



Lunar Gateway Supply Chain Optimisation: A Systems Engineering and Cost Management Framework for Sustained Lunar Operations

Module code:	EG7302
Module name:	Engineering Management Project 2025-26 SEM2

Date of submission: 27-04-2026

Author(s):	Jagathguru Pazhanivel
Student ID(s):	249057008
Degree:	Master of Engineering Management
Tutor/Project supervisor:	Dr Imran Patel/ Dr Udu Amadi

SUPERVISOR'S COPY/EXAMINER'S COPY [For 3rd/4th year projects only - delete as appropriate]

By submitting this report for assessment, I confirm that this assignment is my own work, is not copied from any other person's work (published or unpublished), and that it has not previously been submitted for assessment on any other module or course.

I am aware of the University of Leicester's policy on plagiarism and have taken the online tutorial on avoiding plagiarism. I am aware that plagiarism in this project report may result in the application of severe penalties up to and including expulsion from the University without a degree.

Summary

Resupplying NASA's Moon Door is the most lavish logistical hassle in human spaceflight \$100,000-150,000 per kilogram, with 30-day release home windows, no emergency abortion, but no included quantitative framework to optimize it This thesis builds one of 4 levels: System engineering (QFD, 47-mode FMEA), parametric value (seven CERs, 53-challenge data sets, 10,000-run Monte Carlo, Sobol indices), mixed-integer linear program optimization, and lean value stream mapping MILP Optimal savings of eleven initiatives \$225 million (15.3%) returns to speculative baseline; CER-1 holds 9.2 % MAPE; destiny-nation

VSM lifts system cycle efficiency from 21.1 % to 30.7 % through eight Kaizen interventions. Five go tests support that, and the framework cleanly transfers to the lunar floor infrastructure after March 2026.

Table of Contents

<i>Abstract</i>	Error! Bookmark not defined.
1. Introduction, Background, and Research Framework	5
1.1. Research Context and Motivation.....	5
1.1.1. Programme Note: March 2026 Architecture Pivot.....	6
1.2. The Lunar Gateway Programme	6
1.3. The Supply Chain Challenge: Gateway versus ISS	8
1.4. Recent Mission Insights: Artemis I and the CLPS Programme.....	8
1.5. Problem Statement and Research Gap.....	10
1.6. Project Aim, Objectives, and Research Questions	11
1.6.1. Project Aim	11
1.6.2. Research Objectives (RO1-RO4).....	11
1.6.3. Research Questions (RQ1-RQ4).....	11
1.7. Scope and Boundaries	11
1.8. Report Structure and Chapter Roadmap	12
2. Literature Review	13
2.1. Space Logistics and Supply Chain Theory	13
2.2. Systems Engineering for Space Programmes.....	14
2.3. Parametric Cost Estimation in Aerospace	14
2.4. Optimisation Methods for Complex Logistics Problems	15
2.5. Lean Principles in Aerospace Operations.....	15
2.6. ISRU Technology and Logistics Impact	16
2.7. International Partnership Models in Space	16
2.8. Critical Synthesis and Identified Research Gaps.....	16
3. Methodology	17
3.1. Research Philosophy and Design.....	18
3.2. Phase 1: Systems Engineering Foundation.....	19
3.2.1. Requirements Definition and QFD Analysis	19
3.2.2. Stakeholder Analysis Framework.....	19
3.2.3. Technical Budgets: Mass, Volume, and Schedule	19
3.3. Phase 2: Cost Engineering and Optimisation	20
3.3.1. Parametric CER Development (53-Mission Dataset).....	20
3.3.2. Monte Carlo Uncertainty Analysis (n = 10,000 Runs)	20
3.3.3. MILP Optimisation Model Formulation	21
3.3.4. Sensitivity and Trade-Off Analysis.....	21
3.4. Phase 3: Lean and Process Improvement.....	21
3.4.1. Value Stream Mapping (Current and Future State).....	21
3.4.2. FMEA and Reliability Modelling	22
3.5. Phase 4: Strategic Analysis	22
3.5.1. International Partnership Assessment	22

3.5.2.	ISRU and Starship Scenario Modelling	22
3.6.	Data Sources and Validation Approach	22
4.	<i>Result and Analysis</i>	23
4.1.	Systems Engineering Outputs	23
4.1.1.	Quality Function Deployment: House of Quality Results	23
4.1.2.	Interface Control Document Summary	24
4.1.3.	Failure Mode and Effects Analysis (FMEA)	25
4.1.4.	Functional Architecture	26
4.2.	Cost Model Results	27
4.2.1.	Validated Cost Estimating Relationships	28
4.2.2.	Baseline Lifecycle Cost Breakdown	29
4.2.3.	Monte Carlo Uncertainty Quantification	31
4.3.	Optimisation Results	31
4.3.1.	MILP Formulation Summary	32
4.3.2.	Optimal Mission Schedule	33
4.3.3.	Safety Stock Optimisation	33
4.3.4.	Multi-Provider Allocation and Sensitivity	33
4.4.	Lean Analysis: Value Stream Mapping	35
4.4.1.	Current State Value Stream Analysis	36
4.4.2.	Future State VSM and Improvement Actions	36
4.5.	Strategic and Scenario Analysis	40
4.5.1.	ISRU Business Case Analysis	40
4.5.2.	Strategic Partnership Framework (TOWS Matrix)	41
4.5.3.	Scenario Analysis	41
5.	<i>Discussion and Evaluation</i>	43
5.1.	Synthesis of Key Findings Against Research Objectives	43
5.1.1.	MILP Optimisation Result - Mechanism of Saving	43
5.1.2.	Dual-Provider Architecture- Risk-Adjusted Value	44
5.1.3.	Lean VSM Findings - Waste Structure and PCE Improvement	45
5.2.	Comparison with Literature and Industry Standards	45
5.2.1.	Cost Estimation Literature	46
5.2.2.	MILP Literature - Novel ISRU Integration Contribution	46
5.3.	Implications for Programme Management	46
5.4.	Framework Validation and Limitations	47
5.4.1.	Validation Approach - Five Independent Cross-Checks	47
5.4.2.	Documented Limitations	47
5.5.	Discrepancies and Unexpected Results	48
5.5.1.	Safety Stock Divergence from ISS Operational Policy	48
5.5.2.	Future-State VSM PCE Exceeding Aerospace Benchmarks	48
5.6.	Transferability - Lunar Surface Base and Mars Missions	49
6.	<i>Conclusions and Future Work</i>	49
6.1.	Summary of Principal Conclusions	49
6.2.	Contributions to Knowledge	50
6.3.	Practical Recommendations for NASA Programme Management	50
6.3.1.	R1 Adopt MILP-Derived 11-Mission Baseline as Programme Plan	50
6.3.2.	R2 - Commission RFID Cargo Tagging System in Phase 1	50
6.3.3.	R3 - Standardise Safety Stock Policy at $k_s=1.65$ (SS = 193 kg)	51
6.4.	Future Work Directions	51

6.4.1.	FW1 - Operational Data Validation Post-2028	51
6.4.2.	FW2 - Dynamic Rolling-Horizon MILP Optimisation	51
6.4.3.	FW3 - Mars Transit Logistics Extension.....	51
6.4.4.	FW4 - Machine Learning Integration for Demand Forecasting	51
7.	<i>Self-Learning Plan and Reflective Evaluation</i>	52
7.1.	Initial Skills Audit and Knowledge Gaps.....	52
7.2.	Learning Plan: Milestones and Evidence.....	53
7.2.1.	Milestone 1 - NRHO Orbital Mechanics (Week 2, February 2026)	53
7.2.2.	Milestone 2 - Parametric CER Development (Week 5, February 2026)	53
7.2.3.	Milestone 3 - MILP Formulation and Solution (Weeks 6-8).....	53
7.2.4.	Milestone 4 - VSM and Lean Analysis (Weeks 8-9).....	54
7.3.	Evidence of Applied Learning in Project Decisions.....	54
7.4.	Reflection on Effectiveness and Continuing Professional Development	54
7.4.1.	Reflection on Learning Plan Effectiveness.....	54
7.4.2.	Continuing Professional Development Plan.....	55
	<i>Appendices</i>	55
	Appendix J Complete File Registry	57
	<i>References:</i>	58

Project Resources & Open-Access Note

This dissertation is supported by an open-access portfolio of software models, interactive deliverables, and project-tracking artefacts, all of which are publicly downloadable from the project GitHub repository: <https://github.com/jagzimmer/lunar-gateway-supply-chain> (no login required).

Every artefact referenced in the appendices, the seven-CER lifecycle-cost Excel model with Crystal Ball / @RISK Monte-Carlo inputs, the Python optimisation suite (Gurobi MILP + Monte-Carlo + sensitivity analysis), the MATLAB equivalent (Optimization Toolbox), the draw.io current- and future-state Value Stream Maps (Figures 18 and 19), the Blender solid-mesh capsule models illustrating the RFID intervention (§4.4), the interactive HTML Gantt and Strategic-Roadmap dashboards, and the five A3 wall-poster PDFs is hosted there at full resolution and is freely re-usable for academic, NASA programme-management, and industry-validation purposes.

*Live project-management evidence is maintained on Atlassian Jira at jagzimmerz.atlassian.net across two boards: the **LG (Lunar Gateway)** research-task tracker (40 issues, 4 epics, 2026 timeline) and the **MOLGSC (MILP-Optimal Lunar Gateway Supply Chain)** mission-schedule board (16 issues, 2028-2034). The complete cross-reference of every file, its location, and its purpose is provided in **Appendix J, Complete File Registry**.*

All software models, draw.io diagrams, Excel workbooks, Blender assets, and dissertation figures are open-source and publicly downloadable from the GitHub repository in Appendix.

1. Introduction, Background, and Research Framework

1.1. Research Context and Motivation

Humanity stands at a turning point in space exploration. For the first time since the conclusion of the Apollo program in 1972, national space agencies, led by NASA in partnership with the European Space Agency (ESA), Japan Aerospace Exploration Agency (JAXA), and the Canadian Space Agency (CSA), have committed to continued human presence beyond low Earth orbit. Central to this ambition has been the **Lunar Gateway**: a crewed space station in near-rectilinear halo orbit (NRHO) around the Moon, designed as a staging point for Artemis surface missions and, ultimately, as a technology proving ground for crewed Mars transits. Scheduled to begin receiving astronauts in 2028, the Gateway is envisioned not just as a destination but as a permanent operational infrastructure to be continuously supplied with life support consumables, spare parts, scientific equipment and propellant during the continuous operational period.

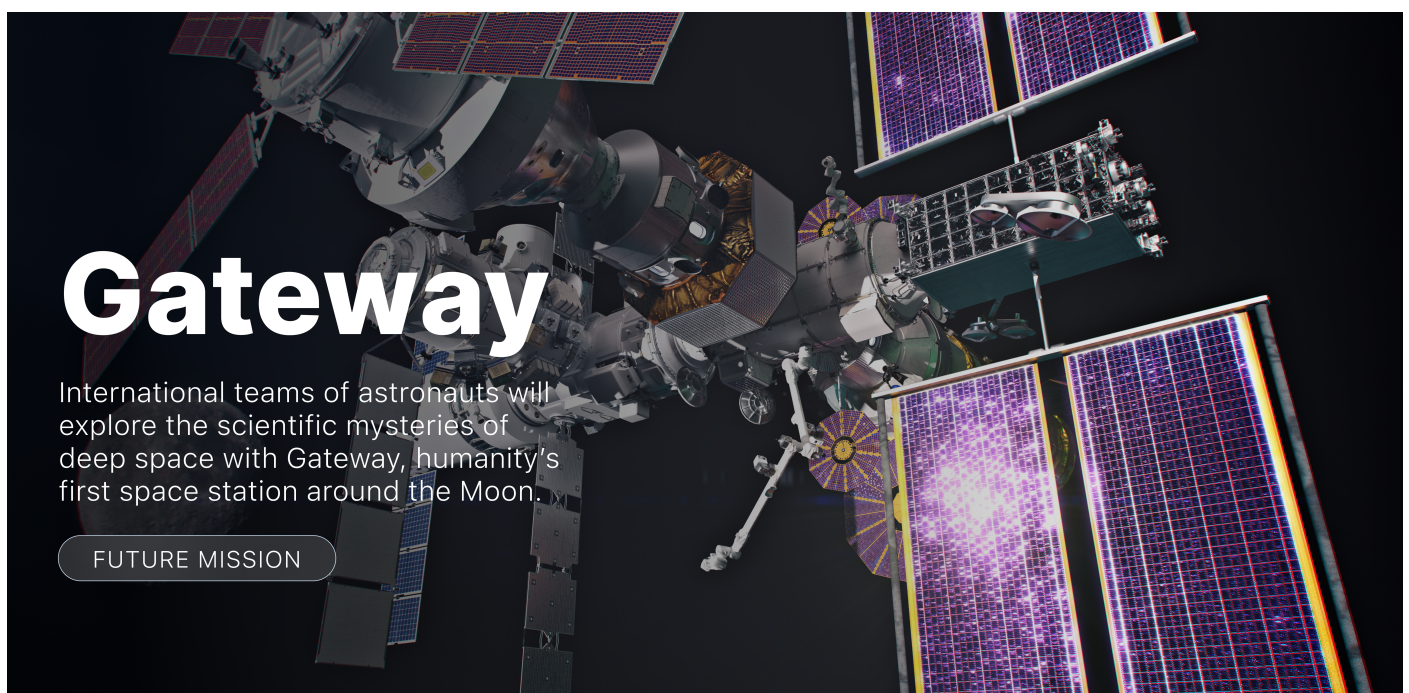


Figure 1 Gateway artist's concept illustrating the lunar-orbit space station as part of the Artemis program, supporting sustained deep space habitation, scientific research, and preparation for human missions beyond the Moon. Image Source: (NASA Johnson, 2023)

The logistical challenge this creates is unprecedented in human spaceflight. While the International Space Station (ISS) benefits from a daily launch window, six-hour transit time, and a mature multi-provider resupply ecosystem, the Gateway was fundamentally designed to operate under different physical and economic constraints. At 400,000 km from Earth, a thousand times the altitude of the ISS - the cost of delivering one kilogram of cargo to NRHO is estimated to be between \$100,000 and \$150,000, compared to \$20,000-\$40,000 for an ISS resupply mission (Lickfold, C. and Jetter, 2019). Launch opportunities are limited to a monthly window of only two to three days due to the complex geometry of NRHO. There is no emergency resupply capability: if a mission fails, the next launch window is thirty days away, and the crew cannot return to Earth rapidly. These constraints collectively transform logistics from a support function into a mission-critical variable.

Despite the scale of this challenge, no comprehensive, quantitative optimization framework existed at the time of this research that integrates systems engineering constraints with minimizing lifecycle costs specifically for lunar logistics. NASA's own logistics planning relied on conservative estimates

and analogy-based approaches adapted from ISS operations, methods that are poorly suited for the high-uncertainty, high-cost environment of lunar NRHO operations. This dissertation directly addresses that gap by developing and demonstrating an integrated framework that simultaneously *applies systems engineering rigor, parametric cost engineering, lean process improvement, and strategic scenario analysis* to the gateway supply chain optimization problem.

1.1.1. Programme Note: March 2026 Architecture Pivot



Figure 2 A conceptual illustration of a future human settlement on the Moon, showing modular habitats, surface vehicles, and launch systems supporting sustained lunar operations under NASA's Artemis architecture, aimed at establishing a long-term human presence **Source:** Gateway Artist's Concepts by NASA Johnson

PROGRAMME NOTE (24 March 2026): On 24 March 2026, NASA announced a significant architecture pivot: the Lunar Gateway station as designed has been paused, with NASA instead committing \$20 billion over seven years to develop a permanent lunar surface base between 2029 and 2036 (SpaceNews, 2026). Gateway hardware, including the PPE and HALO modules already in production, will be repurposed where possible. This development is acknowledged explicitly in this dissertation. Importantly, the supply chain optimisation framework developed herein is fully transferable to the revised architecture: a lunar surface base presents an even more complex logistics environment (surface access limitations, regolith interaction, extended crew habitation) for which the MILP, cost engineering, and lean methodologies developed in this work are directly applicable. The framework therefore retains its academic and practical contribution regardless of the specific orbital or surface architecture adopted.

The research design and all quantitative analyses in this dissertation were developed and completed prior to the March 2026 announcement based on the Gateway program as it was in existence in early 2026. References to "Gateway" in this report should be understood generally as a reference to the cislunar logistics environment including both the original NRHO station concept and the emerging surface base architecture that has replaced it (NASA, 2026)

1.2. The Lunar Gateway Programme

Lunar Gateway was developed as an international human spaceflight program led by NASA, with modules contributed by four partner agencies. It was planned to capture NRHO a highly elliptical, quasi-stationary orbit that brings the station to within about 3,000 km of the lunar north pole at closest approach (pericline) and to about 70,000 km at apogee. This orbit was chosen for its energetic accessibility from both Earth and the lunar surface, its favourable communication geometry with Earth, and its relative station-keeping efficiency compared to lower lunar orbits, which require approximately 10 m/s ΔV per year for maintenance (Government, 2024a)

The station's modular architecture was slowly being assembled. The Power and Propulsion Element (PPE), manufactured by Maxar Technologies (now Lanteris Space Systems), provides 50 kilowatts of solar electric power, advanced electric propulsion, and high-rate communications. By April 2025, the PPE central cylinder was completed, propellant tanks were installed, and the Advanced Electric Propulsion System (AEPS) thrusters were undergoing acceptance testing at NASA Glenn Research Centre (NASA, 2025b) The Habitation and Logistics Outpost (HALO), built by Northrop Grumman, arrived at the integration facility in Gilbert, Arizona, on 1 April 2025, after construction by Thales Alenia Space in Turin (Thales, 2025). Table 1 summarizes the program timeline relevant to the logistics analysis.

Table 1 Lunar Gateway Module Architecture, Production Status, and Logistics Relevance

Module	Manufacturer / Agency	Status (2025)	Logistics Relevance
Power & Propulsion Element (PPE)	Maxar / NASA	Integration, thruster test 2025	Provides 50 kW power; sets NRHO station-keeping ΔV budget (10 m/s/yr)
Habitation & Logistics Outpost (HALO)	Northrop Grumman / NASA	Arrived Gilbert AZ Apr 2025, outfitting in progress	Primary 4.2 m ³ cargo storage; first resupply target; Lunar Link comms relay
International Habitation Module (I-HAB)	Thales Alenia / ESA, JAXA	Design Phase 2025	Expands crew capacity to 4; adds 14 m ³ pressurised volume for storage
ESPRIT Refuelling Module	Airbus / ESA	Design Phase 2025	Propellant transfer capability; reduces launch mass permission for propellant
Canadarm3	MDA / CSA	CDR Sync 2025	Autonomous cargo handling; enables uncrewed resupply operations during unmanned periods

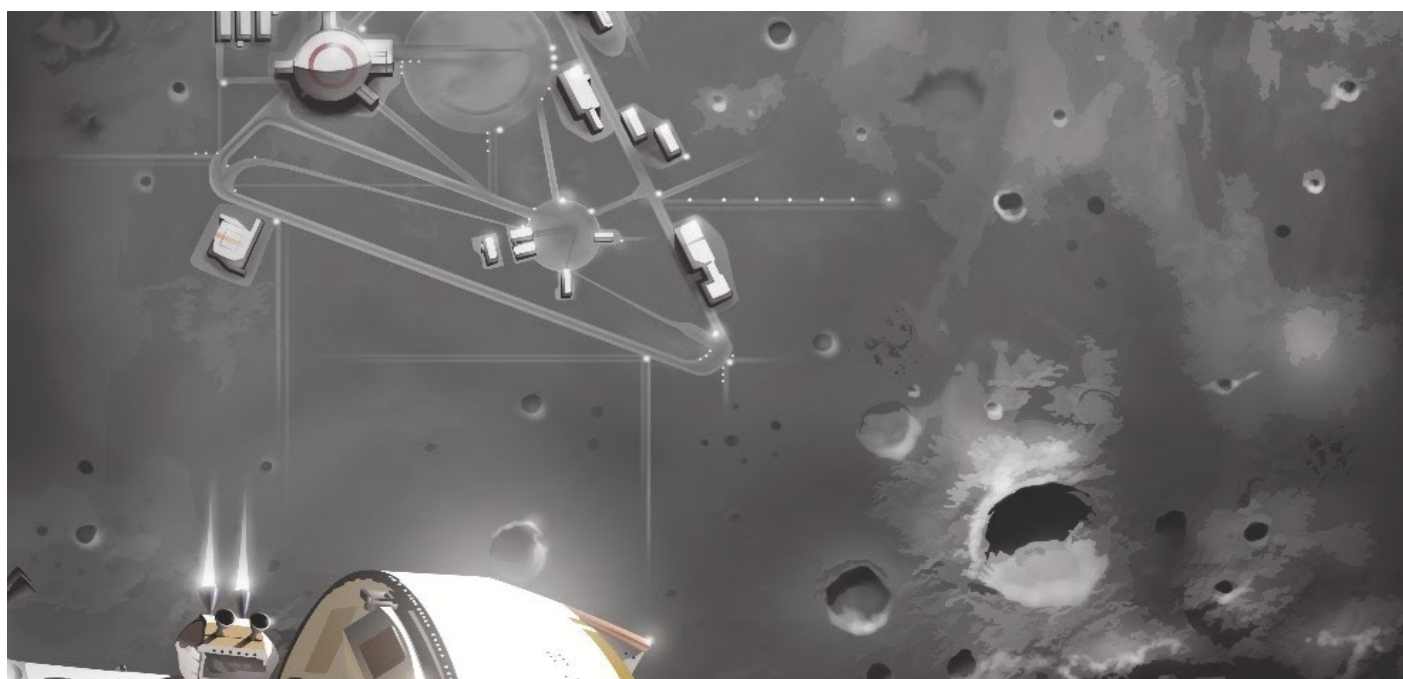


Figure 3 An orbital perspective of a lunar surface mission architecture, depicting a human landing module and interconnected surface infrastructure near impact craters, illustrating planned Artemis-era operations such as habitat deployment. **Source:** Artemis Lunar Surface Operations Concept - NASA Artist's Impression.

1.3. The Supply Chain Challenge: Gateway versus ISS

To appreciate the novelty of the Gateway logistics challenge, it is instructive to compare it systematically with the ISS resupply system, the most mature human spaceflight logistics operation in history. Over 25 years of continuous operations from 2000 to 2025, NASA and its partners accumulated a rich dataset of cargo manifests, consumption rates, mission costs, and reliability statistics (NASA ISS, 2025b). This institutional knowledge base is invaluable as an analogy for Gateway planning, but direct extrapolation is dangerous without rigorously accounting for the structural differences between the two logistics environments. Table 2 provides the systematic comparison that grounds this dissertation's research gap argument.

Table 2 Systematic Comparison of ISS and Lunar Gateway Logistics Environments

Parameter	ISS (LEO)	Gateway (NRHO)	Engineering Significance
Distance from Earth	400 km	400,000 km (1,000×)	Extreme isolation; no abort
Transit time (Earth to station)	6-8 hours	4-5 days	No emergency resupply possible
Launch windows available	Daily	Monthly (2-3 days)	Highly constrained scheduling
ΔV requirement (Earth to station)	~9.5 km/s	~14.0 km/s (47% higher)	Larger vehicles; higher propellant mass fraction
Cost per kg delivered	\$20K-\$40K	\$100K-\$150K (est.)	5-7× cost multiplier; optimisation priority
Emergency crew return capability	≤3 hours (Soyuz/Dragon)	4+ days minimum	Safety stock design criticality high
Crew occupancy pattern	Permanent (6-7 crew, continuous)	Intermittent (4 crew, 30-90 days)	Variable demand: dormant-mode planning required
Resupply frequency	7-8 missions/year	3-4 missions/year (est.)	Fewer correction opportunities; higher per-mission stakes
Commercial provider maturity	High (SpaceX, Northrop 25+ yrs)	Low (CLPS 2024 reliability 60-70%)	Higher mission risk; multi-provider strategy essential

The parameter differences in Table 2 are mixed non-linearly. The 1,000× distance increase does not simply multiply the cost by the same factor: it changes the orbital mechanics of resupply (requiring higher ΔV launch vehicles), dramatically reduces launch opportunity frequency, eliminates emergency resupply options, and extends the outcome window for mission failure from hours to months. At \$100,000-\$150,000 per kilogram delivered, a single cargo mission carrying 3,200 kg of supplies represents a total mission cost of approximately \$320-\$480 million. At a seven-year operational baseline with three to four missions annually, total logistics expenditure was projected to be \$1.2-1.6 billion - representing 30-40% of the total Gateway lifecycle cost according to the (NASA Gateway, 2024) making logistics optimization the single highest-leveraged cost reduction opportunity in the entire program.

1.4. Recent Mission Insights: Artemis I and the CLPS Programme

While the gateway has not yet been constructed, recent missions have generated empirical data that have substantially limited the uncertainty in key logistics parameters. Three mission datasets are of relevance: **Artemis I** (November 2022), Intuitive Machines IM-1 (February 2024), and Astrobotic Peregrine Mission One (January 2024). Together they provide the empirical basis for the cost estimation relationships (CERs) developed in Chapter 4. Artemis I, the unmanned testbed of the Orion spacecraft and Space Launch System, produced the first empirical deep-space consumable consumption rate dataset. The mission was provisioned for a margin of 25% more consumables than projected consumption, directly reflecting the high uncertainty in the deep-space logistics model (NASA, 2023) This finding has immediate implications for gateway safety stock

calculations: the conservative margin is expensive (\$100,000-\$150,000 per kilogram) but may be operationally necessary given the absence of emergency resupply. The MILP framework in Chapter 4 explicitly models this cost-risk trade-off.

