reviews, and frequent early testing. The same results have been observed in case studies performed by Playbook [53], showing an decrease in project cost and time-to-market for hardware projects.

As identified by previous space industry experience [21], faster-better-cheaper methods for space missions has been an area of interest. It is argued that plan-driven systems engineering is unable to be agile [43]. Jim Highsmith [45], one of the signatories of the original Agile Manifesto [42] argues that a large team cannot be as agile as a small team, but a large team can be more agile than a competing large team. Highsmith notes that as teams increase in size, the importance of structure also increases, demanding more coordination and documentation across different sub-teams. However, the structure adopted to larger teams can be more flexible, and responsive to change, when compared to competing teams, enabling them to incorporate new information quicker than the competition.

Applications of Agile continue to be applied in different types of hardware projects [30] [52] [46] [53] [54] [49], showing that there is no one true Agile method for every project. The available information, research, and lessons learned provide the space sector an opportunity to identify useful approaches that are in the spirit of the virtuous cycle as defined by Zee [15].

2.5 Chapter 2 Conclusion

This chapter provided an overview of the traditional project management approach, including a discussion of its roots in the Apollo project. The traditional phase approach allows for project progress to advance the design incrementally, ensuring that all interfaces are updated simultaneously. The method and tools used require detailed and careful planning, creating a rigid structure that facilitates progress monitoring.

Traditional projects assume that the schedule and scope will have minimal changes, but complex space projects can be inherently chaotic. Project managers require a large amount of effort to maintain a constant work throughput to meet deadlines. The level of effort can be observed in the allocation of labour hours, where the consistently largest use of total labour is project management, and is consistently the largest labour category in all analyzed phases.

There are many opportunities to improve how a complex space project is managed that can decrease the direct management labour, such as creating a highly adaptive self-organizing team with effective communication. Project adaptability is improved through facilitated communication using decentralized planning and accessible information. The ability for the development team to understand how the project is progressing is important, and making a shift from EVM to technical status can effectively communicate to the team technical status, correct priorities, and necessary corrective actions.

Chapter 3

Industry Project Data Analysis

This chapter provides a study of data provided by a completed industry satellite project is analyzed to review how labour is distributed and how technical progress occurs during assembly and testing. This analysis provides insight into the best approach to apply non-traditional methods discussed in Section 2.4, and how to mitigate the causes of delays discussed in Section 2.4.1. The analysis of a traditional project evolution provides me with methods to address hypotheses one (reduce schedule by two years) and two (space systems can be adaptive to changes with Agile Philsophy).

3.1 Traditional Industry Project Data Analysis - Introduction

This research has received project health data for phases B through D from a recent space industry project, that is used as a control case study to identify areas for improvement in accordance with hypotheses two and three. The industry project used a traditional management approach similar to the one described in Section 2.2.

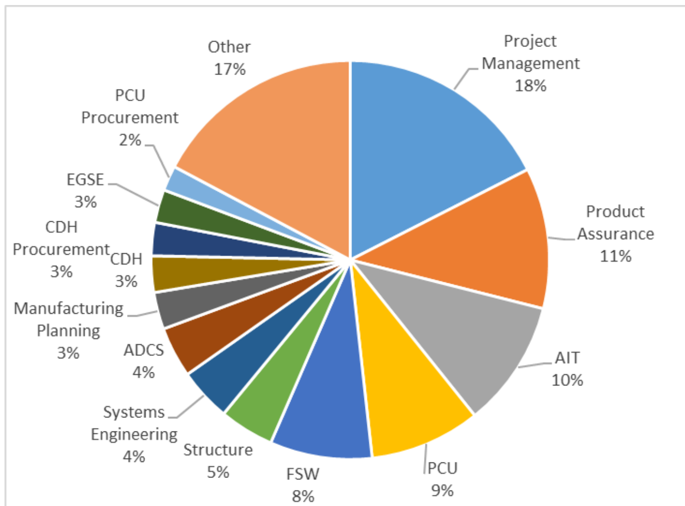
Managers and system engineers controlled and directed many different resources that extended beyond one facility and location, relying on information being distributed between teams. This communication included the project sponsors that received updates at minimum on a quarterly basis or during the reviews discussed in Section 2.2.1.

The company requested confidentiality when analyzing and presenting data they provided, and to ensure that their requests was met, all identifying information was removed. To support this request, I have replaced the time values with percent of the total time and removed any information that may identify the owners. As this industry project has a larger scope than the ManitobaSat-1 project, the percent values provided us with an opportunity to better compare how the two projects evolved.

The following sections present an analysis of how a traditional project behaved as it advanced through phases with consideration of potential causes of delays discussed in Section 2.4.1. I discuss task loading during phases C and D that provide insight into how resources are used, leading into how verification activities are completed through phase D. I conclude this section by reviewing claimed labour hours between different task categories in phases B through D, that represents how work is distributed between project teams. By analyzing how the traditional management method appears in practice, I identify areas where methods and tools discussed in Section 2.4 can have a positive impact for the space sector.

3.2 Traitional Industry Project Data Analysis - Industry Project Labour Hours

Labour hours provide insight into how resources were used in relation to the team task loading, discussed in Section 3.3, during the project. The data received from the industry project included task category, task description, and the amount of time used by resources. Because this was a complex project that needed multi-disciplinary collaboration, there are many different categories of work. To adequately present the information, task categories that had less than two percent of the total are included in the "other" category.



Acronym Legend	
AIT	Assembly, Integration, and Testing
PCU	Power Control Unit
FSW	Flight Software
ADCS	Attitude Determination and Control System
CDH	Command and Data Handling
EGSE	Electrical Ground Support Equipment

Figure 3.1: Total labour hours for Phases B, C, and D.

This figure presents the total allocated labour hours for all development disciplines for phases B through D. Task categories that used less than two percent of the total were included in the "other" category.

Figure 3.1 shows the labour allocation for the full project, showing the three largest task categories are project management, other, and product assurance. Project management is the largest single allocation of effort throughout the whole project, due to the level of effort required to control and direct the project, as defined by Section 2.2. Note that the other category is the sum of all categories that used less than two percent of the total project labour hours. Product assurance activities ensure that the necessary resources are available for production, including materials and facilities, by conducting safety inspections, process audits, and specification reviews. Product assurance activities are undertaken throughout the project, allowing for a connection between product design and manufacturability.

To fully understand the level of commitment required for a project manager, this study further decomposed the labour hours into the separate available phases. Hours are further decomposed for the project management and systems engineering categories to identify areas that planning and decision making can be decentralized into the team. To better understand the project, I present a list and description of common tasks found in all phases below.

3.2.1 Common Labour Hour Categories

The following subsections provide a discussion of the distribution of labour hours for each phase, but there are similarities found within task categories that are important to understand. To ensure confidentiality with the owning space company, all identifying information was removed, but I used task descriptions to create categories that provide meaningful labour information. In the project management and systems engineering categories, I have grouped tasks based on the similarity of their description. Note that not every category appears in each phase (or may be captured in the "Other" section discussed previously). Tables 3.1 and 3.2 presents the most common work categories for project management and systems engineering respectively.

Category	**Description**
Management	Direct input from manager to plan and direct work.
Technical Management	Direct input from the manager for technology development and incorporation.
Documentation	Tasks requiring documentation for various purposes.
Meetings	Any meetings requiring project management presence for either planned or unplanned meetings.
Travel	Instances where project managers need to travel to complete work.
Requirements Review	A detailed review of project requirements.
PMP	Creation or updates of the Project Management Plan (PMP).
Progress Reviews	Detailed reviews of the project's scope, cost and schedule.

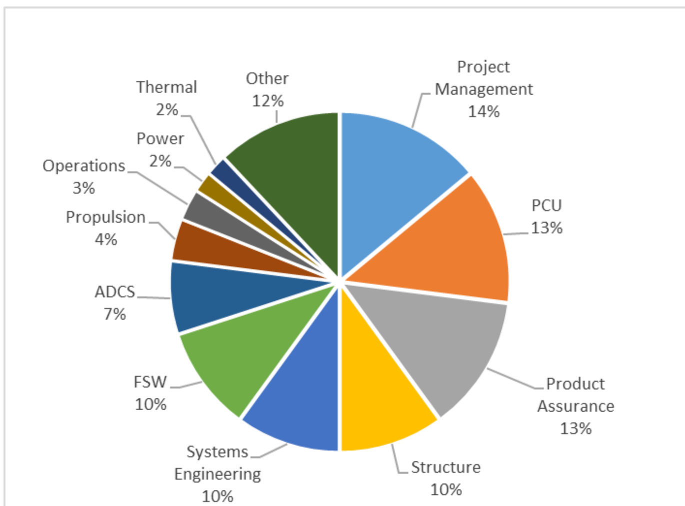
Table 3.1: Project Management Categories

Category	**Description**
SE Management	Direct input from the Systems Engineering (SE) team.
ICDs	Development and updates to the Interface Control Documents/Drawing (ICD).
Req. & Ver.	Development and updates to project requirements and verification activities.
System Analysis	Analysis of the system design.
Documentation	Tasks requiring documentation for various purposes.
SEMP	Creation or updates of the Systems Engineering Management Plan (SEMP).

Table 3.2: Systems Engineering Categories

3.2.2 Phase B Labour Hour Analysis

The NASA Systems Engineering Handbook [4] defines the work in phase B as investigating candidate designs with analysis and documentation, where all subsystems develop designs that best fit the mission. Figure 3.2 provides the labour breakdown during this phase, and shows the three largest categories have a one percent difference from each other. Similar to the total labour hours, project management is the largest category and claims fourteen percent of the total phase B hours.



Acronym Legend	
PCU	Power Control Unit
FSW	Flight Software
ADCS	Attitude Determination and Control System

Figure 3.2: Total Labour Hours for Phase B.

This figure presents the total labour hours claimed in Phase B. Project management is the largest single category at fourteen percent, followed by the Power Control Unit (PCU) development.

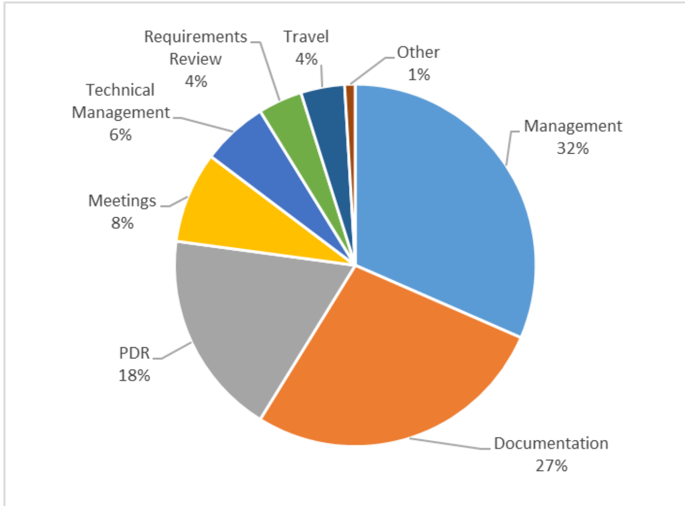


Figure 3.3: Project Management Labour Hours for Phase B.

This figure shows how the project management team allocated their effort during phase B. The largest task group was directly managing the project, followed by documentation.

Figure 3.3 decomposes the project management category into task groups, comparing them as a percent of the total project management hours from Figure 3.2. Management is the largest partition of this category, showing that a project manager is constantly needed in organizing and detailing the project plan. For large complex projects where managers are in a centralized role, they monitor the project status, create and update plans to minimize risks. Their level of control provides direction for the project, but it also required a large time investment on behalf of the team.

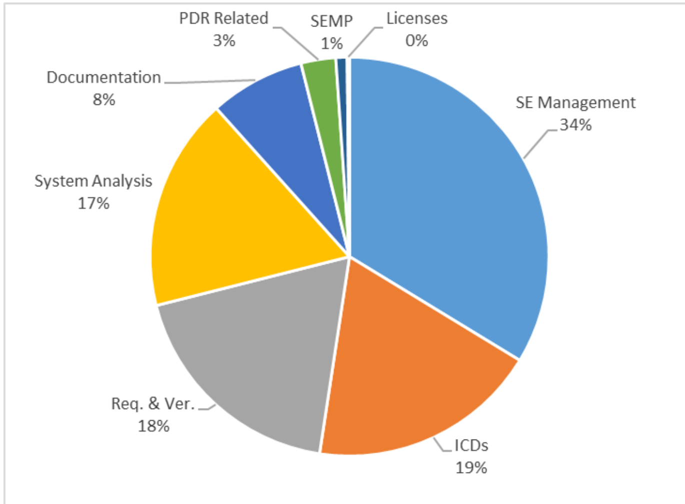


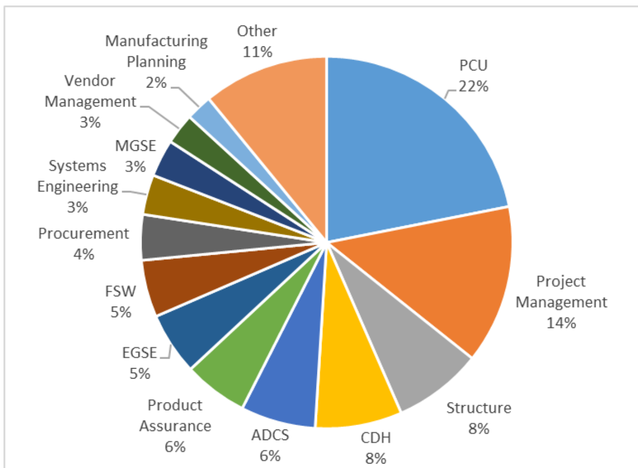
Figure 3.4: Systems Engineering Labour Hours for Phase B.

This figure shows how the system engineering team allocated their effort during phase B. Similar to project management, their largest task was directly managing the technical aspect of the project.

Figure 3.4 provides a visual breakdown of labour hour partition for the systems engineering team. The largest task group is SE management, as system engineers have a central role in the technical aspects of the project by controlling the design of the system. Their responsibilities for the product is also reflected in the next three task groups: ICDs, requirements and verification, and system analysis. Since phase B develops and reviews candidate designs that are subject to change, the system's engineers must ensure that the current design is reflected in the system analysis. As the design continues to be detailed, requirements are updated based on what is achievable. Verification activities need to reflect the current status of their parent requirement to be able to fully capture how a design shows complies with sponsor expectations.

3.2.3 Phase C Labour Hour Analysis

According to the NASA Systems Engineering Handbook [4], Phase C reviews and updates the baseline designs, and is reflected in Figure 3.5. The largest category in this phase is development of the PCU, but other subsystems have a similar allocation of labour. In this phase, project management is the second largest category, but remains proportionally the same as it the phase B project management category. However, phase C systems engineering decreased in labour hours when compared to phase B, with a seven percent drop of labour.



Acronym Legend	
PCU	Power Control Unit
CDH	Command and Data Handling System
ADCS	Attitude Determination and Control System
EGSE	Electrical Ground Support Equipment
FSW	Flight Software
MGSE	Mechanical Ground Support Equipment

Figure 3.5: Total Labour Hours for Phase C.

This figure presents the labour hours claimed in phase C. Project management is the second largest task category, but remained proportionally identical in labour hours as in phase B.

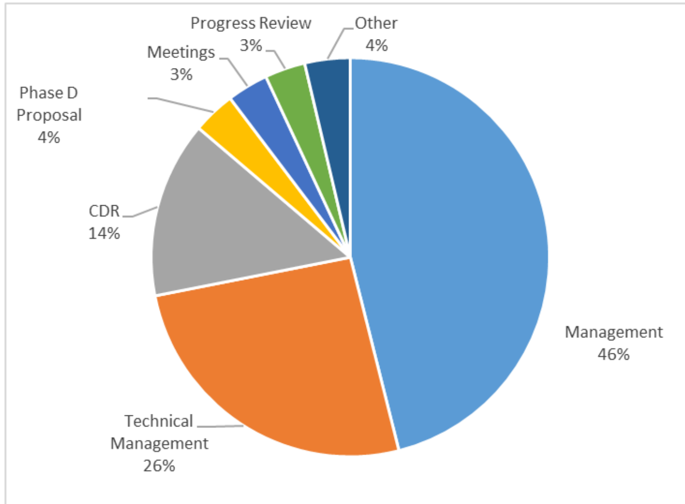


Figure 3.6: Project Management Labour Hours for Phase C.

This figure shows how the project management team allocated their efforts during phase C. The largest task group was management, that increased from phase B by fourteen percent.

Project management was the second highest demand for labour hours, continuing as the central coordinating role for all work packages. Figure 3.6 breaks down the project management work into task groups, showing that there was an increase in the management tasks. During phase C, approximately half of the project management labour was directed at managing the project, including updating management plans, monitoring changes, and directing work.

The technical management category also increased by twenty percent from phase B due to the increase focus in design and technology development. Technical management is a major focus complex space projects, as mitigating risk related to technology follows a strict process, as described in Section 2.2.3. Although only project management hours are presented here, technical management requires input from other project leads to create a development plan that has a low impact on the project schedule and budget.

The third largest use of labour is work related to the Critical Desisgn Review (CDR) and ensures that stakeholders are able to understand the status of the project for an informed decision. Similar to the PDR, this involves collecting design and verification information to provide a detailed review. As mentioned in Section 2.2.1, the CDR is a major decision point as it is the last review before manufacturing activities begin.

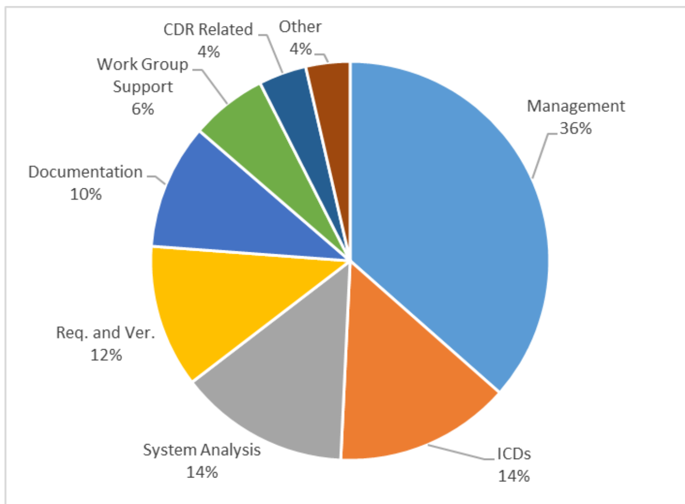
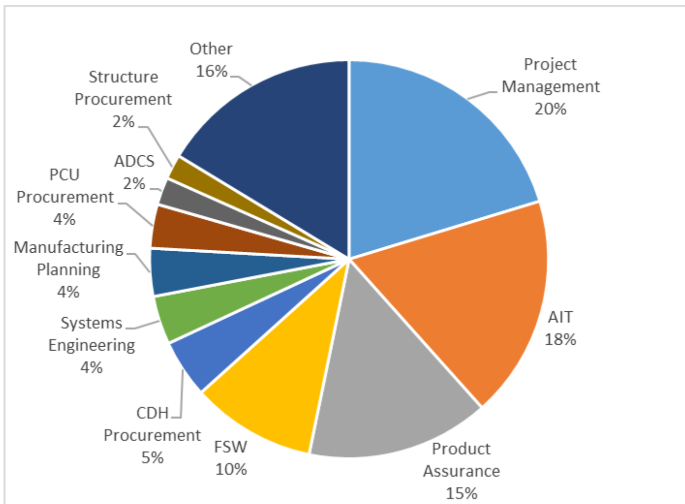


Figure 3.7: Systems Engineering Labour Hours for Phase C.

This figure shows how the system engineering team allocated their effort during phase C. Similar to phase B, their largest task group was SE management, but remained approximately the same in percentage. However, there was a reduction in total systems engineering hours that impact how these hours appear.

Figure 3.7 provides a breakdown of the systems engineering labour in phase C. Similar to project management, the largest partition of work comes from SE management. ICDs remain the second largest task group, requiring updates as subsystem detailed design becomes finalized. System analysis has become the third largest work category, surpassing requirements and verification from phase B, reflecting the need to ensure the system behaviour is understood and thoroughly documented before hardware manufacturing.

3.2.4 Phase D Labour Hour Analysis



Acronym Legend	
AIT	Assembly, Integration, and Testing
FSW	Flight Software
CDH	Command and Data Handling System
PCU	Power Control Unit
ADCS	Attitude Determination and Control System

Figure 3.8: Total Labour Hours for Phase D.

This figure presents the labour hours claimed in phase D. Although phase D is traditionally known as the AIT phase, project management uses the largest amount of labour hours.

According to the NASA Systems Engineering Handbook [4], phase D is where hardware construction, system assembly, and verification testing occur, and can be seen as the second largest category in Figure 3.8. For complex systems, the amount of parallel subsystem assembly requires thorough and disciplined planning. Because of the complexity, project management becomes the largest partition of labour hours with a six percent increase since phase C.

