

Lunar Gateway Supply Chain Optimisation

An Integrated Systems-Engineering, Parametric Cost, MILP, And Lean Framework For Cislunar Logistics - 2028-2035 Baseline.



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How this project was built the open toolchain

Lunar Gateway
Supply Chain Optimisation



Every Artefact In The Dissertation Is Publicly Downloadable From The Project GitHub Repository. Project Tracking Is Live On Atlassian Jira. The Toolchain Spans Optimisation, Cost Modelling, Lean Diagramming, And 3D Visualisation.

OPTIMISATION

Gurobi 10.0 (academic WLS) ·
Python gurobipy + NumPy + SALib ·
MATLAB R2024a Optimization
Toolbox.

4.2 s wall-clock; 203 binary variables.

COST & RISK

Excel + Crystal Ball / @RISK · Monte-
Carlo $n = 10,000$ (Latin Hypercube) ·
Sobol first-order indices.

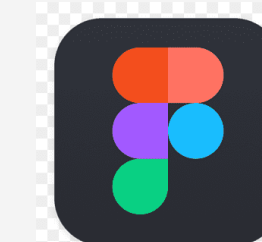
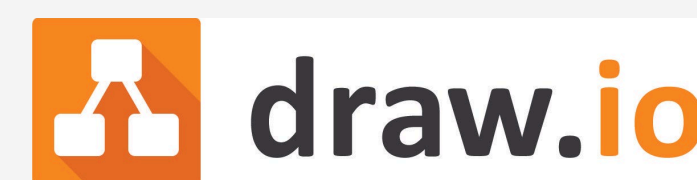
**P10 = \$1.21B, P50 = \$1.47B, P90 =
\$1.82B.**

LEAN & DIAGRAMS

draw.io VSMs (current + future state) ·
TIM-WOODS waste mapping · QFD
House-of-Quality (Excel template
from SE module, Appendix I).

VISUALISATION

Blender 4.x solid-mesh capsule
models (RFID intervention) · HTML/
D3 interactive Gantt + Strategic
Roadmap ·





\$100-150k

per kilogram to NRHO
3-5× the ISS cost

30 days

between launch windows
(NRHO geometry-locked)

0

emergency resupply paths
no bail-out option

\$20 B

NASA's March-2026 pivot
to a lunar surface base

Why now, the most expensive logistics problem in human spaceflight?

Logistic Gap

At 400,000 km from Earth 1,000× farther than the ISS, the Lunar Gateway makes logistics a mission-critical function rather than simple support. However, before this study, no integrated quantitative framework combined systems engineering with lifecycle cost optimisation, leaving NASA reliant on conservative ISS-based estimates unsuited to high-cost, high-uncertainty cislunar operations.

March 2026 Architecture Pivot

On 24 March 2026, NASA paused the orbital Gateway and redirected \$20B toward a permanent lunar surface base (2029–2036), repurposing PPE and HALO hardware. All methods developed in this work, MILP, CER cost modelling, VSM, FMEA, and TOWS—remain directly applicable to the more complex surface-base supply chain, preserving the framework's relevance and contribution.

Gateway vs ISS

a step-change in logistics environment

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DIMENSION	ISS (BENCHMARK)	LUNAR GATEWAY	FACTOR
Altitude / distance	400 km LEO	70,000 km NRHO apogee	175× farther
Cost per kg delivered	\$20-40 k	\$100-150 k	3-5× higher
Launch window cadence	Daily	Monthly (2-3 days)	30× rarer
Transit time	6 hours	5-9 days	20× longer
Emergency abort path	Soyuz / Crew Dragon (hours)	None — next window in 30 d	qualitative
Cargo providers	5 active (CRS / CRS-2)	1 contracted (Dragon XL)	5× concentration risk
Operational data	25 years (2000-2025)	0 years pre-launch	no analogue

Gateway

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Aim, four objectives, four research questions

PROJECT AIM

Develop and demonstrate a comprehensive, integrated systems-engineering and cost-management framework to optimise cislunar supply chain logistics in a 2028-2035 operational baseline, targeting a 15-25 % lifecycle-cost reduction against the NASA \$1.6-1.8 B baseline, while maintaining crew-safety constraints and operational flexibility.