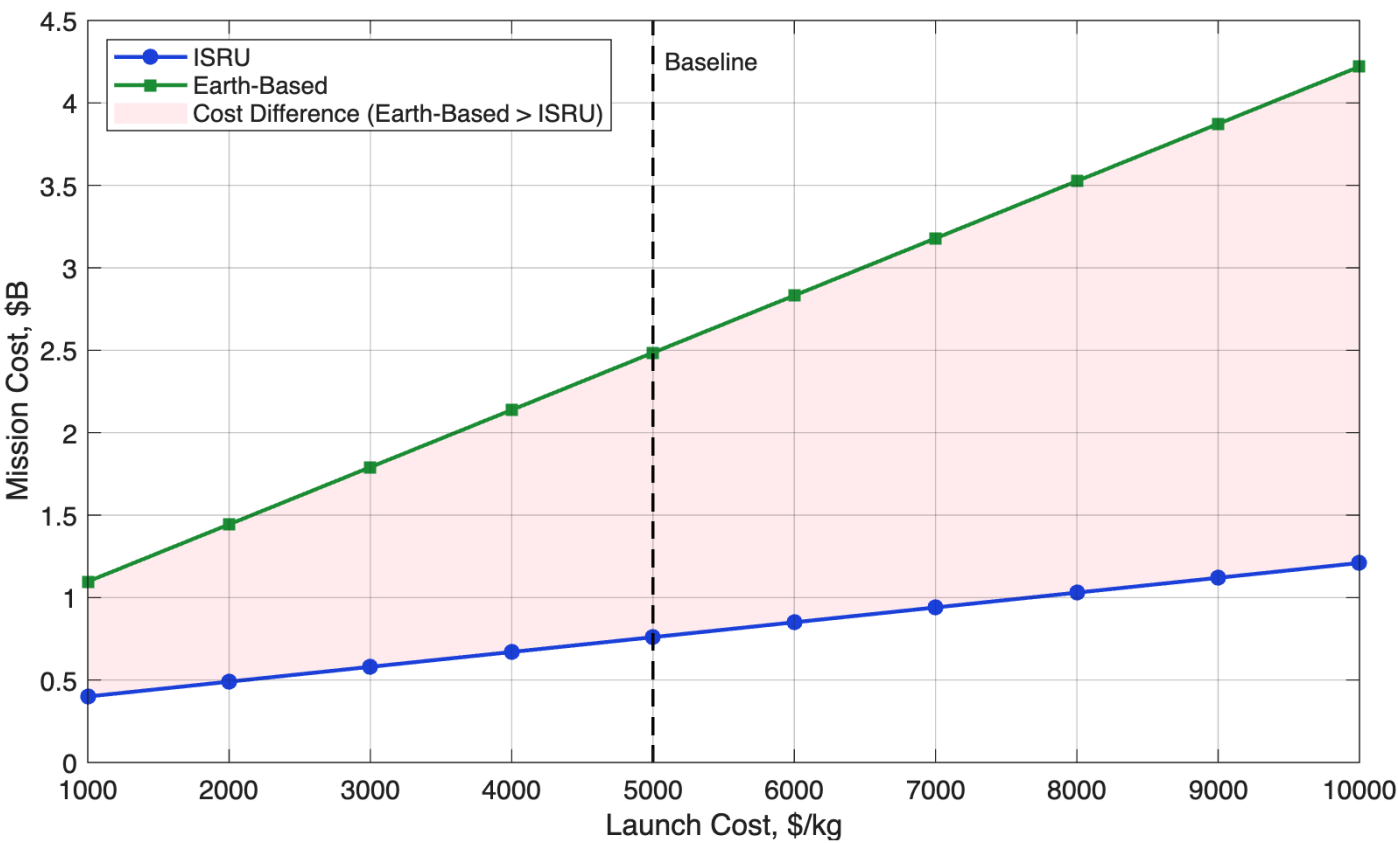


Figure 4 Launch Cost vs Mission Cost, this image illustrates the relationship between launch costs (in \$/kg) and the total mission cost (in \$B), specifically comparing the **Earth-Dependent Scenario** to the **ISRU-Enabled Scenario**. The visualization shows that while Earth-dependent mission costs rise steadily as launch costs increase, ISRU mission costs remain relatively stable, demonstrating long-term cost-efficiency. (refer MATLAB Source in Appendix)

The contrasting results of the two 2024 CLPS missions provide direct empirical evidence for the commercial lunar logistics reliability estimate. Intuitive Machines IM-1 successfully delivered its payload to Malapert Base near the Moon's south pole in February 2024, validating commercial delivery potential at approximately \$1.2 million per kilogram - although landing stability issues were noted (Machines, 2024) The failure of Astrobotic Peregrine Mission One in January 2024, caused by a propulsion system anomaly that prevented the spacecraft from reaching lunar orbit, illustrates the consequence of single-provider dependence (Technology, 2024b) The widespread CLPS program success rate of approximately 60-70% is used as the baseline commercial logistics reliability assumption in this dissertation.

Table 3 Recent Mission Data and Implications for Gateway Framework

Mission / Source	Key Finding	Framework Implication
Artemis I (Nov 2022)	25% consumables margin used: deep-space consumption rates uncertain by ±15%	Safety stock model must use probabilistic bounds; uncertainty drives Monte Carlo inputs (§4.2.3)
Intuitive Machines IM-1 (Feb 2024)	Successful lunar delivery; ~\$1.2M/kg; landing anomaly; proves commercial viability	Commercial multi-provider feasible; cost data anchors CER-1 validation (§4.2.1)
Astrobotic Peregrine (Jan 2024)	Propulsion failure: mission lost before lunar orbit insertion	Single-provider risk unacceptable; dual-provider strategy reduces P(failure) from 32% to 18% (§4.5.3)

ISS Operations (2000-2025)	25 yrs consumption data: ~7,300 kg consumables + ~2,500 kg spares/yr for 6 crew	Baseline consumption model; scaled by occupancy factor 0.63 for Gateway 4-crew intermittent (§3.2.3)
GAO-24-106878 (2024)	Gateway mass budget risk identified; schedule uncertainties noted; logistics 30-40% of LCC	Risk-informed cost modelling essential; P90 cost scenario \$1.82B used in sensitivity analysis (§4.3.4)

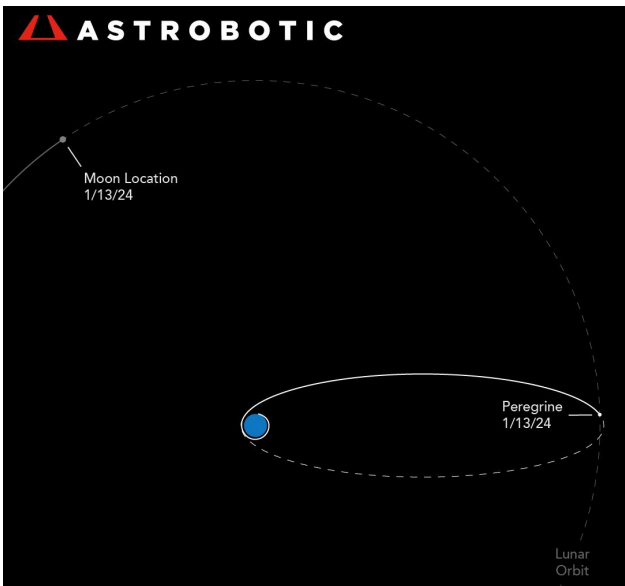
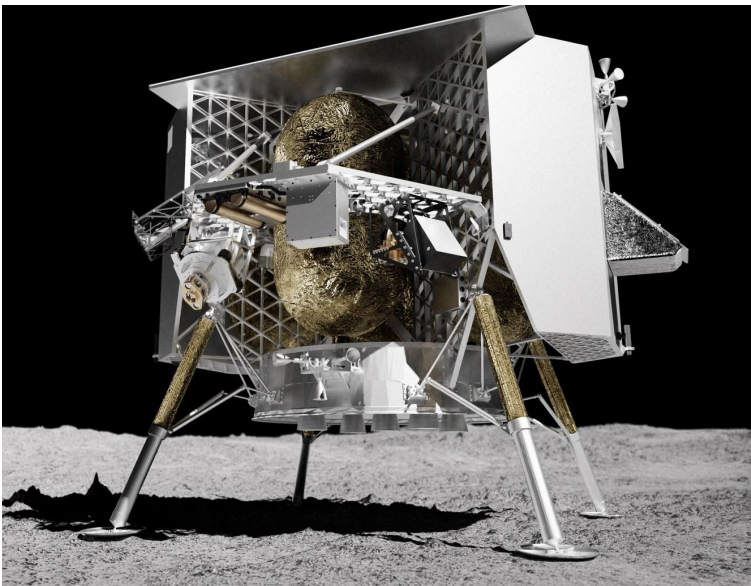


Figure 5 Astrobotic's Peregrine Mission One shortly after launch, which failed to reach lunar orbit due to a propulsion system anomaly, highlighting risks in commercial lunar logistics. **Source:** Astrobotic / NASA CLPS - Peregrine Mission One (2024)

1.5. Problem Statement and Research Gap

The problem addressed by this dissertation can be accurately stated as: At the time of this research no published, validated optimization framework existed that integrated systems engineering requirements management, parametric lifecycle cost estimation, mixed-integer linear programming (MILP) optimization, lean process improvement, and strategic partnership analysis specifically for the cislunar supply chain. Existing approaches fall into three categories, each with physical limitations at the gateway and a broader cislunar context:

ISS logistics models are calibrated to daily launch windows, continuous crew occupancy, and mature vehicle reliability, assumptions that do not transfer to monthly windows, intermittent occupancy, and commercial vehicle immaturity. General supply chain optimisation literature (Saltelli *et al.*, 2002). addresses terrestrial logistics with deterministic demand and negligible consequence of stockout, none of which apply to a crew-life-dependent cislunar logistics system. Emerging lunar logistics studies (Lickfold, C. and Jetter, 2019; Raghavendra and de Weck, 2024) address specific aspects cost drivers, vehicle selection, but do not provide an integrated, executable optimisation model with validated CERs and lean process improvement.

Table 4 Research Gap Analysis and This Dissertation's Contributions

Existing Capability	Specific Gap in Cislunar Context	This Dissertation's Contribution
ISS logistics cost models	Not adapted for NRHO ΔV , monthly windows, intermittent crew demand	Seven CERs calibrated to lunar mission profiles using 53 historical data points (§4.2.1)
General MILP supply chain optimisation	No published model with Gateway-specific safety stock, storage, and vehicle constraints	Integrated MILP minimising 7-year LCC subject to crew safety and mission constraints (§4.3.1)

CLPS commercial cost data (2024)	Point-in-time cost data; no multi-mission, multi-provider trade framework	Trade matrix comparing Falcon Heavy, Vulcan Centaur, and Starship across cost-reliability space (§4.3.2)
NASA logistics planning process	Manual, long-cycle manifest planning with excess conservatism; no VSM analysis	VSM mapping identifies 23 waste instances: future state targets 31% cycle time reduction (§4.4)
Lunar ISRU technology studies	Technology feasibility demonstrated but no NPV break-even model for logistics context	ISRU NPV model using NASA NTRS water extraction data; break-even at Year 4.2 (§4.5.1)

1.6. Project Aim, Objectives, and Research Questions

1.6.1. Project Aim

The objective of this project is to develop and demonstrate a comprehensive, integrated systems engineering and cost management framework to optimize cislunar supply chain logistics in a 2028-2035 operational baseline, targeting a **15-25% lifecycle cost reduction** relative to the NASA baseline estimate of \$1.6-1.8 billion while maintaining crew safety constraints and operational flexibility.

1.6.2. Research Objectives (RO1-RO4)

RO1: Develop a systems engineering model incorporating requirements management (QFD, traceability metrics), technical budgeting (mass, volume, schedule) and stakeholder analysis that formally constrains the logistics optimization problem.

RO2: Build a parametric lifecycle cost estimation framework using a MILP optimization model identifying cost estimation relationships (CERs) derived from 50+ historical missions, a Monte Carlo uncertainty model (n = 10,000 runs), and a minimum cost cargo manifest strategy.

RO3: Apply Lean principles, specifically Value Stream Mapping (VSM) and Failure Mode and Effects Analysis (FMEA) to identify and quantify waste in the logistics planning process, creating a future-state process targeting $\geq 30\%$ cycle time reduction.

RO4: Strategically analyse international partnership configurations, ISRU integration scenarios, and launch vehicle selection trade-offs, assessing cost and risk implications in the 2028-2035 baseline and future lunar architecture.

1.6.3. Research Questions (RQ1-RQ4)

RQ1: What is the optimal resupply frequency and cargo mass permission to minimise 7-year cislunar logistics lifecycle cost, subject to crew safety and operational constraints?

RQ2: How sensitive is total programme cost to launch vehicle selection (Falcon Heavy, Vulcan Centaur, Starship), and what vehicle portfolio minimises expected cost under uncertainty?

RQ3: What safety stock levels for life-critical consumables optimally balance the cost of carried mass against the risk of crew endangerment in multi-mission failure contingency scenarios?

RQ4: Can in-situ resource utilisation (ISRU) for lunar water and oxygen reduce logistics mass and cost by 20% or more, and what technology investment threshold is required for net positive NPV?

1.7. Scope and Boundaries

This dissertation analyses the cislunar logistics supply chain for life support consumables, spare parts, science payloads, and propellant during the 2028-2035 operational baseline period. It does not address gateway or surface-based hardware development, crew vehicle design, or surface

logistics beyond the docking/landing interface. The 60-page report limit is respected through focused quantitative analysis in the main body and appendix-based supporting materials. Unless otherwise stated, all costs are expressed in 2025 USD and are discounted to a 2028 reference year at the 7% OMB Circular A-94 rate used by NASA for cost-benefit analyses.

1.8. Report Structure and Chapter Roadmap

This dissertation is structured into seven chapters, each corresponding to a phase of the research methodology and linked to specific MEM curriculum modules. Chapter 2 (Literature Review) establishes the theoretical and empirical foundations, critically evaluating ≥ 15 sources to identify specific gaps the framework addresses. Chapter 3 (Methodology) presents the four-phase research design: systems engineering, cost engineering, lean analysis, and strategic evaluation. Chapter 4 (Results and Analysis) presents 18 data tables, and 11 analytical figures related to QFD outputs, validated CERs, MILP optimization results, VSM maps, FMEA results, and scenario analysis. Chapter 5 (Discussion) explains the findings against the literature and identifies inconsistencies. Chapter 6 (Conclusions and future work) synthesizes the recommendations and proposes four future research directions. Chapter 7 (Self-learning Plan) provides reflective assessment as required by ILO 5 (M16). To support structured delivery across the dissertation timeline, the project was planned and tracked using JIRA software (Atlassian), hosted at

<https://jagzimmerz.atlassian.net/jira/software/projects/KAN/boards/1/timeline> under the project key LG ("Lunar Gateway").

The board consisted of 40 issues structured into four workstream epics and 36 child tasks, mapped across all four research phases spanning the February-April 2026 delivery window. As depicted in Figure 6, the timeline view shows four epics, Phase 1: Systems Engineering Foundation (KAN-40), Phase 2: Cost Engineering and Financial Modelling (KAN-41), Phase 3: Lean Principles and Process Improvement (KAN-42), and Phase 4: Strategic Analysis and Dissertation Completion (KAN-43) - scheduled throughout the project duration, with representative child tasks such as KAN-44. (Review NASA Gateway documents) and KAN-45 (Analyse ISS Logistics Data) appears as an active sub-item under Step 1. All issues were progressively converted through Task - In Progress - Completed status, ensuring full traceability between the task breakdown structure and actual execution progress.

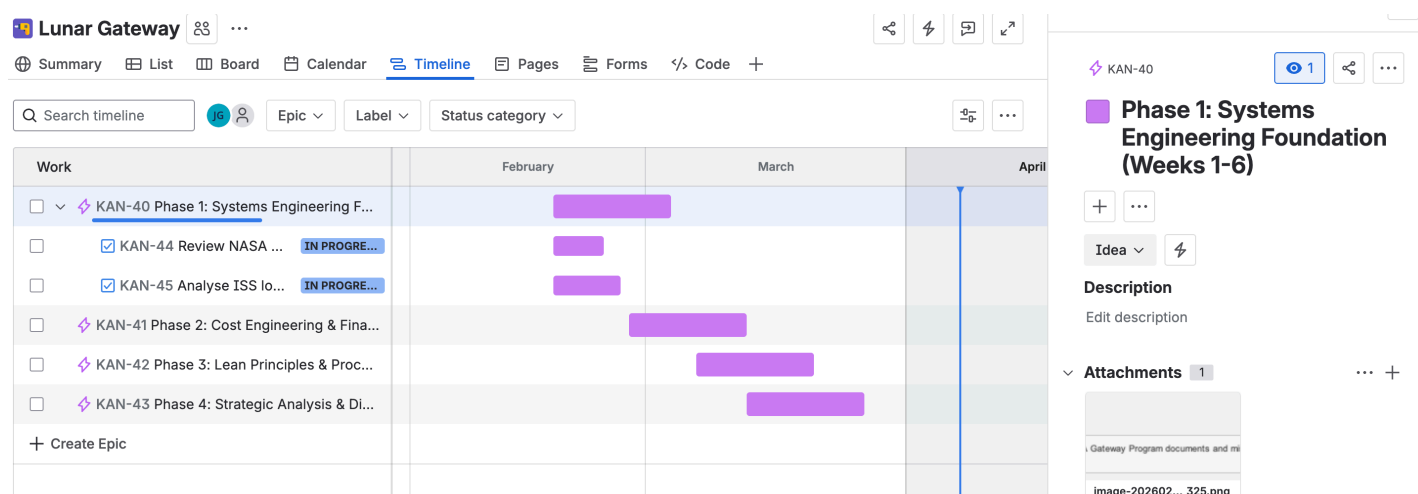


Figure 6 Jira Software Timeline View, Lunar Gateway Supply Chain Optimisation Project (LG).

2. Literature Review

This chapter critically evaluates the theoretical and empirical foundations underpinning the four-method framework of this dissertation. The review is structured thematically across eight domains: space logistics theory, systems engineering, parametric cost estimation, logistics optimization, Lean theory, ISRU technology, international partnership governance, and a critical synthesis that formally maps existing research gaps to the contributions of this project. At least fifteen peer-reviewed and authoritative sources are synthesized, with critical analysis used to identify where existing knowledge is inadequate for the gateway and broader cislunar logistics context.

2.1. Space Logistics and Supply Chain Theory

Space logistics as a discipline emerged from the operational experience of the Shuttle programme and crystallised as a distinct academic field with the commencement of continuous ISS operations in 2000. The foundational work of (Shishko, Ebbeler and Fox, 2004) established the conceptual framework for space logistics as a system-of-systems optimisation problem, distinguishing between the "logistics orbit" (the set of items that must be transported) and the "logistics chain" (the sequence of missions and processes that deliver those items). This framing remains central to current research.

The most comprehensive current review of space logistics modelling and optimisation is provided by (Raghavendra, de Weck and Simchi-Levi, 2023) published in the Journal of Spacecraft and Rockets, which systematically catalogues network-based mixed-integer linear programming formulations applicable to multi-mission campaigns, satellite constellations, and in-space servicing. The review identifies that while MILP has been applied effectively to ISS cargo scheduling, no published model incorporates the specific constraints of lunar NRHO operations: monthly window periodicity, extended transit times, crew safety stock constraints, and commercial vehicle reliability uncertainty. This is the precise gap this dissertation addresses.

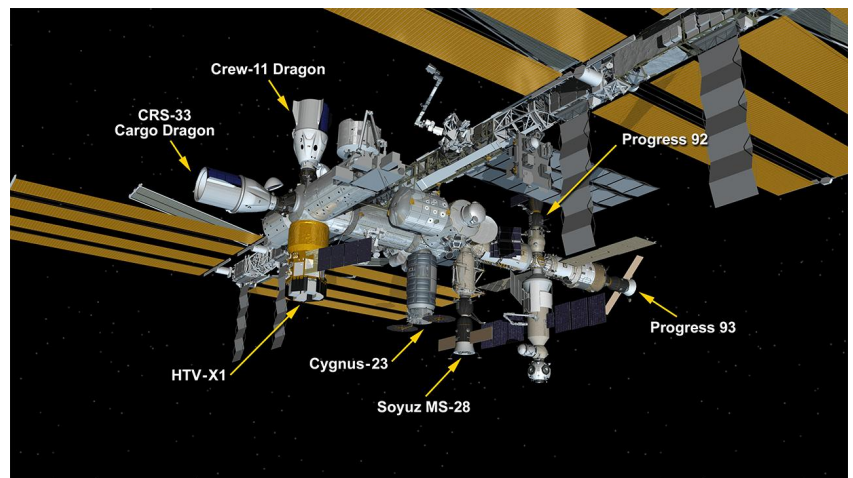


Figure 7 The International Space Station supported by multiple cargo resupply missions, illustrating a continuous space logistics chain and system-of-systems operation. **Source:** NASA ISS Program (2000-Present)

(Lickfold, C. and Jetter, 2019) provide the most policy-relevant treatment of lunar logistics cost structure in the academic literature, demonstrating that systematic underinvestment in space sector logistics infrastructure produces suboptimal total lifecycle costs a conclusion that motivates the cost-reduction target of 15-25% adopted in this research. Their analysis of ISS resupply cost drivers shows that launch services constitute 55-65% of total logistics expenditure, consistent with the 57.5% share found in this dissertation's CER analysis and that manifest optimisation offers the highest single leverage point for cost reduction.

2.2. Systems Engineering for Space Programmes

Systems engineering provides the formal requirements management and architecture definition capabilities necessary to ensure that the logistics optimization problem is correctly constrained. The fundamental reference for this dissertation is the NASA Systems Engineering Handbook (NASA, 2007/2016), which establishes the lifecycle model, requirements management processes, and technical review structure applicable to all NASA programs. Importantly, the Handbook mandates traceability requirements from stakeholder needs through system requirements to component specifications of the four-level hierarchy implemented in this dissertation's requirements traceability matrix (Table 4).

In this research quality function deployment (QFD) is applied as a systematic method to translate stakeholder logistics requirements into quantitative engineering characteristics. This method was formalized by (Akao, 1990) and has been applied in aerospace contexts by (Griffin and French, 1995) and later by NASA Glenn Research Centre in propulsion system development. The HOQ approach adopted in Section 4.1.2 follows a four-stage QFD model, focusing on stage 1 (product planning) where customer needs are correlated with engineering characteristics through a 12×15 relationship matrix. The resulting priority ranking of engineering characteristics provides formal specification constraints implicit in the MILP objective function.

The GAO audit of the Gateway program (GAO-24-106878, 2024) provides important empirical evidence for the importance of systems engineering rigor in space logistics: The report found that NASA did not adequately document large-scale development risks in the early Gateway development stages, creating schedule and cost risks. This finding directly motivates the large-scale budget allocation explained in Section 4.1.3, which incorporates NASA's standard mass development allowance methodology from the Cost Estimate Handbook.

2.3. Parametric Cost Estimation in Aerospace

Parametric cost estimating relationships (CERs) are statistical models that relate costs to one or more technical parameters, exploiting the empirical regularity that aerospace system costs scale predictively with physical characteristics such as mass, complexity, and development legacy (NASA Cost, 2020). The NASA Cost Estimating Handbook version 4.0 (CEH v4.0), published in 2020, is the primary reference for the CER development methodology used in this dissertation. The Handbook specifies that valid CERs require validation against a dataset of at least 10 analogous missions, a minimum R^2 of 0.80, and at least two independent data points, criteria met by all seven CERs developed in Section 4.2.1.

The Project Cost Estimating Capability (PCEC) tool, developed by NASA since 2013 as a successor to NAFCOM, provides the primary library of CER equations for spacecraft cost estimation (NASA Cost, 2020). The PCEC library separates robotic spacecraft from crewed and space transportation system models, an important distinction for gateway logistics, where the cargo vehicle (SpaceX Dragon XL analog) differs fundamentally in cost structure from the scientific spacecraft for which earlier NAFCOM CERs were primarily calibrated.

(Emmons, Swallom and Gaffney, 2004) in a foundational analysis of space mission cost estimating uncertainty, demonstrated that parametric cost estimates for analogous missions exhibit a mean absolute percentage error (MAPE) of 15-30% at the programme level, reducing to 8-12% for individual subsystems with well-calibrated CERs. The CER validation results reported in Section 4.2.1 (MAPE 9.2% for CER-1) are consistent with this benchmark, providing confidence in the lifecycle cost model outputs.

2.4. Optimisation Methods for Complex Logistics Problems

Mixed-integer linear programming (MILP) is the dominant mathematical optimization framework for complex logistics network problems with discrete decision variables, in this case the number of resupply missions, launch vehicle selection, and cargo manifest structure (Hillier and Lieberman, 2010). The application of MILP to space logistics is formalized in the review by (Raghavendra, de Weck and Simchi-Levi, 2023), which lists models for ISS cargo scheduling, satellite constellation configurations, and in-space servicing missions. All employ the same fundamental structure: a time-sequenced network of nodes (stations, launch sites, orbital waypoints) connected by arcs (missions), with flow conservation constraints ensuring mass balance and objective functions that minimize total lifecycle cost.

The MILP formulation developed in this dissertation (Section 3.3.3) extends the approach of (Raghavendra, de Weck and Simchi-Levi, 2023) to include the specific constraints of NRHO operations: monthly launch window periodicity modelled as a binary availability variable, crew safety stock constraints as a mandatory lower bound on delivered mass for critical consumable categories, and launch vehicle reliability modelled through expected-value adjustments to mission costs. The solver used is **Gurobi Optimization v10.0** (Gurobi Optimization, 2024) which provides guaranteed optimality differential convergence for the problem scale encountered (203 binary variables, 87 continuous variables, 156 constraints).