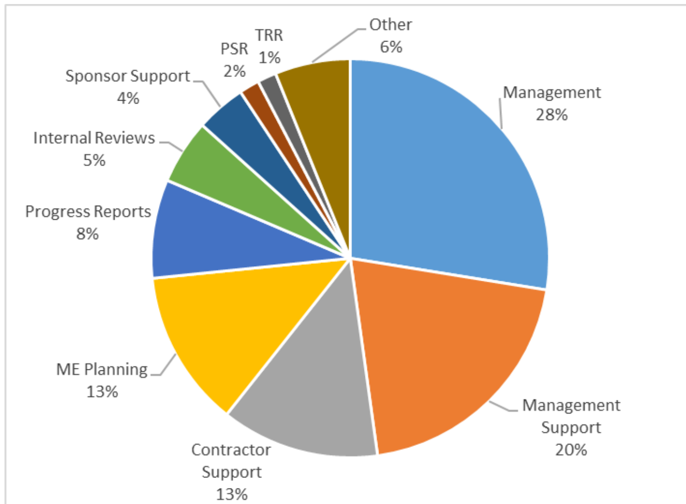


Figure 3.9: Project Management Labour Hours for Phase D.

This figure shows how the project management team allocated their efforts during phase D. Although the largest task group was management, it decreased from phase C in favour of supporting activities for AIT.

Figure 3.9 shows the labour breakdown for the project management team during phase D. Similar to the other phases, the management task group is the largest user of labour hours, but it has drastically reduced since phase C. Management support and contractor support have instead become the second and third largest categories respectively, representing the project manager shifting to a support role to complete hardware development and testing.

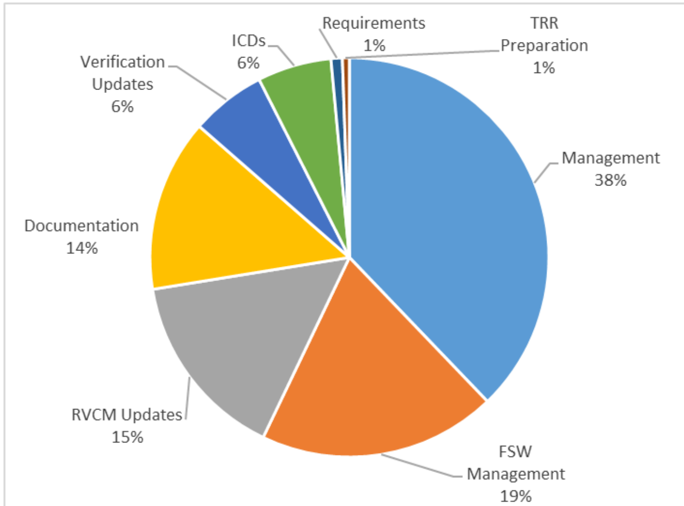


Figure 3.10: Systems Engineering Labour Hours for Phase D.

This figure shows how the system engineering team allocated their efforts during phase D. The SE management category claimed the most labour hours, but has an increase in software management and RVCM documentation.

Figure 3.10 shows the systems engineering use of labour hours, showing similarity to phase C where the largest category is management. In this phase, flight software (FSW) management has become the second largest category. This could be due to the need to incorporate FSW for testing activities, showing compliance with inter-subsystem functionality of the data interfaces. One of the major roles of systems engineering is captured by the maintenance of the RVCM. According the Systems Engineering Handbook [4], the RVCM is a method used to monitor requirement status, and was discussed earlier in this chapter.

3.2.5 Labour Hour Distribution Discussion

The complexity of large space projects demand constant effort by the project manager to maintain all work organized and flowing. The high level of labour used by the project managers can be observed in the labour allocation in Figures 3.1, 3.2, 3.5, and 3.8. Further decomposition showed that the largest task for project managers was direct management. Between phases B and D, project management is the largest use of labour during the preliminary design, and AIT activities. Although PCU was the largest category in phase C, project management was the second largest use of effort, but still was almost double of the other categories.

The high labour loading on project management resources increases the risk of delay due to two sources: multitasking and unavailable resources. As discussed in Section 2.4.2, queue theory notes that resources take exponentially longer to complete work around sixty percent work capacity loading. As work increases for the project management team, they are unable to undertake new or remaining work, potentially causing delays if work in their queue is critical. As the project management resources are a central role, their unavailability can have a cascading impact on the project. The project management resource may be tempted to multitask to finish remaining tasks, but as discussed in Section 2.4.1, multitasking only adds time to tasks. However, by using non-traditional approaches discussed in Section 2.4, such as decentralized management and rolling wave planning, the demand for project management labour can be mitigated.

Decentralized Management

One method to combat the risk of unavailable project management resources is to distribute the project management responsibilities to the team through agile planning. In an adaptive project team, schedule planning changes from the central project manager to the decentralized project team. Decentralized planning shifts schedule control to the subsystem leads that have a strong understanding on subsystem resources and processes. Subsystem leads are supported by the project manager and the systems engineering team to ensure the final product has technical cohesion.

However, there needs to be a culture that supports adaptability, as an adaptive team in a rigid environment can cause frustrations as discussed by Cunningham [48]. It is not enough to just incorporate agile methods at a team level; the parent organization also needs to change the culture to promote adaptive behaviour. Rigby *et al.* [19] provide a discussion on their success developing an adaptive culture in a consumer goods company. They note that leadership and culture are challenges for successful application; therefore, company executives need to create a balanced system that provides structure and agility for innovate solutions with workflow stability. As discussed by Highsmith [45], project managers move away from the central management role and instead take on a guidance role to allow the team to become self-organizing, which allows them creative freedom to apply innovative ideas to a design and be better at adapting to new information. An organizational change from the traditional approach to an adaptive approach would reduce the level of effort needed by the project management team and change the largest work categories to technical development of subsystems.

Rolling Wave Planning and Communication

A self-organizing team can be achieved using methods discussed in Section 2.4. Although these adaptive methods have been developed outside of the space sector, there is interest aerospace applications. Petrini and Muniz [46] presented their study in the effectiveness of the Scrum method in an aircraft manufacturing company, finding that teams were better at planning and implementing changes that provided a business advantage. The Scrum approach provided the manufacturer project visualization, and provided effective communication for the team to make informed design decisions. The application of the Scrum approach would reduce the time needed by the project management and systems engineering teams to directly manage the subsystems.

A variation of the Scrum approach, known as rolling-wave planning [63], can be combined with the traditional phase approach to control the project progress from design to hardware manufacturing. Rolling-wave planning provides a structure that enables organization of the multi-disciplinary tasks required to develop a space product and has flexibility to incorporate new information when needed. The rolling-wave creates a master schedule with enough detail that enables the team to organize work similar to the traditional phase approach presented in Section 2.2.1, but only provides thorough details to the near term plan. As a new phase begins, details are added to the phase schedule to reflect the current status of the project, minimizing the need for constant re-planning as new information is incorporated at the beginning of each phase.

The decentralized rolling-wave approach provides the project team with ownership of their schedule, reflecting their availability and work capacity. In accordance with Agile philosophy, the team is able to reflect on the status of work and their progress when creating the detailed project plan at the beginning of each phase. To ensure that priorities are in line, the team holds a daily meeting to communicate work loads and priorities, mitigating the impact of incorrect priorities and unavailable resources.

Centralized Pull Information Database

Implementing a decentralized planning approach, as recommended by concurrent engineering and Agile philosophy, needs the team to effectively communicate amongst themselves. If the project manager and the systems engineering team move away from the centralized role, the *team* needs to make informed decisions for an innovative design. Complex projects need constant communication to ensure that subsystems can interact and create a cohesive functioning system. To replace the central project management, important information can be provided by a centralized communication pull system.

A central pull system is a database that is available to all team members for them to quickly view the state of the project, review new information, or update the rest of the team on their technical progress. The pull communication approach is contrasted with the push approach, where managers distribute information to team members. Although the traditional management approach is able to take on a complex project through centralized push communication, project managers can soon be overburdened with managing new information as the project progresses, causing the central management resources to become unavailable or forcing them to multitask. The combination of decentralized planning and centralized pull communication enables the project team to self organize and plan their tasks, mitigating project management as the largest category seen in Section 3.2.

The recommendations provided in this section can mitigate the high labour demand for project management to demonstrate control and allows the project team to focus on product development. Project management is consistently one of the largest uses of labour in a project, with most of their efforts focused on directly managing tasks. By decentralizing planning to a self-organizing project team that constantly communicates, more labour would be dedicated to completing technical project work. However, challenges emerge from changing to a decentralized method, such as a continuously changing project plan, increasing the importance of team collaboration and communication. An adaptive project team needs to identify correct priorities, unavailable resources, and ensure that team members do not multitask to create a flexible schedule. The following section analyzes how resources are loaded during phase C and D to find methods to control sources of delay.

3.3 Traditional Industry Project Data Analysis - Project Resource Loading

Data received from the industry project included the first and last dates that tasks were active in phases C and D, providing a method to discern resource loading. The task dates were used to find the number of tasks that are active at the same time that provides a method to view the project through queue theory discussed in Section 2.4.2. Findings are used to establish the framework to evaluate hypotheses one and two.

Project Task Loading Analysis

Playbook [64] explains a queue graph is a useful tool to monitor task loading that provides a visual method to present work-in-progress. Queue graphs record the time an item entered the queue, and the time it exited the queue using vertical axis to sort individual tasks. These graphs provide a view of the quantity of active items in a system by measuring the vertical distance between the start and finish curves.

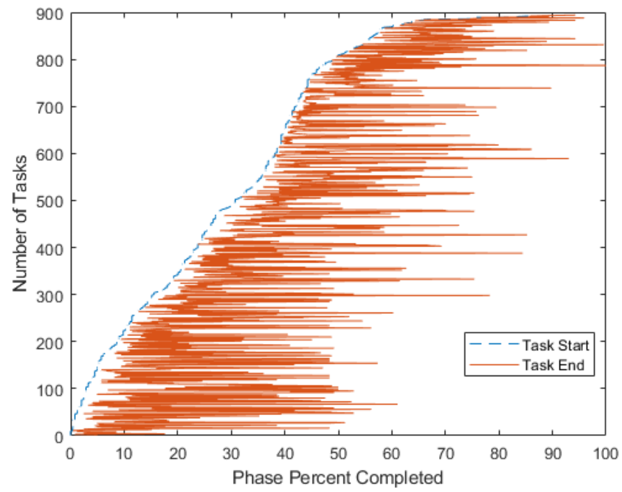


Figure 3.11: Phase C Task Organized by Start Dates

This figure shows individual task start and end dates for phase C. Tasks are organized based on their start dates with their corresponding end date for the y-value.

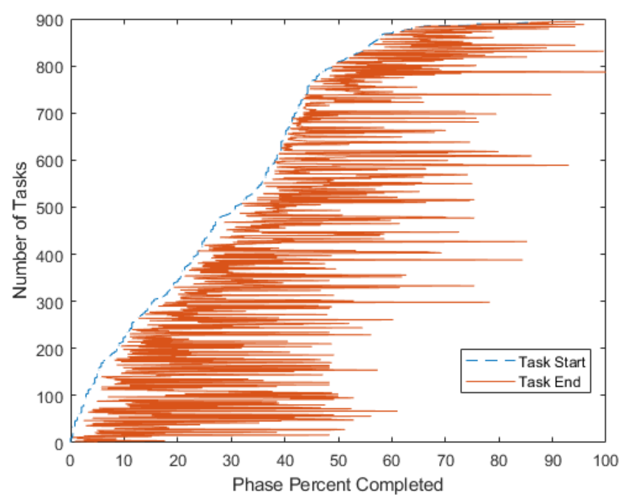


Figure 3.12: Phase D Task Organized by Start Dates

This figure shows individual task start and end dates for phase D. Tasks are organized based on their start dates with their corresponding end date for the y-value.

Figures 3.11 and 3.12 are organized in a fashion as described by queue graphs, where each y-value is a unique task. Each task is arranged by their start dates while maintaining the tasks' corresponding end date value. The resulting graphs display a comb-like pattern that highlights the variability in task duration in their respective phases and shows the chaotic nature of complex projects. A large scale industry project will have a large quantity of different tasks that increase the level of effort needed by project managers to plan and control the schedule.

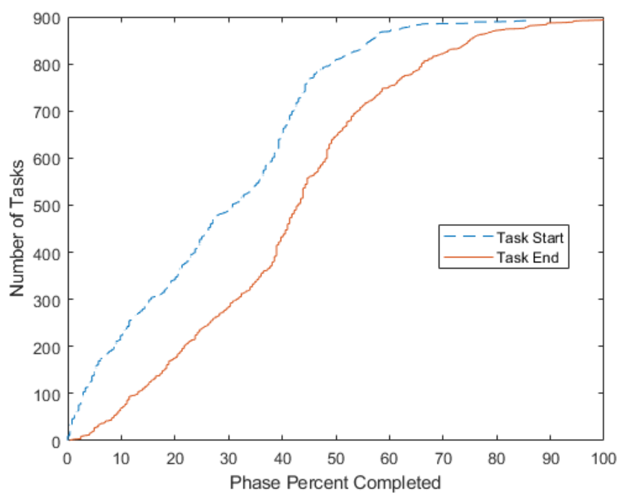


Figure 3.13: Phase C Tasks Organized Chronologically

This figure shows task start dates and end dates for phase C. Contrasted to Figure 3.11, the start and end dates do not correspond with the same tasks, but instead show task loading at any one time.

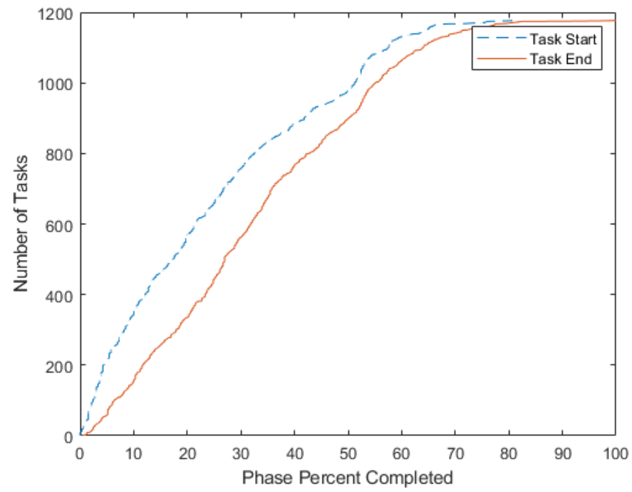


Figure 3.14: Phase D Tasks Organized Chronologically

This figure shows task start dates and end dates for phase D. Contrasted to Figure 3.12, the start and end dates do not correspond with the same tasks, but instead show task loading at any one time.

Figures 3.13 and 3.14 each present two different graphs, task start dates and end dates, that are organized chronologically and independently from each other. These images provide a project queue graph that highlight how work increased or decreased through the project. One useful characteristic of queue graphs is that the vertical distance between the start and end curves provides the number of open tasks at that time.

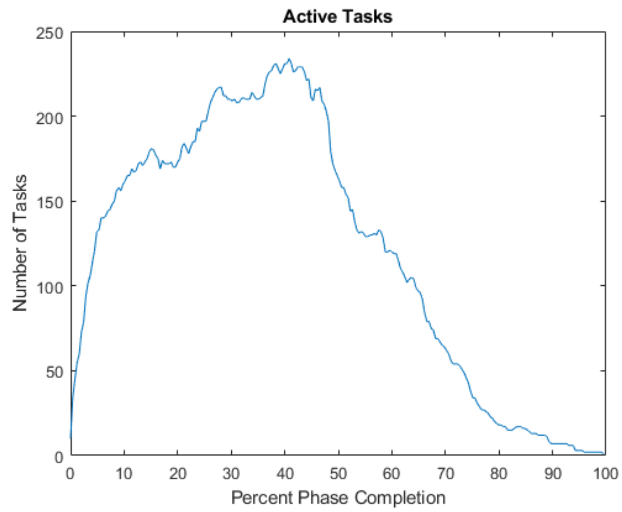


Figure 3.15: Phase C Active Tasks

This figure shows the amount of simultaneous active tasks as phase C progresses.

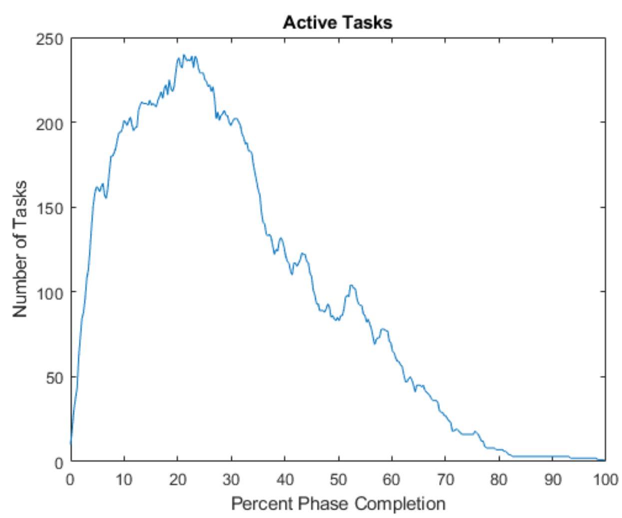


Figure 3.16: Phase D Active Tasks

This figure shows the amount of simultaneous active tasks as phase D progresses.

Figures 3.15 and 3.16 present the amount of active tasks that occur simultaneously throughout both phases. Simultaneous work sharply increases in both cases for the first thirty percent of the phase and will decrease into a trailing end into the review at the end of the phase. This pattern is expected as preparation for the review consists of preparing documentation after active design work is completed.

Although the work growth pattern is similar, phase C contains a longer high work period that had one hundred and fifty or more concurrent tasks when compared to phase D. The sustained high work period can be attributed to the nature of available work for each phase. Phase D includes manufacturing and integration activities, where subsystems can be developed concurrently. As phase D progresses, subsystem integration reduces the available tasks that can be simultaneously undertaken, and can be observed in the long trailing end in Figure 3.16.

This section presented actual work load at different phases of an industry space project, with notable loading in the first half of each phase. Queue theory recommends ensuring that the maximum task loading for teams be sixty percent of our work capacity to account for task variability and improve workflow. Critical chain, discussed in Section 2.4.3, can be applied to find a team and schedule configuration with higher work capacity or identify the workflow bottlenecks that require more support. Once managers understand how resource loading changes with the schedule, they can either change the team and resource configuration to improve task capacity or provide additional support.

The project teams' task capacity is related to the team size, as more team members provide more task capacity to the project. Although this research did not receive data relating to the project team's size, the information I received allows for derivation of how the team changes over time. The following subsection presents an analysis of how the project team changed during phases C and D by combining task dates and labour hours.

Project Team Labour Analysis

Task data presented in the previous subsection was combined with the total task hours to derive the average team size needed to complete each phase. The following assumptions were made for this analysis:

- Team members have a labour capacity of forty hours per week.
- Tasks were completed at the end of their last week.
- There was no variation in task intensity.

This team size analysis combined the total task hours and duration to derive the average team size needed each week. The hour and duration data was used to find the average weekly labour needed to complete each task and was then divided by weekly labour capacity to establish the average task team size. These task team sizes were added for every week that the task was active to provide insight into how project labour changed as the phase schedules progressed and can be seen in Figures 3.17 and 3.18. Note that the team represented in this approximation fully use their labour capacity, where in reality they would work around sixty percent of their capacity. However, the labour hours and task duration remains the same, and highlights the strain on the project team due to labour capacity loading.

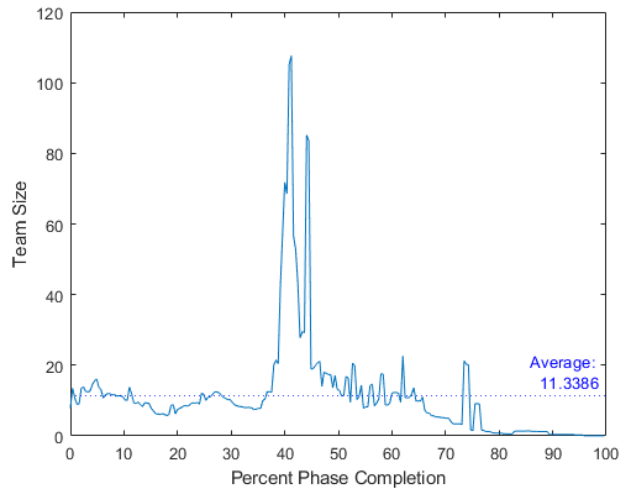


Figure 3.17: Phase C Team Size

This figure shows the average team size needed as phase C progressed, assuming weekly work capacity of forty hours. Phase C had a notable high work period between forty and fifty percent phase completion that overlaps with the highest number of active tasks seen in Figure 3.15.

Phase C had an average team size of eleven individuals that had a weekly work capacity of forty hours, but had a peak of one hundred and seven team members in one week. Comparing Figures 3.15 and 3.17 shows an overlap between the highest simultaneous tasks and active team members. Although the quantity of active tasks was the highest between thirty and fifty percent phase progress, the team labour peaked between forty and fifty percent. This disconnect between the peaks in Figure 3.15 and 3.17 can be attributed to the different levels of effort needed for individual tasks.