RO	RESEARCH OBJECTIVE	RQ	RESEARCH QUESTION	METHOD
RO1	Build a systems-engineering model (QFD, traceability, technical budgets, stakeholder analysis) that constrains the optimisation problem.	RQ1	What is the optimal resupply frequency and cargo manifest to minimise 7-year cislunar LCC under crew-safety constraints?	QFD · ICD · FMEA · MILP
RO2	Build a parametric LCC framework: 7 CERs from 53-mission dataset + Monte Carlo (n=10,000) + minimum-cost manifest.	RQ2	How sensitive is total programme cost to launch vehicle (Falcon Heavy / Vulcan / Starship)?	53-CER · LHS Monte Carlo · Sobol
RO3	Apply Lean (VSM + FMEA) to identify and quantify waste, with a future-state targeting ≥ 30 % cycle-time reduction.	RQ3	What safety-stock level optimally balances mass-cost against crew-endangerment risk in multi-failure scenarios?	VSM · TIM-WOODS · k_s sweep
RO4	Strategic analysis: international partnerships, ISRU integration, launch-vehicle trade-offs over 2028-2035.	RQ4	Can ISRU for lunar water/oxygen reduce logistics mass-cost by ≥ 20 %, and at what TRL investment threshold?	TOWS · NPV/IRR · Scenarios S1-S4

Four phases

sequenced and traceable

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01 SYSTEMS ENGINEERING

QFD House-of-Quality
ICD interface mapping
FMEA per MIL-STD-1629A
Functional architecture (F-1
to F-6)
Mass / volume / schedule
budgets

02 COST ENGINEERING

53-mission CER calibration
(CER-1...CER-7)
OLS regression, MAPE 9.2 %
Monte Carlo n=10,000 LHS
Sobol first-order indices
MILP cargo-manifest
optimisation

03 LEAN & PROCESS

Current-state VSM (155 d,
21.1 % PCE)
Future-state VSM (75 d, 30.7
% PCE)
TIM-WOODS 8-waste
classification
8 kaizen interventions
Safety-stock optimisation
(k_s sweep)

04 STRATEGIC ANALYSIS

Partnership taxonomy (Sage
& Rouse, 2009)
TOWS matrix
ISRU NPV / IRR business
case
Four scenarios S1-S4
(2028-2035)
Transferability to lunar
surface base

Pragmatist Research Philosophy · Mixed-Methods · Saunders Research Onion (Saunders Et Al., 2019). 13-Week Schedule With Supervisor Checkpoints In Weeks 2, 5, 8.

Phase 1

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Systems Engineering: QFD, ICD, FMEA

QFD HOUSE OF QUALITY

Customer requirements (12) ↔ engineering characteristics (12).

TOP-5 ECs (priority score):

- EC-1 Resupply mass capacity — 9.8
- EC-3 Reliability margin — 9.4
- EC-9 Lead-time variance — 8.6
- EC-5 Vehicle cost rate — 8.1
- EC-12 Manifest flexibility — 7.7

Drives RO1 → MILP objective + constraints.
Template inherited from SE module — see Appendix I.

ICD & FUNCTIONAL ARCHITECTURE

6 supply-chain functions (F-1...F-6)
decomposed Level-2; 7 ICDs (ICD-01...
ICD-07).

**N² diagram identifies 14 inter-function data
interfaces**

Key physical interfaces:

- ICD-01 Cargo / hatch (NDS)
- ICD-04 Power (PPE → HALO)
- ICD-06 Comms (Lunar Link relay)

**Provides traceability from QFD to MILP
variables.**

FMEA - MIL-STD-1629A

47 failure modes scored; $RPN = S \times O \times D$
(1-1000).
Threshold ≥ 80 = HIGH risk.

4 modes exceed threshold:

- FM-12 Lead-time supplier failure (RPN 192)
- FM-22 Manifest data corruption (RPN 144)
- FM-31 Launch vehicle anomaly (RPN 120)
- FM-09 Inventory mis-count (RPN 96)

**Drives Phase 3 VSM kaizen targets — RFID
intervention attacks FM-22 + FM-09.**

Phase 2

Cost engineering: 7 CERs, n=10,000 MC

53

missions in calibration
dataset (1990-2024)