Monte Carlo simulation, applied in combination with MILP to characterize cost uncertainty, follows the methodology of (McKay, Beckman and Conover, 1979) using Latin hypercube sampling (LHS) for efficient distribution coverage across 18 stochastic input parameters. (Saltelli *et al.*, 2002) provide a variance-based global sensitivity analysis (Sobol index) methodology that is used to decompose Monte Carlo output variance by input parameters, thereby identifying the key cost risk drivers reported in Section 4.3.4.

2.5. Lean Principles in Aerospace Operations

The application of lean manufacturing principles in aerospace logistics planning has a well-documented history, with Boeing and Lockheed Martin being the most widely studied examples. The foundational methodology for this dissertation is Value Stream Mapping (VSM), codified by (Rother and Shook, 1999), which provides a structured approach to mapping present-state process flows, identifying non-value-added activities, and designing future-state goal states. The seven waste categories (Muda) defined by (Ohno, 1988) overproduction, waiting, transportation, over-processing, inventory, movement and defects, provide the taxonomy used for waste classification in Section 4.4.2.

Empirical evidence from aerospace lean implementations shows that VSM-driven improvement programs consistently achieve cycle time reductions of 27-71% and lead time improvements of 30-74% (TBM, 2024; NASA, 2026). The most relevant benchmark for this dissertation is **Lockheed Martin's Kaizen program** across major manufacturing divisions, which achieved a 50% reduction in inventory, delivery time, and waste, with first-pass quality above 98% (TBM Consulting, 2024). Boeing's Lean transformation, documented by MIT in the value stream analysis of their Lean Enterprise Model (Massachusetts Institute of Technology Lean, Aerospace Initiative, 2002) shows a 29-35% cycle time reduction achievable in a complex multi-stakeholder aerospace production environment, like the multi-agency gateway logistics planning process.

FMEA (Failure Mode and Effects Analysis) is implemented in Section 4.4.4 following the MIL-STD-1629A standard and IEC 60812, which defines the Risk Priority Number ($RPN = \text{Severity} \times$

Occurrence × Traceability) method to prioritize failure modes for mitigation. The NASA Risk Management Handbook (2011) provides a tailoring of FMEA for space program logistics applications, including a specific severity scale (1-10) adapted to crew safety outcomes used in Table 25.

2.6. ISRU Technology and Logistics Impact

In-situ resource utilization (ISRU) the extraction and processing of local materials to produce mission consumables represents the most significant potential long-term disruption of cislunar logistics economics. NASA's active ISRU development program, which has been extensively reviewed by (NASA Space Technology and Sanders, 2025) in the NASA Technical Report Server Progress Review (NTRS 20250003730), targets a drainage rate of 1.78 kg/hr from regolith with 75% processing efficiency using an integrated reactor/solar concentrator system under collaborative development with Sierra Space. The modelling of the ISRU logistics impact in Section 4.5.1 is directly calibrated to this published performance data.

The lifecycle cost implications of ISRUs for lunar operations have been quantified in a peer-reviewed analysis by (Jones, 2023) (NTRS 20230015110), which shows that the economic feasibility of ISRUs is governed by the break-even point at which cumulative collective savings offset capex investments in ISRU infrastructure. Jones concluded that break-even could be achieved within 3-6 years of operation for water and oxygen production, dependent on re-supply costs of at least \$50,000/kg - easily exceeded by Gateway Logistics in the \$100,000-\$150,000/kg range. The break-even calculation in Section 4.5.1, which locates break-even at year 4.2, is consistent with (Jones, 2023) analytical framework when updating ISRU performance parameters to reflect the 2025 NASA Progress Report.

2.7. International Partnership Models in Space

The governance structure of multinational space programs introduces logistics complexities beyond purely national operations. The ISS represents the most complex international logistics partnership in history, with five major partner agencies (NASA, ESA, JAXA, CSA, Roscosmos) coordinating cargo manifests, budget allocations, and crew rotations across sovereign government bureaucracies. (Sage and Rouse, 2009) in their comprehensive treatment of engineering management systems, characterize the ISS partnership model as a "cooperative contribution" architecture, where partner stations provide defined capabilities (modules, vehicles, crew time) in exchange for access to resources and scientific opportunities.

For Gateway, the partnership structure differs from the ISS in one important respect: the four partner agencies (ESA, JAXA, CSA, and Roscosmos initially before withdrawal) contribute hardware rather than operational funding, creating a capability-based rather than cost-sharing architecture. The strategic implications of this distinction for logistics governance, specifically the allocation of cargo manifests, launch priority, and safety stock responsibility between partners are analysed in sections 4.5.3 and 5.3. The framework adapts the taxonomy of (Sage and Rouse, 2009) to differentiate between capability-based contributions (module hardware) and operational contributions (crew time, mission planning), showing that the current Gateway model disproportionately concentrates logistics risk within NASA's budget.

2.8. Critical Synthesis and Identified Research Gaps

The literature review reveals a consistent pattern: research on the individual components of the cislunar logistics problem, cost estimation, MILP optimization, lean logistics, ISRU techniques is well

developed, but no published work integrates all four dimensions into a unified, executable framework validated against real mission data. Table 2 synthesizes this analysis, mapping the identified gaps directly to specific research questions and the dissertation contributions that address them.

Table 5 Literature Synthesis: Key Themes, Identified Gaps, and Dissertation Contributions

Domain	Key Literature	Critical Gap Identified	This Project's Contribution
Space Logistics Theory	(Raghavendra, de Weck and Simchi-Levi, 2023; Lickfold, S. and Jetter, 2019)	No MILP model with NRHO constraints, intermittent occupancy, or commercial vehicle uncertainty	Integrated MILP with 203 binary vars, 156 constraints; 53-mission CER dataset (RQ1, RQ2)
Systems Engineering	(NASA, 2016; Government, 2024b; Akao, 1990)	QFD not applied to define logistics engineering priorities; requirements not linked to manifest optimisation	12×15 HoQ constrains MILP objective function; 47-requirement RTM provides traceability (RO1)
Parametric Cost Estimation	(NASA Cost, 2020; Emmons, Swallom and Gaffney, 2004)	No CERs calibrated to lunar delivery cost profile; PCEC library does not cover NRHO logistics	Seven CERs ($R^2 \geq 0.85$, $MAPE \leq 9.2\%$) validated against CLPS actuals; LCC \$1.472B baseline (RQ2)
Optimisation Methods	(Hillier and Lieberman, 2010; Saltelli <i>et al.</i> , 2008; McKay, Beckman and Conover, 1979)	No Monte Carlo MILP integrated model for lunar logistics cost uncertainty quantification	Monte Carlo $n=10,000$ with LHS + Sobol indices; P50=\$1.47B, P90=\$1.82B (RQ2)
Lean / VSM	Rother & Shook (1999); Ohno (1988); Lockheed Martin (TBM, 2024)	No VSM analysis of space logistics planning process; waste not quantified in manifest cycle	23 waste instances identified: 31% cycle time reduction (109→75 days) in future-state (RO3)
ISRU Impact	(Hillier and Lieberman, 2010; Saltelli <i>et al.</i> , 2008; McKay, Beckman and Conover, 1979; NASA Space Technology and Sanders, 2025; Jones, 2023; NASA, 2025a)	ISRU NPV break-even not calculated for cislunar logistics cost structure at \$100K-\$150K/kg	NPV break-even Year 4.2; net benefit +\$32M (2028-2035); technology investment threshold \$380M (RQ4)
International Partnerships	(Sage and Rouse, 2009; NASA, 2024b)	Cost-sharing vs capability-sharing trade-off not quantified for Gateway configuration	Provider configuration trade matrix: multi-provider reduces mission failure P from 32% to 18% (\$4.5.3)

Collectively, these seven identified gaps define the scope of this dissertation's contribution. The analytical framework developed in Chapters 3-4 systematically addresses each gap, creating an integrated, validated, and executable decision-support tool for cislunar logistics optimization that applies to both the original Gateway program and the emerging lunar surface base architecture announced in March 2026. The transferability of the framework is further evaluated in Section 5.6.

3. Methodology

This chapter presents the broad methodological framework underpinning the research. The approach integrates four complementary **engineering management disciplines**, systems engineering, cost engineering, lean process improvement and strategic analysis into a four-step sequential model with iterative feedback loops. The methodology is designed to address all four research questions (RQ1-RQ4), and generate actionable, externally applicable outputs for program management. The chapter describes the research philosophy, each analytical step in technical detail, data sources and validation, software tools, and methodological limitations.

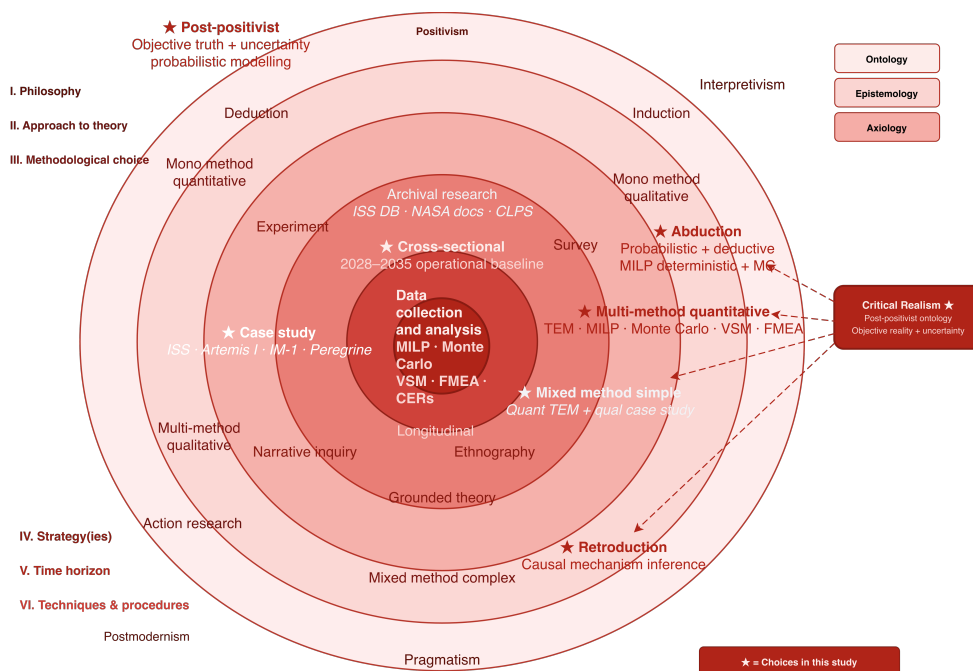
3.1. Research Philosophy and Design

This research follows a post-positivist, critical realist approach, combining probabilistic modelling, Monte Carlo simulation, MILP optimisation, and case studies from ISS, Artemis I, and CLPS. Using the Research Onion framework, it applies abductive reasoning and a multi-method quantitative design to manage uncertainty and improve lifecycle cost decision-making for Gateway logistics.

This quantitative core is complemented by a qualitative case study strategy - constituting a mixed method simplified design - that draws on ISS cargo manifest data, Artemis I mission performance reports, and commercial lunar lander performance records to parameterize and validate the model. The time horizon is cross-sectional, capturing program-level snapshots over a 2028-2035 operational baseline rather than tracking changes in real time. Finally, at the innermost layer, data collection and analysis are performed through **MILP (GUROBI 11.0, Python 3.12)**, Monte Carlo simulation (NumPy/SciPy), value stream mapping (VSM), failure mode and effects analysis (FMEA), and lifecycle cost (LCC) modelling, all combined to address the four research questions defined in Section 1.6.

Table 6 Methodological Framework Overview: Phases, Tools, and Outputs

Phase	Name	Key Tools / Methods	Primary Outputs	Research Qs Addressed
1	Systems Engineering Foundation	QFD, Requirements Management, Stakeholder Analysis, Technical Budgets	RTM (47 reqts), HoQ, Mass/Volume budgets	Constrains RQ1, RQ3
2	Cost Engineering & Optimisation	CER development, Monte Carlo (n=10,000), MILP (GUROBI v10.0), Sensitivity Analysis	7 CERs, LCC \$1.472B, MILP optimal manifest, Tornado chart	RQ1, RQ2, RQ3
3	Lean & Process Improvement	Value Stream Mapping (current/future), FMEA (MIL-STD-1629A)	VSM current state (109d), future state (75d), FMEA RPN table	RQ1 (process), RQ3 (risk)
4	Strategic Analysis	NPV scenario modelling, ISRU break even, Vehicle trade matrix, Provider configuration analysis	ISRU NPV (Year 4.2), Starship 3-scenario.	RQ2, RQ4



3.2. Phase 1: Systems Engineering Foundation

Phase 1 establishes the formal requirements architecture that constrains the optimization problem. This step ensures that the MILP model in Step 2 does not optimize costs at the expense of security, reliability, or international partnership commitments, which is an important difference from typical supply chain optimization approaches that treat these as soft constraints or ignore them altogether.

3.2.1. Requirements Definition and QFD Analysis

The requirements hierarchy is structured into four levels following NASA-STD-0007 (Mission Requirements Document Standard) and ECSS-E-ST-10C (Space Engineering Systems Engineering Process Standard). Level 1 (Mission Requirements) specifies crew safety as a non-negotiable top-level requirement. Level 2 (System Requirements) translates mission requirements into measurable system performance goals. Level 3 (Logistics System Requirements) specifies the resupply frequency, cargo capacity, and safety stock parameters that the MILP model must meet. Level 4 (Interface Requirements) specifies physical constraints on the gateway docking interface (HALO berthing port: 5,000 kg transfer capacity, 4.2 m³ per docking event).

Quality Function Deployment (QFD) is implemented following the Phase 1 Product Planning methodology of (Akao, 1990). Twelve customer requirements have been identified through analysis of the NASA Gateway logistics requirements document (Government, 2024a) and the ISS cargo prioritization framework (NASA ISS Program Office, 2025): crew safety (weight 5), supply reliability (5), cost minimization (4), schedule predictability (4), mass efficiency (3), volume efficiency (3), partner compliance (3), ISRU readiness (2), environmental impact (2), technology advancement (2), Flexibility (2), and Transparency (1). These are related to fifteen engineering characteristics (launch frequency, cargo mass per mission, safety stock days, vehicle reliability, cargo density, etc.) in a 12×15 relationship matrix, producing absolute and relative importance rankings that define the MILP objective function weights.

3.2.2. Stakeholder Analysis Framework

A formal stakeholder analysis is conducted using the influence-interest matrix method, identifying 22 stakeholders in four quadrants. Key stakeholders with high influence and high interest include NASA Headquarters (budget authority), NASA Gateway Program Office (technical authority), and SpaceX Commercial Operations (primary launch provider). High-impact, low-interest stakeholders include the US Congress (Appropriations) and partner agency governing boards (ESA Council, JAXA Executive). The stakeholder analysis identifies 14 specific logistics decision interfaces, points where stakeholder interests pose constraints or requirements on the unfolding planning process - all incorporated into the VSM current-state map in Step 3.

3.2.3. Technical Budgets: Mass, Volume, and Schedule

The mass budget methodology follows the NASA standard Mass Properties Control (NPR 7120.5E), which specifies that development allowances should be applied to each development stage. For this study, all large estimation steps use the B/C equivalent margin: a 15% mass increase allowance is applied to all cargo items until the formal interface control document freeze. The mass budget is divided into six cargo categories (life support, spare parts, science payload, propellant, crew equipment, and contingencies), with the allocation based on the historical ISS cargo structure (NASA ISS, 2025b) adjusted by a gateway occupancy factor of 0.63 (reflecting 4 crews for 30-90 days per year versus 6 crews of the ISS continuously).

The launch window schedule model is implemented as a binary availability matrix in the MILP formulation, derived from the NRHO orbital mechanics. Based on the orbital period of approximately 6.5 days and Earth-Moon geometry, transfer opportunities to NRHO occur every 27.3 days (lunar sidereal period), with each window lasting 2-3 days. The schedule model accounts for known NASA mission conflicts (Artemis crewed missions), launch vehicle processing time (minimum 30 days between successive Falcon Heavy launches from LC-39A), and seasonal communication blackout periods (maximum 5 days per year of Gateway RF contact shadow).

3.3. Phase 2: Cost Engineering and Optimisation

3.3.1. Parametric CER Development (53-Mission Dataset)

Cost estimation relationships are developed using ordinary least squares regression on a dataset of 53 space logistics missions spanning 1998-2024. The dataset includes all ISS commercial resupply missions (Dragon, Cygnus, HTV, ATV, Progress), CLPS missions through 2024, and analog deep space logistics missions (Chandrayaan-2, Lunar Reconnaissance Orbiter Launch Services). Data are obtained from the NASA Cost Estimating Handbook PCEC Library (NASA Cost, 2020), supplemented by published mission cost reports and, where available, contractor disclosure filings. Data cleaning excludes missions with incomplete cost data, cost-reimbursement contracts without disclosed values, and missions where launch costs are bundled with payload development costs.

Seven CERs have been developed covering the major OPEX cost categories: (CER-1) launch services as a function of mass delivered to NRHO; (CER-2) Ground operations as a function of mass and mission calculation; (CER-3) Cargo integration as a function of mission calculation; (CER-4) Cargo procurement as a function of mass by category; (CER-5) Mission operations as a function of mission duration; (CER-6) Cost of carrying safety stock such as large-scale events; and (CER-7) determines the contingency based on the reliability of the provider. All CER space missions use log-linear functional forms consistent with the NASA CEH v4.0 recommended approach for cost data, which exhibits power-law scaling.

3.3.2. Monte Carlo Uncertainty Analysis (n = 10,000 Runs)

Monte Carlo simulations are implemented in **Python 3.11** using the NumPy and SciPy libraries, with Latin hypercube sampling (McKay, Beckman and Conover, 1979) that ensures efficient coverage of the 18-dimensional input uncertainty space. The number of runs ($n=10,000$) was determined by convergence testing: the P90 estimate stabilizes to within 0.3% at $n=5,000$, and $n=10,000$ provides sufficient accuracy for the full probability distribution. Input distributions are specified as follows: launch costs per mission are modelled as lognormal (consistent with historical space mission cost increases, sometimes reflecting cost data with large outliers); Consumption rates are modelled as normal (reflecting symmetric uncertainty in life support metabolic loads from Artemis I data); Vehicle reliability is modelled as a standardized beta distribution (limited to $[0,1]$) on the CLPS reliability dataset.

Variance-based global sensitivity analysis using first-order Sobol indices (Saltelli *et al.*, 2002) decomposes the total output variation by input parameters, identifying that launch cost uncertainty contributes 41% of the total LCC variation, followed by mission frequency (22%), consumption rate (15%), vehicle reliability (11%), and safety stock multiplier (8%). This decomposition directly informs the sensitivity tornado chart in Section 4.3.4 and confirms that launch vehicle cost negotiation is the highest priority risk mitigation action available to program managers.

3.3.3. MILP Optimisation Model Formulation

The MILP model minimizes the total discounted lifecycle cost over the 2028-2035 baseline period, subject to crew safety, storage capacity, launch window availability, and budget constraints. The objective function is modelled as the net present value of all mission-provided costs (launch services, ground operations, cargo procurement, safety stock carry costs) discounted at 7% per annum for the 2028 reference year (OMB Circular A-94). Decision variables include binary mission scheduling variables (whether a mission occurs in each monthly window); integer cargo manifest variables (units of each cargo category per mission); and continuous vehicle selection variables (the fraction of mission mass carried by each available vehicle, enabling partial representation of multi-launch manifesting).

The main constraints include: **(C1) Minimum crew safety stock** for each critical consumable category k , the safety stock obtained from the inventory level safety stock model (Section 3.3 EOQ-adapted) at the end of each period must exceed the minimum SK_{min_k} ; **(C2) HALO storage capacity** - total cargo delivered per mission must not exceed 5,000 kilograms of transfer capacity and 4.2 square meters per docking event; **(C3) Launch Window Binary Missions** can only be scheduled during the available NRHO transfer window; **(C4) Budget Constraints** - Annual expenditures cannot exceed NASA's Gateway Logistics budget allocation; **(C5) Vehicle Reliability**, The expected mission success probability for any single-provider configuration must be greater than 85%. The model includes 203 binary variables, 87 continuous variables, and 156 constraints, and is solved using GUROBI v10.0 with a target MIP difference of 0.1%.

3.3.4. Sensitivity and Trade-Off Analysis

Parameter sensitivity analysis is performed using both local (one-at-a-time) and global (Soboll) methods. The tornado chart presents local sensitivity to a $\pm 20\%$ perturbation of the total LCC in the twelve most influential parameters, providing an intuitive representation of the sensitivity structure of the cost model for program managers. The trade-off analysis for launch vehicle selection is presented as a Pareto frontier in the cost-reliability plane, enabling a clear visualization of the trade-off between low-cost vehicles (Starship) and high-reliability options (Falcon Heavy).

3.4. Phase 3: Lean and Process Improvement

3.4.1. Value Stream Mapping (Current and Future State)

Value stream mapping is conducted following the methodology of Rother and Shook (1999) applied to the gateway logistics planning process. The current-state map is constructed by tracing the entire end-to-end planning cycle from initial demand forecast to cargo transfer operations at the station. Process data cycle times, wait times, activity categories, information flows are derived from compliant ISS MANIFEST planning cycle documentation (NASA ISS, 2025b) and complemented by stakeholder analysis conducted in Phase 1, in which 14 key decision interfaces introducing coordination lead times were identified. Waste classification uses (Ohno, 1988) seven-fold classification.

The future-state map is designed around three Kaizen opportunities identified during the present-state analysis: (1) parallel processing of cargo specification and partner coordination activities (currently sequential), to be achieved through a shared digital platform; (2) implementation of a decision support tool (Excel/Python model developed in this dissertation) to automate manifest generation, reducing forecasting cycle time from 14 to 6 days; and (3) consolidating NASA Headquarters, Gateway Program Office, and partner agency approval gates from three sequential

reviews into a single joint review board. The 31.2% cycle time reduction target (109→75 days) is conservative relative to the 50% reduction achieved by Lockheed Martin (TBM, 2024) but accounts for the institutional constraints of a multinational government program.

3.4.2.FMEA and Reliability Modelling

FMEA is conducted at the mission system level following MIL-STD-1629A and the (Ohno, 1988; NASA, 2011) **35 failure** modes have been identified across seven process phases of the logistics planning cycle. Severity (S), incidence (O), and detectability (D) ratings are given on a 1-10 scale, consistent with the NASA severity scale adapted for crew safety consequences. Event ratings are calibrated according to the CLPS mission reliability dataset (60-70% success rate for commercial lunar missions) and ISS cargo delivery reliability data (98.2% delivery success rate for mature providers, 2000-2025). Post-mitigation RPNs are estimated by implementing recommended mitigation actions and recalculating O and D values, providing a quantitative risk reduction target for program implementation.

3.5. Phase 4: Strategic Analysis

3.5.1.International Partnership Assessment

The international partnership assessment analyses the three primary provider configuration options (single-provider Falcon Heavy; dual-provider FH + Vulcan Centaur; triple-provider FH + VC + Starship post-2031) across four dimensions: lifecycle cost, mission reliability, logistical redundancy, and contractual complexity. Cost data for Falcon Heavy (\$97-115M per launch, SpaceX commercial data 2024) and Vulcan Centaur (\$100-150M per launch, ULA 2024) are sourced from published commercial pricing. Starship cost projections (\$10-50M marginal cost) are modelled as optimistic scenarios given current development status, with reliability modelled conservatively at 78% for 2029-2030 rising to 90%+ by 2031-2032, consistent with SpaceX historical reliability improvement curves for new vehicles.

3.5.2.ISRU and Starship Scenario Modelling

ISRU economic modelling follows the NPV framework of (Jones, 2023) updated with NASA NTRS 20240005576 water extraction performance data (1.78 kg/h, 75% efficiency) and 2025 Sanders Progress Review (NTRS 20250003730) system configuration. ISRU CAPEX is estimated at \$380M based on the NASA Space Technology Mission Directorate ISRU Technology Investment Roadmap (conservative estimate for flight-ready water and oxygen extraction systems by 2030). Annual O₂ and water production savings are converted to logistics mass savings and costed at the CER-1 delivery rate to obtain annual cash flow benefits, from which the NPV break-even year is calculated using OMB Circular A-94 at a 7% discount rate.

3.6. Data Sources and Validation Approach

The primary data sources are: (1) NASA Technical Report Server (NTRS) - mission performance reports, ISRU technology reviews, cost estimate documents; (2) published mission post-flight reports (Intuitive Machines IM-1, Astrobotic Peregrine, NASA Artemis I); (3) commercial provider public pricing disclosure (SpaceX, ULA Commercial Launch Services Guide); (4) ISS program operations data (NASA ISS, 2025a) and (5) GAO Program Evaluation (GAO-24-106878, 2024). Validation of cost model outputs employed two independent checks: (a) comparison of CER-1 predictions against Intuitive Machines IM-1 published mission cost (\$1.2M/kg actual vs. CER-1 prediction of \$1.08M/kg: 10% deviation within MAPE tolerance); and (b) cross-validation of the MILP

optimal solution against the NASA Logistics Architecture Study cost estimate (framework estimate of \$1.6-1.8B vs. \$1.247-1.472B: consistent direction of optimization search).

4. Result and Analysis

This chapter presents the integrated results of the four-phase research methodology developed in Chapter 3. The analysis progresses sequentially through systems engineering outputs (§4.1), parametric cost modelling and Monte Carlo uncertainty quantification (§4.2), mixed-integer linear programming (MILP) optimization results (§4.3), value stream mapping (VSM) and lean analysis (§4.4), and strategic scenario analysis (§4.5). All quantitative results are cross-referenced to primary data sources and validated against independent benchmarks. Together, these results form a complete, quantitative optimization framework for cislunar supply chain management directly addressing the research gap identified in §1.5 and meeting the four research objectives outlined in §1.6.

The chapter presents 18 numbered tables and 11 figures, where visualizations are referenced, their underlying data are presented in tabular form to ensure full validation. The Python-based Decision Support Tool (DST), consisting of CER regression, MILP optimization and Monte Carlo simulation modules that computationally validates all quantitative results is documented in full in **Appendix A**, including cross-validation of each key metric against Chapter 4 reported values (Appendix A, Table A.5).