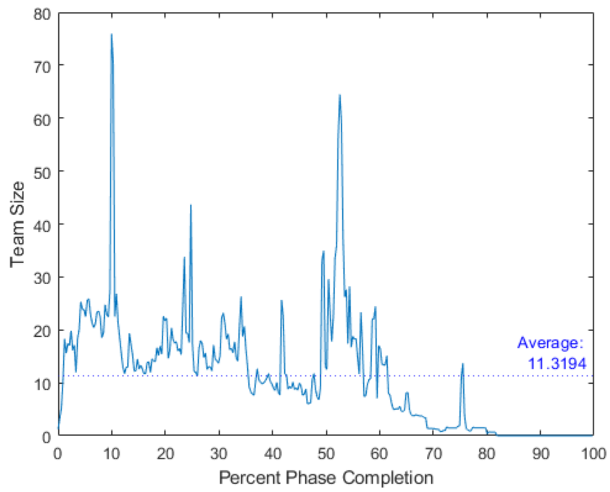


Figure 3.18: Phase D Team Size

This figure shows the average team size needed as phase D progressed, assuming weekly work capacity of forty hours. Phase D has two notable high work periods at ten and fifty percent, but do not perfectly overlap with the high active active task periods seen in Figure 3.16. This disconnect can be attributed to the difference in task labour intensity required for individual tasks.

Phase D had an average team size of eleven individuals with a weekly work capacity of forty hours, with two peaks at seventy five and seventy individuals at ten and fifty five percent phase completion respectively. Comparing Figures 3.16 and 3.18 show a disconnect between active tasks and team labour, but can be attributed to the nature of AIT activities, as described in the following paragraph.

As discussed in Section 2.2.1, subsystem manufacturing activities occur early in phase D and occur concurrently, demanding a high level of effort to organize and assemble each subsystem. Once assembly verification is completed, integration activities and system testing are undertaken until preparation for the FRR begins. In Figure 3.18, the second labour peak occurs at fifty percent, at the same time as the active task decrease in Figure 3.16, implying that although there are less available active tasks, the high labour tasks, such as system verification testing, are being undertaken.

The different types of work and how they impact team work capacity provides enough information to identify how non-traditional methods can be applied. The following subsection discusses how methods discussed in Section 2.4 can be implemented in future space projects.

3.3.1 Project Team Resource Loading Discussion

Understanding how the team's task capacity is impacted as the project progresses illuminates areas where adaptability can be improved. Changing from a rigid traditional planning approach to a rolling wave approach that is supplemented by critical chain scheduling can improve how the team undertakes work. The following subsections discuss how the non-traditional methods can be used to improve the project task throughput by monitoring resource availability with the phase schedule.

Critical Chain Schedule

The team size average was approximately the same for both phases, but the high peaks represent an unsustainable level of growth for a real project team. This team size approximation used the assumption that all team members have a work capacity of forty hours per week, and that no team members used overtime to meet deadlines. Although the project team size may have changed throughout the project development time, drastic increases and decreases seen in Figures 3.17 and 3.18 would not be possible. However, this analysis allows us to view how the level of required labour evolved through the critical design and AIT phases of the project through the critical chain method.

Data presented in Figure 3.17 and 3.18 provide important information to apply critical chain, which focuses on the team members' work capacity to reduce the unavailable resource source of delay. As the team size decreases, the risk of unavailable resources increases as the remaining team members' workload increase. As the derived team size may not be representative of the actual project team, the derived data does present how labour demand in the phases can increase and decrease. Understanding how the labour loads change enables critical chain to create a realistic schedule that reflects expected labour and resource work capacity.

The team needs to understand the status of parallel work and resources when creating their respective plans, requiring awareness of project priorities to ensure the team acts like a cohesive whole. To successfully implement decentralized planning with critical chain, the team needs to be able to effectively communicate with each other what their priorities are and their labour capacity load. Implementing a centralized communication architecture would ensure that all information is available to each team member.

Team Communication

As discussed in Section 3.2.5, ensuring that the team has access to project information, including tasks and schedule, enables them to identify correct priorities. The schedule created by each subsystem should reflect team loading to mitigate unavailable resources and multitasking, but also focus on critical priority tasks. When the information is available to the team, risks can be quickly identified and amended without thorough rework of the whole project plan.

Task completion and team work loads provides insight into how resources are used during a project, but does not necessarily reflect progress. To understand how the traditional approach directs work towards a goal, the following section provides an analysis on how the project requirement verification status evolved throughout Phase D.

3.4 Traditional Industry Project Data Analysis - Progress Management During Phase D

Earned Value Management (EVM) information used by the industry project management team was unavailable for this research, but the development team likely focused instead on the quantity of requirements verified. I propose using verification activity status as an alternative to EVM, as it would demonstrate product compliance in the spirit of the seventh Agile principle, "working software is the primary measure of progress," discussed in Section 2.4.5. The following subsections provide analyses of how the project progressed through verification activities and team labour.

3.4.1 Project Verification Progress During Phase D

Although no EVM data was available for this research, I reviewed the verification activity status through phase D as an alternative measure of technical progress. The industry project provided quarterly updates to the Requirements Verification Compliance Matrix (RVCM) that documents verification activity status, including if it has been undertaken, results, and if the results were accepted by the sponsor. Examining the RVCM updates provides insight into how the satellite testing advanced and if it met sponsor expectations. Note that a sponsor can accept verification results that are either partially compliant, non-compliant, or not applicable with evidence and justification. Data is presented in a fashion similar to burn graphs, described in Section 2.2.4, where total activities act as a PV metric to meet, and accepted activities act as a EV and AC to demonstrate progress.

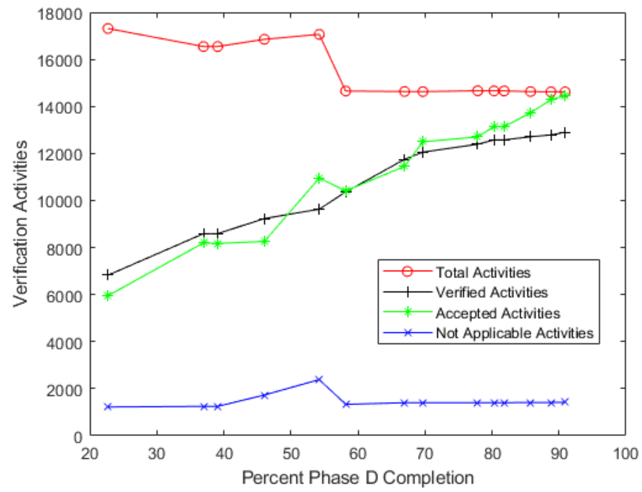


Figure 3.19: Verification Progression During Phase D.

This figure shows how the verification activities changed through phase D, with each mark as a version of the RVCM as it was released. To complete the phase, sponsors need to accept the results of all activities, which may include partially compliant results, deleted activities, or activities found to be not applicable.

Figure 3.19 shows how the verification activities changed over the duration of Phase D in the baseline industry project. I investigated four categories that provide an informative trend for a complex project:

- **Total Activities**

  Activities that are ideally established early in the project and remain unchanged, giving the development team a goal to meet.

- **Verified Activities**

  Activities that are completed through tests, analyses, demonstrations, or inspections that demonstrate compliance with requirements, but are not necessarily accepted by the sponsor.

- **Accepted Activities**

  Verification activities that have been approved by the sponsor, but may not always be compliant to requirements.

- **Not Applicable**

  Activities deemed not applicable are verification tasks that were removed because of changing requirements or corrective actions, and may be deleted in subsequent RVCM versions.

In an ideal project, total activities would remain unchanged until the end of the project, and would appear as a horizontal line. This industry project demonstrates how total activities change over time, and can be observed by the increase of planned activities between forty and fifty percent and a sharp decrease between fifty and sixty percent. This change can be attributed to the not applicable category, where activities were quickly removed around the sixty percent mark. Note that a scope change occurs when a verification activity is categorized as "Not Applicable," but the removal of these requirements from the RVCM is a clerical change. Discussion with project leads attributed this to inconsistent documentation, noting that although the team agreed to a certain format for RVCM updates, it was not always followed.

The quantity of accepted and verified activities increases slowly towards the total number, and appears to be linear when compared to the active tasks shown in Figure 3.16. It is important to note that for Phase D, there are more verification activities than there are available tasks, showing how multiple verification activities can be completed by one task. The level of detail used by verification activities provides a thorough snapshot of the technical status of the project, and demonstrating how closely aligned the product is to sponsor goals and expectations.

Using verification activities as a measure of progress is available throughout the project, as verification activities can be undertaken early. Phase D begins with approximately one third of all activities accepted by the sponsor. The trend seen in Figure 3.19 implies that verification activities have already started and accepted before the start of Phase D, but further investigation is needed to identify the trend. However, by implementing methods and technologies to undertake early testing as recommended by lean manufacturing and Agile philosophy, verification status can provide a thorough and reliable method to measure technical progress.

Figures 3.19 and 3.16 shows the relationship between the level of effort and technical progress of the product. As discussed in Section 2.2.1, phase D consists of subsystem assembly that allows for concurrent tasks before integration to the final product. Although a large amount of effort is required to build all subsystems in parallel, the verification is done incrementally as a system from the beginning to the end of the phase. As a final note, the quantity of verification activities is higher than the quantity of tasks, allowing for a high resolution metric to measure the progress.

Verification activities can be displayed in a similar fashion as burn-graphs, as presented in Figure 3.19. Similar to the application in Agile projects, verification activities can be tracked in burn-graphs to measure progress and how the project changes. The total number of verification activities changes in phase D, demonstrating that changes can happen late in the development phase. Using verification activities as a progress metric ensures that the project managers and sponsors are able to adapt to changes by understanding project progress as activities are added or removed.

Verification activities can be used to effectively present the project progress and can be demonstrated by comparing how the industry project is presented through team labour and the verification status discussed in this subsection. The following subsection compares the verification status approach with the team labour presented in Section 3.3.

3.4.2 Project Progress Analysis Comparison: Verification Status Versus Earned Value

To demonstrate the effectiveness of measuring progress through verification status of the product, I have compared it with the derived phase D team size data, presented in Section 3.3, and integrated it providing an approximate equivalent to EV. The derived team size was a combination of total task hours, task duration, task start and end dates. Although EVM data for the project industry was not provided, the cumulative team effort provides a metric that loosely represents the earned value of the project.

Figure 3.20 shows the comparison between the earned value and the verification status of the project. Although the two data sets use different units to demonstrate the project progress, the coefficient of correlation is 0.9509. The strong correlation shows that both approaches are representative of project progress and can lead to easy industry adoption of the verification progress analysis metric.

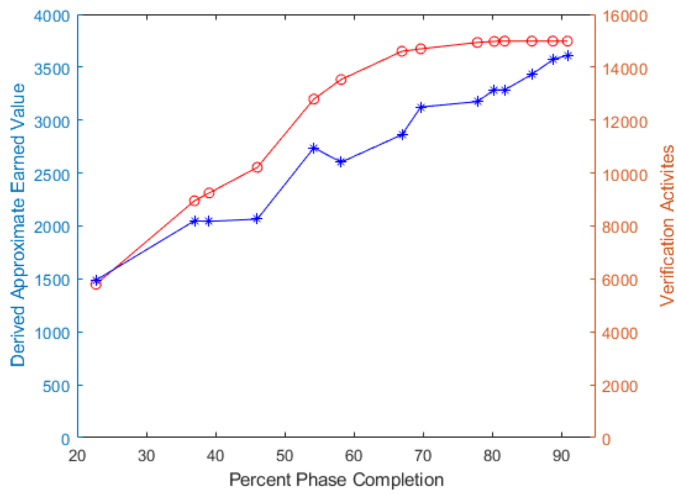


Figure 3.20: Progress Analysis: Cumulative Team Size Versus Verification Status

This figure compares the integration of team size presented in Section 3.3 and the verification status presented in Section 3.4. The cumulative team size presents the team's labour as the project progressed. The two data sets had a coefficient of correlation of 0.9509.

The high correlation between the derived EVM and verification activity completion suggest that if verification is undertaken in a timely manner, engineering teams are likely to remain cash neutral throughout the project for different types of contracts. Because EVM focuses on the value of work complete, it allows project teams to effectively work in a cash neutral structure, receiving pay for the cost of work completed at agreed upon milestones. This structure ensures that the project team receive payment for actual costs of project tasks plus agreed value earned and limits the risk of needing financial aid to complete work between milestones. Changing from EVM introduces risks into the project of being unable to properly track project progress, and by extension, project payment.

However, if the systems engineering team carefully plans verification activities, the project will have a more detailed progress management approach and a cash neutral method that provides the same safety as EVM. As can be seen in Figure 3.19, approximately a third of the initial verification activities have been verified and accepted at the beginning of phase D. Using early prototype testing and systems engineering planning, verification activities can be steadily verified throughout the project.

Incorporating verification activity as an alternative to EVM does not require additional administrative effort to use effectively, but does provide a more detailed metric to monitor the technical development of the product. The detailed progress updates provide a constant throughput of milestones that demonstrate value to the sponsors. Due to the different methods that engineering projects receive payments, verification activities can be applied to different types of engineering contracts. Samuels and Sanders [65] explain that most project contracts are defined by the method of payment. The common payment contract types are described below:

- **Fixed-Price Contracts**
  This contract provides goods or services to the project sponsor in exchange for a fixed budget.
- **Cost-Plus Contracts**
  This contract where the project team is paid the actual cost of materials plus a fee for work completed. The fees are established early in the project and can be combined with payment plans.
- **Unit Price Contracts**
  This contract provides payment to the project team for each unit provided to the sponsor.

The verification status metric can embody the third agile value (Customer Collaboration over Contract Negotiation) to identify verification tasks that demonstrate to the project sponsor the technical progress and conformance to requirements. Completed verification activities provide payment milestones that have a high correlation with project labour and ensures that the development team is paid proportionally to the work completed.

Verification activities provide a useful alternative to traditional EVM to monitor and demonstrate project progress that can be easily adapted into space projects. As no EVM information was received for this study, the cumulative team size was used to approximate earned value provided to the customer. Verification status had a high correlation with the cumulative labour value, highlighting how both demonstrate progress. Although the verification status data was only provided for phase D, methods and technology can be implemented for early verification testing throughout the project, and is discussed in the following subsection.

3.4.3 Project Progress Metrics Comparison Discussion

Although verification data was only presented for phase D, existing technology is able to facilitate early testing that creates an opportunity to provide constant verification activities through the project. Liseitsev *et al.* [66] reviewed the aircraft design process and how it can be improved, calling for implementation of modern technology to further assist in product design. New tools include fabrication of components using nanotechnologies and additive manufacturing, allowing for opportunities to close the hardware designer-manufacturer gap discussed by Carson [43].

The fabrication tools recommended by Liseitsev *et al.* enable project teams to undertake early verification testing that demonstrates value to the sponsor through working product. Early testing can be combined with the verification progress approach to create a consistent and unambiguous progress definition. The combination allows the development team and the sponsor to collaborate and create a functioning final product.

As explained by Cabri and Griffiths [59], the traditional management method to monitor progress is EVM which assumes that the project is thoroughly detailed at the beginning of the project. However, as shown in Figure 3.19, project details can change late in the project. Verification activities are useful metric to monitor progress, as they are clear, concise, and widely known to the team. Because of the familiarity with verification activities, when changes occur, the team is able to quickly understand the impacts, and reorganize their tasks as priorities and team availability changes.

Ensuring that the team is able to understand project progress to align priorities is important, but there are different methods to monitor project progress. Although burn graphs are used in the traditional approach, it has found use in non-traditional approaches. Nikravan & Foreman [67] discuss the benefits of using EVM in Agile projects, noting that the ability to track planned work provides structure. Agile projects thrive in chaotic environments where plans and baselines may not necessarily be stable, creating a challenge in monitoring the project budget. However, Nikravan & Foreman note that software development uses burn charts to monitor the planned features in the software, creating a more stable progress metric than budget for highly adaptive projects.

Verification activities as a metric for progress provide the technical health of the project and can be clearly displayed through a burn-graph. A verification burn-graph visualizes the status of the project and how it has changed with new information or changes, as shown in Figure 3.19. Project progress is made available to the project team through the central communication system and provides guidance in the critical project activities, allowing the team to update their rolling-wave schedules with minimal impact to the project plan.

Recommendations made in this chapter can reduce the labour needed to directly manage a complex space project, allowing the team to focus on their work. The traditional management approach uses a rigid organization method that requires more labour to maintain than to develop the product subsystems. Applying non-traditional methods presented in Section 2.4, complex space projects would be able to reduce the labour needed for organization and be able to adapt to changes. The majority of these recommendations have been implemented in an ongoing nanosatellite mission that is presented in the next chapter.

3.5 Chapter 3 Conclusion

This chapter provided an analysis of a recently completed space industry project that was traditionally managed to identify the areas where adaptive methods are best applied. The data received from the industry project includes project labour hours, concurrent tasks, and requirement verification status.

Project Labour hour distribution for phases B through D was studied to identify project management and systems engineering resource labour loading, finding that project management resources tends to be the highest use of labour for all three phases. The high labour demand of the project management team increases the risk of multitasking and unavailable resources, and increases the risk of the project team working on incorrect priorities without available management. However, implementing a decentralized management approach allows project teams to mitigate these sources of delay, allowing the project management team to provide support and guidance.

The quantity of concurrent tasks for phases C and D was analyzed to understand the labour loading of the project team. Concurrent tasks was combined with labour hours from phases C and D to create an equivalent team size to fully understand the needed resources for project teams. For phases C and D, teams were found to be on average approximately eleven fully loaded team members, but had unsustainable team growth that exceeded seventy simultaneous team members. In reality, this would manifest as overtime for team member, and can have adverse effects on individual team members, increasing the risk of team members being unavailable for necessary work. However, team availability can be used when creating project schedules to ensure a steady work flow and mitigating the risk of unavailable resources.

Additionally, an alternative method to measure project progress through requirement verification activity was evaluated as a metric that is meaningful to project sponsors and technical leads. The traditional project management approach uses Earned Value Management (EVM) to ensure that, but does not always reflect the technical state of the project. This research proposes using requirement verification activities as an alternative, finding a 0.9505 correlation coefficient with a derived Earned Value metric from project tasks and labour. The high correlation suggests that requirement verification as an alternative metric allows teams to maintain a cash neutral progress management approach.

Recommendations from this chapter are applied to the ManitobaSat-1 project, an ongoing nanosatellite project that is part of the Canadian CubeSat Project (CCP). The ManitobaSat-1 project provides an opportunity to apply non-traditional approaches to a complex space project. As part of the CCP, the ManitobaSat-1 project is able to compares scheduled review dates as a measure of project progress. The mission, project management plan, and results are presented in the next chapter.

Chapter 4

ManitobaSat-1 Project Management

The previous chapter recommended improvements for the traditional project management approach used in the space sector, providing the groundwork for the ManitobaSat-1 management plan. The ManitobaSat-1 project is an ongoing nanosatellite project that aims to expose geological samples to the space environment and observe space weathering effects on their optical properties. I am the project manager for the ManitobaSat-1 project and have developed the project management plan to evaluate the thesis hypotheses, presented below:

1. I hypothesize that a two year spacecraft project schedule can be shortened by two months by applying the agile philosophy to certain aspects to the project.

2. I hypothesize that a complex space system is able to quickly adapt to external project changes using Agile Philosophy.

3. I hypothesize that communication services that use Kanban and Scrum information structures, along with additive manufacturing for rapid prototyping will

decrease schedule without affecting the quality work completed.

In the following section, I provide background on the Canadian CubeSat Project (CCP) and the ManitobaSat-1 project to provide a groundwork to present research data.

4.1 ManitobaSat-1 Background

ManitobaSat-1 is one of fifteen nanosatellites that are currently being developed as part of the Canadian CubeSat Project (CCP) [12]. The CCP is providing students from the University of Manitoba an opportunity to directly interact with the Canadian Space Agency (CSA) and receive expert advice and guidance from the space sector. The following subsections provide details on the CCP, the ManitobaSat-1 science mission, and how the ManitobaSat-1 project team interacts internally and externally.

4.1.1 Canadian CubeSat Project (CCP)

The CCP is an initiative by the CSA to create Highly Qualified Personnel (HQP) for the Canadian space sector by providing post-secondary institutions an opportunity to design and build a nanosatellite [12]. The CSA chose fifteen institutions to develop unique space missions that receive feedback and guidance through design and manufacturing activities. At the end of development, each nanosatellite project will be launched from the International Space Station (ISS) to begin their respective missions. The fifteen chosen institutions and their nanosatellite names are presented in Table 4.1.

Academic Institution	**CubeSat Mission**
Aurora College	AuroraSat
Concordia University	Space Condordia's Orbital Dust Imaging Nanosatellite (SC-ODIN)
Dalhousie University	Dalhousie University CubeSat (DUCS)
McMaster University	NEUDOSE
Memorial University	Kilick-1
Université de Sherbrooke	Quantum Magneto Satellite (QMSat)
University of Alberta	Ex-Alta 2
University of Manitoba	ManitobaSat-1
University of New Brunswick	VIOLET
University of Prince Edward Island	SpudNik-1
University of Saskatchewan	RADSAT-SK
University of Victoria	ORCA2Sat
Western University Nunavut Arctic College	Western University/Nunavut Arctic College CubeSat Project
York University	Educational Space Science and Engineering CubeSat Experiment (ESSENCE)
Yukon University	YukonSat

Table 4.1: Canadian CubeSat Project Teams

The CCP nanosatellites have a variety of mission types that include outreach, technology demonstrations, and science missions. Although the goal of each mission is different, the satellite development plans follow a traditional phase approach similar to the one described in Section 2.2.1. The end of phase reviews are used as major milestones for the teams to present development progress and for the CSA to provide feedback and guidance. Major milestones for all CCP teams are presented in Table

4.2.