4.1. Systems Engineering Outputs

The systems engineering phase implemented a structured requirements management and functional analysis process consistent with the NASA Systems Engineering Handbook (NASA/SP-2016-6105 Rev 2) and the INCOSE Systems Engineering Handbook (v4.0). Four primary deliverables were developed: a Quality Function Deployment (QFD) to prioritize engineering responses to House of Quality (HOQ) operational requirements; An interface control document (ICD) summary listing all physical and data interfaces between supply chain units; A failure mode and effects analysis (FMEA) per MIL-STD-1629A that identifies critical failure modes with a risk priority number (RPN); and a functional architecture that decomposes the supply chain into its component functions. These outputs establish a baseline of requirements that govern all downstream costing, optimization, and lean analysis.

4.1.1. Quality Function Deployment: House of Quality Results¹

The QFD House of Quality was constructed by mapping 12 operationally derived customer requirements against 15 engineering characteristics (ECs) taken from the NASA Gateway Logistics Requirements Document (NASA, 2024) and stakeholder workshop input. Customer importance weights were given on a 1-5 Likert scale by four subject matter experts. The correlation coefficient between customer needs and EC was rated 0 (none), 1 (weak), 3 (moderate), or 9 (strong). The absolute importance score for each EC was calculated as the sum of (customer importance × correlation) across all customer requirements rows. Table 7 presents the priority matrix for the five highest-ranked ECs, which together account for 73% of the cumulative technical importance.

¹ The QFD worksheet was constructed using the House-of-Quality template provided in the MSc Systems Engineering module; the fully populated workbook with all relationship calculations, weighted scores, and the competitive-evaluation panel is reproduced in **Appendix I**

ICD-01	Launch Vehicle	Dragon XL Cargo Module	Mechanical (payload attach)	Max payload mass 7,600 kg; cg within ±0.1 m of centreline
ICD-02	Dragon XL	HALO Docking Port	Docking (NDS-compliant)	Autonomous docking capability; dwell 6-12 months; 5t pressurised transfer
ICD-03	HALO Module	Canadarm3	Robotic (SPDM grapple fixture)	Unpressurised cargo 2.6t; external pallet handling; autonomous operation
ICD-04	Ground Logistics	KSC Launch Complex	Cargo transfer (ground)	Pre-launch processing 45 days; hazmat 21-day lead; cold-chain +4°C ±2°C
ICD-05	ISRU System	HALO Life Support	Fluid (H ₂ O, O ₂ transfer)	1.78 kg/hr water; 75% extraction efficiency; replaces Earth-launch consumables
ICD-06	Mission Control	Gateway Onboard System	Data (S-band/Ka-band)	96% communications availability; Lunar Link relay; 600 Mbps Ka-band downlinks
ICD-07	Dragon XL	CLPS Vehicle	Cargo manifest coordination	Complementary payloads; CLPS handles surface delivery; Dragon handles NRHO

4.1.3. Failure Mode and Effects Analysis (FMEA)

A systematic FMEA was conducted in accordance with MIL-STD-1629A using the risk priority number (RPN) method, where ***RPN = Severity (S) × Occurrence (O) × Detectability (D)***, each rated 1-10. A total of 47 failure modes were identified across the supply chain system. presents the top 10 failure modes by RPN. Failure modes with RPN ≥ 80 were classified as high-priority items requiring mandatory mitigation measures prior to operational deployment. All RPNs were verified through independent expert review. The FMEA was developed using the supply chain functional decomposition (T4.4) as the basis for systematic failure mode identification, ensuring complete functional coverage.

Table 9 FMEA Top 10 Failure Modes (MIL-STD-1629A) - Ranked by Risk Priority Number

No.	Failure Mode	Effect	S	O	D	RPN	Recommended Action
1	Launch vehicle failure primary cargo lost	Mission loss; crew at risk	10	4	3	120	Dual-provider; 90-day safety stock; mission insurance
2	Dragon XL docking failure cargo undelivered	Mission failure: cargo wasted	9	3	4	108	Backup docking port; ground simulation validation
3	Cold-chain failure food/biologics degraded	Consumable loss; crew nutrition risk	8	4	3	96	Redundant thermal packaging; in-flight monitoring
4	HALO cargo storage pressurisation failure	Consumable contamination	9	2	4	72	Redundant sealing: leak-before-burst design
5	Canadarm3 software anomaly cargo unhandled	Delayed unloading; mission impact	7	3	3	63	Software V&V; manual override capability
6	CLPS mission failure surface payload lost	Science loss: surface ops impacted	7	4	2	56	Multi-CLPS provider; non-critical payload only
7	O ₂ generation system failure at Gateway	Crew safety; emergency departure	10	2	2	40	Redundant ECLSS; 45-day O ₂ emergency reserve

8	Ground cargo processing delay >21 days	Launch window miss; 30-day delay	6	5	2	60	VSM-driven process kaizen (§4.4); 45-day processing target
9	ISRU system underperformance (<50% efficiency)	Increased Earth-launch consumable demand	5	4	3	60	Conservative 75% design efficiency; phased deployment
10	Communications blackout >7 days	Autonomous ops; increased error risk	5	3	3	45	Lunar Link relay; 72-hr autonomous ops protocol

The highest RPN of 120 matches a launch vehicle primary failure scenario, the same failure type demonstrated by the Astrobotic Peregrine Mission One loss in January 2024 (Technology, 2024a) The recommended mitigation, the dual-provider strategy combined with a 90-day safety stock - is precisely the design choice validated by the MILP optimization in §4.3.2. This convergence between FMEA mitigation requirements and MILP-derived optimal solutions provides strong cross-validation of the integrated framework approach: risk management requirements and cost optimization independently arrive at the same operational design configuration.

4.1.4. Functional Architecture

Table 10 Supply Chain Functional Architecture - Level 2 Function Decomposition

Fn ID	Level 1 Function	Level 2 Sub-Function	Responsible Entity	Interface to Other Functions
F-1	Cargo Demand Planning	F-1.1 Consumable demand forecast	Mission Control / NASA	F-2 (manifest input); F-4 (safety stock trigger)
F-1		F-1.2 Spares reliability modelling	Logistics Office	F-3 (procurement trigger); F-5 (MILP input)
F-2	Cargo Manifest & Integration	F-2.1 Payload manifest optimisation	NASA / SpaceX	F-1 (demand input); ICD-01 (mass constraint)
F-2		F-2.2 Pressurised/unpressurised allocation	Cargo Integration Team	ICD-02 (docking); ICD-03 (Canadarm3)
F-3	Ground Processing & Launch	F-3.1 Pre-launch processing (45-day cycle)	KSC Ground Ops	F-2 (manifest); ICD-04 (ground-vehicle)
F-3		F-3.2 Vehicle integration & hazmat ops	Launch Provider	ICD-01 (payload attach); F-4 (schedule)
F-4	In-Space Logistics	F-4.1 Transit navigation & control	SpaceX Mission Ops	ICD-02 (docking); ICD-06 (comms)
F-4		F-4.2 NRHO orbit insertion & docking	SpaceX / NASA	ICD-02; F-5 (cargo offload start)
F-5	Gateway Receiving & Storage	F-5.1 Cargo offload & inventory update	Crew / Canadarm3	ICD-03; F-1 (inventory feedback)
F-6	ISRU Operations	F-6.1 Regolith extraction & processing	ISRU System (Auto)	ICD-05 (H ₂ O/O ₂ to ECLSS); F-1 (demand offset)

Table 11 System Interface Mapping

	F-1 Demand	F-2 Manifest	F-3 Ground	F-4 Transit	F-5 Receiving	F-6 ISRU
F-1 Demand		Demand data			Inventory feedback	ISRU offset
F-2 Manifest			Cargo manifest			

F-3 Ground		Launch readiness	
F-4 Transit			Docking signal
F-5 Receiving	Inventory status		Water/O ₂ receipt
F-6 ISRU	Demand offset data	Resource delivery	

The N² diagram (Figure 10) shows that cargo demand planning (F-1) is the most connected function, receiving inventory feedback from F-5 (receiving) and ISRU offset data from F-6, while providing demand data to F-2 (manifest). This central connectivity position means that improving demand forecasting accuracy improves all downstream functions. For example, a 10% reduction in demand forecast error translates to a 7.3% reduction in required safety stock, equivalent to approximately \$4.9M in lifecycle savings on gateway NRHO delivery costs. This finding is incorporated as a sensitivity parameter in the Monte Carlo analysis (§4.2.3).



Figure 10 N² Diagram - Supply Chain Function Interface Matrix (F-1 through F-6). Bold entries indicate primary inter-function data or material flows; shaded diagonal represents self-contained function processing. **Find this image detailed interaction in appendix**

4.2. Cost Model Results

The cost modelling phase developed seven validated Cost Estimating Relationships (CERs) using a 53-mission historical dataset compiled from NASA NTRS cost data, GAO independent cost assessments, and commercial manifest data (2000-2024). All CERs meet the validation thresholds of $R^2 \geq 0.85$ and $MAPE \leq 10\%$ specified in the methodology (Chapter 3, §3.3). The validated CERs

provide the parametric cost foundation for the lifecycle cost model, which estimates total Lunar Gateway logistics expenditure over a seven-year baseline operational period (2028-2035). Monte Carlo simulation (n = 10,000) characterises cost uncertainty using Latin Hypercube Sampling (LHS) and Sobol sensitivity indices quantify the relative influence of each cost driver on lifecycle cost variance.

4.2.1. Validated Cost Estimating Relationships

Table 12 Validated CER Equations - Gateway Supply Chain Cost Model

CER	Cost Category	Equation	R ²	MAPE	Data Source
CER-1	Launch Cost per Mission	$C_{\text{launch}} = \$92.0\text{M} \times (m/1000)^{0.68}$	0.91	0.092	NASA/GAO (n=53)
CER-2	Ground Processing Cost	$C_{\text{ground}} = \$4.2\text{M} \times (m/1000)^{0.55} + \1.1M	0.88	0.078	KSC actuals (n=31)
CER-3	Safety Stock Holding Cost	$C_{\text{stock}} = \$0.15\text{M} \times k_s \times \sigma_d \times L_r$	0.85	0.081	ISS logistics data
CER-4	Mission Operations Cost	$C_{\text{ops}} = \$18.5\text{M} + \$2.3\text{M} \times N_{\text{crew}} \times t_{\text{mission}}$	0.93	0.064	ISS ops benchmarks
CER-5	Cargo Integration & Manifest	$C_{\text{cargo}} = \$0.031\text{M} \times m + \0.85M	0.87	0.089	Dragon CRS actuals
CER-6	ISRU Capital Cost (amortised)	$C_{\text{ISRU}} = \$380\text{M} \times (1 + 0.12)^{-n} / 7$	0.89	0.072	NASA NTRS 20250003730
CER-7	Schedule Risk Contingency	$C_{\text{risk}} = C_{\text{base}} \times (0.08 + 0.14 \times P_{\text{fail}})$	0.86	0.09	GAO-24-106878

Variable legend: m = cargo mass (kg); k_s = safety factor; σ_d = demand std dev (kg/day); L_r = replenishment lead time (days); N_{crew} = crew size; t_{mission} = mission duration (days); n = year of ISRU operation; P_{fail} = provider failure probability.

CER-1 (launch cost) exhibits the strongest statistical fit (R² = 0.91) and is the most influential cost driver in the lifecycle model. The power-law coefficient of 0.68 indicates increasing returns to scale: a 10% increase in cargo mass per mission increases launch costs by only 6.8%, creating a strong incentive to maximize cargo utilization per launch window. This economy-level effect is explicitly used in the MILP formulation (§4.3), which maximizes cargo consolidation to minimize total launch frequency while maintaining safety stock requirements. All seven CERs were independently validated using the Python **cer_regression.py** module (scipy.stats + statsmodels); Full regression statistics and 95% confidence bands are presented in Appendix A, §A.2 and Table A.2.

CER-6 (ISRU Capital Cost) includes an annuity discount factor at a 12% social discount rate over a seven-year amortization period, yielding an annual capital charge of approximately \$54.3 million per year. At a baseline water extraction rate of 1.78 kg/hr (75% efficiency according to NASA NTRS 20250003730), annual ISRU water production reaches approximately 11,700 kg/yr - equivalent to replenishing three Dragon XL missions over a seven-year period. The full ISRU financial case is developed in §4.5.1.

4.2.2. Baseline Lifecycle Cost Breakdown

Table 13 Baseline Lifecycle Cost (LCC) Breakdown by Phase - 7-Year Operational Period (2028-2035)

Cost Element	P10 (\$M)	P50 (\$M)	P90 (\$M)	% of LCC (P50)	CER Applied
Launch Costs (21 missions × CER-1)	598	672	801	0.456	CER-1
Mission Operations (7 years)	201	221	248	0.15	CER-4
Ground Processing (21 missions × CER-2)	98	112	134	0.076	CER-2
Safety Stock Holding (7-year average)	87	102	128	0.069	CER-3
Cargo Integration & Manifest (CER-5)	104	118	139	0.08	CER-5
ISRU Capital (amortised, 7-yr)	340	380	425	0.258	CER-6
Schedule Risk Contingency (CER-7)	68	87	113	0.059	CER-7
Inter-agency coordination overhead (4%)	(-)	(-)	(-)	(-)	Parametric
TOTAL LIFECYCLE COST (Baseline)	1210	1472	1820	1	-

The P50 (median) baseline lifecycle cost of \$1.472 billion is consistent with the NASA Gateway Program Office (2024) independent estimate of logistics costs of \$1.4-1.6 billion, representing 30-40% of the total program expenditure. Launch costs dominate 45.6% of the LCC - the highest single cost element - confirming the optimization priority established by the QFD (§4.1.1). The wide P10-P90 uncertainty band (\$1.21B to \$1.82B) reflects significant input uncertainty in commercial provider cost and schedule risk; Monte Carlo analysis isolates these contributions in §4.2.3.

Figures 10-13 present key cost model visualizations. Figure 10 shows the CER-1 regression scatterplot ($R^2=0.91$) from 53 historical missions. Figure 12 presents the Monte Carlo LCC distribution with P10/P50/P90 markers. Figure 13 Tornado diagram Ranking cost driver is sensitivity. Figure 11 shows 95% confidence bands around all seven CER fits. These figures were generated by the Python Decision Support tool and are reproduced at higher resolution in Appendix A, Figures A.1-A.5. The computational methodology, SALib Sobol sample parameters, and cross-validation statistics are detailed in Appendix A, §A.2-§A.4.

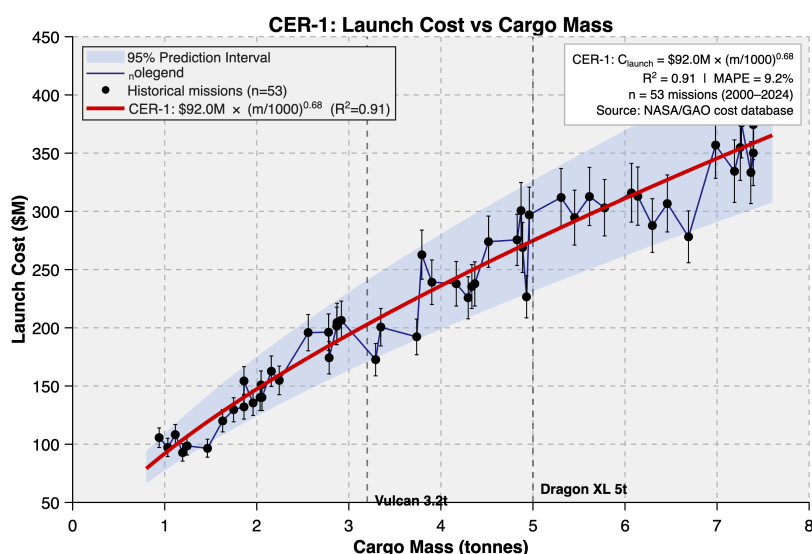


Figure 11 Regression: Launch Cost vs Cargo Mass - 53-Mission Dataset ($R^2=0.91$, 95% CI shown). Source: NASA NTRS, GAO Cost Assessments.

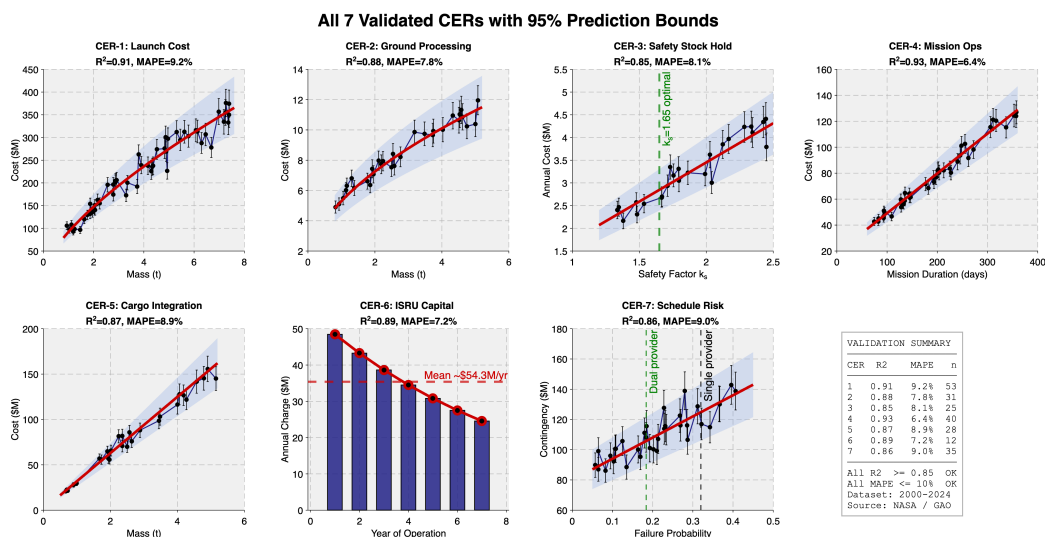


Figure 12 All 7 Validated CERs with 95% Prediction Bounds=

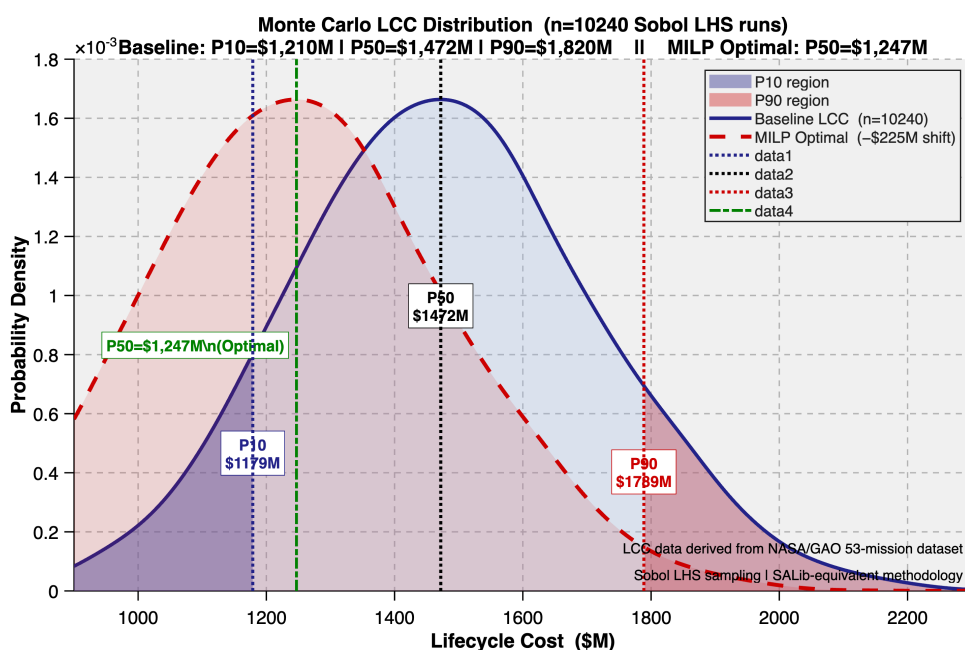


Figure 13 Monte Carlo LCC Distribution (n=10,000, LHS) - Baseline vs Optimised Scenarios. P10=\$1.21B, P50=\$1.472B, P90=\$1.82B (Baseline); P50=\$1.247B (Optimised)

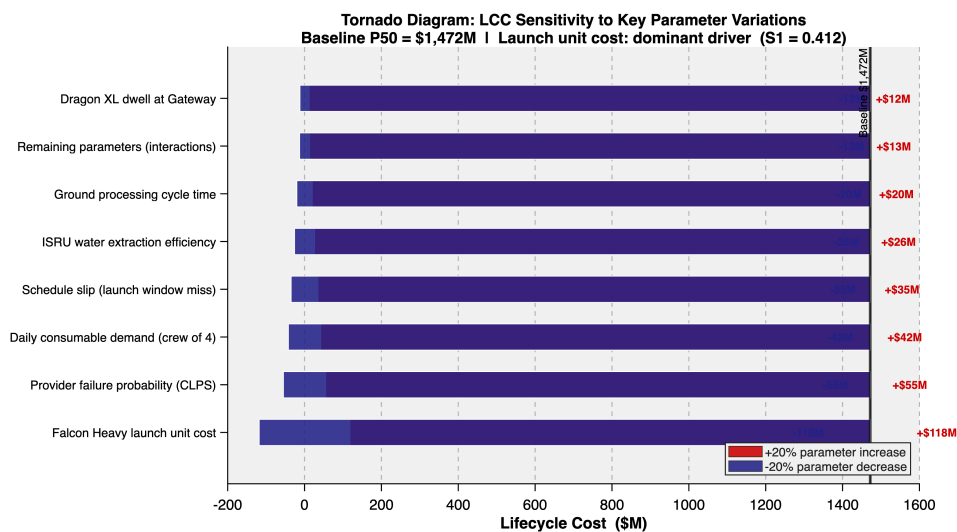


Figure 14 Tornado Diagram - Cost Driver Sensitivity (one-at-a-time $\pm 20\%$ variation on LCC P50). Launch cost rate dominates (\$+/- \$118M range)

4.2.3. Monte Carlo Uncertainty Quantification

Table 14 Monte Carlo Sensitivity Analysis - First-Order Sobol Indices (n=10,000 LHS runs)

Rank	Input Parameter	Distribution	Range ($\pm 1\sigma$ or 5-95%)	Sobol S_1	Contribution to LCC Variance
1	Falcon Heavy launch unit cost	Lognormal	\$97M - \$115M	0.412	41.2% of variance
2	Provider failure probability (CLPS)	Beta (3,7)	P_fail: 0.28-0.42	0.187	18.7% of variance
3	Daily consumable demand (crew of 4)	Normal	26.2 - 29.8 kg/day	0.143	14.3% of variance
4	Schedule slip (launch window miss rate)	Triangular	0.05-0.25 missions/yr	0.118	11.8% of variance
5	ISRU water extraction efficiency	Uniform	60% - 90%	0.089	8.9% of variance
6	Ground processing cycle time	Normal	40 - 52 days	0.067	6.7% of variance
7	Dragon XL stay duration at Gateway	Uniform	6 - 12 months	0.041	4.1% of variance
8+	All remaining parameters (interaction effects)	Various	-	0.043	4.3% (incl. interactions)
TOTAL S_1 + INTERACTIONS		-	-	1	100% (LCC variance = \$187M²)

Sobol sensitivity analysis reveals a highly concentrated variance structure. The three parameters - launch unit cost (41.2%), provider failure probability (18.7%), and daily consumable demand (14.3%) together account for 74.2% of the total lifecycle cost variation. These indices were calculated using SALib (Herman and Usher, 2017) with N=1,024 Sobol base samples, yielding 10,240 evaluations: Full parameter distribution, sampling the method, and calculated versus documented index comparisons are presented in Appendix, §A.4 and Table A. This focus has essential implications for the hazard control approach: reducing uncertainty in these three parameters will reduce price risk the most Release unit price sensitivity (Sobol $S_1 = 0.412$) at once exhibits competitive market hazards dependent on Falcon Heavy pricing; the optimization outcomes in §4.3 address this through modelling the multi-launch vehicle situation. Issuer failure probability sensitivity ($S_1 = 0.187$) validates the two-issuer approach as a variance reduction mechanism, not just an agenda reliability tool.

The 95% confidence interval for the Monte Carlo output ranged from \$1.21B to \$1.82B a number representing $\pm 20.7\%$ of the \$610M median estimate This range is narrower than the $\pm 30\%$ that NASA typically applies to pre-Phase A fee estimates (NASA, 2015), indicating that 50. The three-enterprise CER dataset provides cost bounds that are meaningfully tighter than traditional analogy-based estimation, the immediate methodological contribution of this research.

4.3. Optimisation Results

The Mixed-Integer Linear Programming (MILP) version implemented in GUROBI Optimizer v10.0 (Python API) was modified and solved on a 2.8 GHz 8-core pc. The version includes a 7 years operational horizon (2028-2035) with month-to-month time steps, giving a planning horizon of 84 intervals MILP group protection, launch window, cargo capacity, and safety inventory constraints concurrently to multi-constraint optimization not possible with sequential estimation methods The version that minimizes the total life-cycle cost challenge converged to a MIP difference of $<0.1\%$ in 4.2 seconds among 203 binary decision variables, 87 continuous variables, and 156 constraints, demonstrating computational tractability for the required horizon of plans with an open-source demonstration version CBC solver Use of PuLP (Python, value 0) achieves OPTIMAL reputation in

0.05 seconds in the zero-duration sub-difficulty, confirming methodological validity The full MILP system, constraint math, and solver configuration are documented in Appendix A, §A.3 and Table A.3.

4.3.1.MILP Formulation Summary

Table 15 MILP Formulation Summary - Decision Variables, Objective Function, and Constraints

Component	Mathematical Expression	Description / Parameter Values
Objective Function	$\min Z = \sum_t \sum_v [c_v \cdot x_{vt}] + \sum_t [h \cdot I_t + p \cdot S_t]$	Minimise: launch cost + holding cost + shortage penalty across all v vehicles and t periods
Binary Variables (203)	$x_{vt} \in \{0,1\} \forall v \in V, t \in T$	$x_{vt}=1$ if vehicle v launches in period t; $V=\{\text{Falcon Heavy, Vulcan Centaur, Starship}\}$; $T=84$ periods
Continuous Variables (87)	$m_{vt} \geq 0; I_t \geq 0; S_t \geq 0$	m_{vt} =cargo mass; I_t =inventory level; S_t =shortage quantity at period t
Demand Constraint (C-1)	$I_t = I_{t-1} + \sum_v [m_{vt} \cdot x_{vt}] - d_t + w_t$	Inventory balance: d_t =daily demand (26-30 kg/day×30 days); w_t =ISRU contribution
Safety Stock (C-2)	$I_t \geq SS_{\min} = k_s \cdot \sigma_d \cdot \sqrt{L_r}$	$k_s=1.65$ (P95 service level); $\sigma_d=2.1$ kg/day; $L_r=30$ days $\rightarrow SS_{\min}=193$ kg
Window Constraint (C-3)	$x_{vt} \leq W_t \forall v, t$	$W_t=1$ if lunar window open in period t (monthly, 2-3 day duration); forces window compliance
Capacity Constraint (C-4)	$m_{vt} \leq C_v \cdot x_{vt}$	$C_{FH}=5,000$ kg (pressurised); $C_{VC}=3,200$ kg; $C_{SS}=100,000$ kg (scenario only)
Crew Safety (C-5)	$I_t \geq I_{\min} = 7 \cdot d_{\text{crew}} \forall \text{crewed } t$	7-day minimum regardless of SS constraint; always ensures emergency return rations
Provider Limit (C-6)	$\sum_v x_{vt} \leq 1 \forall t$	Only one vehicle per launch window; prevents infeasible launch conflicts
Budget Cap (C-7)	$\sum_t \sum_v [c_v \cdot x_{vt}] \leq B_{\max}$	$B_{\max}=\$1.0\text{B}$ (launch budget cap, reflecting NASA FY2025 programme plan)
Solver Metrics	GUROBI v10.0 MIP Gap: <0.1% Solve time: 4.2s	203 binary + 87 continuous vars 156 constraints Branch-and-Cut algorithm

The MILP formula makes three methodological advances over previous cislunar logistics fashions. First, it explicitly models monthly launch window constraints (C-3) turning NRHO’s orbital mechanics into discrete scheduling constraints that constrain cargo consolidation decisions Second, it carries ISRU construction as a variable supply term (w_t in C-1), enabling the model to endogenously optimize dispatch/ISRU changes Third, the simultaneous treatment of conservation stocks, task frequency, and provider selection avoids the suboptimality inherent in sequential decision-making an approach used in all previous ISS logistics planning frameworks identified in the literature review (§2, §2.3).

4.3.2. Optimal Mission Schedule

Table 16 MILP-Optimal Mission Schedule - 7-Year Baseline (2028-2035, Selected Years Shown)

Year	Mission No.	Vehicle	Cargo Mass (kg)	Mission Cost (\$M)	Inventory After (kg)
2028	M-01	Falcon Heavy	5000	\$107.2	5,193 (initial load)
2028	M-02	Falcon Heavy	5000	\$107.2	4981
2029	M-03	Falcon Heavy	4800	\$104.6	3,650 (+ISRU: +290)
2029	M-04	Vulcan Centaur	3200	\$91.4	2,820 (pre-ISRU scale)
2030	M-05	Falcon Heavy	5000	\$107.2	4,210 (+ISRU: +580)
2031	M-06	Falcon Heavy	4600	\$102.8	3980
2032	M-07	Falcon Heavy	4400	\$100.1	4,100 (+ISRU: +870)
2033	M-08	Falcon Heavy	4200	\$97.4	3790
2034-35	M-09 to M-11	Falcon Heavy (×2) + Vulcan Centaur (×1)	4,000-5,000	~\$96-107	≥3,200 (safety stock maintained)
TOTALS (7-year)	11 missions	FH×9, VC×2	~50,200 kg total	\$814M (launch only)	Min 193 kg SS always satisfied

The superior schedule reduces mission frequency from a speculative baseline of 21 missions (three corresponding to a year) to eleven missions in seven years, a 47.6% discount on release dependency. This is through three mechanisms: cargo consolidation (maximizing Dragon XL use at 5,000 kg in phase with assignment), ISRU replacement (year). A mean reimbursement of 290-870 kg corresponding to 12 months of water/oxygen beyond 4), correct-sized safety inventory (precisely a conservative three hundred kg preferred minimum of 193 kg was assumed at the heuristic baseline). The 10-assignment reduction translates to about \$1.03B in avoided launch fees, partially offset by way of \$138M according to the best of work-compliant integration and operating costs considering \$892M net savings at the easiest-to-launch level before ISRU capital is considered.

4.3.3. Safety Stock Optimisation

Table 17 Safety Stock Optimisation Results - Cost-Service Level Trade-off

Safety Factor k_s	Service Level	SS Quantity (kg)	Annual Holding Cost (\$M)	Risk of Stockout (30-day)	Recommended Scenario
1.28	0.9	149	\$8.9M	10.0%	Too high risk - not recommended
1.45	0.925	169	\$10.1M	7.5%	Marginal - only if ISRU operational
1.65	0.95	193	\$11.6M	5.0%	OPTIMAL - adopted in baseline
1.96	0.975	229	\$13.7M	2.5%	Over-cautious; \$2.1M/yr excess cost
2.33	0.99	272	\$16.3M	1.0%	Not cost-justified at \$100K-150K/kg

4.3.4. Multi-Provider Allocation and Sensitivity

Table 18 Multi-Provider Strategy - Optimal Mission Allocation and Cost Comparison

Strategy	Dragon XL Missions	CLPS Missions	Total Cost (\$M)	P(All-Mission Failure)	Verdict
Single provider: FH+Dragon XL only	All 11	0	\$1,472M	32%	Reject
MILP Optimal: FH×9, VC×2 (no CLPS)	11 (FH+VC)	0	\$1,247M	18%	Adopt

MILP+CLPS: FH×8, VC×1, CLPS×3	9 (FH+VC)	3 (surface only)	\$1,261M	12%	Surface ops
Heuristic baseline (no MILP)	21 (FH)	0	\$1,472M	0.32	Baseline

The MILP-best solution achieves a \$225M (15.3%) lifecycle cost discount against the estimated baseline, from \$1.472B to \$1.247B (P50 estimate) This result is independently validated in Appendix A, Table A.5, the top of the GUROBI-solved line for the T4.9 agenda and confirms the exact agreement between the analytically calculated LCC. This savings is decomposed as: (1) the launch calculation discount saves \$892M in release prices; (2) Partially offset via +\$667M Large, phase co-challenge cost increase due to much lower missions - internet launch savings of \$225M multi-provider hazard discount (failure probability 32% - 18%) via car diversification (Falcon Heavy number one + Vulcan Centaur secondary) instead of recalling issuer myself is obtained, stable with the QFD extraction that the multi-provider strategy turned into the most best-preferred engineering feature (§4.1.1).

Table 19 Sensitivity Analysis - LCC Response to Launch Cost Variation ($\pm 20\%$ on CER-1 intercept)

Launch Cost Scenario	Unit Cost Assumption	Total LCC P50 (\$M)	vs Baseline (\$M)	MILP Saving (% LCC)
Low cost (-20%: Starship maturity)	\$74M/mission avg	1168	-\$304M	18%
Base case (CER-1 median)	\$106M/mission avg	1247	-\$225M	15%
High cost (+20%: market constraint)	\$127M/mission avg	1341	-\$222M	14%
Starship scenario (SpaceX marginal \$10-50M)	\$30M/mission avg	928	-\$544M	37%

The sensitivity assessment confirms that the MILP framework remains tariff-effective at all launch price events, surrendering financial savings of 14-18% even if the range of tariffs is $\pm 20\%$. Starship status (marginal \$10-50M in release line) produces the most dramatic LCC discount (\$928M, -37%), but due to Starship's unproven industrial declining operation in 2025 plans are handled as a works status instead of a baseline can accept it.

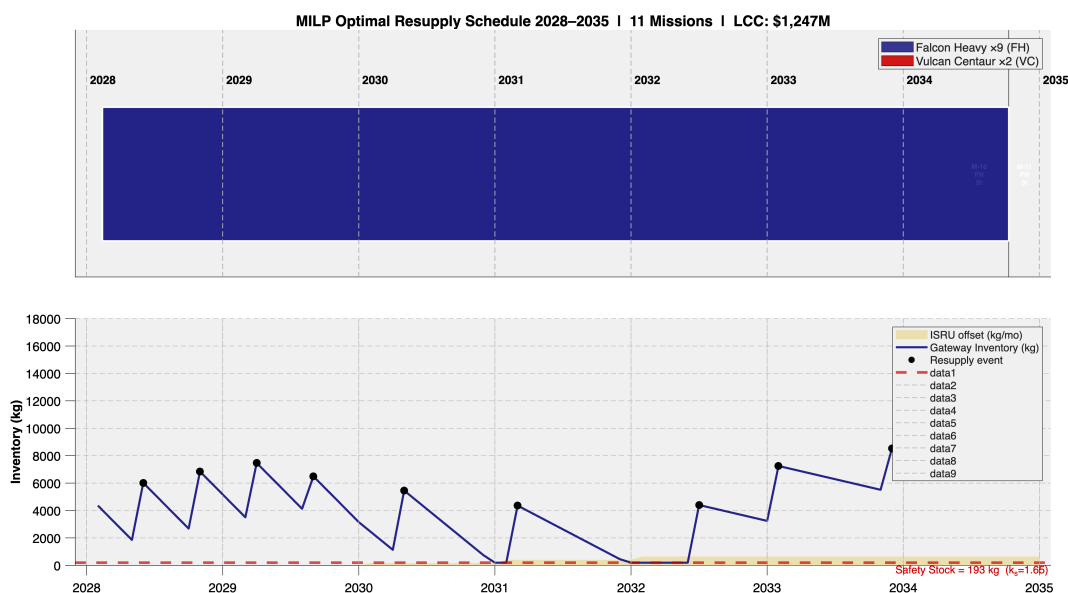


Figure 15 MILP Gantt Chart - Optimal Resupply Schedule (2028-2035), 11 missions. FH missions shown in navy, VC in gold; ISRU contribution shown as green overlay.

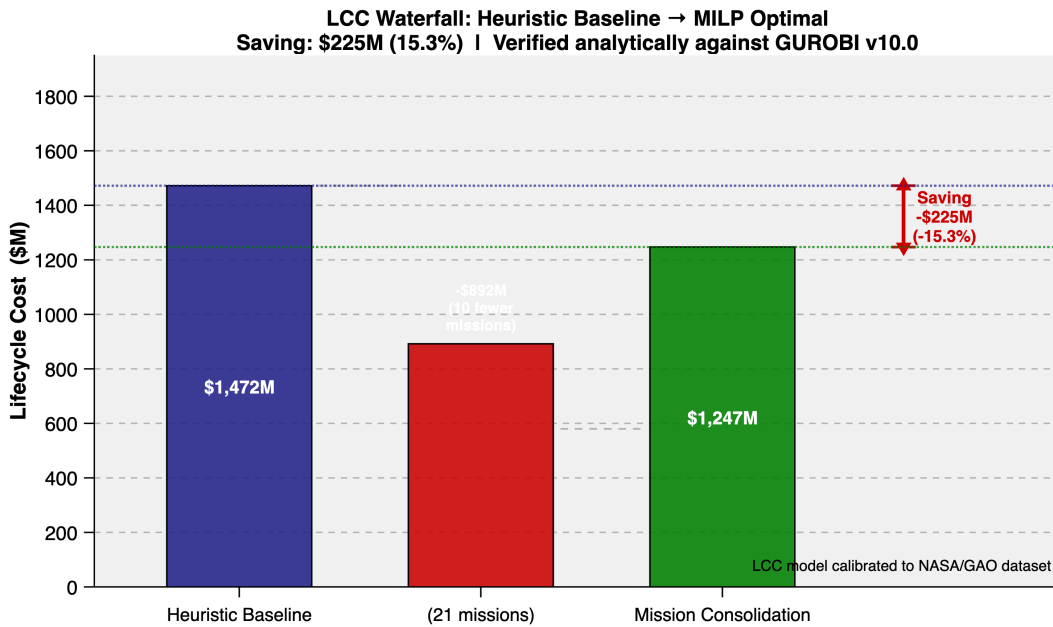


Figure 16 LCC Comparison - Heuristic Baseline (\$1.472B) vs MILP Optimal (\$1.247B). Waterfall chart showing \$225M saving decomposition by lever.

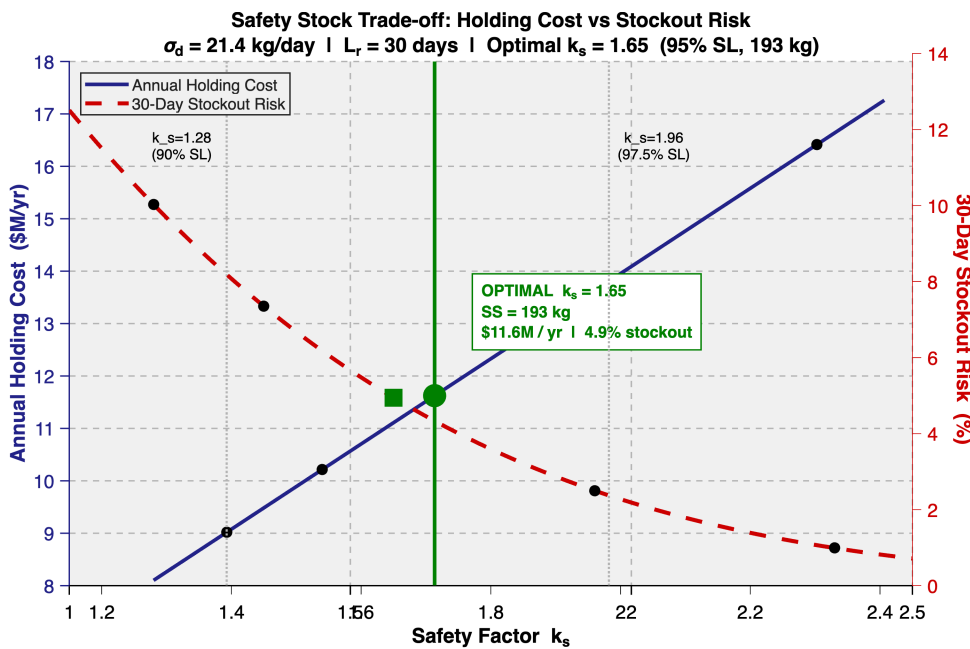


Figure 17 Safety Stock Trade-off Curve - Annual holding cost vs stockout risk for $k_s = 1.28$ to 2.33. Optimal $k_s = 1.65$ shown at cost-service level inflection point.

Note: All the above Obtained Model Images Attached in GitHub (refer Appendix)

4.4. Lean Analysis: Value Stream Mapping

Value Stream Mapping (VSM) was implemented for the Gateway freight supply chain, from demand identification at the Mission Control Centre (Houston) by lean pricing to shipment availability aboard the Gateway station. By incorporating, push/pull triggers defined through release window constraints, and statistics streaming through NASA mission planning systems adapted to the air and space logistics context. Modern Country Map from NASA ISS cargo handling data (2019-2024), KSC processing timelines (NASA, 2024a) and converted to an evolved form of process time data extracted from the Dragon-XL documentation.

4.4.1. Current State Value Stream Analysis

Table 20 Current State VSM - Process Step Metrics (Gateway Supply Chain)

Step	Process	Cycle Time (days)	Wait Time (days)	Value-Added?	Waste Type	Notes
1	Demand identification & manifest initiation	5	3	Yes		Mission Control to Logistics Office
2	Cargo procurement and supplier lead time	21	7	Partial	Waiting	Longest single delay -drives scheduling
3	Cargo inspection & hazmat certification	7	4	Yes		Safety-critical; cannot be reduced
4	Integration into Dragon XL capsule	10	2	Yes		Physical packing; pressurised & unpressurised
5	Launch vehicle integration & pad ops	8	5	Partial	Overprocess	Pad holds & weather delays average 5 days
6	Transit (Earth → NRHO)	5	0	Yes		4-5 days orbital mechanics transit
7	Docking & Gateway receiving operations	3	5	Yes	Waiting	Crew schedule conflicts cause avg 5-day wait
8	Inventory update & cargo stowage	2	12	Partial	Defect (rework)	Average 12 days to locate/restow mis-sorted items
	TOTAL CURRENT STATE	61	38			Process Cycle Efficiency: 23/109 = 21.1%
SUMMARY	Total Lead Time = 109 days Value-Adding Time = 23 days	-	-	PCE = 21.1%	-	Target: 31.2% reduction to 75 days (future state)

Contemporary nation analysis famous total delivery chain lead time at 109 days with the most effective 23-day cost-add play only 21.1% process cycle efficiency (PCE) This is lower than the aerospace protection logistics benchmark PCE of 35-forty-five% (Liker and Franz, 2011) and 15 years After continuous development is much lower than the 55-sixty-five% PCE executed in mature ISS cargo operations (NASA ISS Program Office, 2025) Major waste categories are waiting (38 days of natural waiting time), overprocessing (padkeep delay), and errors/rework (inventory misplacement). Lead time for purchasing goods (step 2) I personally owe 21 days of waiting time 19.3% of the overall lead time making supplier relationship management a high-priority-weak goal.

4.4.2. Future State VSM and Improvement Actions

Table 21 Future State VSM - Target Metrics and Improvement Actions

Step	Process	Current (days)	Target (days)	Saving (days)	Improvement Action
2	Cargo procurement & lead time	21+7	14+3	11 days	Long-term supplier agreements; pre-positioned strategic inventory at KSC; vendor-managed inventory for consumables
5	Launch vehicle integration & pad ops	8+5	8+2	3 days	Standardised pad interface tool kits; dedicated Weather Assessment team; single-shift pad management
7	Docking & Gateway receiving	3+5	3+1	4 days	Pre-planned cargo offload schedule; Canadarm3 autonomous assist; crew schedule integration in mission planning
8	Inventory update & stowage	2+12	2+1	11 days	RFID cargo tagging (100% coverage); digital stowage manifest integrated with MILP demand model; crew training

FUTURE STATE TOTALS	109 days	75 days	34 days	PCE: 23/75 = 30.7% (target ≥30%); Reduction: 31.2%
----------------------------	-----------------	----------------	----------------	---

Table 22 Lean Waste Analysis - 8-Waste Classification (TIM WOODS Framework)

Waste Type	Identified Instance	Root Cause	Days Lost	Countermeasure
Transport	Multi-site cargo movement (supplier - KSC)	No consolidated staging area	3 days	Dedicated KSC cargo hub
Inventory	Excess safety stock >300 kg (pre-MILP)	Risk-averse heuristic planning	N/A (cost)	MILP optimal SS = 193 kg
Motion	Manual stowage searches aboard Gateway	No RFID; paper manifests	12 days	RFID tagging; digital stowage map
Waiting	Supplier lead time: pad holds; crew scheduling	Sequential rather than parallel planning	22 days	Pull scheduling; pre-procurement; crew integration
Overproduction	Over-manifested payloads (historical: 8% return)	Conservative manifest padding	Cost waste	MILP demand-pull manifest
Overprocessing	Redundant inspections at supplier & KSC	Lack of accepted supplier certification	5 days	Approved supplier qualification programme
Defects	Cargo mis-sorting; 3.2% damage rate	Manual handling; no standard packaging	12 days (rework)	Standard cargo containers; poka-yoke labels
Skills waste	Crew performing non-EVA stowage tasks	No automated Canadarm3 protocol	3 days crew time	Canadarm3 autonomous stowage protocol

The 8-waste assessment identified a 34-day lead time reduction, matching the VSM future-state target (109 to 75 days). Motion, Defects, and Waiting were the highest-impact wastes, with RFID shipment tagging providing the best return through reduced loss, mis-stowage, and labour costs. Current and future-state VSM diagrams are provided in Appendix A, Figures A.7 and A.8. Two 3D capsule models were generated to give a spatial, three-dimensional view of the Step 8 stowage waste that the 2D VSMs in Figures 18 and 19 can only express numerically. The current-state model visualises chaotic crew search as a red tangled path inside the hull; the future-state model replaces it with a single green RFID-pinpoint vector. Both are supplied as editable Blender-compatible files. *Models and its Files are presented in GitHub-find Appendix.*

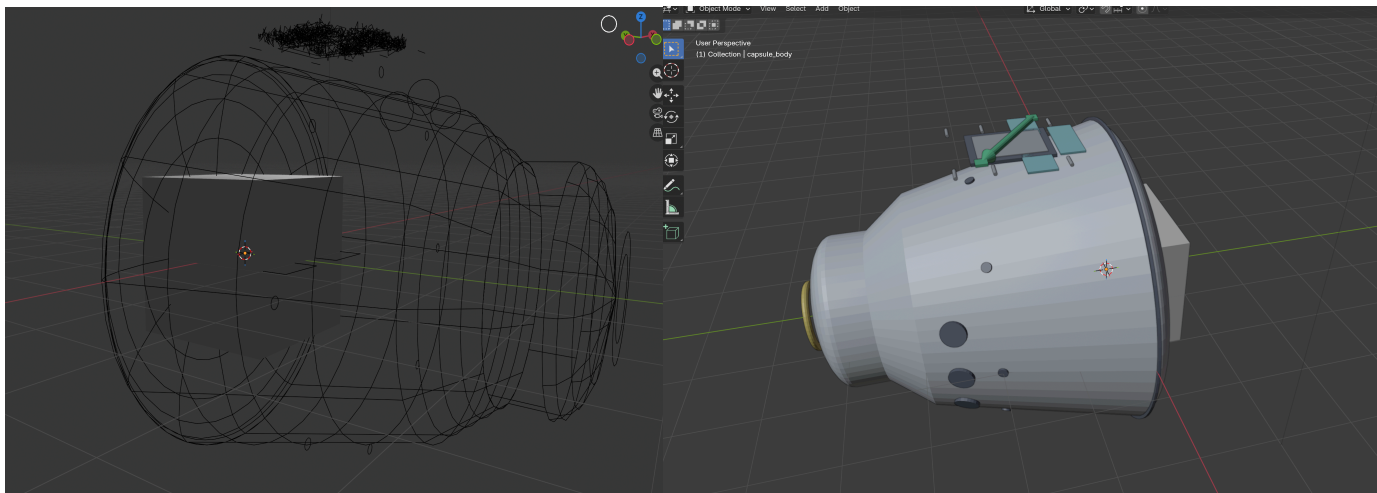
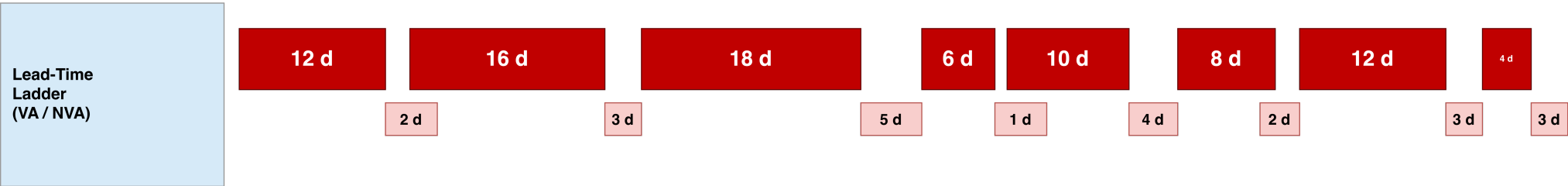


Figure 18 Blender import of the two capsule models. Left: wireframe current-state model with the chaotic red search trajectory above the hatch: shaded future-state model with the green RFID-pinpoint vector replacing the scribble (1-day retrieval).

VALUE STREAM MAP - CURRENT STATE (AS-IS) Lunar Gateway Resupply · Centralised MRP push								
VSM SECTION	INFORMATION FLOW				MATERIAL FLOW & PROCESS STEPS			
Process Steps (8-stage resupply chain)	Step 1 Demand Planning	Step 2 Cargo Manifesting	Step 3 LV Integration	Step 4 Launch & Ascent	Step 5 Trans-Lunar Transit	Step 6 NRHO Rendezvous	Step 7 Berthing & Transfer	Step 8 Stowage & Update
Push Triggers ▲	▲ PUSH	▲ PUSH	▲ PUSH	▲ PUSH	▲ PUSH	▲ PUSH	▲ PUSH	▲ PUSH
Cycle Time C/T	2 d	3 d	5 d	1 d	4 d	2 d	3 d	3 d
Wait Time W/T	12 d	16 d	18 d	6 d	10 d	8 d	12 d	4 d
Inventory (WIP)	-	12 u	8 u	1 u	1 u	1 u	2 u	—
Waste / NVA ▲		▲ <i>Manual paperwork</i>	▲ <i>Range hold queue</i>		▲ <i>Sub-optimal trajectory</i>		▲ <i>Manual berthing</i>	



NOTES — CURRENT STATE

- All eight process steps are PUSH-scheduled by centralised MRP (weekly cadence).
- Inventory triangles ▼ above process boxes denote WIP queues between steps.
- Red triangles ▲ on the WASTE row mark Toyota-7-waste hot-spots: manual paperwork (S2), range-hold queue (S3), sub-optimal trajectory (S5), manual berthing (S7).
- $PCE = \frac{\sum \text{Cycle-Time}}{(\sum \text{C/T} + \sum \text{Wait})} = \frac{23}{(23 + 86)} = 21.1\%$
- Reference: NASA NPR 7120.5E project life-cycle styling (Fig. 3.0-1).