Major Milestone	**Phase**	**Date**
Mission Concept Review	A	January 2019
Preliminary Design Review	B	October 2019
Critical Design Review	C	February 2021
Flight Readiness Review	D	Late 2021
Launch	D	Early 2022

Table 4.2: Canadian CubeSat Project Milestones

The milestones dates presented in Table 4.2 were originally planned to be within a two year development cycle that began in mid 2018 and ended with a planned launch in November 2021. Most changes to the schedule were due to CSA and review location availability, but the schedule has been severely impacted by the ongoing COVID-19 pandemic. The original date for the Critical Design Review (CDR) was August 2020, Flight Readiness Review (FRR) was September 2021, and nanosatellite launch was November 2021. As the ongoing pandemic situation progresses, the CCP CDR is set to be in February 2021 and will follow precautions dictated by health officials.

The University of Manitoba is a participant of the CCP, and is currently undertaking critical design activities as phase C continues. An outline of the ManitobaSat-1 project is provided in the following sections.

4.1.2 ManitobaSat-1 Science Mission

The ManitobaSat-1 project is a collaboration between the University of Manitoba, York University, the Interlake School Division, and the University of Winnipeg. The ManitobaSat-1 project has four major objectives presented below:

1. To train students in key aspects of space science and satellite engineering.
2. To explore how the space environment changes the optical properties of asteroids and the Moon over time.
3. To demonstrate a new sun sensor from York University.
4. To promote space technology and engineering to youth and young adults.

Objectives one and four outline our outreach goals for the satellite, to provide students with training and resources to develop a complex satellite system, but objectives two and three present our science mission. ManitobaSat-1 has a primary mission goal to document how space weathering affects the optical properties of geological samples with known material compositions. To document how the optical properties change, we plan to record how the average red, blue, and green intensity of reflected light from selected samples change over the duration of the mission. Our mission expects to provide a useful connection between asteroid optical properties and their material content.

Our secondary mission goal is to provide York University's attitude determination and control system (ADCS) hardware an opportunity to gain additional flight heritage for their sun-sensors [68]. The selected geological samples for our science experiment need to be exposed to the space environment and to direct solar radiation. York University have developed highly accurate sun-sensors that have been integrated in the DESCENT flight mission [69], that are also being used in the ManitobaSat-1 mission. The sun-sensors will provide the science team with sample illumination history data, the attitude control system with the pointing direction, and York University with performance data and flight heritage.

The main science mission was designed by the University of Winnipeg's Centre for Terrestrial and Planetary Exploration (C-TAPE) [70] to expose geological samples to the space environment and direct solar radiation to observe changes in optical properties. Figure 4.1 shows the scientific experiment configuration used during the project to document reflected light data. The science mission exposes a minimum of ten samples chosen and provided by C-TAPE to improve the space community's ability to visually link asteroids' optical properties to material composition.

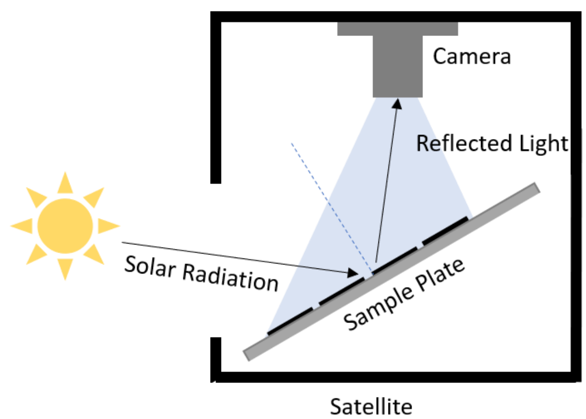


Figure 4.1: ManitobaSat-1 Payload Concept

This figure shows the basic concept for the ManitobaSat-1 science mission. The nanosatellite exposes geological samples, including asteroid and lunar samples, to the space environment and direct solar radiation. Reflected light is captured by an on-board camera that analyzes the average red, blue, and green intensities for each sample.

By exposing geological samples that are representative of asteroids observed by a spacecraft, we can develop a data catalogue relating optical properties to material compositions. In the ManitobaSat-1 mission, each sample is exposed to the space environment and incoming solar radiation over a maximum mission duration of two years, where an on-board internal facing camera captures sample images. The image is processed by the satellite's Command and Data Handling (CDH) unit to measure the average red, blue, and green pixels per sample. The mission will record the average red, blue, and green reflected light intensities at a weekly frequency and compare how the values change over the mission lifetime.

Exposing geological samples to the space environment and direct solar radiation requires accurate pointing and careful control of satellite orientation, providing a demand for an accurate and low cost ADCS. Gyroscopes, magnetometers and York University's sun sensors provide the ADCS information about the pointing direction of the spacecraft.To provide orientation control, York University is also providing torque rods that create a magnetic dipole, causing a torque as the dipole interacts with the Earth's magnetic field.

The Interlake School Division is involving their space club in developing a gnomon: a vertical rod that casts a shadow on a dial, as a backup method to collect orientation information. The gnomon and dial is integrated directly on the sample plate to capture satellite orientation relative to the sun from captured images. The gnomon brings two benefits to the ManitobaSat-1 project: a) another method to find the direction of solar radiation and b) to provide design ownership to the Interlake School Division that meets mission goals one and four.

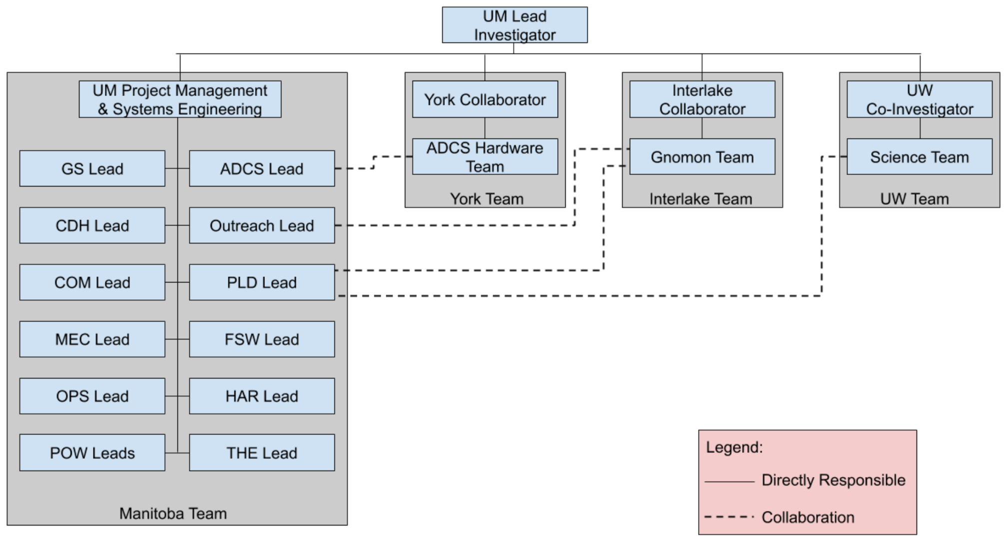
The University of Manitoba's Space Technology and Advanced Research Laboratory (STARLab) is developing the nanosatellite that integrates the previously presented elements and undertakes the science mission. To ensure that the samples are exposed to the sun inside a nanosatellite, ManitobaSat-1 has an opening in the sun-facing direction. The opening used to illuminate the samples is facing the same direction as the solar arrays used to generate power. Placing the solar arrays and the geological samples on the same face of the satellite removes a risk of having to sacrifice either maximum power generation or sample illumination.

In this section, I have presented the ManitobaSat-1 mission and project goals, including how each collaborator contributes to the hardware development and science experiment. Although we all understand the mission goals, team organization and communication are an important part of project progress. The following subsection provides an overview of the ManitobaSat-1 project team structure, including internal and external communication architecture.

4.1.3 ManitobaSat-1 Project Team Structure

The ManitobaSat-1 project is a collaborative effort using a team of teams architecture to design, test, build, and operate a nanosatellite. As presented in the previous section, the ManitobaSat-1 project team is composed of teams from the University of Manitoba STARLab , the University of Winnipeg C-TAPE Lab, York University, and the Interlake School Division. The teams are self-organizing and need to communicate effectively between different facilities that may not be in the same city to be able to coordinate efforts to build a functioning satellite.

Figure 4.2 shows the ManitobaSat-1 team architecture, highlighting the direct communication and collaboration relationships. The STARLab payload development team works with the C-TAPE lab and the Interlake space club to develop the sample plate and camera configuration to record critical data. The STARLab ADCS development team works together with the York University ADCS hardware developers to have a functioning orientation control subsystem to ensure that payload and power components are adequately illuminated by the sun.



Acronym Legend	
ADCS	Attitude Determination and Control System
CDH	Command and Data Handling
COM	Communications
FSW	Flight Software
GS	Ground Station
HAR	Harnessing
MEC	Mechanical
PLD	Payload
POW	Power
THE	Thermal
UM	University of Manitoba
UW	University of Winnipeg

Figure 4.2: ManitobaSat-1 Project Team Architecture

This figure presents the ManitobaSat-1 project team architecture. The University of Manitoba STARLab develops the nanosatellite, but collaborates with other ManitobaSat-1 teams.

Although project investigators and collaborators are accountable for their respective team's work, the ManitobaSat-1 project is a student led development process. The students plan and organize project activities and are directly responsible for meeting deadlines and ensuring due diligence in satellite development. The students interact directly with the CSA to report project progress, satellite design, and mission operations. In addition, the CSA has created communication options for the CCP teams to communicate freely with each other, allowing communication with any team member to promote collaboration and sharing of ideas.

This section has provided background information for the ManitobaSat-1 project, including its place in the CCP. The ManitobaSat-1 project is one of fifteen nanosatellite projects currently in development with different mission goals and objectives. We are undertaking a scientific experiment to understand space weathering effects on the optical properties of geological samples. The ManitobaSat-1 team structure provides an easy method to collaborate between the different parts of the project. The complexity of assembling a nanosatellite where resources are located in different parts of the country require an agreed upon plan. The following section outlines the ManitobaSat-1 project management plan for the STARLab team.

4.2 ManitobaSat-1 Project Management Approach

The ManitobaSat-1 project is a complex space project with different student led teams that are located in different facilities or cities, requiring an agreed-upon management plan to maintain organization and progress. The management plan developed for the University of Manitoba STARLab team incorporated recommendations made in chapter two, and is provided in Appendix A. The following subsections discuss how the recommendations were incorporated.

4.2.1 Adaptive Project Management Methods

The ManitobaSat-1 project management method incorporates non-traditional approaches discussed in Section 2.4 with the traditional project management approach presented in Section 2.2. My goal in developing the project management plan was to create an environment where the team is able to self-organize and communicate effectively to create innovative solutions to new information or changes, without impacting the schedule. The self-organizing nature of the team reduces the need for direct management, allowing for me to act in a guidance and support role to the team.

Although we followed the traditional phase approach of the space sector, presented in Section 2.2.1, we incorporate Agile philosophy to plan and organize our work. As part of the CCP, we are organizing our project tasks in order to meet established reviews, shown in Table 4.2, but the CSA is supportive of our request to organize and present progress in a non-traditional fashion. The following subsections discuss how the ManitobaSat-1 project applies non-traditional methods to a complex space project with a traditional phase structure.

Management Theory and Team Dynamics

The methods used to organize and plan project tasks and communication has a notable impact on how project teams are able to respond to change. Canadian Professional Engineering and Geoscience Practice and Ethics [71] describes management philosophies as part of the education for engineers and geoscientists in training. The book provides two major management styles known as theory X and Y. Theory X assumes that the team naturally avoids work, but their behaviour can be mitigated by subjugating workers to a strict and rigid system. In contrast, theory Y assumes that individuals want to work but need a favourable environment to be able to meet their full potential.

Eklund and Simpson [72] discuss the history and methods of theory X and theory Y. Theory X was born from a scientific and engineering perspective, focusing on minimizing the task variability to create a system that maximizes work throughput.

This approach is effective for factory settings and assembly lines where work flow can be maximized by following a strict set of instructions. To ensure that the human factor in the system acts as expected, the workers follow a strict set of rules that improve task efficiency. Theory X traditionally uses a control and reward system to provide incentives for high worker productivity.

In contrast, theory Y was developed from more human focused disciplines, such as political science and philosophy, where finding the best solution was more important than expedited production. Theory Y focuses on developing a dynamic team that is able to find innovative solutions that are built by an individual's creativity. This approach promotes the involvement of individuals by fostering participation, creating an integrated team environment where all members contribute to the project progress and providing them a sense of ownership. Although this approach relies on an individual's discipline and work ethic, theory Y develops a sense of shared responsibility for completing work and shared rewards when meeting milestones.

Eklund and Simpson note that since the goal of both management styles are fundamentally different, there is no possibility of creating a hybrid management theory that has optimal work throughput and creative solutions for a project, but both approaches can be implemented in different aspects of a project. The ManitobaSat-1 team implemented theory Y in the form of decentralized planning to maximize creativity and problem solving during the development of the nanosatellite design, and can be seen in the new member orientation package presented in Appendix B. To ensure that accurate records of designs and requirements are maintained, documentation and version control uses the traditional systems engineering approach of disciplined record keeping and management, similar to theory X.

As discussed by Cunningham [48], the organization's management environment has an impact on the successful implementation of Agile philosophy. Although the

CSA has the CCP teams using the traditional phase approach, the CSA has been supportive of the adaptive management methods used by the ManitobaSat-1 team, including the application of theory Y through our decentralized planning approach, and the centralized information management system that are presented in the following subsections.

Decentralized Project Planning

The ManitobaSat-1 project is a student led development project, where work is undertaken based on their changing availability, making the ability to adapt to changes important. Changes can occur either internally, such as changing class schedules or individual's roles, or externally, such as sponsor requests or unforeseen circumstances. Additionally, because the team is student led, the team is inexperienced in designing and manufacturing a nanosatellite, and this has caused changes in satellite design or team structures. To increase project adaptability, the ManitobaSat-1 team incorporates the "rolling wave" approach [26].

The ManitobaSat-1 rolling wave planning method, outlined in Figure 4.3, is a Scrum inspired approach that enables the team to combat multitasking by dedicating their efforts to completing a set amount of work within a time frame. Where the Scrum approach for software is focused on completing software features within a set time frame, rolling wave applies the same tools and structures to undertake tasks. Both Scrum and rolling wave use a work backlog from which the team is able undertake work, controlling the scope of work within the allocated time. In both methods, the team lead monitors project progress through short daily meetings that allows team members to provide work updates, communicate priorities, and discuss work blockages.

Because the nature of software and hardware are different, the rolling wave approach begins by creating a project schedule outline that provides guidance to the team when planning. The ManitobaSat-1 project plan began with a project task outline for phases A through D, that the subsystem leads detail and update throughout the project. At the end of each phase, the development leads create a detailed phase schedule for their subsystem and compile a task backlog to organize their work. During the active phase, team members plan the work they will undertake for the next week, and focus on completing all assumed tasks, just like the Scrum approach. At the end of the week, team members review the status of their work and update their schedules based on the task status.

The rolling wave approach uses daily short meetings also used in the Scrum approach, referred to as huddles in Figure 4.3, for the team to align their priorities and monitor availability. Huddles are ideally a maximum of fifteen minutes for the team to present tasks they have planned for the day, communicate blockages, or resolve task bottlenecks. Huddles provide visibility to task progress, which is valuable during phases A through C where design work is not easily visible. The progress visibility gives the team an opportunity to align priorities and allocate their efforts to resolve problems, request assistance from available team members, or observe the impact to schedule changes.

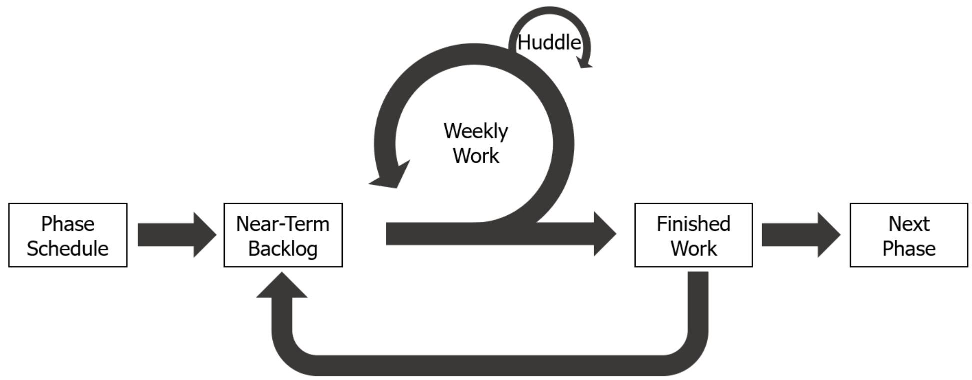


Figure 4.3: Rolling Wave Planning

This figure shows the rolling wave planning approach used by the ManitobaSat-1 project STARLab team. Rolling wave planning builds on the Scrum planning method by developing a detailed schedule for the upcoming phase. On a weekly basis, team members begin work from the phase backlog based on task priorities. At the end of the week, responsible team members update the schedule based on finished work or changes, and schedule high priority tasks.

Detailed schedules are developed using queue theory and the critical chain approach, presented in Sections 2.4.2 and 2.4.3 respectively, to capture the responsible team member's work capacity and available resources (such as summer students or external resources). This approach creates an initial phase schedule that reflects the expected task duration and the labour capacity of subsystem resources. The schedule is combined with the Kanban format, shown in Figure 4.4 to mitigate multitasking and highlight labour loads of each resource.

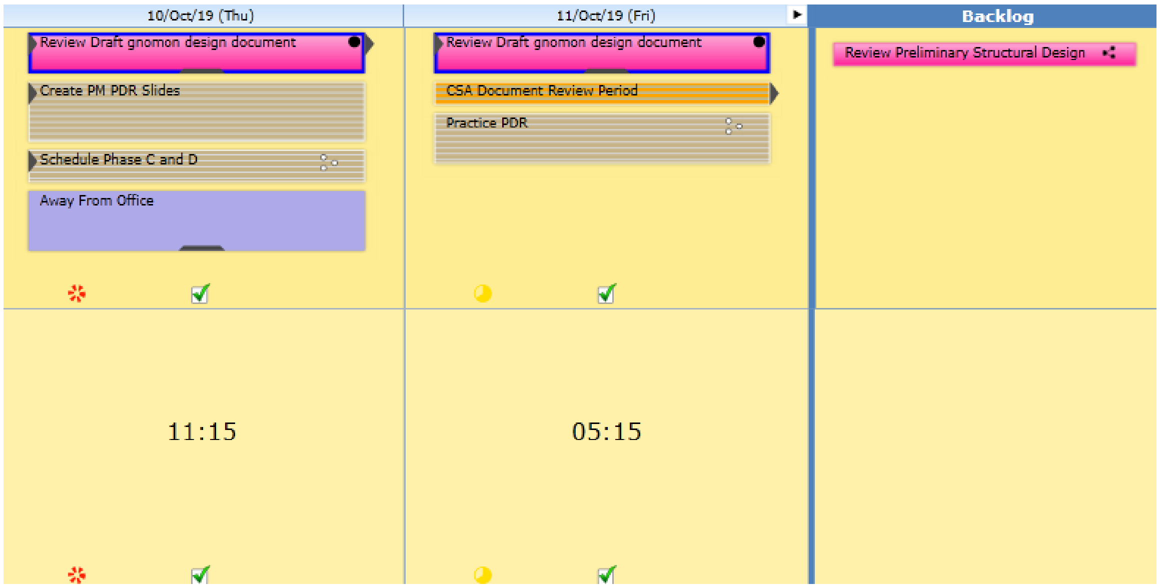


Figure 4.4: Playbook Kanban Board

This figure shows the Kanban format provided by Playbook for the ManitobaSat-1 project. Tasks are colour coded to highlight task criticality, providing guidance in selecting high priority tasks. The task backlog is located in the column on the furthest right. During huddles, the team is able to see everyone's Kanban board for the week, and can coordinate and align priorities. The times displayed in the bottom rows show the team members task loads for that day.

As the project manager, I have taken a supporting role for the team by providing guidance in developing plans and schedules. I assist in coordinating efforts and providing feedback for design decisions. The team's autonomy created a project plan that evolved as new information was introduced or team dynamics changed.

The ManitobaSat-1 project management plan incorporated a self-organizing team approach where the provided tools enable the team to create a plan that reflect their availability, but to make effective decisions, the team needs effective communication. Although the team is located in different facilities, the ability to communicate and pass information quickly improved our ability to adapt to changes. The following section details the ManitobaSat-1 communication and data management (CADM) method.

4.2.2 Communication and Data Management (CADM)

To ensure that ManitobaSat-1 team members make informed decisions and understand the impact of change, we use a centralized CADM database, as recommended in chapter two, in the form of a Wikipedia-inspired website [73], shown in Figure 4.5. The ManitobaSat-1 wiki provided a central information repository for the STARLab team and also a design database available to all stakeholders. The wiki further removed project management and systems engineering roles from the central communication position by making information easily accessible and allowing a more natural communication scheme found in concurrent engineering [36].

The ManitobaSat-1 project uses the integration of the Google Drive into the wiki to record and present the current design of the nanosatellite. The STARLab team uses an online Google Drive to store and archive information for reference, and provides links in the wiki to relevant folders, documents, and images. The drive integration simplifies the wiki update process and enables it to be a fully living document that reflects the current technical state of the nanosatellite. The constantly updating nature of the wiki provides the team with up to date information when making design decisions or investigating the impact of change.