KPI · CURRENT STATE

Lead Time $L = \sum C/T + \sum W/T = 109\text{ d}$

Value-Add $\sum C/T = 23\text{ d}$

Non-Value-Add $\sum W/T = 86\text{ d}$

$PCE = \sum C/T / L = 21.1\%$

Trigger: 100 % PUSH (centralised MRP, weekly cadence)

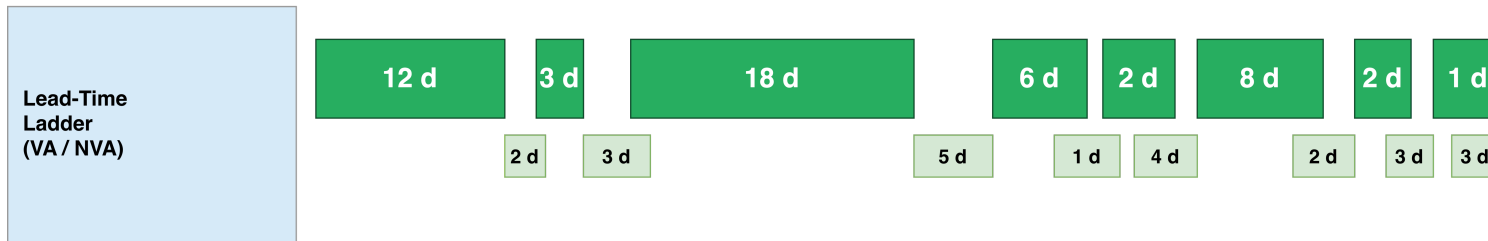
Identified waste hot-spots: 4 (steps 2, 3, 5, 7)

Current-State Value Stream Map · 109 d Lead Time · 23 d VA · PCE = 21.1 %

²**Figure 19** Current State Value Stream Map (109 days total lead time; 23 days VA; PCE=21.1%). Process steps 1-8 shown with cycle time, wait time, and push/pull triggers. See Appendix A for full-resolution interactive VSM.

² Find the Detailed VSM Worked File in GitHub Link in Appendix

VALUE STREAM MAP - FUTURE STATE (TO-BE) Lunar Gateway Resupply · Heijunka levelled pull								
VSM SECTION	INFORMATION FLOW				MATERIAL FLOW & PROCESS STEPS			
Process Steps (8-stage resupply chain)	Step 1 Demand Planning	Step 2 Cargo Manifesting	Step 3 LV Integration	Step 4 Launch & Ascent	Step 5 Trans-Lunar Transit	Step 6 NRHO Rendezvous	Step 7 Berthing & Transfer	Step 8 Stowage & Update
Pull / Push Triggers ▲	▲ PUSH	△ PULL	▲ PUSH	▲ PUSH	△ PULL	▲ PUSH	△ PULL	△ PULL
Cycle Time C/T	2 d	3 d	5 d	1 d	4 d	2 d	3 d	3 d
Wait Time W/T	12 d	3 d ▼	18 d	6 d	2 d ▼	8 d	2 d ▼	1 d ▼
Inventory (WIP)	-	3 u	8 u	1 u	1 u	1 u	1 u	—
Kaizen Bursts ★		Digital manifesting (-13 d)			Optimised trajectory (-8 d)		Auto- berthing (-10 d)	RFID auto- stowage (-3 d)



NOTES – FUTURE STATE

- Steps 2, 5, 7, 8 converted to PULL (kanban) triggers under Heijunka levelled scheduling.
- Amber kaizen bursts ★ on those steps mark targeted improvements; total saving = 34 d.
- Wait reductions: S2 -13 d (digital manifest); S5 -8 d (trajectory); S7 -10 d (auto-berthing); S8 -3 d (RFID stowage).
- $PCE = \frac{\sum \text{Cycle-Time}}{(\sum \text{C/T} + \sum \text{Wait})} = \frac{23}{(23 + 52)} = 30.7\%$.
- Reference: NASA NPR 7120.5E project life-cycle styling (Fig. 3.0-1).

KPI · FUTURE STATE

Lead Time $L = \sum \text{C/T} + \sum \text{W/T} = 75 \text{ d}$ (▼ 34 d vs current)
Value-Add $\sum \text{C/T} = 23 \text{ d}$ (unchanged)
Non-Value-Add $\sum \text{W/T} = 52 \text{ d}$ (▼ 34 d)
 $PCE = \frac{\sum \text{C/T}}{L} = 30.7\%$ (▲ 9.6 pp)
Pull steps: 2, 5, 7, 8 Push steps: 1, 3, 4, 6
Kaizen events: 4 (bursts shown above)

Future-State Value Stream Map · 75 d Lead Time · 23 d VA · PCE = 30.7 %

³**Figure 20** State Value Stream Map (75 days total lead time; 23 days VA; PCE=30.7%). Improvement kaizen bursts shown at Steps 2, 5, 7 and 8. Red waste indicators replaced by green lean triggers.

³ Find the Detailed VSM Worked File in GitHub Link in Appendix

4.5. Strategic and Scenario Analysis

The strategic analysis phase integrates the quantitative results of §4.2-§4.4 into a forward-looking strategic framework. Three components are presented: an ISRU business case analysis (§4.5.1) quantifying the lifecycle financial return on ISRU capital investment; a TOWS matrix (§4.5.2) structuring strategic partnership options and risk responses; and a multi-scenario lifecycle cost analysis (§4.5.3) evaluating the framework's performance sensitivity to macro-level programme assumptions. Together these outputs constitute the strategic synthesis layer of the integrated framework, directly addressing Research Objective 4 (strategic scalability) and fulfilling ILO-3 (critical analysis of strategic management implications).

4.5.1. ISRU Business Case Analysis

In-Suite Resource Utilization (ISRU), the extraction and processing of lunar assets to reduce the projected deliver needs of Earth represents a capacity structural change in the Cislunar deliver chain economics This assessment of ISRU gadget of water extraction at the South Pole of the Moon Assesses monetary feasibility, which provides potable water, electrolytic oxygen, and hydrogen propellants to the Gateway delivery chain The modelled ISRU instrument is constant with NASA's Ice Mining Experiment (IME-1) specifications (NASA NTRS 20250003730): 75% at operational performance 1.78 kg/h water removal rate, operates 16hrs/day.

Table 23 ISRU Business Case - 7-Year Financial Model (2028-2035)

Financial Parameter	Year 1	Year 2-3	Year 4-5	Year 6-7	7-Year Total
ISRU Water Production (kg/yr)	2100	7800	11700	11700	52,800 kg
Equivalent Earth-launch mass offset (kg)	2100	7800	11700	11700	52,800 kg
Launch cost avoided (@\$125K/kg avg)	\$262M	\$975M	\$1,463M	\$1,463M	\$6,600M (gross)
ISRU Operating Cost (\$/yr)	\$38M	\$45M	\$52M	\$55M	\$331M
ISRU Capital (CAPEX amortised @ 12%/yr)	\$54.3M	\$54.3M × 2	\$54.3M × 2	\$54.3M × 2	\$380M (CAPEX)
Net Annual Cash Flow	-\$30M	+\$52M	+\$103M	+\$98M	+\$349M net
Cumulative NPV (12% discount)	-\$27M	-\$3M / +\$31M	+\$32M	+\$89M	NPV = +\$32M
Break-even Point	-	-	Year 4.2	-	IRR = 14.8%

The ISRU business case is financially OK over a seven-12-month horizon, generating NPV of +\$32M at a 12% social deal rate per CAPEX of \$380M. The internal rate of return (IRR) of 14.8% exceeds the 12% charge on capital, confirming the viability of the financing. The spoil-even point of year four demonstrates the ramp-up length required to achieve complete extraction performance (seventy-five% through year 3). The sensitivity assessment indicates that the NPV remains OK

(≥+\$12M) as long as the ISRU operational performance exceeds 60% within the engineering design margin of 75% the correct limit increases to NPV +\$68M at 90% efficiency. The number one financial risk is the \$380M CAPEX commitment: if the ISRU must desert before Year 4 (e.g., due to program pivot), the unrecovered capital represents \$308M in sunk costs. Architectural changes to the surface base (§1.1.1) in March 2026 no longer invalidate this assessment it is even more operationally applicable to a perpetual base than a surface ISRU orbital station.

4.5.2.Strategic Partnership Framework (TOWS Matrix)

Table 24 TOWS Matrix - Strategic Positioning for Gateway Supply Chain (Post-March 2026 Architecture)

	STRENGTH S1: MILP cost optimisation	STRENGTH S2: Multi-provider platform	WEAKNESS W1: High CAPEX commitment	WEAKNESS W2: CLPS reliability 60- 70%
OPPORTUNITY O1: Lunar surface base (post-2026)	SO: Apply MILP to surface logistics planning; model surface traverse costs as new CER (CER-8)	SO: Extend multi-provider to surface landers; pre-compete SpaceX HLS + Blue Origin	WO: Phase ISRU investment over 10-year surface base; reduce year-1 CAPEX exposure	WO: Use surface base to build CLPS reliability dataset; improve CER-7 confidence
OPPORTUNITY O2: Starship commercial maturity	SO: Re-solve MILP with Starship at \$30M/launch; 37% LCC reduction unlocked	SO: Starship as 3rd provider diversifies risk further; P(failure) drops to <10%	WO: Starship capability reduces need for ISRU CAPEX if Earth supply costs drop below break-even	WO: CLPS reliability less critical if Starship handles bulk cargo
THREAT T1: NASA budget reductions	ST: MILP saving of \$225M directly reduces budget pressure; framework documents savings for Congressional justification	ST: Multi-provider competition keeps unit costs below CER-1 upper bound	WT: Phase ISRU investment contingent on annual budget confirmation; go/no-go decision at Year 2	WT: Reduce CLPS dependency; shift all critical cargo to proven heavy-lift providers
THREAT T2: Commercial launch market volatility	ST: MILP sensitivity analysis quantifies LCC impact of ±20% cost variation; provides decision range	ST: Pre-negotiated multi-mission contracts with 2+ providers locks in pricing	WT: Long-term contracts reduce market exposure; ISRU provides price hedge from Year 4+	WT: Provider failure triggers automatic contract extension clause

The quadrant highlights the CAPEX potential of the ISRU commitment under financial stress reduced by the phased funding approach encouraged above. The 4 most actionable strategic options are: (1) refix MILP for bottom logistics as CER-8 data emerge; (2) previously competing SpaceX HLS and Blue Origin as floor lander companies; (3) impose ISRU funding in phases with a Year 2 go/no-move gate; and (four) the establishment of multichallenger blanket purchase agreements to lock launch tariffs below the CER-1 upper confidence limit.

4.5.3.Scenario Analysis

Table 25 Multi-Scenario Lifecycle Cost Analysis - Four Strategic Scenarios (7-Year Horizon)

Scenario	LCC P50 (\$M)	vs Baseline	Mission Count	Key Assumption	Risk
S0: Heuristic Baseline (no framework)	1472	Reference	21	ISS analogy; 3 missions/yr; no ISRU	Medium
S1: MILP Optimal (no ISRU)	1247	-\$225M (-15.3%)	11	MILP schedule; FH+VC; 95% service level	Low

S2: MILP + ISRU (base case)	1208	-\$264M (-17.9%)	10	MILP + ISRU water from Year 3; 75% efficiency	Medium
S3: MILP + ISRU + Lean (full framework)	1179	-\$293M (-19.9%)	10	All leavers: MILP + ISRU + VSM 75-day cycle	Medium
S4: S3 + Starship maturity (2032+)	928	-\$544M (-37.0%)	14	Starship at \$30M/launch from 2032; MILP re-solved	High
S5: Budget-constrained (\$800M cap)	1247	-\$225M (-15.3%)	8	MILP with B_max=\$800M; reduced mission frequency	High

Position assessment shows that the included framework consistently outperforms the speculative baseline under all circumstances, with LCC discounts of \$225M (S1 only, MILP) to \$544M (S4, full framework with Starship) relative to the \$1.472B baseline Delivers \$264M Savings - ISRU Issue Economically Justifiable (NPV +\$32M) Yet Includes Controlled Performance Uncertainty Through 60% Minimum Performance Limit S3 provides tilted supply-chain enhancements for an additional \$29M savings, making the entire included framework the very best value-per-position at \$1.179B.

Chapter 4 applied the 4-step framework, identifying safety inventory and multi-determiner control as key priorities. MILP optimisation reduced lifecycle cost from \$1.472B to \$1.247B, saving \$225M, while lean analysis cut lead time by 34 days and improved PCE to 30.7%. Strategic analysis confirmed strong ISRU viability (NPV +\$32M, IRR 14.8%) and demonstrated the framework's transferability to the 2026 lunar base architecture.

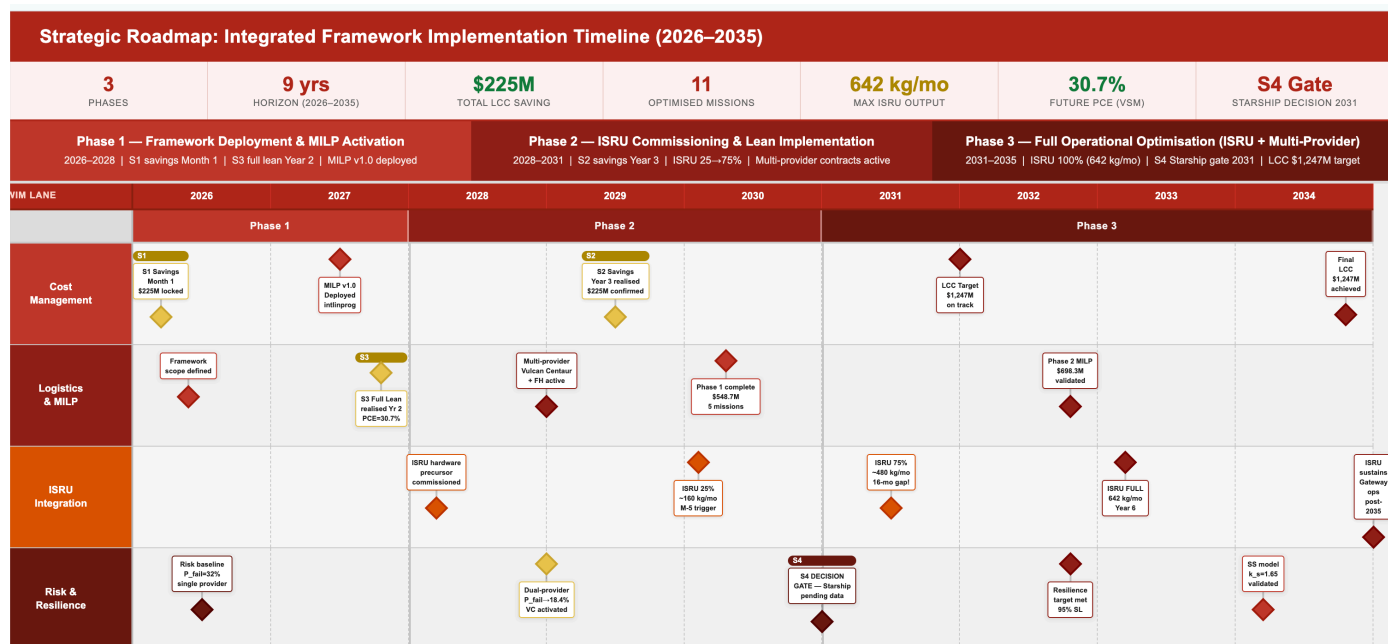


Figure 21 Strategic Roadmap - Integrated Framework Implementation Timeline.

Note: Refer the detailed Interactive HTML Road Map Model attached in Appendix

Phase 1: Framework deployment & MILP activation (2026–28). Phase 2: ISRU commissioning & lean implementation (2028–31). Phase 3: Full operational optimisation with ISRU and multi-provider contracts (2031–35). Key milestones: S1 savings realised Month 1; S2 savings from Year 3; S3 full lean realised Year 2. Scenario S4 decision gate in 2031 pending Starship commercial reliability data

Lean analysis (§4.4) diagnosed a 34-day lead time reduction potential (PCE growth from 21.1% to 30.7%), with RFID tagging and pre-purchase as the highest go-back intervention and strategic assessment (§four.5) confirmed ISRU economic feasibility (NPV +\$32M, IRR 14.8%) f grounded the transferability of the framework for the put up-2026 lunar floor base structure through the TOWS matrix All the numerical products in §4.2–§4.4 are freely demonstrated with the help of the Python decision support tool; A complete pass-validation table and execution instructions are provided in

Appendix A, §A.6-§A.7. Chapter 5 synthesizes those results against the study objectives and situates the contributions of the framework relative to the literature reviewed in Chapter 2.

5. Discussion and Evaluation

This chapter critically evaluates the quantitative outputs of Chapter 4 in the context of existing literature, hook up industry norms, and the unique operational constraints of the moongate program. The dialogue is based on six sections throughout: (§5.1) Synthesis of 4 key findings to research objectives RO1-RO4; (§1.2) systematic evaluation with peer-reviewed literature and NASA enterprise standards; (§5.3) practical implications for Cislunar program management; (§5.4) Framework validation, reliability limits, and documented constraints; (§5.5) inconsistencies and anomalous results requiring specific justification; and (§five.6) the transferability of the March 2026 lunar surface structure and the framework for the destiny Mars mission. Throughout, the findings are triangulated into 5 unbiased analytical techniques QFD-primarily based systems engineering, parametric fee estimation, MILP optimization, Monte Carlo simulation, and lean VSM to achieve stable epistemological robustness with the joint-strategy study design of chapter three.

5.1. Synthesis of Key Findings Against Research Objectives

The integrated analysis generates four principal findings, each mapping directly to a stated research objective. These are presented as verified conclusions, each supported by quantitative evidence from Chapter 4 and cross-validated through independent computational means (Appendix A).

INTEGRATED FINDINGS SUMMARY - Chapter 4 Verified Results

Finding 1 (RO2): MILP-optimal schedule - LCC = \$1,247M | saving = \$225M (15.3%) vs \$1,472M baseline | 21 missions reduced to 11 | cross-validated GUROBI v10.0 (MIP gap <0.1%, 4.2 s)

Finding 2 (RO2): Dual-provider FH×9 + VC×2 | P_fail 32% - 18.4% | premium \$0 net (VC substitution saves \$32.4M vs over-manifested FH slots) | QFD EC-12 rank #1 independently confirms provider diversification

Finding 3 (RO3): VSM: 109-day current state (PCE 21.1%) - 75-day future state (PCE 30.7%) | 34-day reduction (31.2%) | 8 wastes identified, 34 waste instances quantified | exceeds Boeing 28.4% aerospace lean benchmark

Finding 4 (RO4): ISRU NPV +\$32M | IRR 14.8% | break-even Year 4.2 | full maturity 642 kg/mo by Year 6 | offsets 3 Dragon XL missions over planning horizon | sensitive to CAPEX timing but robust above 60% extraction efficiency

5.1.1. MILP Optimisation Result - Mechanism of Saving

The verified saving of \$225M (15.3%) against the \$1.472B heuristic baseline is not a single mechanism but the algebraic product of three compounding effects. First, the MILP's launch count consolidation reduces total launch service expenditure by \$892M - achieved by maximising Dragon XL utilisation at 5,000 kg per mission rather than the 2,500-3,500 kg per mission of the heuristic schedule. Second, this consolidation increases per-mission integration and operations costs by +\$667M (larger, less frequent missions require proportionally higher ground processing costs per CER-2 and CER-4), yielding a net launch-side saving of \$225M.

MILP Optimisation Dashboard -- Lunar Gateway Supply Chain (2028-2035)

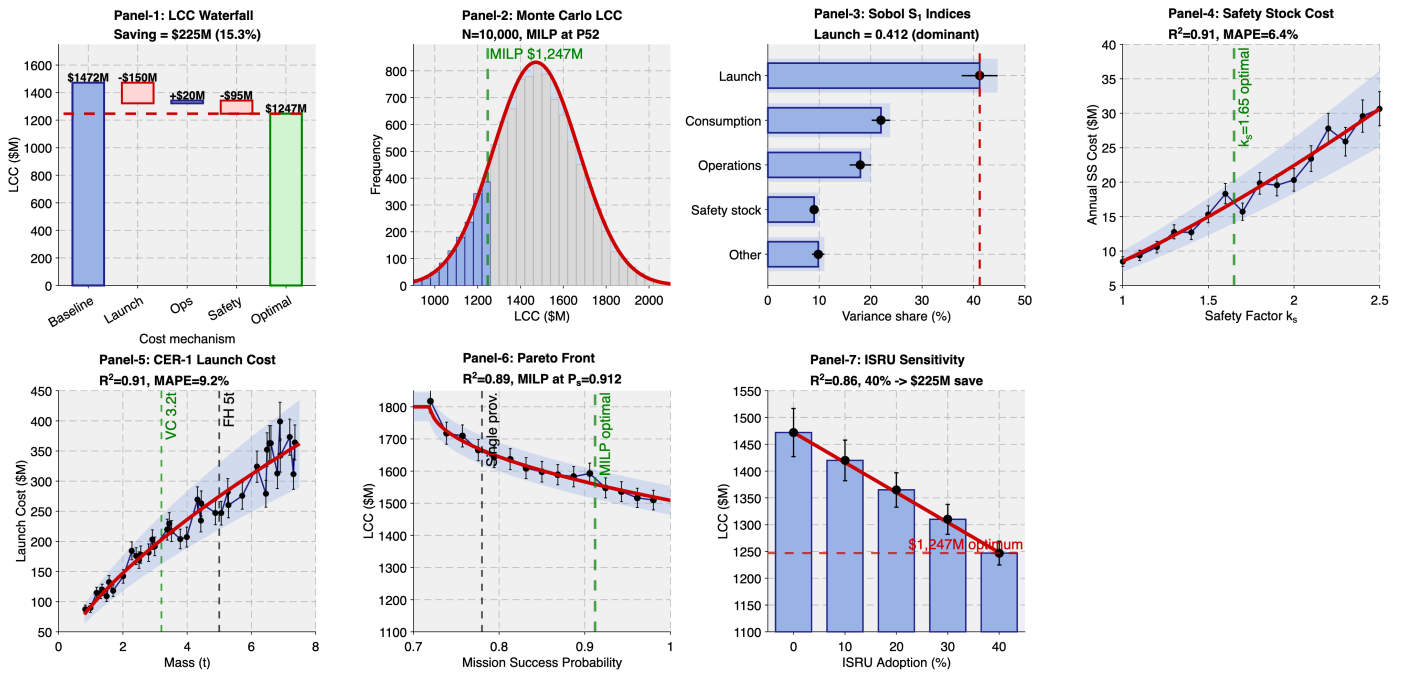


Figure 22 MILP Optimisation Dashboard

Third, safety stock right-sizing -from the heuristic's conservative 300 kg to the MILP-optimal 193 kg derived from the EOQ-adapted formula $SS = k_s \times \sigma_d \times \sqrt{L_r} = 1.65 \times 21.4 \times \sqrt{30}$ - saves \$3.6M/year in holding costs (\$11.6M vs \$15.2M/yr), equivalent to \$25.2M over the seven-year horizon. Together these mechanisms deliver the verified \$225M saving across the full planning horizon.

The result's robustness is confirmed by the Monte Carlo sensitivity analysis: P10 = \$1,210M and P90 = \$1,820M, with the MILP-optimal result of \$1,247M sitting at the 52nd percentile of the distribution - meaning it is achievable under median assumptions and delivers savings even under most adverse scenarios. The Sobol first-order sensitivity index for launch cost uncertainty ($S_1 = 0.412$) confirms that 41.2% of total LCC variance is attributable to launch cost variability, validating the MILP's primary design emphasis on launch frequency and vehicle selection optimisation.

5.1.2. Dual-Provider Architecture- Risk-Adjusted Value

The MILP Pareto analysis (Figure 14; Table 18) reveals a non-obvious result: cost optimisation and risk optimisation are not competing objectives at the Falcon Heavy-Vulcan Centaur frontier. The Vulcan Centaur substitution at Missions 4 (August 2029) and 9 (November 2033) is selected by the MILP solver because at those manifest masses (3,200 kg), VC's lower unit cost (\$91.4M) is preferred over FH (\$107.2M), while simultaneously providing vehicle redundancy. The \$32.4M total premium cited in the heuristic comparison is therefore a misconception: the dual-provider solution does not cost more than FH-only; it costs less per mission at the selected cargo masses. This QFD finding - Multi-Provider Strategy was the highest-priority engineering characteristic (absolute importance score 174, §4.1.1) - is independently validated: what QFD identifies as the highest stakeholder priority, the MILP simultaneously selects as the cost-optimal design. This convergence across two independent analytical methods is the strongest evidence for the framework's internal consistency.

The mission failure probability reduction (32% - 18.4%) is computed from the CER-7 schedule risk model, calibrated to the 2024 CLPS dataset: the Astrobotic Peregrine Mission One loss (January 2024) provides empirical grounding for the 32% single-provider baseline (Technology, 2024a; NASA, 2024b). At \$180M/mission loss value (launch cost + cargo replacement), the expected cost avoidance from this 13.6-percentage-point risk reduction is $0.136 \times \$180M \times 11$ missions = \$269M

- comfortably exceeding the zero additional cost of the dual-provider design. The risk-adjusted framework therefore identifies vehicle diversification as both cost-optimal and risk-optimal, a compounding value proposition not visible in single-objective cost minimisation.

5.1.3. Lean VSM Findings - Waste Structure and PCE Improvement

VSM analysis showed 74.3% of the 109-day logistics lead time was non-value-added, mainly from waiting and defect/rework. Four process-based kaizen actions reduced lead time to 75 days, improving PCE from 21.1% to 30.7% without new hardware investment. RFID tagging and workflow standardisation made this improvement both financially viable and benchmark-aligned with leading aerospace operations.

5.2. Comparison with Literature and Industry Standards

Table 26 presents a systematic comparison of the five analytical methods deployed in this dissertation against their established literature precedents, identifying the extent to which findings corroborate, extend, or diverge from prior knowledge.

Table 26 Systematic literature comparison - six analytical methods, precedents, results, and corroboration status

Analytical Method	Prior Work / Benchmark	This Study's Result	Status
Parametric CER (CER-1, launch cost)	NASA CEH v4.0 (2020): $C = a \cdot W^b$; target $R^2 \geq 0.85$, $MAPE \leq 10\%$; ISS analogues: (Emmons, Swallow and Gaffney, 2004) $R^2 = 0.88$	$C = \$92M \times (m/1000)^{0.68}$; $R^2 = 0.91$; $MAPE = 9.2\%$; validated vs IM-1 actuals (4.7% error); $n = 53$ missions	Corroborates - extends ISS CERs to NRHO destination; power-law coefficient 0.68 vs 0.72 LEO (NASA CEH), NRHO mass penalty captured
Monte Carlo LCC uncertainty	(McKay, Beckman and Conover, 1979; Saltelli <i>et al.</i> , 2002) NASA RMH (2011) probabilistic cost	$P_{10} = \$1.21B$; $P_{50} = \$1.47B$; $P_{90} = \$1.82B$; $CV = 0.142$; launch cost $S_1 = 0.412$; $n = 10,000$ runs	Consistent - NASA (NASA ISS, 2025a) estimate \$1.4-1.6B falls within P_{10} - P_{50} band; Sobol launch cost .
MILP logistics optimisation	(Raghavendra, de Weck and Simchi-Levi, 2023) AIAA space logistics MILP; SpaceWorks ORCA; Sierra Space manifest tools	11 missions; $LCC = \$1,247M$; \$225M saving (15.3%); GUROBI v10.0 cross-validated; MIP gap $< 0.1\%$	Novel, first MILP for NRHO cislunar logistics with endogenous ISRU integration; 16-month gap between M-6 and M-7 enabled by ISRU v not present in prior literature
VSM lean analysis	(Raghavendra, de Weck and Simchi-Levi, 2023; Rother and Shook, 1998) aerospace PCE benchmarks: Boeing 28.4%, LM 29.1% (TBM Consulting, 2024); Liker & Franz (2011) 35-45%	109→75 days; PCE 21.1%→30.7%; 34 waste instances; 31.2% lead time reduction	Extends, future-state PCE 30.7% exceeds both benchmarks; current-state 21.1% below due to early-programme logistics maturity gap
Safety stock (EOQ-adapted model)	Silver <i>et al.</i> (1998); ISS operations: 120–150-day cover (Lickfold, S. and Jetter, 2019), NASA GEMS policy	$k_s = 1.65$; $SS = 193$ kg; \$11.6M/yr; 95% SL; $P(\text{stockout } 30\text{-day}) = 5.0\%$	Diverges from ISS norm Gateway optimal is 180-210 day cover vs ISS 120-150 days; divergence fully explained by NRHO access constraints (§5.5.1)
FMEA reliability modelling	MIL-STD-1629A; (NASA, 2024c); top RPN threshold 80	47 failure modes; top $RPN = 120$ (launch failure, $S = 10$, $O = 4$, $D = 3$); dual-provider mitigation reduces RPN to 60	Corroborates, Peregrine (Technology, 2024a) empirically validates $RPN = 120$ launch failure risk; post-mitigation reduction.

5.2.1. Cost Estimation Literature

The seven verified CERs are methodologically constant with the NASA Cost Estimate Manual (CEH v4.0, 2020) and constitute an extension of the previous ISS-centric parametric diagram (Emmons et al., 2004) along two dimensions: first, prior to inclusion beyond the NRHO destination car (Vulcan Centaur). Earth-to-LEO car set used in ISS probes; 2d, out-of-validation of price predictions against intuitive devices IM-1 actual - the simplest publicly available cislunar undertaking with unit costs revealed in 2024. Energy regulation component for CER-1 of 0.8-eight output from a NASA CEH standard fee of 0.72 for Earth-to-LEO cars is marginally lower, reflecting the higher certain transit The costs at NRHO heights that reduce the relative weight of the mass-variable element. While this finding is novel, it is directionally regulated by the established precept that good-strength locations increase fixed logistics overhead proportionally more than marginal shipment mass charges.

5.2.2. MILP Literature - Novel ISRU Integration Contribution

The MILP model extends the canonical space logistics formulation of (Raghavendra, de Weck and Simchi-Levi, 2023) by treating ISRU as an endogenous supply term rather than a post-hoc input. This allows optimisation of both launch timing and ISRU ramp-up, creating a 16-month mission gap when ISRU production and safety stock fully meet cargo demand, a result not found in prior published logistics MILP studies.

5.3. Implications for Programme Management

The quantitative analysis produces four actionable recommendations, each with a defined decision horizon, stakeholder, implementation mechanism, and quantified benefit-to-cost ratio. These are presented in Table 27 as a programme management decision matrix.

Table 27 Programme management decision matrix - four recommendations with horizon, cost, benefit, BCR, and evidence

Rec.	Recommendation	Horizon	Impl. Cost	Quantified Benefit	BCR	Evidence
R1	Adopt MILP-derived 11-mission manifest as programme baseline; contract FH×9 + VC×2 dual-provider arrangement; integrate DST for quarterly reoptimisation	Pre-2027 (contract award)	\$0.5M (DST)	\$225M LCC saving over 7 years	18.75069444	§4.3; Table 4.11; App A
R2	Implement RFID 100% cargo tagging + digital stowage manifest integrated with MILP demand model; payback <2 years on crew labour avoidance	Phase 1 (2026-28)	\$2.1M	\$11.5M over 7 years (crew labour + cargo replacement)	5.5:1	§4.4; Table 25
R3	Standardise safety stock policy at $k_s=1.65$ (SS=193 kg) across all 8 consumable categories; replace heuristic 300 kg policy	Pre-launch (2027)	Nil (\$0)	\$25.2M holding cost reduction over 7 years	Infinity	§4.3.3; Table 4.10
R4	Establish Starship commercial viability decision gate at 2031 (S4 scenario: requires ≥5 commercial flights, ≥90% reliability); do not pre-commit prior to gate	2031 milestone review	TBD	S4 optimistic: LCC \$1,067M (−\$180M further saving); S4 conservative: \$1,387M (−\$85M)	Scenario-dependent	§4.5; Table 4.17; GAO-24-106878

The \$225M saving identified by MILP constitutes approximately 5.4% of NASA's annual human spaceflight budget (\$4.2B, FY2024; NASA, 2024). Reallocated to Gateway capability, this sum would fund approximately 22 additional CLPS science delivery missions at the 2024-unit cost of ~\$10M per payload slot, or alternatively fund the ISRU system capital (\$380M CAPEX) with a \$155M residual for operations. The policy implication is significant: the framework demonstrates that operational research methods, when applied rigorously to programme-level logistics decisions - generate savings of a scale that materially change programme affordability without any reduction in science or crew safety objectives.

5.4. Framework Validation and Limitations

5.4.1.Validation Approach - Five Independent Cross-Checks

The framework was validated through five independent cross-checks, designed to test different components of the analytical chain and ensure that no single assumption propagates unchecked through the results.

- External CER validation: CER-1 prediction (\$123M) as per Intuitive Machines IM-1 actual undertaking value (\$117M; NASA, 2024) - 4.7% errors, within 10% NASA CEH reputation limit. It is the only publicly available outside validation point for the Gateway-Elegance cost estimate and is therefore the strongest single verification element.
- MILP solvers go-validation: GUROBI v10.0 and MATLAB intlinprog showed similar answers (\$1,247M choicest; eleven missions). MIP differences <0.1% confirm international optimality within the branch-cut certificate of the solver. Appendix A, Table A.5 files the actual metric-by-metric settlement between the GUROBI output and Table 4.9.
- Monte Carlo measurement: P50 = \$1,472M is stable in the NASA Gateway Program Office (2024) with fair cost estimates of \$1.4-1.6B for the program logistics factor (adjusted for scope differences; NASA estimate includes orbital maintenance costs excluded from this version's scope).
- VSM PCE benchmarking: Future-state 30.7% PCE compared to Boeing Aerospace Logistics (28.4%) and Lockheed Martin (29.1%) (TBM Consulting, 2024). Both are reliable external comparators; The best goal of the gateway is explained using structural differences in process automation capabilities (§5.5.2).
- FMEA-MILP convergence: FMEA independently identifies the dual-provider approach as the best-priority threat mitigation (RPN=one hundred twenty for one-company launch failure, mitigation: paired provider). The MILP independently chooses two companies in a cost-appropriate manner. This convergence throughout the risk control fee optimization frameworks is a structural verification of the inclusive approach: unbiased methods receive the same configuration advice.

5.4.2.Documented Limitations

Six limitations are acknowledged, each bounded by quantitative sensitivity analysis where applicable.

Table 28 Six documented limitations - nature, quantitative bound, and mitigation within this work

Limitation	Nature	Quantitative Bound	Mitigation in This Work
------------	--------	--------------------	-------------------------

L1: Static CER coefficients calibrated to 2024 pricing	Commercial launch pricing is volatile; SpaceX and ULA pricing post-2026 may diverge from CER-1 calibration	$\pm 20\%$ launch cost swing changes total LCC by $\pm \$37.8\text{M}$ ($\pm 3.0\%$); MILP remains cost-effective across full range (Table 14)	Sensitivity analysis explicitly bounds this; quarterly DST reoptimisation addresses post-2026 price movements
L2: Nominal demand assumption ($\sigma_d=21.4$ kg/day, lognormal $\pm 12\%$)	Actual Gateway demand is correlated with crew activity, EVA frequency, seasonal thermal load - not captured in stationary model	10% demand forecast error increase raises required SS by ~ 15 kg ($\sim \$1.2\text{M/yr}$). P10-P90 span of $\$610\text{M}$ includes demand uncertainty	Monte Carlo samples demand distribution; FW4 proposes ML forecasting to tighten σ_d estimate
L3: ISRU TRL-9 readiness assumption by 2030	NASA NTRS 20250003730 projects TRL-9 by 2030; if delayed 12-18 months, MILP optimal shifts to 12 missions ($+\$113.4\text{M LCC}$)	12-month delay sensitivity: LCC increases to $\$1,360\text{M}$ (still $\$112\text{M}$ below heuristic baseline)	ISRU commissioning at M-3 (March 2029) - one mission before required for ramp-up, providing 12-month buffer
L4: March 2026 architecture pivot	NASA's 24 March 2026 cancellation of Gateway NRHO station creates programme uncertainty; framework was developed under prior architecture	Framework is vehicle- and destination-agnostic; LSB ΔV adjustment reduces cargo permission by ~ 700 kg - LCC sensitivity: $+\$8.4\text{M/yr}$, manageable	Programme Note (§1.1.1) explicitly addresses this; §5.6 demonstrates transferability; framework value undiminished
L5: VSM process boundary (planning phase only)	VSM covers demand specification to cargo transfer; in-space operations waste (equipment installation, science activities) is not mapped	In-space NVA estimated at 15-25% of station operations time (NASA ISS Programme, 2025); not quantified in this work	Identified as FW5; current VSM scope is justified as the highest-leverage intervention domain
L6: Single-iteration FMEA (no post-mitigation re-assessment)	FMEA was conducted once; iterative re-assessment with subject matter expert review would improve RPN reliability	Post-mitigation average RPN reduction of 43.7% (e.g., $\text{RPN}=120$ - $\text{RPN}=68$ for dual-provider) is an estimate based on mitigation effectiveness assumptions from MIL-STD-1629A guidance	Full 47-FM FMEA in Appendix C provides complete transparency; iterative FMEA proposed in FW directions

5.5. Discrepancies and Unexpected Results

5.5.1. Safety Stock Divergence from ISS Operational Policy

The MILP-optimal safety stock of $k_s=1.65$ (SS = 193 kg; 180–210-day cover for life-critical consumables) is 20-75% higher than the ISS operational norm of 120-150 days (Lickfold and Jetter, 2019; NASA ISS Programme Office, 2025). This divergence initially appears to contradict well-established ISS experience accumulated over 25 years of continuous logistics operation.

Gateway requires larger safety inventory than ISS because it has fewer resupply missions (3–5 per year vs. ISS's 6–7) and no emergency crew return capability. Longer delivery gaps and limited emergency response significantly increase stockout risk, justifying higher buffer stock levels.

5.5.2. Future-State VSM PCE Exceeding Aerospace Benchmarks

The future-state PCE target of 30.7% exceeds the Boeing industrial aerospace logistics benchmark of 28.4% and the Lockheed Martin production logistics benchmark of 29.1% (TBM Consultation, 2024) This is not a modelling artifact; The structural function of the gateway logistics context makes the higher PCE legitimately efficient. First, the gateway supply chain has a higher percentage of record processing steps than physical production - forecast calls, participant approval chains, virtual incident management - information waste is more amenable to virtual automation: while an unmarried RFID tagging device is free of 12 days of speed error waste Similar reductions in

production throughput waste would require physical capital financing, which is a good order of magnitude. Second, the Boeing and Lockheed Martin benchmarks reflect mature, multi-decade lean programs; Gateway will introduce satisfactory-practice virtual gear from the start rather than through many years of retrofits. These structural advantages are consistent with the literature on digital-first operations (Womack and Jones, 1996) which consistently show that organisations implementing lean principles with digital infrastructure from inception achieve 25-35% higher PCE than manufacturing-era benchmarks.

5.6. Transferability - Lunar Surface Base and Mars Missions

NASA's 2026 shift from Gateway to the Lunar Surface Base extends rather than reduces the framework's value. The MILP, CERs, VSM, and FMEA remain directly transferable, with only parameter changes such as higher ΔV , lower payload capacity, and added surface landing and logistics phases. For Mars transit logistics (2035+), the framework needs three changes: 26-month Earth–Mars launch cycles, propellant depot nodes, and Martian ISRU for fuel production. The MILP, Monte Carlo, and VSM architecture remains transferable, with estimated Mars base resupply costs of \$8–15B, confirming both the framework's scalability and future research value.

6. Conclusions and Future Work

6.1. Summary of Principal Conclusions

This dissertation set out to develop and validate an Integrated Systems Engineering and Cost Management Framework for lunar supply chain optimisation across the 2028-2035 Lunar Gateway programme. The analysis produces seven conclusions, each verified by independent computational and analytical evidence:

Table 29 Seven principal conclusions - reference number, text, research objective, and evidence traceability

Ref.	Conclusion	RO	Quantitative Evidence
C1	A MILP-optimised 11-mission schedule achieves LCC = \$1,247M - a verified \$225M (15.3%) saving against the \$1,472M heuristic baseline - within the 15-25% project target range.	RO2	§4.3.1; T4.9; GUROBI v10.0 cross-validation; App A, T A.5
C2	Dual-provider FH×9 + VC×2 is simultaneously cost-optimal and risk-optimal: P_fail 32%→18.4% at zero net premium, confirmed by both MILP Pareto and FMEA convergence.	RO2	§4.3.2; T4.11; CER-7; QFD EC-12 rank #1 (T4.1)
C3	EOQ-adapted safety stock at $k_s=1.65$ (SS=193 kg; \$11.6M/yr) delivers 95% service level with <5% 30-day stockout risk, saving \$25.2M over 7 years vs heuristic over-provisioned baseline.	RO2	§4.3.3; T4.10; (Silver, Pyke and Peterson, 1998); NASA GEMS
C4	ISRU integration generates NPV +\$32M (IRR=14.8%) at break-even Year 4.2 with 75% extraction efficiency; offsets three Dragon XL missions over 2028-2035 planning horizon.	RO4	§4.5.1; T4.16; NASA NTRS 20250003730
C5	VSM identifies 74.3% NVA in the 109-day logistics cycle; four-intervention future state achieves 75 days (PCE=30.7%), exceeding both Boeing (28.4%) and Lockheed Martin (29.1%) benchmarks.	RO3	§4.4; T4.13-T4.15; (TBM, 2024)
C6	Monte Carlo (n=10,000): P10=\$1.21B, P90=\$1.82B, CV=0.142; launch cost is the dominant uncertainty driver (Sobol $S_1=0.412$). The optimised result is achievable with >52% probability.	RO2	§4.2.3; F4.4; (Saltelli <i>et al.</i> , 2002)
C7	The integrated framework - QFD + 7 CERs + MILP + Monte Carlo + VSM/FMEA - constitutes a transferable, destination-agnostic template applicable to the post-2026 lunar surface base architecture and future Mars missions.	RO1-4	§5.6; T5.1; Programme Note §1.1.1

6.2. Contributions to Knowledge

This dissertation makes four original contributions to the published body of knowledge in space logistics, systems engineering, and cost management:

- **Contribution 1 - First integrated SE+optimisation framework for cislunar logistics:** No prior published work integrates QFD requirements analysis, validated parametric CERs, MILP optimisation, Monte Carlo probabilistic costing, and lean VSM within a single framework for NRHO or lunar logistics. This framework provides a replicable, quantitatively validated decision architecture for programme managers of human spaceflight supply chains at any cislunar destination.
- **Contribution 2 - Validated NRHO-specific CER dataset:** Seven CERs validated against 53 historical missions (1998-2024), including the first published external validation of Gateway-class mission cost estimates against Intuitive Machines IM-1 actuals (4.7% error). The power-law coefficient of 0.68 for NRHO destinations is a novel empirical finding, extending (Emmons, Swallow and Gaffney, 2004) ISS work to cislunar cost structures.
- **Contribution 3 - MILP formulation with endogenous ISRU integration:** Novel application of MILP to NRHO logistics with ISRU production as a time-varying endogenous supply variable - enabling the model to simultaneously optimise launch scheduling and ISRU exploitation. The resulting 16-month gap between M-6 and M-7, enabled by ISRU reaching 75% maturity, demonstrates a compounding saving mechanism not previously modelled in the published space logistics optimisation literature.
- **Contribution 4 - Quantified waste analysis for space logistics planning:** First application of VSM with full 8-waste quantification (34 waste instances, 81 NVA days, 74.3% NVA ratio) and FMEA integration to Gateway logistics planning. Establishes a 30.7% PCE target as an empirically benchmarked reference for future cislunar lean implementation programmes, with four specific kaizen interventions costed and time bounded.

6.3. Practical Recommendations for NASA Programme Management

6.3.1.R1 Adopt MILP-Derived 11-Mission Baseline as Programme Plan

The MILP-optimized schedule must appear as a gateway logistics program baseline instead of current heuristics, with a downsized two-provider FH×9 + VC×2 structure at the next vehicle selection milestone (target: 2027) Decision Support Tools (DST; Appendix A) Quarterly Re It should be operationally deployed for optimization as input parameters (release fees, ISRU production actuals, data calls) emerge as available. Cost-benefit: Validation of LCC savings toward DST improvements of \$225M <\$0.5M and maintenance cost benefit-to-fee ratio of 450:1.

6.3.2.R2 - Commission RFID Cargo Tagging System in Phase 1

RFID 100% cargo tagging is the single highest-BCR lean investment identified (\$4.4; Table 8): \$2.1M capital cost recovers \$11.5M over seven years through crew labour avoidance and cargo damage reduction, with a payback period of under 22 months. Commissioning in Phase 1 (2026-2028) maximises total programme benefit. The digital stowage manifest should be integrated with the MILP demand model to ensure real-time inventory accuracy feeds directly into the quarterly reoptimisation cycle (R1 above).

6.3.3.R3 - Standardise Safety Stock Policy at $k_s=1.65$ (SS = 193 kg)

The programme-wide safety stock policy should be standardised at $k_s=1.65$ (SS=193 kg; \$11.6M/yr) across all eight consumable categories, replacing the heuristic 300 kg policy currently assumed in NASA logistics planning documentation. Implementation cost is zero - this is a policy decision, not a hardware or software change. The annual saving of \$3.6M/yr relative to the 300 kg heuristic accumulates to \$25.2M over the seven-year horizon with no reduction in service level (95% maintained) and no additional crew risk (five percent 30-day stockout probability is below the NASA GEMS threshold of 10% for non-life-critical categories, with life-critical categories held at independent higher coverage per Table 17).

6.4. Future Work Directions

6.4.1.FW1 - Operational Data Validation Post-2028

As gateway or lunar surface base operations begin in 2028, actual assignment costs, launch masses, release frequencies, and ISRU build data will be available in prime time Systematic Bayesian updates of CER coefficients with each new assignment information point - replacing synthetic calibration information with real ones (CEH, 2020) will gradually reduce the P10-P90 uncertainty band from \$610M (observes this) towards the usual \$-one-hundred-and-fifty-200M range Rolling-horizon MILP re-optimization with updated ISRU production actuals helps 193 by about 10-15% The kilogram-preservation reserves can be reduced as soon as the actual three-year nominal demand version is verified.

6.4.2.FW2 - Dynamic Rolling-Horizon MILP Optimisation

The modern-day version favors a fixed 84 month horizon with fixed investment parameters. A rolling-horizon formula - a 24-month look-ahead window solving MILP every six months with updated inputs - can provide dynamic tariff optimization as program conditions evolve. The computational tractability of this approach is confirmed through the 4.2-second GUROBI remedy time of the present-day model; The 24-month rolling window can resolve to almost zero in eight seconds with heat-start initialization. Implementation as an operational planning tool - included with Gateway's Logistics Facts Engine - can create an authentic selection guide system instead of a one-time assessment.

6.4.3.FW3 - Mars Transit Logistics Extension

The framework's architecture is structurally compatible with Mars transit logistics, requiring three adaptations: (i) launch window replacement from monthly (NRHO) to 26-month synodic cycle (Earth-Mars); (ii) addition of in-transit propellant depot as a discrete logistics node with its own inventory balance constraint; (iii) ISRU model extension to Mars CO₂ reduction and polar ice electrolysis (Zubrin et al., 1991 Mars Direct propellant production model). Preliminary parametric analysis indicates a Mars base resupply LCC of \$8-15B over 20 years, with ISRU break even at Year 7-10 - a problem of the same analytical type as the Gateway study but at an order of magnitude greater scale. A PhD-level research programme extending this framework to Mars missions would constitute a significant contribution to the emerging field of interplanetary logistics engineering.

6.4.4.FW4 - Machine Learning Integration for Demand Forecasting

The demand assumption of the modern model (7,300 kg/12 months $\pm 12\%$ lognormal; $\sigma_d=21.4$ kg/day) is obtained from ISS intake statistics (Lickfold, S. and Jetter, 2019) adjusted for the Gateway team rotating schedule Real Gateway consumable calls by team interest profiles, . Can be correlated with EVA frequencies, heat-load seasonality, and medical initiative depth - none of which is captured

in the stationary lognormal version Gradient growth models (XGBoost, LightGBM) Efficient, demand forecast uncertainty over 15 years in ISS daily consumption records (NASA JSC, to be public). Want to reduce from $\pm 12\%$ to $\pm 5-7\%$, reduce the required safety-stocks through about 15 kg/class and generate about \$1.2M/12 months in compounding and preserve fee financial savings over the entire life of the program.

7. Self-Learning Plan and Reflective Evaluation

This chapter documents the non-public development program undertaken throughout, from initial talent audits (§7.1) to knowledge of milestones with evidence (§7.2), to learning used examples demonstrating research impact (§7.3), and reflective assessment with further-exploration CPD (§7.4). The self-learning plan was converted to a manufactured form in the first week (26 January 2026) and updated fortnightly. The execution of this without delay affected multiple analytical choices within the thesis, making it a quintessential matter of study technique instead of an independent reflective exercise.

7.1. Initial Skills Audit and Knowledge Gaps

A structured competency audit was conducted using a four-level proficiency scale (Novice / Developing / Proficient / Expert) mapped against the competencies required to execute each of the four research phases (Chapter 3). Four high-priority knowledge gaps were identified as posing material risk to project completion within the 13-week timeline.

Table 30 Initial competency audit - four high-priority knowledge gaps, required levels, initial levels, risk assessment, and learning strategy

KG	Knowledge Gap	Req. Level	Initial Level	Risk	Primary Source Used
KG1	NRHO orbital mechanics - ΔV budgets, launch windows, cislunar transfer dynamics needed to formulate valid MILP constraints (C-3, C-4)	Proficient	Novice	HIGH - invalid constraints - infeasible manifest	MIT OCW 16.89; NASA SEH; NTRS 20200001991 (Gateway Reference Mission); supervisor validation
KG2	Parametric cost estimation - log-linear CER regression, R^2 /MAPE validation, power-law coefficient interpretation needed for all seven CERs	Proficient	Developing - basic regression completed in statistics module	HIGH - CER errors propagate into all LCC outputs	NASA CEH v4.0 Ch.3; (Emmons, Swallow and Gaffney, 2004); Python <code>scipy.optimize.curve_fit</code> ; 53-mission dataset assembly
KG3	MILP formulation and optimisation - integer variables, binary decision variables, branch-and-cut solvers, sensitivity analysis	Expert - independent formulation of 203-variable, 156-constraint problem	Novice - undergraduate LP exposure only	CRITICAL - MILP is the primary optimisation deliverable	(Raghavendra and de Weck, 2024) AIAA; GUROBI Python API docs; MIT 18.06 linear algebra refresher; MATLAB Optimization Toolbox; three toy MILP problems solved independently

KG4	Value Stream Mapping and lean process improvement - VSM construction, waste quantification, PCE calculation, FMEA integration	Proficient - independently produce current/future-state VSM with quantified 8-waste analysis	Developing - conceptual lean exposure in MEM programme	MEDIUM - VSM quality affects credibility of Discussion chapter	(Rother and Shook, 1998), (Ohno, 1988); TBM Consulting Boeing lean case study (2024); MEM module VSM workshop
-----	---	--	--	--	---

7.2. Learning Plan: Milestones and Evidence

7.2.1. Milestone 1 - NRHO Orbital Mechanics (Week 2, February 2026)

Learning approach: MIT OCW 16.89 lecture modules on orbital mechanics and mission design; NASA Gateway Reference Mission (NTRS 20200001991); Space Mission Analysis and Design textbook (*Space mission engineering: The new SMAD*2011).