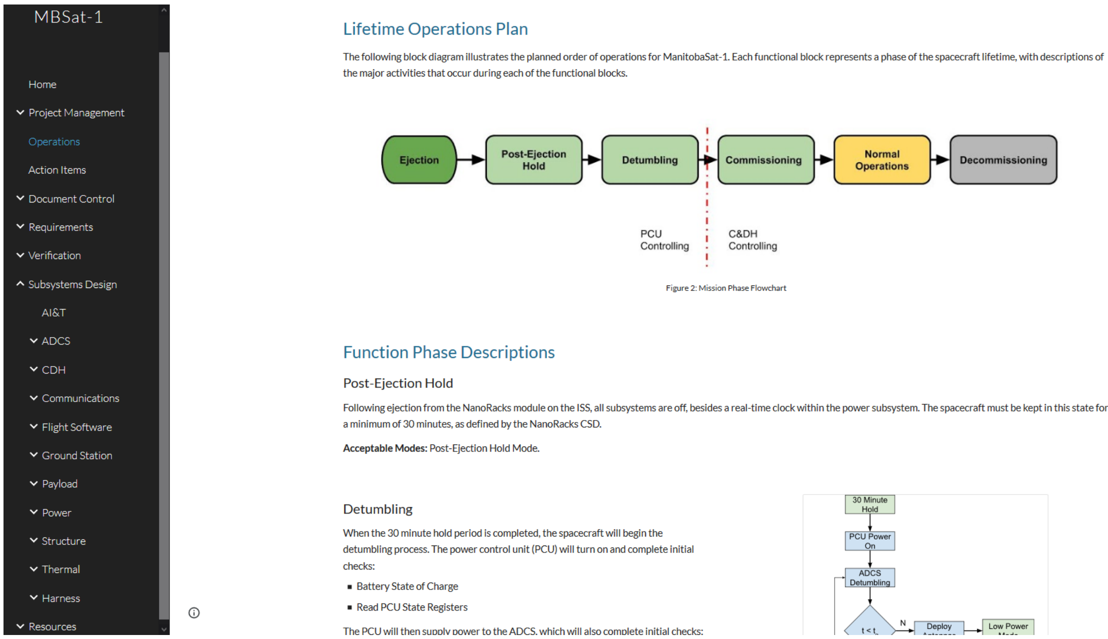


Figure 4.5: ManitobaSat-1 Wiki Database

This figure presents the operations page and the table of contents for the central ManitobaSat-1 wiki website. The wiki is intended to be a project-wide living document that is updated as the project progresses. Information captured includes project design, subsystem interfaces, requirements, verification activities, reports, and reference material.

Information captured in the wiki includes requirements and verification activity reports that provide an easy to navigate structure for project reviews. Verification reports are sorted by verification identification (ID) to easily sort through verification activity reports. Evidence in the form of analysis, recorded test data, and inspection reports are stored on the project drive, but links are included in the wiki verification reports. The reporting system provides the necessary structure to fully document the verification of a complex product, but with enough capacity to be able to respond to change quickly.

The ManitobaSat-1 wiki and drive are open for all stakeholders to review and update, ensuring an easy method for the STARLab team to share information with the rest of the ManitobaSat-1 team. The wiki and drive allows for information to be shared with any device that is connected to the internet and ensures that information is easily accessible to teams that are not co-located to understand project progress.

Although the CCP has a traditional phase structure, the CSA has supported the use of the ManitobaSat-1 wiki as a design document for phase reviews. Because the ManitobaSat-1 wiki behaves as the living document for nanosatellite design, information presented is current and continuously evolving. However, during reviews with the CSA, we archive a copy of the wiki into the ManitobaSat-1 Google Drive for appropriate version control.

By allowing information to be readily available to all stakeholders, the ability to quickly and effectively communicate within the team is important. In accordance with the first Agile value (people and interactions over processes and tools), the ManitobaSat-1 project promotes direct communication by incorporating available telecommunication software. In addition to the huddles, discussed in the previous section, the STARLab also holds weekly meetings that includes the York University hardware team. The weekly meeting provides an opportunity to discuss large meeting decisions that can impact the project, and brainstorm for the best solution.

The ManitobaSat-1 project uses decentralized cross-team communication, shown in Figure 4.2, to remove possible information barriers and allow for a free flow of ideas. The decentralized communication scheme does not always involve the project management or systems engineering roles, but allows the subsystem leads to easily work with relevant resources to create novel solutions. When new information is found by a team member, the wiki is updated and any changes are reported to the impacted team members through acceptable communication channels.

The CSA has also promoted cross-CCP team communication to allow all teams to share ideas or provide solutions to problems they may have previously addressed. CCP communication is done in an open forum for all active members to read and respond. CCP discussion has benefited the ManitobaSat-1 mission with new problem perspectives, possible satellite components, and CCP solidarity.

The ability to quickly and effectively communicate information and ideas allows the team to adapt to changes, but the complexity of constructing a satellite needs organizational structure. One tool that the traditional project management approach uses to organize tasks is the systems engineering role, discussed in Section 2.3. However, the project management and systems engineering roles can be combined to provide adequate technical support and guidance for a dynamic project team. The following section discusses the ManitobaSat-1 combined project management and systems engineering role.

Project Management Systems Engineering Overlap

The ManitobaSat-1 project has combined the roles of project management and systems engineering to create a technical and administrative support for the adaptive STARLab team. As discussed in Section 2.3, systems engineering is a multidisciplinary role that balances the technical and administrative aspects of a project through control of requirements and verification activities. The overlap between project management and systems engineering is an area of active study due to systems engineering being a critical success factor in many industries [74]. The similarities between project management and systems engineering can cause confusion in roles and responsibilities if not established early in the project.

Considine [75] compared the two disciplines, noting the similarities in organizing work and system approach for planning. He notes that the main focus of project management is to direct the project in terms of scope, cost, and schedule while systems engineering focuses on product development and requirement verification. Although the focus is different, the two disciplines specialize in organizing work and information, allowing for a unified position to be accomplished.

Boswell *et al.* [76] notes that training and methods for both disciplines are similar, providing an opportunity for both fields to benefit from each other. Both disciplines use similar methods, such as using a hierarchical method to organize work, and scheduling tasks to meet requirements. In the ManitobaSat-1 project, the combination of project management and systems engineering provides a unique opportunity for the University of Manitoba STARLab team leadership to be involved in both a technical and project guidance/reporting role. This combination allows me to implement the use of verification activities as a metric of progress as the project advances through the phases and make recommendations for corrective actions.

The overlap of the project management and systems engineering roles is facilitated by the similarities of responsibilities. Both disciplines have identical methods to organize work and information, facilitating the merging of the roles without creating additional work. The combination allows the ManitobaSat-1 project manager to implement the verification activity progress metric and interpret it in a fashion similar to Earned Value Management (EVM), as presented in chapter 2.

In this section, I have presented the project management approach developed for the ManitobaSat-1 project, including team interactions, communication structure, and project management and systems engineering roles. The ManitobaSat-1 project is currently undertaking phase C activities and has adapted to changes in CCP dates and the COVID-19 pandemic. The following section outlines the tools used by the team to monitor the project status and provide data to this research to evaluate the hypotheses.

4.3 Project Health Data Collection Tools

The ManitobaSat-1 project has different methods to record and monitor project progress that is used through the lifetime of the project. We have chosen software and services that are easy for the ManitobaSat-1 team to access and use. The following subsection provides a description of how we recorded our task, labour hours, requirements, and verification status.

4.3.1 Playbook Task Planning and Team Organization

Playbook is a lean-agile project management program that combines traditional Gantt task organization with Kanban. Playbook allows users to quickly create and modify the project schedule in a decentralized fashion. Major information captured by Playbook includes task name and description, labour hours and duration, and resources needed to complete the project. The team members create links in a Gantt chart interface, shown in Figure 4.6

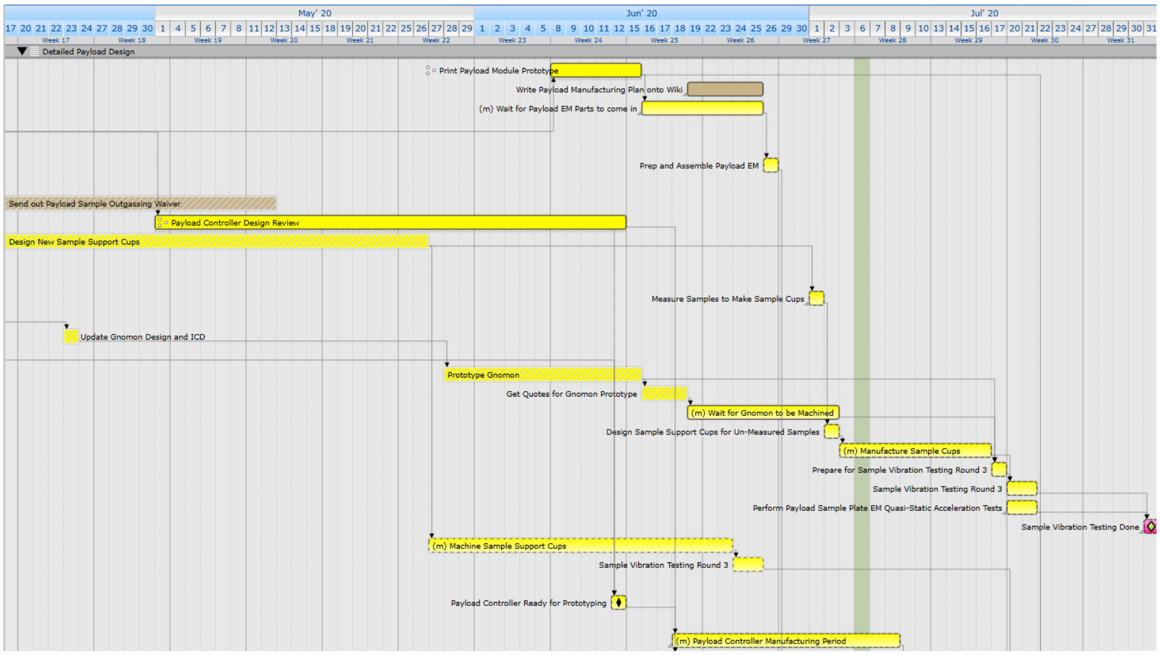


Figure 4.6: Playbook Gantt Interface

This figure shows the Gantt interface used by the ManitobaSat-1 team to create project hours and schedules. Information recorded in this part of Playbook is automatically transferred to the Kanban interface, shown in Figure 4.4.

Information recorded in Playbook is reflected in both the Gantt interface, containing the project wide schedule, and the Kanban interface, shown in Figure 4.4. This function allows the team to easily create a phase backlog from the project schedule and identify critical tasks using the colour coding function built in Playbook. The user friendly interface enables each team member to create and maintain schedules, and update it on a weekly basis to capture new information or unexpected changes.

Playbook provides various report methods that allow a quick overview of hours used and resource loading. I have used the data collected by these reports to evaluate hypotheses two and three. While the ManitobaSat-1 project uses Playbook to organize tasks, we use a different method to track how our requirement verification is progressing. As recommended in chapter 2, we are using our verification activity status to demonstrate project progress. The following subsection details our requirements management tool.

4.3.2 Valispace Requirements Management

The ManitobaSat-1 project uses Valispace, a requirements and verification control program that tracks parent-child relationships, verification methods and status. Each subsystem lead was responsible for creating child requirements from the mission requirements that demonstrated how each subsystem would meet project goals and sponsor expectations.

The ManitobaSat-1 project created verification activities as described in Section 2.2.2, where verification activities are children of the subsystem requirements. Valispace was used to track verification activities needed for each requirement, select appropriate verification methods, and provide an outline of the activity. The Valispace verification activity interface is shown in Figure 4.7

Valispace maintains the connection between parents and children, providing the necessary structure to fully address existing requirements and verification activities but in an easily accessible method. The complexity of a satellite generates many requirements that are reviewed and updated frequently.

REQUIREMENT	COMPONENT	REQUIREMENT TEXT	VERIFICATION METHOD	VERIFICATION STATUS	VERIFICATION COMMENT	STATUS	COMPLIANCE	REQUIREMENT TAGS
V-PLD-0010	**Payload_Sub**	Verify that Payload contains no less than 10 geological samples as specified by the science PI by reviewing the design CAD files.	Review + Add	Verified	Sample Plate CAD file	1 / 1 verified	Compliant	CAD B
V-PLD-0011	**Payload_Sub**	Verify that Payload contains no less than 10 geological samples as specified by the science PI by inspecting the flight sample plate assembly.	Inspection + Add	Select...	Sample Plate flight model	0 / 1 verified	...	FLIGHT D
V-PLD-0015	**Payload_Sub**	Verify maximum sun vector angle in X,Y, and Z before samples are shaded by reviewing the CAD model.	Analysis + Add	Verified	Payload CAD model	1 / 1 verified	Compliant	CAD B
V-PLD-0020	**Payload_Sub**	Verify maximum sun vector angle in X,Y, and Z before samples are shaded by putting the EM payload module on a turnstyle in a dark room with a single bright light source at a known angle from the module. Slowly rotate the module until samples are shaded. Record this angle.	Test + Add	Select...	Whole Payload Module, dark room, bright light source	0 / 1 verified	...	EM C
V-PLD-0030	**Payload_Sub**	Verify that Payload samples are all embedded within the sample plate by reviewing the CAD file.	Review + Add	Verified	Sample Plate CAD file	1 / 1 verified	Compliant	CAD B

Figure 4.7: Valispace Verification Activity Record for the ManitobaSat-1 Payload Module

This figure shows the verification activity record for the ManitobaSat-1 project as seen in Valispace. The project team is able to record the verification method, the status, and compliance of each activity. Note that requirements may need more than one verification activity to be fully compliant, and can be completed between phases B, C, or D.

I am using the total quantity of verification activities and the quantity that have been verified compliant to evaluate hypotheses two and three. The information derived from the progress of verification activities can be used to demonstrate project progress between phases B and C, similar to my analysis in Section 3.4.

In this section, I have presented the main tools used to collect project health data, including labour hours, task durations, and requirement verification status. Although the ManitobaSat-1 project is still undergoing phase C activities, data has been collected through phase B and the current state in phase C. Data and analyses are presented in the following section.

4.4 Results and Analysis of the ManitobaSat-1 Project Data

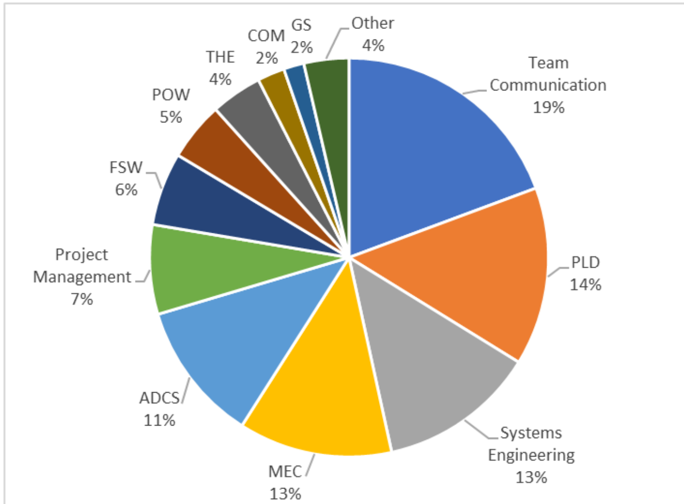
In the previous sections, I have provided background information of the CCP, the ManitobaSat-1 project management methods, and how data was collected. Our nanosatellite project is currently undertaking critical design activities to meet our CDR date with the CSA for late October 2020, four months ahead of schedule for the February 2021 CCP reviews. As the phases advance, project health data used to monitor progress has been used by this research to analyze the impact of the non-traditional management recommendations discussed in the previous chapter.

The ManitobaSat-1 project is a student led project that came with benefits and challenges. The team was composed of bright and dedicated team members that brought value to the satellite design through their experience, knowledge, and design perspectives. Although each team member had valuable work ethic and completed their tasks, discipline of labour documentation varied between each person. Throughout the project, I have collected, consolidated, and verified the information that was available to be used for this research. The following sections presents the ManitobaSat-1 project health data collected up to 30 June 2020.

4.4.1 ManitobaSat-1 Project Management Analysis - Labour Hours

The ManitobaSat-1 project schedule was outlined by me as the project manager, and detailed by each subsystem lead to include task labour hours and duration in days. The detailed schedule was recorded by each subsystem lead using the Playbook scheduling and planning software. Each subsystem lead was responsible for ensuring that their respective tasks were reflective of the work being completed, where I provide support in record keeping when requested or confirm if there was a lack of communication.

To reflect that team communication was a shared responsibility that did not always involve the project manager, the "team communication" labour category for the following analyses was created to capture internal team meetings and discussions. Figure 4.8 shows the labour breakdown of all hours recorded for phases B and C of the project.



Acronym Legend	
ADCS	Attitude Determination and Control System
COM	Communication System
FSW	Flight Software
GS	Ground Station
MEC	Mechanical/Structure
PLD	Payload
POW	Power
THE	Thermal

Figure 4.8: Total labour hours for the ManitobaSat-1 project

This figure presents the total labour hour distribution for the ManitobaSat-1 project phases B and C. Task categories that used less than two percent of the total were included in the "other" category. Team communication was separated from the project management category as team communication and meetings did not always involve the project manager.

Since the ManitobaSat-1 project team is self-organizing, team communication is the main method for the team members to express and understand project priorities and identify available resources. By removing the project manager as the central planning and communication role, the increased team communication becomes a valuable asset to the team. As can be seen in Figure 4.8, the team allocated a large amount of time to communication that was used to present different viewpoints, discuss problem perspectives, and share ideas about the best solution. Frequent meetings captured in team communication include the huddles and the ManitobaSat-1 project weekly meeting.

The project management labour category is a small labour hour consumption compared to the industry project, where the industry project management used eighteen percent of the total labour hours in Figure 3.1, the ManitobaSat-1 project management consumed seven percent. This demonstrates a clear decrease in the direct management labour needed by the ManitobaSat-1 project management role, but instead shifted into a supporting role for the team through rolling-wave planning. Because each team member is responsible for planning and organizing their schedules, technical subsystem teams develop a schedule that reflects their knowledge and capabilities, but needs constant communication to coalesce the project schedule.

However, internal team communication is the largest use of ManitobaSat-1 labour hours at nineteen percent for the ManitobaSat-1 project, larger than the total project management category in the industry project analysis by one percent. Although this appears as large consumption of labour, the internal team communication category does not always involve the project manager or every team member. Because of the collective nature of communication, cross-subsystem meetings or conversations are categorized together to reflect the active communication within the team.

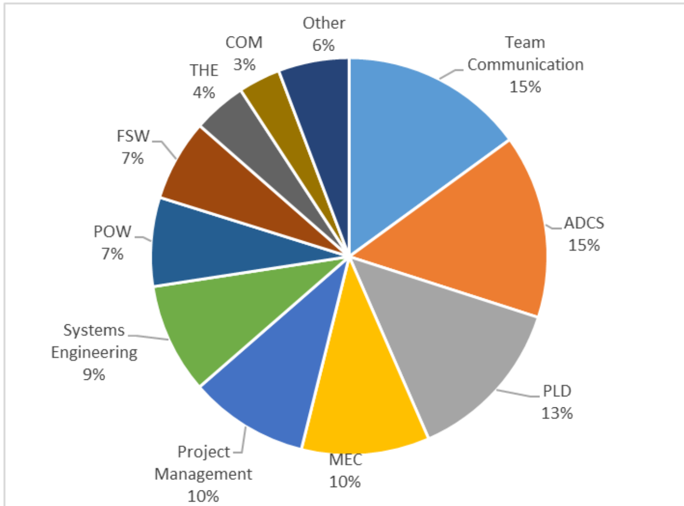
In addition, the ManitobaSat-1 systems engineering role was thirteen percent, approximately nine percent larger than the total industry labour hours systems engineering category. This increase can be attributed to the coordinating role of the systems engineering in a decentralized planning team, where ensuring that requirements reflect the project goals is critical for success. However, the direct systems engineering management was reduced, as each subsystem lead is responsible for creating and maintaining subsystem requirements.

The increase in team communication and the decrease in direct project management liberates project resources for the technical development of nanosatellite subsystems. The comparatively small project management category is a consequence of shifting from the central direct management and planning role to a supportive leadership role. However, the combination of systems engineer and project manager positioned me to provide administrative guidance and technical support to develop the complex technical design of ManitobaSat-1.

I have presented the total labour distribution for the ManitobaSat-1 project for phases B and C, but the nature of the work may differ as the project advances. The following subsections investigate how the labour changes between phases B and C, including a breakdown into the project management and systems engineering categories.

Phase B Hours

As described in Section 2.2.1, phase B undertakes preliminary design activities by creating the basic structure of the spacecraft, to be reviewed by the project sponsor during the Preliminary Design Review (PDR). The ManitobaSat-1 project phase B began in January 2019 with a major focus on a satellite design that reflects mission requirements. Each subsystem was responsible for creating subsystem requirements that would provide guidance for their design decisions. Figure 4.9 shows the labour distribution for the ManitobaSat-1 team during phase B.