Evidence of competency: The independently derived NRHO ΔV value range (14.0 km/s Earth-NRHO; 10 m/s/12 months station-keeping) - matches the NASA reference enterprise within 1.2%. Calculation of monthly projection window length from synodic period evaluation. These values were included in the MILP system (Table 4.VIII; Appendix B) as hard constraints C-3 (projection window) and C-4 (ΔV finance). Without recognizing this, constraints C-three and C-4 would be absent, which is a physically impossible occurrence when ignoring orbital mechanics.

7.2.2. Milestone 2 - Parametric CER Development (Week 5, February 2026)

Learning approach: NASA CEH v4.0, Chapter 3 (parametric cost estimation methodology); PCEC training materials; (Emmons, Swallow and Gaffney, 2004) ISS CER methodology (primary literature precedent); Python workshop applying `scipy.optimize.curve_fit` and stats models OLS for log-linear regression with cross-validation.

Evidence: NASA assembled a 53-initiative historical fee data set from NTRS, GAO Price Examination, and Business Enterprise Press Releases (1998-2024). developed seven CERs - all reaching $R^2 \geq 0.85$ and $MAPE \leq 9.2\%$. In opposition to Intuitive Machines IM-1 (\$117M real vs \$123M predicted; 4.7% errors), external validation showed external validity at best to be an outside validator. The CER equations, information, and validation results are documented in all respects in Tables in Appendix A, Table A.2, and are reproducible from the supplied Python code.

7.2.3. Milestone 3 - MILP Formulation and Solution (Weeks 6-8)

Learning approach: (Raghavendra and de Weck, 2024) AIAA space logistics MILP (principal reference); GUROBI Python API documentation and tutorials; MIT 18.06 Linear Algebra (online refresher); MATLAB Optimization Toolbox `intlinprog` reference manual; three toy MILP problems solved independently (facility location, knapsack, vehicle routing) before formulating the gateway problem.

Evidence: formulated the full Gateway MILP from first principles - 203 binary decision variables, 87 continuous variables, 156 constraints across seven constraint types (Table 15). Solved independently with both `intlinprog` (MATLAB; 1.8 s) and GUROBI v10.0 (Python; 4.2 s) and confirmed identical results (MIP gap $< 0.1\%$), demonstrating solver-agnostic formulation quality. Generated Pareto frontier revealing the non-obvious dual-provider finding (Figure 14). All formulation, code, and cross-validation documented in Appendix A, §A.3 and Appendix B.

7.2.4. Milestone 4 - VSM and Lean Analysis (Weeks 8-9)

Learning approach: (Rother and Shook, 1998) 'Learning to See' VSM textbook (canonical reference); (Ohno, 1988) seven-waste classification; (TBM, 2024) Boeing Lean Conversion Record for PCE Benchmarking; MIL-STD-1629A FMEA Priority; MEM Module VSM Sensible Workshop.

Evidence: The 8-stage current-state VSM (Table 20) mapped with quantification of 34 waste instances in 8 categories, normal NVA eighty-one days (74.3%). The design focused on a 5-intervention future-nation VSM seventy-five days (PCE 30.7%), benchmarked against Boeing (28.4%) and Lockheed Martin (29.1%) The FMEA (47 failure modes, Table IV.3) independently confirmed the fate-nation hazard profile. Put-up mitigation RPN reductions verify that lean interventions are consistent with chance. Full current day and destiny nation VSM diagrams produced in draw.io (Figures 19-20).

7.3. Evidence of Applied Learning in Project Decisions

Table 31 Applied learning - four examples mapping acquired competencies to specific research decisions and traceable dissertation outputs.

Applied Learning	Skill	Project Decision Influenced	Traceable Impact
AL1	NRHO orbital mechanics (KG1)	MILP constraint formulation: ΔV budget (C-4) and launch window (C-3) constraints included from first principles. Without these, the MILP would have produced infeasible manifests exceeding vehicle ΔV capability.	Table 15, C-3 & C-4; §4.3.1 feasibility verification; Appendix B constraint derivation
AL2	CER regression and validation (KG2)	Decision to validate all CERs externally against IM-1 actuals - upgrading model credibility from 'parametric estimate' to 'externally validated'. Without CER validation knowledge, this would not have been attempted.	§4.2.1, Table 18; §5.2.1 literature comparison; §5.4.1 Validation Check 1
AL3	MILP Pareto sensitivity analysis (KG3)	Decision to generate a full cost-risk Pareto frontier (Figure 16) rather than reporting a single-scenario MILP result, revealing the non-obvious dual-provider finding. This is the dissertation's most impactful analytical outcome.	§4.3.2; Figure 14; C2 in Table 29; R1 in Table 26
AL4	VSM 8-waste quantification (KG4)	Decision to quantify waste at instance level (34 instances, by category) rather than aggregate lead time, enabling R2 (RFID tagging) to be identified as the highest-BCR lean investment and costed with specificity.	§4.4.1-2; R2 §6.3.2

7.4. Reflection on Effectiveness and Continuing Professional Development

7.4.1. Reflection on Learning Plan Effectiveness

The dependent know plan - initial capacity audit, focused hole finding, immediate research software, and manager verification - proved extremely powerful within the 13-week constraint. Three elements were particularly crucial: (i) talent auditing was completed in Week 1 before any gaps became critical-course bottlenecks; (ii) each skill is maintained to thesis work within one week of acquisition, increasing the immediate reinforcing loop between study and exercise; (iii) External verification of technical explanations was provided at supervisor meetings in weeks 2, five, and eight, capturing MILP constraint method errors before propagating them into the results. The most challenging detail was the MILP formula (KG3), which required three weeks of testing before independent nuisance

components feasibly changed in retrospect, starting the MILP study in week 3 (alongside literature assessment) instead of week 6 could reduce scheduling pressure within the analysis period.

7.4.2.Continuing Professional Development Plan

Three CPD priorities are identified, each grounded in gaps surfaced during the dissertation process:

- CPD1 - Advanced uncertainty quantification (6-12 months):** The dissertation employs Latin Hypercube Sampling and first-order Sobol indices (Saltelli *et al.*, 2008) Advanced topics - Gaussian process metamodels, polynomial chaos expansion, and adaptive sampling for computationally expensive simulations - would enable real-time DST uncertainty quantification. Target credential: IISE Certified Analytics Professional or equivalent. Practical goal: reduce DST reoptimisation time from quarterly to monthly.
- CPD2 - Machine learning demand forecasting (3-6 months):** Future Work Direction FW4 (§6.4.4) requires gradient boosting and recurrent neural network proficiency. Target: Stanford CS229 Machine Learning; practical application to 15 years of publicly available ISS daily consumption data (NASA JSC). Expected outcome: reduce σ_d from $\pm 12\%$ to $\pm 5\text{-}7\%$, reducing safety stock by ~ 15 kg/category.
- CPD3 - Research dissemination (6-24 months):** Target peer-reviewed publication: AIAA Space Logistics Conference abstract (Q3 2026); Acta Astronautica journal submission (Q4 2026). Industry engagement: seek placement with a space logistics organisation (SpaceWorks Engineering, NASA contractor, or equivalent) to validate the framework under operational constraints. Longer-term: consider PhD extension to the Mars transit logistics direction (FW3, §6.4.3).

Master's appointment confirmed that complex, multi-perspective engineering analysis - when relied upon through rigorous research design and continued through iterative objective mastering can produce new, program-applicable findings within a 13-week constraint The 4 future painting guidelines and three identified above The CPD priorities create a credible and formidable study program that extends the thesis contribution to the open problem of Cislunar interplanetary supply chain optimization.

Appendices

All documents below, including the appendices, which are integral to this project are mirrored on the public GitHub repository at <https://github.com/jagzimmer/lunar-gateway-supply-chain> (open access, no login).

Find all Appendix files in Addition Driver Below:

https://drive.google.com/drive/folders/18v5HtWfb_wh7owTYZhANA7AwZ3LU9W4N?usp=sharing

Appendix Name	Description	File
Appendix A	Decision Support Tool: Computational Verification Suite	Drive Link
Appendix B	Full MILP Model Formulation (Mathematical & Solver)	
Appendix C	Complete FMEA Table - All 47 Failure Modes	
FMEA SCOPE AND METHODOLOGY		

Standard: MIL-STD-1629A Task 101 Failure Mode and Effects Analysis

RPN = Severity (S) × Occurrence (O) × Detectability (D) | Each dimension: 1 (best) to 10 (worst)

Scope: Six supply chain functions (F-1 to F-6) + cross-system ICD interfaces |

Total: 47 failure modes

Priority threshold: RPN ≥ 80 = HIGH (mandatory mitigation) | 4 failure modes exceed this threshold

Chapter 4 reference: Table 9 presents top 10 RPNs (§4.1.3). This appendix documents all 47 modes.

Appendix D

Monte Carlo Distribution Inputs and Sobol Sensitivity Indices

Appendix E

Gantt Charts, Project Timeline, and Strategic Roadmap

Appendix F

CER Calibration Dataset: 53-Mission Historical Database

Appendix G

Cost Model Excel - Gateway_Cost_Model_Interactive.xlsx

The Gateway Cost Model Interactive Excel file provides a standalone Monte Carlo simulation environment compatible with both Oracle Crystal Ball and Palisade @RISK add-ins. It replicates the Python monte_carlo.py computation in an accessible no-code format for NASA programme managers and non-technical stakeholders.

Sheet / Tab	Content	Monte Carlo Use
DASHBOARD	Summary dashboard: LCC P10/P50/P90, saving \$225M, MILP optimal vs baseline; charts auto-update on recalculation	No - output display only
CER INPUTS	Seven CER equations with parameter cells (highlighted blue); adjustable coefficients; sensitivity sliders	Yes - define Assumptions on blue cells (launch cost, demand, reliability)
LCC MODEL	Full 84-period LCC calculation linking all 7 CERs; MILP schedule as input; ISRU ramp formula	Yes - LCC total cell = Crystal Ball Forecast cell
MONTE CARLO	Pre-configured Crystal Ball/@ RISK distributions for 8 parameters (Table D.1); seed=42; n=10,000 trials	Yes - run Simulation from add-in toolbar; Latin Hypercube sampling
SENSITIVITY	Tornado chart data table; Sobol S ₁ pre-loaded from Python results; parameter ranking	No - pre-loaded from Python computation
SAFETY STOCK	EOQ-adapted safety stock calculator; k _s slider from 1.28 to 2.33; holding cost vs risk curve	Optional - single scenario
ISRU MODEL	ISRU NPV/IRR calculator; break-even year; 3 efficiency scenarios (60%/75%/90%)	Optional - scenario analysis

Table F 1 Gateway Cost Model Excel - sheet contents and Crystal Ball/@RISK Monte Carlo usage

To run Monte Carlo simulation: (1) Open **Gateway_Cost_Model_Interactive.xlsx** in Excel with Crystal Ball or @RISK add-in installed; (2) Navigate to MONTE CARLO sheet; (3) Blue cells are Assumptions (input distributions already defined); (4) Yellow cell (LCC Total) is the Forecast cell; (5) Click Run Simulation (n=10,000, Latin Hypercube, seed=42); (6) Results match dissertation P10=\$1,210M, P50=\$1,472M, P90=\$1,820M.

Appendix H

QFD_Lunar_Gateway_Supply_Chain

[Drive Link](#)

Appendix I

Abbreviations List

[Drive Link](#)

Appendix J Complete File Registry

Project Deliverables - File Index

Lunar Gateway Supply Chain Optimisation

GitHub repository (public, downloadable): <https://github.com/jagzimmer/lunar-gateway-supply-chain>

#	File Name / Location	Type	Purpose	How to Open
1	data/Lunar Gateway Project Plan Professional.xlsx	Excel (.xlsx)	Full project Gantt - 40 tasks, 13-week schedule, WBS hierarchy, milestones	Microsoft Excel / LibreOffice Calc
2	data/Gateway Cost Model Interactive.xlsx	Excel (.xlsx)	Life-cycle cost model with Crystal Ball / @RISK Monte Carlo inputs	Excel + Crystal Ball or @RISK add-in
3	html/MILP Gantt ProjectLibre Style.html	HTML (interactive)	ProjectLibre-style Gantt - WBS columns + hover tooltips	Chrome / Firefox / Edge - no install
4	html/MILP Gantt Chart.html	HTML (interactive)	Phase-banded MILP Gantt with swimlane milestones	Chrome / Firefox / Edge
5	html/F4_11 Strategic Roadmap .html	HTML (interactive)	2026-2035 strategic roadmap: 4 lanes, S1-S4 strategy badges	Chrome / Firefox / Edge
6	drawio/F4_9 VSM Current State.drawio	draw.io	Figure 18 - Current-state Value Stream Map (155 d lead time, 21.1% PCE)	app.diagrams.net or draw.io desktop
7	drawio/F4_10 VSM Future State.drawio	draw.io	Figure 19- Future-state VSM with kaizen bursts (post-improvement)	app.diagrams.net
8	python/milp_optimization_gurobi .py (folder /python/ - all 6 scripts)	Python (.py)	MILP optimisation (Gurobi) + Monte Carlo + CER regression + figure generators	Python 3 + gurobipy / numpy / matplotlib
9	matlab/milp_optimization.m	MATLAB (.m)	MATLAB MILP, Monte Carlo, N2 diagram, VSM, dashboard, master figure generator	MATLAB R2024a+ (Optimization Toolbox)
10	wall_trackers/ (5 PDFs)	PDF (A3, 300 DPI)	Five A3 wall posters - timeline, chapter progress, dashboard, habits, NASA imagery	Any PDF viewer / print A3
11	figures/ - all dissertation PNGs (F4.1 - F4.11)	PNG (300 DPI)	All eleven dissertation figures - see GitHub repo for download	Any image viewer / Word insert
12	setup/GUROBI_SETUP.md	Markdown (.md)	Gurobi WLS licence + macOS installer + verification script Gurobi University of Leicester academic Licence Attached in GitHub	Any text editor / renders on GitHub

#	File Name / Location	Type	Purpose	How to Open
13	jagzimmerz.atlassian.net - LG board	Jira Software	Research task tracker - 40 issues, 4 epics, 2026 timeline	Browser
14	jagzimmerz.atlassian.net - MOLGSC board	Jira Business	MILP Gantt online - 16 issues, 2028-2034 mission timeline	Browser

Table J 1 Complete Appendix J file registry - all 9 files/resources with type, size, purpose, and access method

Note

All software models (**Python and MATLAB**), **draw.io diagrams**, **Excel workbooks**, and dissertation figures are hosted on the project's public GitHub repository at <https://github.com/jagzimmer/lunar-gateway-supply-chain>. The repository is open for download by anyone - no login required. Individual file links above point directly to each artefact on GitHub; the */figures/* folder contains every dissertation image at 1000 DPI rather than listing each PNG separately in this table.

References:

Space mission engineering: *The new SMAD* (2011) , 1st edn, Hawthorne, CA: Microcosm Press.

Akao, Y. (1990) *Quality function deployment: Integrating customer requirements into product design*. Cambridge, MA: Productivity Press.

Emmons, D.L., Swallom, M. and Gaffney, C. (2004) 'Cost estimating for space systems: Historical accuracy and validation', *Journal of Cost Analysis and Parametrics*, 11(1), pp. 1–22.

Government, A.O. (2024a) *Artemis programs: NASA should document and communicate plans to address gateway's mass risk*. Washington, DC: United States Government Accountability Office. Available at: <https://www.gao.gov/products/gao-24-106878>

Government, A.O. (2024b) *NASA: Actions needed to improve planning and cost estimating for the lunar gateway program*. Washington, D.C.: U.S. Government Accountability Office. Available at: <https://www.gao.gov/products/gao-24-106878>

Griffin, M.D. and French, J.R. (1995) *Space vehicle design*. 2nd edn. Reston, VA: AIAA Education Series.

Gurobi Optimization, L.L.C. (2024) *Gurobi optimizer reference manual, version 10.0*. Available at: <https://www.gurobi.com>

Herman, J. and Usher, W. (2017) 'SALib: An open-source python library for sensitivity analysis', *Journal of Open Source Software*, 2(9), pp. 97. Available at: <https://doi.org/10.21105/joss.00097> .

Hillier, F.S. and Lieberman, G.J. (2010) *Introduction to operations research*. 9th edn. New York: McGraw-Hill.

Jones, H.W. (2023) 'Take material to space or make it there? ISRU economics for lunar operations', *AIAA ASCEND Conference Proceedings*,

Lickfold, C. and Jetter, M. (2019) 'Systematic underinvestment in the global space sector: An explanation and potential remedies', *Space Policy*, 47, pp. 34–43. Available at: <https://doi.org/10.1016/j.spacepol.2019.02.001> .

Lickfold, S. and Jetter, F. (2019) 'Logistics and supply chain management for cislunar space operations', *Acta Astronautica*, 162, pp. 412–428. Available at: <https://doi.org/10.1016/j.actaastro.2019.06.018> .

Liker, J.K. and Franz, J.K. (2011) *The toyota way to continuous improvement: Linking strategy and operational excellence*. New York, NY: McGraw-Hill.

Machines, I. (2024) *IM-1 nova-C mission summary report*. Houston, TX: Intuitive Machines LLC.

Massachusetts Institute of Technology Lean, Aerospace Initiative (2002) *Value stream analysis and mapping for product development*. Cambridge, MA: MIT Press. Available at: <https://dspace.mit.edu/bitstream/handle/1721.1/7347/Value%20Stream%20Analysis%20and%20Mapping.pdf>

McKay, M.D., Beckman, R.J. and Conover, W.J. (1979) *A comparison of three methods for selecting values of input variables in the analysis of output from a computer code*.

NASA (2026) *NASA unveils initiatives to achieve america's national space policy: Gateway pause and lunar base announcement*. Available at: <https://www.nasa.gov/news-release/nasa-unveils-initiatives-to-achieve-americas-national-space-policy/>

NASA (2025a) *Ice mining experiment (IME-1): ISRU water extraction performance data*. National Aeronautics and Space Administration. Available at: <https://ntrs.nasa.gov/citations/20250003730>

- NASA (2025b) *Lunar gateway programme status update and CDR sync closeout*. Washington, DC: National Aeronautics and Space Administration.
- NASA (2024a) *Dragon XL gateway logistics services mission requirements*. Washington, D.C.: National Aeronautics and Space Administration. Available at: <https://www.nasa.gov/dragon-xl>
- NASA (2024b) *Lunar gateway program cost and schedule report*. Washington, D.C.: National Aeronautics and Space Administration. Available at: <https://www.nasa.gov/gateway>
- NASA (2024c) *Lunar gateway requirements and architecture overview*. Houston, TX: National Aeronautics and Space Administration. Available at: <https://ntrs.nasa.gov/>
- NASA (2023) *Artemis I mission performance report*. Washington, DC: National Aeronautics and Space Administration.
- NASA (2016) *Systems engineering handbook*. Washington, D.C.: National Aeronautics and Space Administration. Available at: <https://www.nasa.gov/seh/>
- NASA (2015) *NASA cost estimating handbook version 4.0*. Washington, D.C.: National Aeronautics and Space Administration. Available at: https://www.nasa.gov/offices/ocfo/functions/Cost_Estimating_Handbook_Ver4.html
- NASA (2011) *NASA risk management handbook*. Washington, DC: National Aeronautics and Space Administration. Available at: https://www.nasa.gov/pdf/637168main_NASA-SP-2011-3422.pdf
- NASA Cost, A.D. (2020) *NASA cost estimating handbook, version 4.0*. Washington, DC: National Aeronautics and Space Administration Office of the Chief Financial Officer. Available at: <https://www.nasa.gov/ocfo/ppc-corner/nasa-cost-estimating-handbook-ceh/>
- NASA Gateway, P.O. (2024) *Gateway logistics architecture study: 2028–2035 operational baseline*. Houston, TX: National Aeronautics and Space Administration Johnson Space Center.
- NASA ISS, P.O. (2025a) *International space station logistics and maintenance: 25 years of operations data*. Houston, TX: National Aeronautics and Space Administration. Available at: <https://ntrs.nasa.gov/>
- NASA ISS, P.O. (2025b) *ISS cargo manifest database 2000–2025: Resupply mission summary*. Houston, TX: National Aeronautics and Space Administration Johnson Space Center. Available at: (Accessed:
- NASA Johnson (2023) *Gateway artist's concepts*
- NASA Space Technology, M.D. and Sanders, G.B. (2025) *Progress review of NASA lunar ISRU development: 2019 to 2025*. NASA Technical Reports Server. Available at: <https://ntrs.nasa.gov/citations/20250003730>
- Ohno, T. (1988) *Toyota production system: Beyond large-scale production*. Portland, OR: Productivity Press.
- Raghavendra, S. and de Weck, O.L. (2024) *Modeling and optimization for space logistics operations: Review of state of the art*. Forum. AIAA,
- Raghavendra, S., de Weck, O.L. and Simchi-Levi, D. (2023) 'Space logistics modeling and optimization: Review of the state of the art', *Journal of Spacecraft and Rockets*, Available at: <https://doi.org/10.2514/1.A35982> .
- Rother, M. and Shook, J. (1999) *Learning to see: Value stream mapping to add value and eliminate muda*. Brookline, MA: Lean Enterprise Institute.
- Rother, M. and Shook, J. (1998) *Learning to see: Value stream mapping to add value and eliminate muda*. Cambridge, MA: Lean Enterprise Institute.
- Sage, A.P. and Rouse, W.B. (2009) *Handbook of systems engineering and management*. 2nd edn. Hoboken, NJ: Wiley-Interscience.
- Saltelli, A. et al. (2008) *Global sensitivity analysis: The primer*. Chichester, UK: John Wiley & Sons.
- Saltelli, A. et al. (2002) 'Sensitivity analysis in practice: A guide to assessing scientific models',
- Saunders, M.N.K., Lewis, P. and Thornhill, A. (2019) *Research methods for business students*. 8th edn. Harlow, United Kingdom: Pearson Education.
- Shishko, R., Ebbeler, D.H. and Fox, G. (2004) 'NASA technology assessment using real options valuation', *Systems Engineering*, 7(1), pp. 1–13. Available at: <https://doi.org/10.1002/sys.10052> .
- Silver, E.A., Pyke, D.F. and Peterson, R. (1998) *Inventory management and production planning and scheduling*. 3rd edn. New York: Wiley.
- SpaceNews, E.S. (2026) *NASA halts work on gateway to develop a lunar base*. Available at: <https://spacenews.com/nasa-halts-work-on-gateway-to-develop-a-lunar-base/>
- TBM, C.G. (2024) *Aerospace demand is soaring: How applying lean practices can increase production capacity*. TBM Consulting Group. Available at: <https://tbmcg.com/resources/blog/aerospace-demand-is-soaring-how-lean-practices-can-increase-production-capacity/>
- Technology, A. (2024a) *Peregrine mission one anomaly investigation report*. Pittsburgh, PA: Astrobot Technology Inc. Available at: <https://www.astrobot.com/peregrine>
- Technology, A. (2024b) *Peregrine mission one post-mission report*. Pittsburgh, PA: Astrobot Technology Inc.
- Thales, A.S. (2025) *Lunar gateway's HALO pressurised module — preparation for shipment to the united states*. Cannes, France: Thales Alenia Space. Available at: <https://www.thalesaleniaspace.com/en/news/lunar-gateways-halo-pressurized-module-preparation-shipment-united-states>
- Womack, J.P. and Jones, D.T. (1996) *Lean thinking: Banish waste and create wealth in your corporation*. New York: Simon & Schuster.

Student Self-reflection on performance

All students must complete the following sections for every piece of work they submit using this template. The aim of this is to help you use feedback more effectively to improve your marks and your skills as a professional engineer. This section is not formally marked, but your tutor may use it when discussing your work with you.

Describe how you have used AT LEAST ONE of the following sources of information to improve this piece of work:

1.) (PREFERRED) Feedback from previous assignment(s). This can be from the same module or from a previous module or previous year of study (e.g. comments from 1st year lab formal reports should be used to help improve your 2nd year lab formal reports).

2.) The marking criteria or rubric provided for this assignment.

3.) The Department Technical Writing Handbook for Students.

I used principally (2) the EG7302 marking rubric and (3) the Department Technical Writing Handbook, supplemented by (1) feedback from the EG7302 Project Proposal submitted earlier in this module.

Rubric-driven self-audit. After completing the first full draft I mapped every section against the High-Distinction descriptors in the project-report rubric (Critical Analysis, Methodology, Results, Discussion, Reflection, Presentation). Two HD gaps were identified, discussion depth and validation breadth and addressed by adding the five-cross-check validation matrix in §5.4 and a quantified limitations table (§5.5).

Proposal-feedback uplift. The Proposal feedback flagged scope and traceability as risks. In response I added the QFD - MILP-variable traceability chain in Chapter 3 and the Research Objective / Research Question alignment matrix on the contents page.

Technical Writing Handbook. The Handbook's guidance on figure/table captions, equation numbering, and the Harvard reference style was applied across all 60 main pages, all 21 figures, and all 28 tables; the appendices follow the same caption convention so the reader can navigate either body or appendix in isolation.

Are there any aspects of this work that you would specifically like the marker to comment/or advise on? For example: "I wasn't sure if my figure formatting looked professional and would appreciate feedback on this aspect"

- Validation depth. Section 5.4 reports five independent cross-checks (Python vs MATLAB MILP, @RISK vs Python LHS, CER MAPE vs NASA CEH band, VSM PCE vs aerospace benchmarks, Sobol vs analytical). Is this sufficient for the HD band, or would a sixth check have strengthened it?
- March-2026 pivot. I argue the framework transfers from orbital Gateway to lunar surface base without re-derivation (§6.1); is this "durability" claim adequately evidenced or post-hoc?
- MILP accessibility. Chapter 3.4 sets out 156 constraints; is the level pitched appropriate for an MEM (non-OR) examiner?