Acronym Legend	
ADCS	Attitude Determination and Control System
COM	Communication System
FSW	Flight Software
MEC	Mechanical/Structure
PLD	Payload
POW	Power
THE	Thermal

Figure 4.9: ManitobaSat-1 Phase B Labour Hours

This figure presents the labour distribution for the ManitobaSat-1 team during phase B. Task categories that used less than two percent of the total were included in the "other" category. Similar to the total labour hours shown in Figure 4.8, the team communication is the largest labour category recorded.

Similar to the total labour hours in the previous subsection, the largest labour category for the ManitobaSat-1 project during phase B was team communication, consuming fifteen percent of phase B labour hours. Since the ManitobaSat-1 team is self organizing, constant and effective communication is critical to be able to have the situational awareness needed to adapt to changes or new information. This replaces traditional project management labour that would have been needed to directly manage and organize work to instead share ideas for subsystem design.

Project management was the fifth largest ManitobaSat-1 labour category with ten percent of phase B labour hours, notably smaller than the industry phase B project management labour hours of fourteen percent, shown in Figure 3.2. The difference between the ManitobaSat-1 project and the industry project management categories highlight the difference in direct management labour needed between the two approaches, allowing for an increase in team communication to provide a path forward for the development team. Although the ManitobaSat-1 team communication was approximately one percent larger than the industry direct management category, team communication did not always involve the project manager, but enabled team members to communicate and plan their work. The increase in communication instead demonstrates how the project management role guides and harmonizes the team schedule, instead of directly controlling project progress. Figure 4.10 shows the break down of direct project management labour during phase B.

The ManitobaSat-1 systems engineering role used nine percent of the phase B labour hours, one percent less than the industry project systems engineering category for phase B, shown in Figure 3.2. The ManitobaSat-1 systems engineering role during phase B coordinated technical information to ensure that a nanosatellite design was created from the combination of subsystem designs. The systems engineering labour encompassed requirements management and preparation for the PDR. Figure 4.11 shows the break down of systems engineering labour during phase B.

The combined systems engineering and project management roles in the ManitobaSat-1 project provided administrative training and technical support to the team, ensuring they understood the underlying management philosophy and the requirements control methods used. Each subsystem lead is responsible for maintaining their respective subsystem requirements, but the systems engineering role maintained the mission requirements and ensured that the links between parents and children were appropriate.

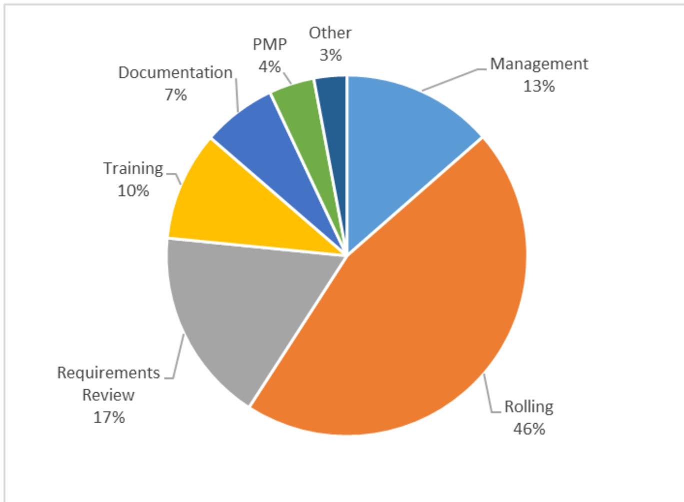


Figure 4.10: ManitobaSat-1 Phase B Project Management Labour Hours

This figure presents the direct project management labour distribution during phase B. Task categories that used less than two percent of the total were included in the “other” category. Direct management of the team took less than thirteen percent of the total labour hours. The “rolling” category were set times allocated for the team to review their respective schedules and backlogs to be updated based on new information.

During phase B, direct management used thirteen percent of the total project management labour, a large decrease from the industry phase B project management labour use of thirty two percent, shown in Figure 3.3. The largest ManitobaSat-1 project management task category was “rolling”, which were set times that the team would review and update their schedule. This time was not only allocated for the project manager, but used by the team to undergo rolling wave planning as presented in Figure 4.3. As the team became more comfortable with the process, team members continued undertaking rolling-wave planning independently as I continued to monitor the schedule.

Although the "rolling" category was used by the project team to record labour hours to organize and plan phase tasks, the ManitobaSat-1 project management category was smaller than the industry project. The collective nature of rolling wave planning suggests that the team's self-organizing and decentralized planning nature enables them to create an easily maintainable schedule that allows them to focus on technical development. The remaining task groups for the project management category demonstrate the guidance and training role in the team, where the largest notable task category was in requirements reviews.

Similar to project management, systems engineering shifted to a coordinating and support role to ensure that the technical design and requirements were a cohesive whole. Subsystem leads were responsible for creating children from the mission requirements, providing guidance for their design decisions. During this period, the ManitobaSat-1 wiki underwent formatting updates in preparation for the preliminary design review (PDR), coordinating the wiki format and information required by each subsystem. The systems engineer labour distribution is presented in Figure 4.11.

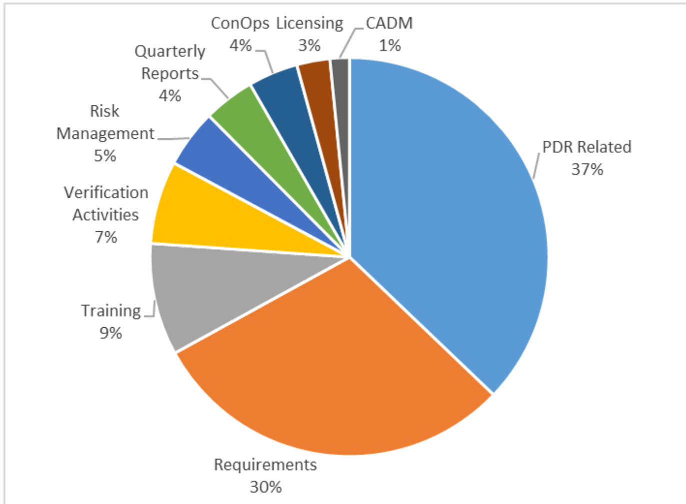


Figure 4.11: ManitobaSat-1 Phase B Systems Engineering Labour Hours

This figure presents the systems engineering labour hours for phase B. The largest task category was to prepare for the Preliminary Design Review (PDR) that consists of collecting nanosatellite design information in a presentable format. Requirements were the second largest task category to ensure that the project properly interpreted mission requirements and stakeholder goals.

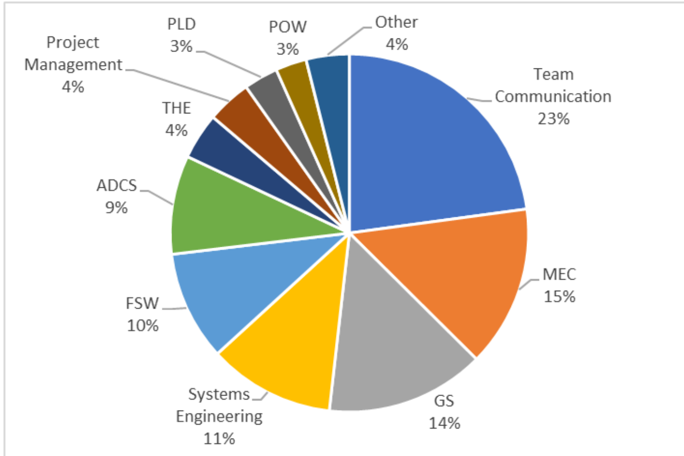
The largest ManitobaSat-1 systems engineering task group was PDR related work, which used thirty seven percent of recorded labour hours. In comparison, the same task group in the industry project was smaller, which used three percent of the total labour, shown in Figure 3.4. However, the ManitobaSat-1 systems engineering category did not directly manage technical work, but the industry project used thirty four percent of their recorded labour hours. The difference in the task groups suggest a difference in role philosophy, where the industry project undertook direct systems engineering activities through management and analysis. In contrast, the ManitobaSat-1 systems engineering role enabled the subsystem teams to develop subsystem requirements, and collected technical information in the ManitobaSat-1 wiki.

Additionally, the ManitobaSat-1 systems engineering role undertook training activities to provide team members with the tools and knowledge needed to organize requirements and verification activities, compile design information for sponsor reports, and manage risks. The majority of the labour for the PDR and requirements management was developed by the project team, but it needed to be recorded in a uniform format in the wiki.

In the combined ManitobaSat-1 project lead role, I supported the development team during phase B by coordinating information and communication methods to decentralize planning. The combined role allowed me to establish the groundwork for the project management plan that the ManitobaSat-1 team could change to fit their needs. As work changed from preliminary design to critical design, the project labour distribution changed as well. The following subsection describes the labour distribution for the ManitobaSat-1 project phase C activities.

Phase C Hours

As described in Section 2.2.1, phase C further details the satellite design that was approved by the sponsor during the PDR. The ManitobaSat-1 project phase C began in October 2019 with a major focus on project requirements and the interfaces between subsystems. The team structure underwent various internal changes, including students transitioned out of the project, amended roles, and changing class schedules, and one major external change, the COVID-19 pandemic. However, the CADM and adaptive project management approach allowed the team to maintain constant communication that facilitated adapting to changes. Figure 4.12 shows the labour distribution for the ManitobaSat-1 project during phase C.



Acronym Legend	
ADCS	Attitude Determination and Control System
COM	Communication System
FSW	Flight Software
MEC	Mechanical/Structure
PLD	Payload
POW	Power
THE	Thermal

Figure 4.12: ManitobaSat-1 Phase C Labour Hours

This figure presents the ManitobaSat-1 team labour distribution during phase C. Task categories that used less than two percent of the total were included in the "other" category. Team communication is the largest hour category, which was expected with the increase in design detail and changes in work environments due to COVID-19.

Although Phase C is currently ongoing, internal team communication has a proportional labour consumption of twenty three percent, approximately eight percent larger than phase B. The increase in communication can be attributed to the increased detail and complexity in subsystem designs, that includes inter-subsystem interfaces that were compounded with the social distancing protocols implemented during the COVID-19 pandemic. Critical design activities include detailing inter-subsystem interfaces that require further analysis and review in how subsystem properties and connections with the rest of the satellite.

The University of Manitoba began implementing safety precautions on the 13th of March 2020 [77] to mitigate the spread of COVID-19, which included restricting co-location of students and faculty. As of this writing, many of those distancing protocols are still in place. Although in-person team communication was unavailable due to social distancing precautions, the project's central CADM architecture and off-site software availability allowed for work to continue. The adaptive nature of decentralized planning, free-form communication, and central information database allowed for easy transfer of knowledge for the ManitobaSat-1 team to design their subsystems with matching interfaces.

In this phase, the project management role has further evolved into a support position as the team becomes more comfortable with planning and organization. Although tighter coordination is needed, the phase C project management category saw a decrease in labour hours from ten percent in phase B down to four percent in phase C. The large decrease can be attributed to shifting rolling wave planning activities to individual subsystems, allowing for the project management category to be work that reflects the ManitobaSat-1 project management role.

The industry project project management role used fourteen percent of phase C labour hours, approximately ten percent higher than the ManitobaSat-1 management labour category. Also taking into consideration the internal team communication, the labour hour difference between the ManitobaSat-1 project and the industry project demonstrates the team's ability to effectively self-organize through communication and tools. The direct project management task groups breakdown is detailed in Figure 4.13.

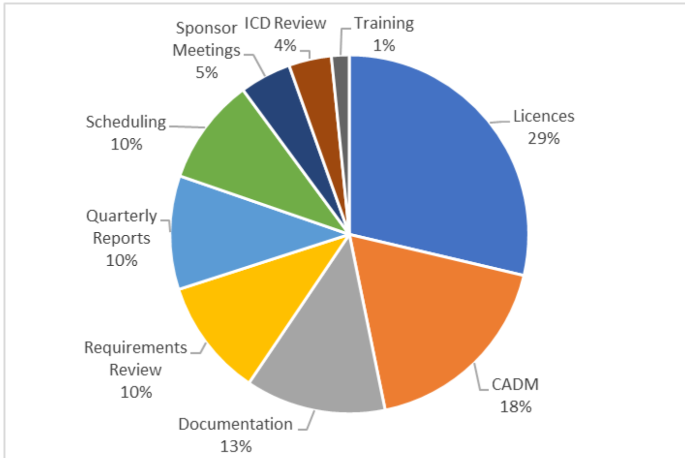


Figure 4.13: ManitobaSat-1 Phase C Project Management Hours

This figure presents the project management labour distribution for the ManitobaSat-1 project phase C. The largest use of effort was developing applications for legislation licences, including the Remote Sensing Space Systems Act (RSSSA). Other major responsibilities are maintaining the ManitobaSat-1 wiki and consolidating project information in the project's Google Drive.

The ManitobaSat-1 project management had minor direct management tasks, including scheduling and training that add up to eleven percent, where the industry phase C had forty six percent project management labour hours, shown in Figure 3.6. The large difference in direct management demonstrates the ManitobaSat-1 management role shift from controlling to supporting the project team through license applications, CADM maintenance, and other forms of documentation. In contrast, the industry project undertook directly management activities for the majority of recorded labour hours, and also undertook technical management activities twenty six percent of the recorded labour hours. This demonstrates that the industry project dedicated seventy two percent of the phase C project management labour hours to organize and direct project activities.

The ManitobaSat-1 project management role continued to support the team through different administrative activities, including licence applications and maintaining the CADM systems, such as the project drive and the wiki. The project management role assumed responsibility for applying to the Remote Sensing Space Systems Act (RSSSA), requiring a system description of the satellite and information on the science mission. License applications required consolidation of existing nanosatellite design and data distribution methods.

Although the project manager labour decreased, the systems engineering activities increased from nine percent in phase B to eleven percent in phase C, but was notably higher than the industry phase C systems engineering labour use of three percent. The ManitobaSat-1 systems engineering is largely involved in linking project requirements to nanosatellite design, demanding more attention as the nanosatellite design becomes more detailed. To ensure that the satellite design developed in accordance with mission goals and expectation, phase C undertook major requirements review and coordination activities. Figure 4.14 details the ManitobaSat-1 systems engineering labour distribution.

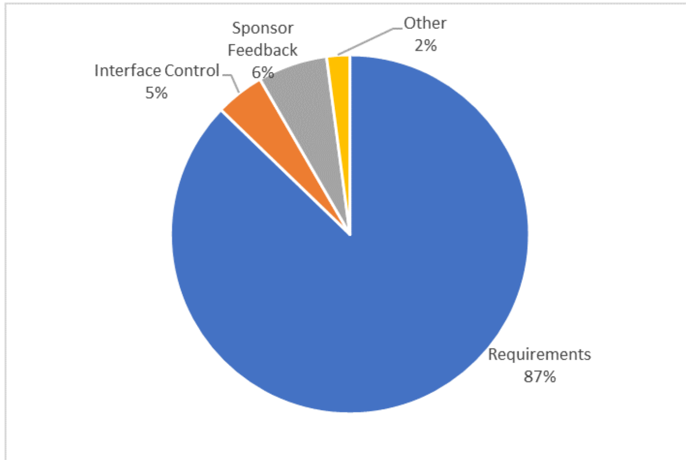


Figure 4.14: ManitobaSat-1 Phase C Systems Engineering Hours

This figure presents the systems engineering labour hours for the ManitobaSat-1 project phase C. Task categories that used less than two percent of the total were included in the "other" category. The largest use of labour was ensuring that ManitobaSat-1 requirements are in accordance with mission objectives and sponsor goals, providing enough detail to the development team for guidance in design decisions.

Because the ManitobaSat-1 systems engineering role shifted from direct technical management to a coordinating role, there was large change in harmonizing project requirements, from thirty percent in phase B to eighty seven percent in phase C. This is also a large increase from the industry phase C systems engineering requirements and verification tasks that used twelve percent of the allocated systems engineering labour hours, shown in Figure 3.7. The large difference in requirements labour can be attributed to two factors: the ManitobaSat-1 team's inexperience in creating adequate requirements and the importance of the link between requirements and design. ManitobaSat-1 requirements reviews continued to find requirements that did not capture mission goals, were unclear, or were difficult to verify, but were amended and updated through requirements reviews.

The ManitobaSat-1 systems engineering role during phase C shifted to a more central coordinating role to ensure that the satellite design was in accordance with stakeholder goals and expectations. The ManitobaSat-1 team underwent detailed requirement reviews for mission and subsystem groups to ensure that the design guidelines would lead to a successful mission. Although the reviews are categorized as systems engineering, team members were involved in the requirement reviews to identify possible disconnects from goals and discuss the best corrective actions.

Additionally, the industry project allocated twelve percent of recorded labour hours to ICDs related tasks, which was larger than the ManitobaSat-1 ICD tasks using five percent of recorded labour hours. The ManitobaSat-1 team shifted ICD development responsibilities to subsystem leads, where systems engineering support provides feedback and guidance to mitigate differences nanosatellite interfaces. The coordination provided by systems engineering provides structure for concurrent detailed design activities, enabling the team to create a fully detailed and functioning satellite system.

In this section, I have presented the labour distribution for the ManitobaSat-1 project team, highlighting the decreased labour needed by the project manager and systems engineering roles when compared to the industry project presented in Section 3.2. There has been an increase in internal team communication as the phases progress that reflects the team's ability to share important information and share ideas to develop a creative design. I have demonstrated that the ManitobaSat-1 project team extensively uses internal communication throughout the project, providing the groundwork to evaluate hypothesis three (Communication services that use Kanban and Scrum benefit the project). The following subsection investigates how the ManitobaSat-1 project management impacts the team's labour capacity.

4.4.2 ManitobaSat-1 Project Management Analysis - Resource Loading

Although the ManitobaSat-1 team size has remained between eleven and fourteen simultaneous core team members, the active tasks have fluctuated as the project progressed. One important part of the ManitobaSat-1 project management philosophy is the team resource loading to control the impact of unavailable resources. We are using the Playbook Kanban interface to promote working on a single active task to mitigate overloaded and unavailable team members. Figure 4.15 shows the queue graph for phase B.

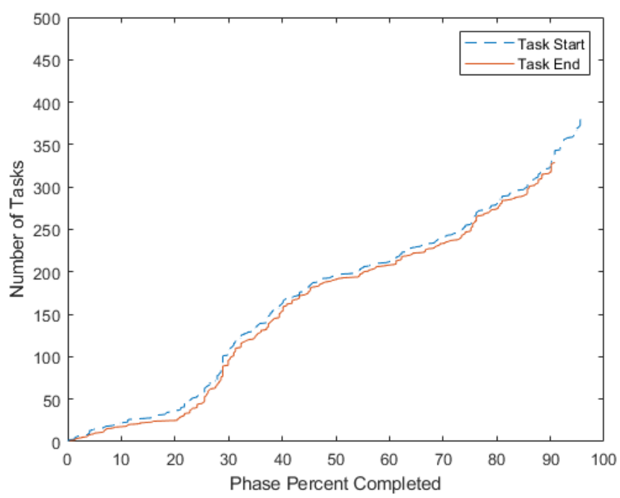


Figure 4.15: ManitobaSat-1 Phase B Tasks Organized Chronologically

This figure shows the start and end dates for the ManitobaSat-1 project phase B activities. The vertical distance between the curves show the quantity of active tasks assumed by the nanosatellite development team. The activities progressed from January 2019 to October 2019.

Figure 4.15 shows the start and end dates chronologically, but independently from each other, such that the start dates of one task does not necessarily correspond with the end dates on the same horizontal line. The vertical distance between the start and end curves provide a visual representation of the quantity of active tasks simultaneously undertaken by the team. The phase B queue graph is very thin, highlighting that the project team maintained a low count of simultaneous active tasks. Figure 4.16 shows a daily count of active tasks.

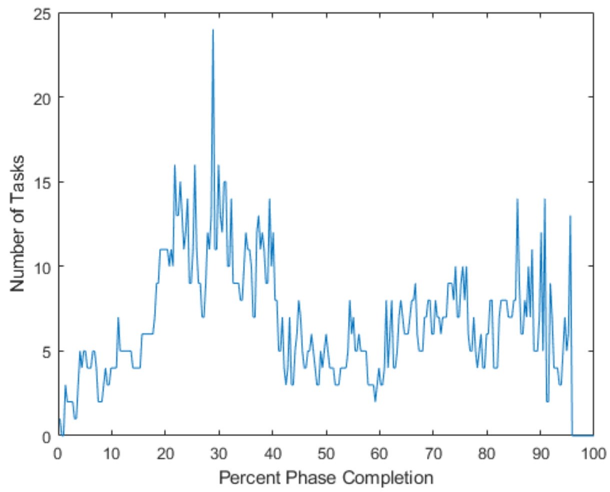


Figure 4.16: ManitobaSat-1 Phase B Active Tasks

This figure shows the daily active tasks during the ManitobaSat-1 project phase B. Using the Kanban approach, team members are restricted to taking on only one active task, two if they are blocked. The maximum active task count has twenty four activities in a single day.

The team's labour capacity was maintained relatively low, demonstrated by an average of six daily tasks, and a maximum of twenty four in a single day. Assuming the smallest team size of eleven members, the project team had one or less active tasks on average throughout phase B. Although it may appear to be less than optimal, tasks presented in this research are ManitobaSat-1 related only and do not reflect off-project task loading (such as course work or other degree research). Because the

ManitobaSat-1 project is a student led development process, team members created their subsystem schedule based on classes and research deadlines. Each subsystem schedule took into consideration the personal availability of the subsystem leads, and limiting their tasks to work that can be undertaken with their available work capacity.

To further analyze the project team's resource loading, this research created an equivalent team size based on an eight hour work capacity per day. The fully loaded project team capacity is presented in Figure 4.17.

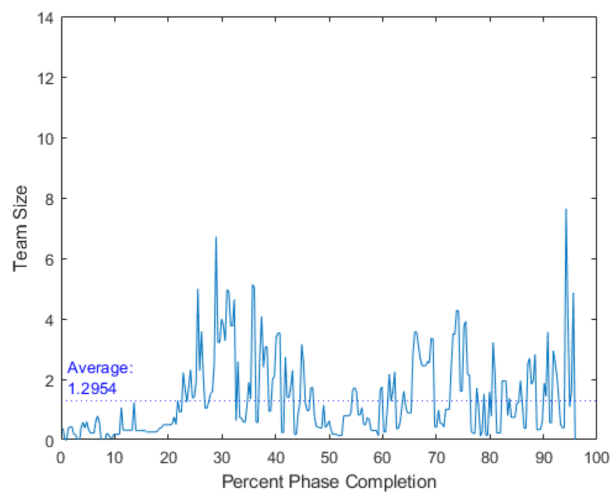


Figure 4.17: ManitobaSat-1 Phase B Equivalent Full Time Team

This figure shows an equivalent team of eight hour capacity workers for the ManitobaSat-1 project phase B activities. This graph combines the labour hours, presented in Section 4.4.1, and the task start and end dates, presented in Figure 4.15,to provide an equivalent full-time team. As the smallest team size during this phase was eleven core team members, a high demand of work was needed at certain parts of the phase.

Assuming an industry equivalent of an eight hour work day, the ManitobaSat-1 project team had the equivalent of approximately one full-time worker during phase B. High work periods demanded more labour to be undertaken by the team, leading to equivalents of seven and eight full time workers. The phase B ManitobaSat-1 team had at the lowest point eleven core workers, and implies that resource capacity was maintained at sustainable levels. Note that Figure 4.17 is only captures hours attributed to the ManitobaSat-1 project and does not reflect individual's class schedule or off-project activities.

As phase B neared completion, the team continued completing tasks until the end of the PDR. After the successful review, the ManitobaSat-1 team continued on to phase C activities, shown in Figure 4.18.

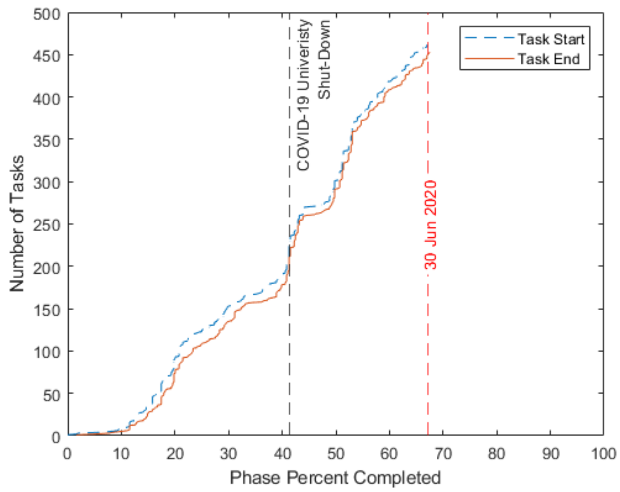


Figure 4.18: ManitobaSat-1 Phase C Tasks Organized Chronologically

This figure shows the task start dates and end dates for the ManitobaSat-1 project phase C. The vertical distance between the curves show the quantity of active tasks assumed by the nanosatellite development team. At the time of writing, the ManitobaSat-1 project is still undertaking phase C activities. Markers have been added to this figure to show when the COVID-19 social distancing protocols were implemented at the University of Manitoba, and the last day data was collected.

As of this writing, the ManitobaSat-1 project is currently about sixty seven percent through phase C, but has continued work through the COVID-19 pandemic, as presented by the marker in Figure 4.18. On the 13th of March 2020, the University of Manitoba announced the implementation of safety precautions, including social distancing and off-site activities for students and faculty [77]. Although the team was unable to be co-located, the CADM system implemented at the start of the project allowed us to continue design activities without disruption. Although planned test activities are postponed until further notice, the subsystem leads are updating their schedules as they continue to monitor the situation.

The ManitobaSat-1 phase C queue graph is notably thicker than the phase B burn graph, but very small compared to the industry phase C burn graph, shown in Figure 3.13. The change between phases B and C are expected, as the scope of work in phase C is larger than phase B. Additionally, the difference between industry and ManitobaSat-1 is also expected, as the industry project scope and available resources are much larger than the ManitobaSat-1. However, the comparison with the industry project provides a useful method to analyze the impact of the ManitobaSat-1 project management approach has on resource loading.

Phase C further develops the designs approved during the PDR by further detailing each subsystem to create a functioning satellite. As phase C is the last set of design activities before manufacturing begins, designs needs to be sufficiently detailed before manufacturing and assembly. The increased effort to ensure working interfaces and manufacturability can be observed in the quantity of active tasks, shown in Figure 4.19.

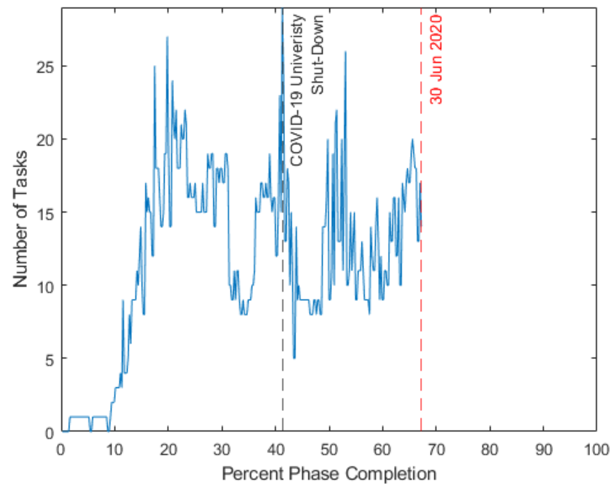


Figure 4.19: ManitobaSat-1 Phase C Active Tasks

This figure shows the daily active tasks during the ManitobaSat-1 project phase C. Using the Kanban approach, team members are restricted to taking on only one active task, two if they are blocked. The maximum active task count has twenty nine activities in a single day, with the second and third highest single active day as twenty seven and twenty six respectively.

During phase C, the teams average daily task load was twelve simultaneous tasks, with the three most loaded days of twenty nine, twenty seven, and twenty six simultaneous activities. Although this is an increase from phase B, the team maintained a low average task load. This phase has had thirteen development team members, making the average task load per team member have one or less active tasks per day.

The industry phase C had a distinct daily task pattern that rose drastically in the first ten percent of the phase, peaked around forty percent of the phase, and slowly decreased until the end, shown in Figure 3.15. Although the industry project pattern is not present in the ManitobaSat-1 project, a series of increases and decreases can be observed. The ManitobaSat-1 pattern continues past the COVID-19 shut down dates until the last day data was collected, reflecting the teams ability to assume tasks in a constantly changing situation.

On the date where the University of Manitoba began COVID-19 safety protocols, the ManitobaSat-1 project was undergoing requirements reviews and can be observed around forty percent phase progress. After the requirement reviews, a concurrent activity plateau can be seen, as follow-up activities were undertaken by individual team members. Although the activity count appears low, it is higher than the average count for phase B, suggesting that work was not fully disrupted by the change in work environments. However, to fully understand the impact of the COVID-19 related changes, an analysis of labour hours and tasks duration needs to be analyzed. Figure 4.20 shows the equivalent team size assuming an 8 hour capacity dedicated only to the ManitobaSat-1 project tasks.

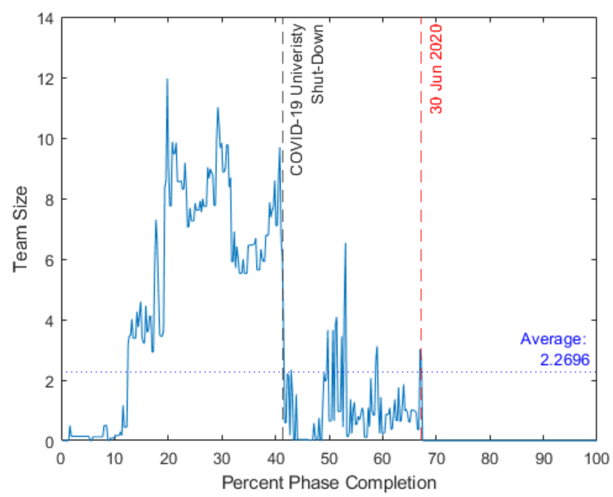


Figure 4.20: ManitobaSat-1 Phase C Equivalent Full Time Team

This figure shows an equivalent team evolution of eight hour capacity workers for the ManitobaSat-1 project phase C activities. This graph combines the labour hours, presented in Section 4.4.1, and the task start and end dates, presented in Figure 4.18,to provide an equivalent full-time team.

The level of work before the pandemic related shutdowns saw a peak of twelve equivalent team members, but drastically dropped to between zero and six. This drastic drop can be attributed to the student body of the project team, as this period coincides with the end of the winter semester and the beginning of the final thesis documentation for the graduating students. At the time of writing, the STARLab has four team members fully documenting their theses, limiting their available work capacity for the ManitobaSat-1 project.

The ManitobaSat-1 equivalent team size is notably different from the equivalent industry project team size shown in Figure 3.17. The industry project maintained a team size close to the average throughout the phase, with one major peak around forty percent. In contrast, the ManitobaSat-1 had an increase in equivalent team size until a drastic decrease at the beginning of COVID-19 safety protocols. Although comparison is difficult for phase C during social distancing, the initial forty percent of both projects followed a similar pattern of increasing and decreasing equivalent team size.

COVID-19 has impacted the ManitobaSat-1 project by limiting in person communication and creating unavailable testing resources, but design and development activities have continued. At this time, structure and ADCS activities continue to detail the final design and ensure that inter-subsystem interfaces conform to requirements. Major system activities include reviewing and adapting current verification activities in preparation for testing facilities to become available or finding verification alternatives. The ManitobaSat-1 project has continued work through the COVID-19 pandemic by implementing thorough communication and centralized information storage available to the team.

At the time of writing, the ManitobaSat-1 project is expecting to complete phase C activities in late October or early November 2020, four months ahead of the current schedule for the CCP project. Although the project is approximately sixty seven percent though phase C, the existing schedule shows a reduction when compared to the CCP general schedule, but does not provide sufficient evidence that hypothesis one is true.

The ManitobaSat-1 project has undergone many different internal changes through phase B and C, such as changing team availability and requirements, and underwent COVID-19 as a major external change. COVID-19 has had a major impact in business and projects through implementation of social distancing safety measures and self-isolation that leads to a reduced workforce [78], but the adaptive ManitobaSat-1 project management approach has allowed for project activities to continue. The team is actively adapting to different factors that cause change, including the COVID-19 safety protocols that restrict co-location and students completing their graduation programs, that have notable impact our labour capacity. The teams' ability to persistently undertake project activities demonstrates our ability to adapt to external changes, providing partial evidence that hypothesis two and three are true.

4.4.3 ManitobaSat-1 Project Management Analysis - Verification Activities

Because the requirements are the links between goals and design, the verification status of the project can be used to demonstrate how the project is advancing to meeting the mission goals. As demonstrated in Section 3.4, verification activity status is highly correlated with the labour used during development.

At the time of this writing, the ManitobaSat-1 project is currently undergoing verification activity reviews in two sequences, to ensure that the project has adequate verification activities, and that the activities are detailed enough to complete. Unfortunately, the data at this time is incomplete for phase C, but a full count was available for the version presented during the PDR at the end of phase B.

Although the team has been able to create a schedule that reflects team member's availability, documenting verification activities has been an area that has been inadequate for this study. Although there have been minimal verification activity updates for this phase, the current version of verification activity registry has shown an increase in activities that are verified and ongoing. The ManitobaSat-1 project is still undertaking phase C activities until the end of October 2020, and verification activities are expected to demonstrate product conformance as we near the CDR.

This section has presented and analyzed data collected through phases B and C of the ManitobaSat-1 project. The data shows trends that present the benefit of the non-traditional methods, notably the ability to adapt to the COVID-19 pandemic without a notable disruption to work. The following section discusses trends found in the ManitobaSat-1 project data.

4.5 ManitobaSat-1 Discussion and Hypothesis Evaluation

The previous section analyzed and presented ManitobaSat-1 project health data for phases B and the majority of phase C, and has documented the impact of the COVID-19 pandemic response on the project. The ManitobaSat-1 project management plan incorporated the recommendations made from the industry project analysis, presented in chapter 2, that benefited the student led ManitobaSat-1 development team. The ManitobaSat-1 project had many internal changes, including changing availabilities and individual's project roles, but the largest impact was due to the COVID-19 pandemic that restricted our team co-location and increased our need to communicate. The following subsections discuss the evaluation of this research's hypotheses using the available ManitobaSat-1 project data.

4.5.1 Hypothesis One Evaluation

My first hypothesis is that a two year spacecraft project schedule can be shortened by two months by applying Agile philosophy to certain aspects of the project. Through background research presented in Section 2.4 and analysis of space industry data in Section 3.1, I identified areas where non-traditional adaptive methods can be implemented in the ManitobaSat-1 project. At the time of this writing, the ManitobaSat-1 project is currently undertaking phase C critical design activities and has scheduled the Critical Design Review with the CSA in late October 2020. This is notably four months ahead of the CCP planned schedule, presented in Table 4.2 that also have undergone schedule growth.

Although the ManitobaSat-1 project has a comparatively shorter design schedule compared to the current CCP review dates, the ManitobaSat-1 project is an ongoing nanosatellite development project that has not begun phase D Assembly, Integration, and Testing (AIT) activities. The ManitobaSat-1 project continues to undertake critical design activities, continuously adapting to the evolving COVID-19 situation, and updating project schedule and verification activity plans. Although there is insufficient information to demonstrate hypothesis one as fully true, the ManitobaSat-1 project demonstrates a shorter schedule compared to the CCP timeline.

4.5.2 Hypothesis Two Evaluation

My second hypothesis is that a complex space system is able to quickly adapt to external project changes using Agile Philosophy. As presented in Section 4.2, the ManitobaSat-1 project management plan incorporated recommendations made in chapter two to create an adaptive management approach for a complex nanosatellite project. The ManitobaSat-1 project had many internal changes, including changes in schedules and evolving roles as the project advanced, but the most notable external change was the COVID-19 pandemic.

The University of Manitoba began taking safety precautions on the 13th of March 2020 [77], including social distancing and closed student facilities. The safety precautions led to the STARLab members to begin working from home as the situation evolved, but the centralized wiki and project drive ensured that information was available to complete design activities. In addition to the central CADM system, the ManitbaSat-1 project used available communication technologies, such as emails and Zoom video meeting service, to maintain the weekly meetings and huddles. Team members were free to schedule project related meetings using the STARLab's Zoom account to maintain constant team communication.

As safety precautions came into effect, the team was faced with major changes to internal team interactions, work environments, and resources available for verification activities. Although the design activities continued without major disruptions, the recorded labour hours demonstrate that the team needed time to adapt to the change. This period also impacted the ManitobaSat-1 team's labour capacity as four students began fully undertaking thesis documentation and defence activities.

Figures 4.19 and 4.20 demonstrate the teams ability to adapt to the ongoing COVID-19 pandemic by continuing to undertake work, but at an initial reduced capacity. The reduced labour loading shown in Figure 4.20 can also be attributed to high off-project loading for individual team members as they complete requirements for their academic programs. As the internal and external situations change, project development is ongoing providing evidence that hypothesis two is true. However, further analysis is needed as the ManitobaSat-1 project advances to phase D.

4.5.3 Hypothesis Three Evaluation

My third hypothesis is that communication services that use Kanban and Scrum information structures, along with additive manufacturing for rapid prototyping will decrease schedule without affecting the quality of work completed. The established CADM architecture was used extensively by the team as shown in Section 4.4.1, where internal team communication was consistently the largest categories between phases B and C. The team used the Playbook management software's Kanban interface to mitigate multitasking and identify team member's availability. The Kanban board was supplemented by rolling wave approach and huddles to communicate and align project priorities to ensure a constant flow of work.

As each team member was responsible for detailing and updating their respective subsystem schedules, that was supported with Playbook's visual representation of work and availability. The visibility allowed for the creation of schedules based on availability. The schedules could easily be changed as team members received new class schedules. The ManitobaSat-1 project used available telecommunication services, such as Skype or Zoom, to ensure communication was available even if team members were unable to be co-located. These services allowed the meeting host to share their screen, and was incorporated into the huddles as co-location was restricted.

Although the team was able to continue nanosatellite development with Agile communication structures, we did not implement additive manufacturing during phase B, but are currently investigating opportunities in phase C. At the time of writing, the ManitobaSat-1 development team is undergoing verification activity reviews to ensure that we have adequate verification coverage of established requirements. Although COVID-19 has limited our ability to implement additive manufacturing of test articles, we continue working to identify opportunities to implement prototype testing.

Suggestions have been made to the best early prototype creation for phase C verification, but investigation is ongoing. Due to the limitations of current additive manufacturing for test articles, I am unable to fully evaluate hypothesis three. However, hypothesis three can be evaluated as partially true as the application of a Scrum communication structure using Kanban organization was extensively used and resulted in activity progress discussed in Section 4.4.2.

4.6 Chapter Conclusion

This chapter presented management data collected from the ongoing ManitobaSat-1 nanosatellite project. To ensure that the necessary level of detail is available to understand the data, I have discussed the CCP and their planned milestones, the ManitobaSat-1 management philosophy, and software used to collect research data. The CCP is managed through a traditional management phase approach that advances projects from design to manufacturing and testing. The ManitobaSat-1 used the phase transition periods to implement the rolling wave approach that details the schedule outline for the duration of the phase, enabling the team to create schedules that incorporate new information.

The ManitobaSat-1 project saw an increase in internal team communication as the role of direct project management changed into a support role. Team communication is an important indicator of team collaboration, reflecting the first Agile value of team interactions over processes and tools. The team was able to effectively create subsystem schedule in accordance with resource availability and project priorities that are constantly updated as the project progresses.

COVID-19 presented a major challenge to the CCP and the ManitobaSat-1 mission, impacting how everyone undertakes work and interactions. Although the ManitobaSat-

1 project implemented a CADM system that allows for off-site work, labour decreased as the University of Manitoba applied safety protocols that restricted student and faculty co-location. In addition, four of the fourteen students have begun the thesis documentation and defence preparation, that have drastically changed their availability.

The ManitobaSat-1 project demonstrated the ability to effectively adapt to internal team availability and responsibility changes, and demonstrated persistence in continuing work through large external changes. Although the CCP schedule has changed as the project progressed, the ManitobaSat-1 project is expected to be ready for the phase C review four months in advance of the CDR date for the other teams. Project labour has remained consistent in the self-organizing team structure through phase B, but is continuing to adapt as the COVID-19 pandemic evolves. This research has provided sufficient evidence to partially verify hypothesis three, demonstrating that the application of Kanban and Scrum positively impact project schedules.

Chapter 5

Conclusions

For this research, I have studied non-traditional management methods that can improve space projects by reducing the labour needed for direct management. In chapter one, I presented background non-traditional methods such as Agile philosophy and lean manufacturing. In chapter two, I presented the traditional space project management approach that has been used by the space sector since the Apollo program. I analyze data from recently completed industry project to investigate the best areas to apply non-traditional methods. Chapter three presents the ManitobaSat-1, an ongoing nanosatellite mission that incorporated recommendations in chapter two to create an adaptive management system for a complex space project.

This research provides recommendations to improve adaptability of complex space projects and how progress can be monitored to reflect the product's technical maturity. I found that project management requires the most labour hours for the industry project, using eighteen percent of total labour hours for phases B through D. Of the recorded project management hours, the majority of project management tasks are due to directly managing and planning project tasks. The large task loading of the central project management creates a risk of unavailable resources that can cause devastating delays for complex projects.

I conducted a study of how project labour and tasks growth as the project progresses through phases C and D, providing a method to monitor required resources. The industry project team had an average equivalent team size of eleven individuals working forty hours a week for both phases, but demanded an unsustainable team growth at different points of the project. Understanding the how the project resource needs change enable adaptive teams to be able to create schedules based on required and available resources.

Project labour and task growth were combined to derive an approximate representation of the industry project's Earned Value (EV), a traditional metric to monitor progress, and was compared to requirement verification progress. This research found that using the status of the verification activities as an alternative metric to Earned Value Management (EVM), with a correlation coefficient of 0.9509. The strong correlation suggests using verification activity progress can be easy to implement without negatively impacting the project team. The high correlation between the derived EV and verification activities suggest that changing progress management from EVM to verification status maintains a cash neutral project. If verification activities are planned throughout the project, including early prototype testing, they can be used as payment milestones as part of different engineering contracts.

This research has made recommendations to improve adaptability of a complex space project: decentralized rolling-wave/Scrum planning, and a central pull communication and data management (CADM) architecture. Decentralized planning enables the project team to organize and plan their tasks that is reflective of the scope of work and their labour capacity and mitigates the risk of a central management resource being overloaded and unavailable. A central CADM architecture enables to team to make design and scheduling decisions based on the current state of the project or the team capacity. Rolling-wave/Scrum planning provides a framework for the team to create plans that are easy to change when new information becomes available, taking into consideration team availability and task blockages.

Recommendations were incorporated into the ongoing ManitobaSat-1 project that is developing a nanosatellite to undertake a geological space experiment. The nanosatellite development is a student led effort that incorporates the recommendations made from the analysis of the industry project. This research analyzed the impact of the non-traditional approaches and evaluated three hypotheses:

1. I hypothesize that a two year spacecraft project schedule can be shortened by two months by applying the agile philosophy to certain aspects to the project.

2. I hypothesize that a complex space system is able to quickly adapt to external project changes using Agile Philosophy.

3. I hypothesize that communication services that use Kanban and Scrum information structures, along with additive manufacturing for rapid prototyping will decrease schedule without affecting work completed.

The ManitobaSat-1 data showed trends that supports all three hypothesis, but further observation and research is needed to fully analyze the effects of adaptive methods in a complex space project. The ManitobaSat-1 was part of the Canadian CubeSat Project (CCP) that provides funding and guidance for fifteen nanosatellite development projects that occur concurrently. The CCP created a traditional phase schedule with reviews milestone dates that provide a reference frame to partially evaluate hypothesis one. The ManitobaSat-1 project has schedule the Critical Design Review (CDR) four months ahead of schedule compared to other CCP teams, but as the ManitobaSat-1 is currently undergoing phase C activities, further observation is required.

The adaptive nature of the ManitobaSat-1 project management plan and execution allowed us to accomodate for extensive internal changes, such as changing availability due to class schedules, but the COVID-19 pandemic has provided a large external case study to evaluate hypothesis two. Although the ManitobaSat-1 has a notable decrease in team labour coinciding with when University of Manitoba began COVID-19 social distancing and safety precautions, team labour capacity has also been impacted by four team members undergoing thesis defence activities. However, phase C critical design activities are still progressing and we are currently monitoring the COVID-19 pandemic as verification resources become available. Although the ManitobaSat-1 project's labour throughput was impacted, the continuation of project activities partially demonstrates hypothesis two to be true.

Although the ManitobaSat-1 did not implement additive manufacturing for early and rapid prototyping, I can partially evaluate hypothesis three through the use of Scrum and Kanban communication structures. The ManitobaSat-1 extensively used rolling wave planning, a Scrum inspired scheduling and planning approach that allows team to adapt to new information. Rolling wave is combined with Kanban to mitigate project multi-tasking, communicate team members priorities, and visualize labour loading. The ManitobaSat-1 has been able to adapt to internal changes through rolling wave approach, and has allowed for the team to continue work through the COVID-19 pandemic. Although more observation is required, the ManitobaSat-1 teams persistence in undertaking work suggests hypothesis three is partially true.

5.1 Areas for Improvement

Additive manufacturing for early verification testing was an area of interest, but was not fully implemented for the ManitobaSat-1 project. Although early and frequent testing is recommended by Agile philosophy and lean manufacturing, identifying the best areas to use additive manufacturing for representative test articles was challenging. The ManitobaSat-1 project is currently reviewing verification activities and has identified candidate activities that can use test models created from additive manufacturing. Further studies are required in the application of early prototyping beginning in Phase B to demonstrate compliance or identify non-conformances.

This research used information recorded to monitor ManitobaSat-1 project health used by the ManitobaSat-1 STARLab team to take corrective actions when sources of delays were identified. Because the ManitobaSat-1 relied on self-reporting to document project progress, data presented was estimated if reporting occurred at a later date. In some situations, labour hours were recorded based on team members recollection and may not be fully reflective of the actual time needed to complete the work. The task start and end dates were closely monitored and updated on a weekly basis, providing framework to create estimates of labour. Labour reporting can be further improved by either applying recommendations to an industry project with rigid reporting systems or have incentives to document labour. However, implementing incentive systems can cause a possible area of incompatibility between a dynamic team and a rigid system.

Similarly, requirements and verification activity monitoring underwent internal reviews to maintain the link between product design and mission goals, but were on occasion updated retroactively. The ManitobaSat-1 was also challenged by requirement documentation consistency that differed between team members, creating different interpretations for inter-subsystem requirements or interfaces. As the combined project management and systems engineering roles dedicated labour towards aligning requirement interpretations and providing suggestions for methods to demonstrate compliance. However, both ManitobaSat-1 and the industry project faced constant challenges in maintaining a consistent format for requirements, and reviews provided frequent updates and coalescence in documentation.

The ManitobaSat-1 team also underwent changes in communication methods and documentation control as the project progressed and continued to discover internal team dynamics. Although we found and implemented better tools, such as the team changing from Skype to Zoom, the team became restricted with only one meeting at a time, creating a challenge in communication. Because the team Zoom account was available to all team members, scheduling and controlling meetings became a challenge, notably during social distancing as communication became critical. For a dynamic team that has frequent communication, the project manager role began scheduling the Zoom account availability, but challenges still rose from meetings overrunning their scheduled times.

Providing the baseline training for new team members in their project roles has also changed as the project progressed. I provided new team members with training in using Playbook, Valispace, and the wiki and Google Drive, but allowed the subsystem leads to provide technical training and guidance in the respective subsystems. The quality of information and training provided to new members varied, with results ranging from proving appropriate guidance for team members to be self-sufficient to having team members that required constant monitoring and schedule updates to ensure they were contributing to the project.

5.2 Closing Remarks

This research investigated the impact of non-traditional and adaptive management methods applied to the ManitobaSat-1 nanosatellite project and compared results to a traditional space project. Although the ManitobaSat-1 project is ongoing, it has demonstrated adaptive characteristics while maintaining a consistent work throughput. At the time of writing, we are currently undertaking phase C critical design activities, including requirements and verification reviews.

The ManitobaSat-1 project has demonstrated an ability to continue work during the COVID-19 pandemic and student availability changes. The nanosatellite development project demonstrated an increase in internal team communication as project management labour has decreased compared to the industry project. This trend demonstrates the development team's ability to self-organize, communicate task issues, and identify project priorities to ensure a constant work throughput. The ability to adapt and recover from changes provides evidence to the space sector that projects can break from the tradition of planning and risk control, to instead allow for the team to develop innovative solutions to project problems that can provide the first steps into the virtuous cycle.

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Appendix A

ManitobaSat-1 Project Management Plan

This appendix gives the ManitobaSat-1 Project Management Plan used through the project.

A.1 Introduction

This document has been compiled to provide guidance in management and completion of the ManitobaSat-1 project. The ManitobaSat-1 Program will explore how the space environment changes the optical properties of asteroids and the Moon over time. Asteroid surfaces exposed to the space environment undergo various changes that relate to factors such as solar heating, vacuum desiccation, and solar wind bombardment. These factors are termed ”space weathering” and they change the visual appearance of asteroids, which affects our ability to relate asteroids as seen by spacecraft and telescopes to meteorites as measured in the laboratory.

ManitobaSat-1 will investigate how space weathering affects asteroids and the

Moon by exposing a variety of meteorites and lunar analogues to the space environment in low Earth orbit and monitor changes in their optical (spectral properties) over the lifetime of the mission. The results will help us improve our ability to link asteroids to meteorites and enhance the science value from the upcoming CSA-NASA OSIRIS-REx asteroids sample return mission.

The ManitobaSat-1 program will provide valuable space heritage data for York University on their new, experimental sun sensor. By demonstrating functionality on a real space mission, it will increase the technology readiness level and provide a potential new space product for the Canadian space industry. The ManitobaSat-1 project is undertaken by a team of teams bringing together a wide range of knowledge and experience. To manage this project, the team will take a non-traditional approach by incorporating elements of Agile Philosophy, Lean Manufacturing and Theory of Constraints.

A.2 Scope Management

Project Scope: The work performed to deliver a product, service, or result with the specified features and functions. (PMBOK 6th ed.)

In order to control how the project scope is defined, validated, and controlled, the project scope will be defined by the ManitobaSat-1 objectives and requirements. Requirements will be reviewed every quarter and updated as needed. Based on the updated requirements, affected subsystems will update their project tasks and verification activities to reflect the current scope.

Scope validation will be completed through verification activities defined by each subsystem lead. Verification activities include 4 archetypes: Testing, Inspection, Analysis, and Document Review. Such activities will be completed throughout the life of the project and will be documented, including work done and criteria for acceptance.

A.3 Schedule Management

Project Schedule: An output of a schedule model that represents inked activities with planned dates, duration, milestones and resources. (PMBOK 6th ed.)

ManitobaSat-1 will be delivered to the CSA and Nanoracks in October 2020. The schedule will be defined and controlled by the core ManitobaSat-1 team. Each subsystem schedule will be controlled by its respective subsystem lead and updated as need be. The progress of each created task will be reviewed daily in a huddle for the purposes of collaboration and coordination.

Tasks will be created by each subsystem lead, based on expected task duration, definition of done, and projected resource availability. All tasks will be created to support the completion of major milestones, and will capture the following information: Expected duration, hours of work, task description, and definition of done. On a weekly basis, each sub-system lead will undertake a rolling wave activity, reviewing their schedule at least 8 weeks in advance and making changes in accordance with the current status of the project.

As changes in schedule are expected, each subsystem lead is in charge of non-critical path tasks, taking care that changes will not cause schedule overrun. In events that there is schedule overrun, the project leads will review the schedule changes and identify all options changes.

A.4 Quality Management

Quality: The degree to which a set of inherent characteristics fulfills requirements. (PMBOK 6th ed.)

High level requirements will be verified through the verification of all its children and progeny. For the requirements without children, subsystem leads will be responsible for creating verification activities that adequately test for compliance.

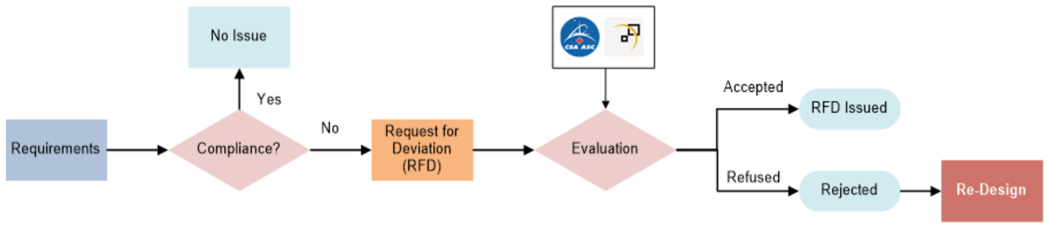
For phases B, C, and non-system level activities in phase D, subsystem leads are responsible for organizing and executing verification activities, documenting all tasks in the schedule. Sub-system leads will coordinate with AIT lead to ensure that all necessary equipment is available. The team may use any available method to generate tests, including additive manufacturing, breadboard models, external test beds, etc. Frequent testing through the early phases is encouraged to identify and resolve non-conformances when change has a lower impact in schedule and budget.

For Phase D, verification activities shall be coordinated with the AI&T lead for all tests that require system level testing. Verification procedures will be documented in a method that is easy to access and understand for outside observers and operators. All results shall be recorded in full detail, including time, verification ID and test deviations.

Non-conformances shall be handled in a case by case basis at different phases of the project through Request for Deviation (RFD) and Request for Waiver (RFW). For step by step instructions for filling out the forms, follow the Instructions to Create RFD's. When a non-conformance is identified, the ManitobaSat-1 team will pursue corrective actions to amend the issue.

If the non-conformance cannot be removed before phase D, the ManitobaSat-1 team will submit a RFD to the Canadian CubeSat Project team for CSA and

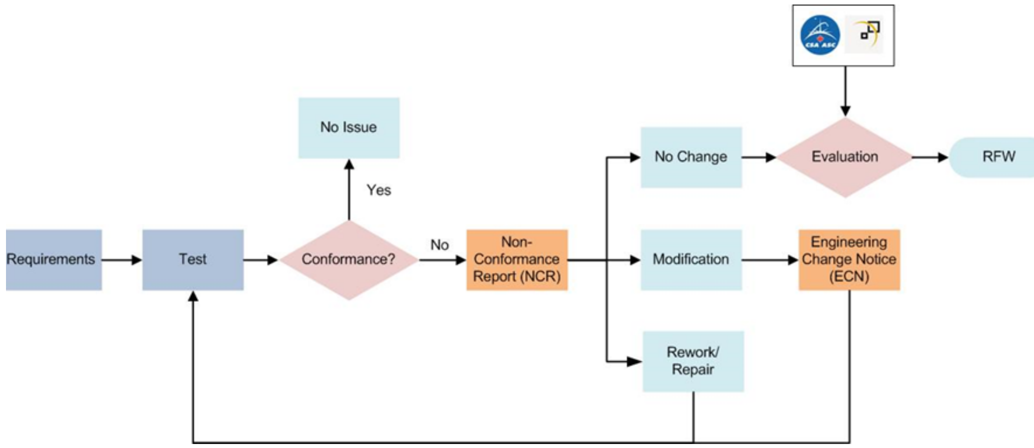
Nanoracks considerations. If the RFD is rejected, ManitobaSat-1 team is responsible for changing the design.



During phase D, when a non-conformance is found, the ManitobaSat-1 team will create a Non-compliance report detailing requirements tested, test procedures and results. The report shall address the following:

- To analyze all root causes of the non-compliance
- Identify if non-conformance can be fixed through rework/repair
- Identify if modification is a possibility
- If rework, repair or modification are not an option, identify impact on safety review

If the non-conformance can be corrected, the ManitobaSat-1 team will exercise activities and will test again. If repair, rework or modifications are not an option but the non-conformance can be used without change, a RFW will be submitted to the CSA and Nanoracks for consideration.



A.5 Resource Management

Resource: A team member or any physical item needed to complete the project. (PMBOK 6th ed.)

Team member availability shall be primarily managed through Playbook. Each team member will manage their tasks, and to the best of their knowledge, accurately estimate the amount of time needed for a task. Upon completion, each member will return to the task and update the expected duration with the actual amount of time for completion.

Materials will be coordinated among team members to ensure that double booking events for assembly or test equipment is not needed. Magellan Aerospace assets will be coordinated through the University of Manitoba Co-Investigator long in advance for any affected testing or assembly activities. If lab equipment needs to be taken out of the lab, members will fill out the equipment sign out sheet.

A.6 Communications Management

Communication Method: A systematic procedure, technique, or process used to transfer information among project stakeholders. (PMBOK 6th ed.)

The ManitobaSat-1 design team shall primarily communicate with agreed upon methods, including: talking, emails, texting services and skype conversations. All communication shall adhere to the Team Norms, outlined in the New Member's Package in Appendix B, and shall be used to promote professionalism in all members.

Frequent 15 minute meetings will be used to coordinate ManitobaSat-1 tasks and identify resource availability, blockages, and methods to address blockages. Weekly update meetings will be used for large scale decisions, technical updates and discussing opportunities to for additional outreach and collaboration. Quarterly meetings will be made to review all requirements and risks. At the beginning of each school season (i.e. Fall, Winter, and Summer Semester) the management team will request schedules to identify new meeting times.

All technical information will be handled in an information pull system through the ManitobaSat-1 Wiki website. Sub-system leads are responsible for maintaining their respective website entries up to date and reflective of technical information.

Communications with the other ManitobaSat-1 stakeholders will occur through designated points of contacts by either email or telephone call. Milestone Reviews will occur at the request of the CSA or Nanoracks, all required information will be submitted one month before the review is set to take place.

A.7 Risk Management

Risk: An uncertain event or condition that, if it occurs, has a positive or negative effect on one or more project objectives. (PMBOK 6th ed.)

Risks will be identified by any member of the ManitobaSat-1 team. All affected members, including the systems lead and project manager, will define the impact and probability of the risk event occurring. The Risk scales define the criteria for each score for impact and probability and can be found in the risk registry. Each risks will have a severity level applied to it based on the impact and probability score defined by the risk matrix.

Risk plans will be discussed and developed by all affected parties and will be identified as one of the following definitions:

- Avoid – Acts to eliminate the threat or protect the project from its impact.
- Mitigate – Action taken to reduce the probability of occurrence and/or impact threat.
- Accept – Acknowledge the existence of a threat, but no proactive action is taken.

When a risk mitigation or avoidance activity is agreed upon by all affected members, work tasks will be created and documented within Playbook and the risk registry. Upon completion of the risk tasks, the risk registry will be updated with the current status of the threat. If more actions are needed, all affected parties will be consulted.

A.8 Procurement Management

Strategy: The approach by the buyer to determine the project delivery method and the type of legally binding agreements(s) that should be used to delivered desired results. (PMBOK 6th ed.)

When a member identifies material that needs to be purchased, they will request approval from the University of Manitoba co-investigator. If approved, the responsible team member will request the lab technician to make the purchase. The team member will create an entry in the Lab Purchases sheet.

For commercial-off-the-shelf (CotS) components, in addition to the steps above, the purchasing team member will identify any special storage, handling, and installation information and record it into the Component Storage and Handling Instructions. Upon receiving the item, the purchasing team member will undertake acceptance testing and inspection to ensure that the purchased item operates as needed. The operator will fill out an inspection report and begin a traveler document to track travel and activities. Report templates can be found in Document Control Templates folder.

If multiples of the same component are purchased, batch acceptance testing will be undertaken.

Appendix B

ManitobaSat-1 New Member Orientation Package

This appendix gives the ManitobaSat-1 orientation package provided to new members when they join the STARLab.

B.1 What is the STARLab

Our goal is to make space more accessible for everyone by creating opportunities for new technologies to be tested and implemented at a lower cost compared to traditional methods. We are dedicated to creating an environment where students will be exposed to industry wisdom and academic knowledge, a fertile ground where students can develop professionally. As a member of the STAR Lab, don't be afraid of making mistakes, there is always something to be learned.

> There is never a single right solution. There are always multiple wrong ones, though.

-Akin's Law no. 12

B.2 STARLab Team Expectations

To provide an environment of professionalism and mutual respect, the STAR Lab expects each team to follow the following norms:

B.2.1 Professionalism

1. Each team member will arrive to each meeting on time if not early.
2. If unforeseen circumstances prevent a team member from attending, they will notify at least one other team member prior to the meeting.
3. All work will be completed in an accurate, organised and timely manner.
4. The work will be fully completed in a manner to fulfill project objectives.
5. Each team member will treat others with respect.
6. Each team member will come to project activities with a positive attitude and a focus on project objectives.
7. Each team member will responsibly provide insight into topics that they are knowledgeable.

B.2.2 Communication

1. Each team member will participate in active listening during meetings and discussions.

2. Each team member is responsible for completing work in an organized, well documented manner to facilitate communication with others.

3. Each team member will respond to emails within 2 business days.

4. If communication outside of business days is needed, it shall be agreed upon by affected team members.

B.2.3 Respect

1. Team members will wait for an opportunity to speak rather than interrupt others to get a point across.

2. Team members will listen to the speaker in turn rather than have side conversations during meetings or discussions.

3. Acknowledgement will be given for the work of others.

B.2.4 Good Practice

1. Upon completing an action item, the responsible team member will close out the item unless a discussion or update is needed at the next meeting.

2. When suggesting agenda items to the chair, provide expected discussion length.

3. Team members will take turns to record notes from meetings or discussions.

4. Minutes taken for meetings will be made available to the team in a timely manner.

5. Distractions will be kept out of team meetings and discussions to stay on time.

6. Agendas will be provided to meeting members at least 2 hours prior to the meeting.

B.3 Health and Safety

The STAR lab is committed to ensuring the safety of every team member and visitors. As such, each member must be both aware and conscious of health and safety information and procedures. Each STAR lab member is expected to have undergone University provided safety training in accordance with the University of Manitoba's Environmental Health and Safety Training.

B.3.1 Expected Training

Each team member must have completed level 1 of the Safety Training Flow Diagram. The mandatory training is shown below:

- Introduction to Health and Safety Programs at the University of Manitoba.
- WHIMIS 2015 Online Training.
- New Worker General Orientation Online Training.

Upon completion of the training, new members are to complete the Training Declaration document with the following evidence:

- Health and Safety Acknowledgement.
- WHMIS 2015 Training Certificate.
- New Worker Orientation Certificate.

Once all certificates are printed and collected, it is to be submitted to the Mechanical Engineering Office (E2-327).

B.3.2 Working Alone or In Isolation

In case a team member needs to work after hours, they need to follow the University of Manitoba's Work Alone or In Isolation Policy. It is strongly encouraged for each member to read the policy in full. A summary of the policy is provided below. A person is considered working alone if:

- Nobody can hear or see you (being completely by yourself).
- None of your coworkers can hear or see you (you might be surrounded by other people but you are still considered to be working alone when you are the only person from your employer performing work at that specific location).
- When your employer or your supervisor is not directly supervising you.

Before working alone, the lab members and supervisor will identify potential hazards that are associated with the task, workplace and circumstances for working alone. For each identified risk, strategies to reduce and eliminate risks will be made.

B.3.3 Additional Procedures

Before beginning with any new activities, contact the lab technician for best practices and safe procedures.