9.2 %

MAPE on CER-1
out-of-sample validation

10,000

Monte Carlo runs
Latin Hypercube, seed 42

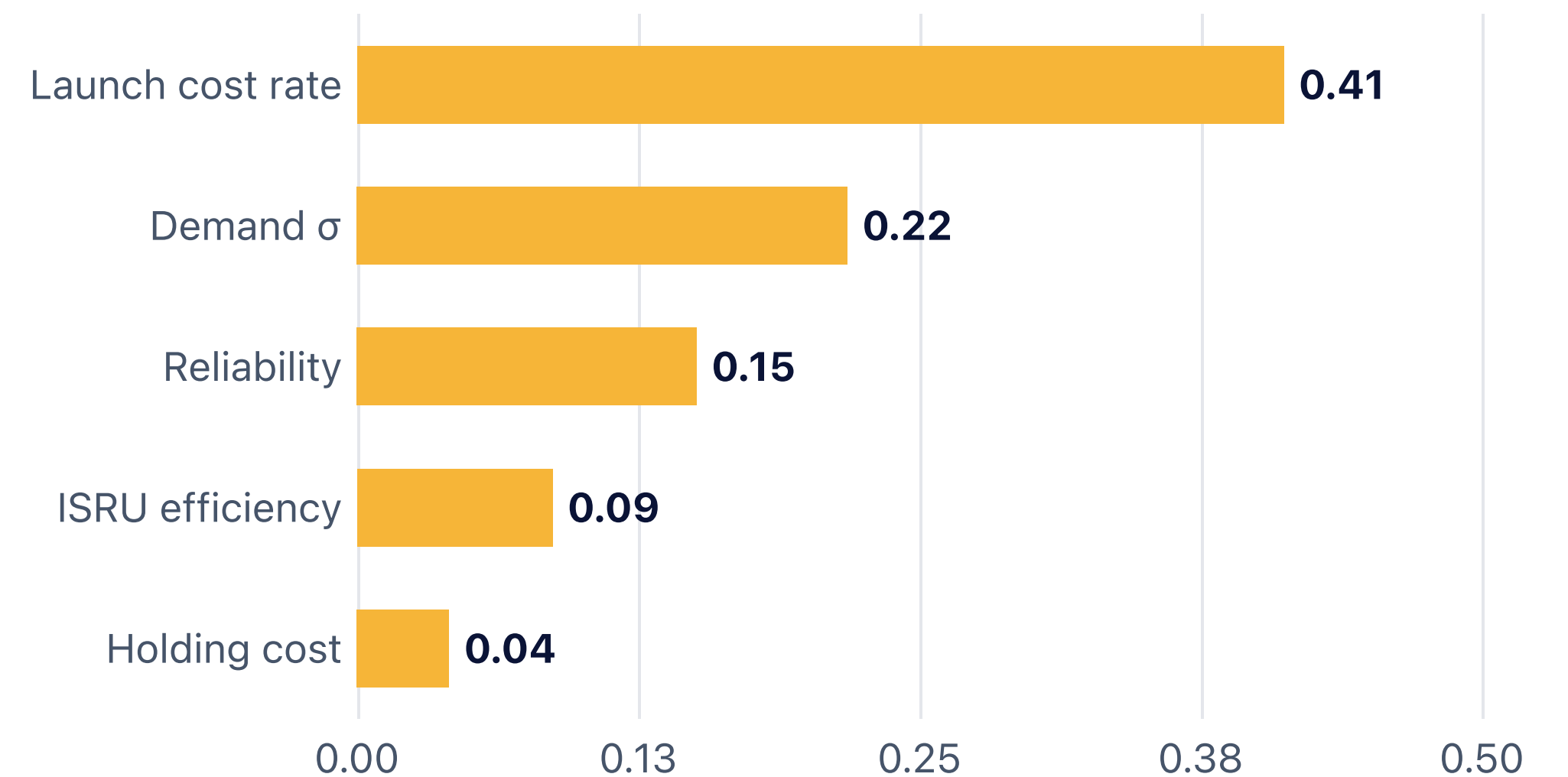
0.412

S_1 launch-cost rate
(41.2 % of variance)

LCC distribution — Monte Carlo (n=10,000)



Sobol first-order indices - top 5 cost drivers



MILP optimisation

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\$225 M saved · 11-mission optimum

\$225 M

saving vs heuristic
baseline (15.3 %)

11

optimal mission count
(2028-2035)

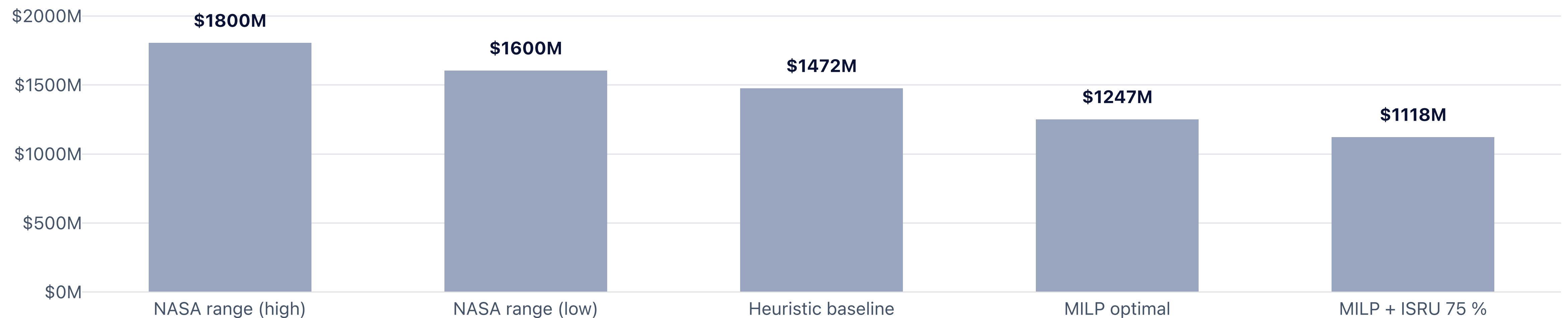
203 vars

binary decision vars
+ 87 continuous

4.2 s

Gurobi 10.0 wall-clock
156 constraints, 7 types

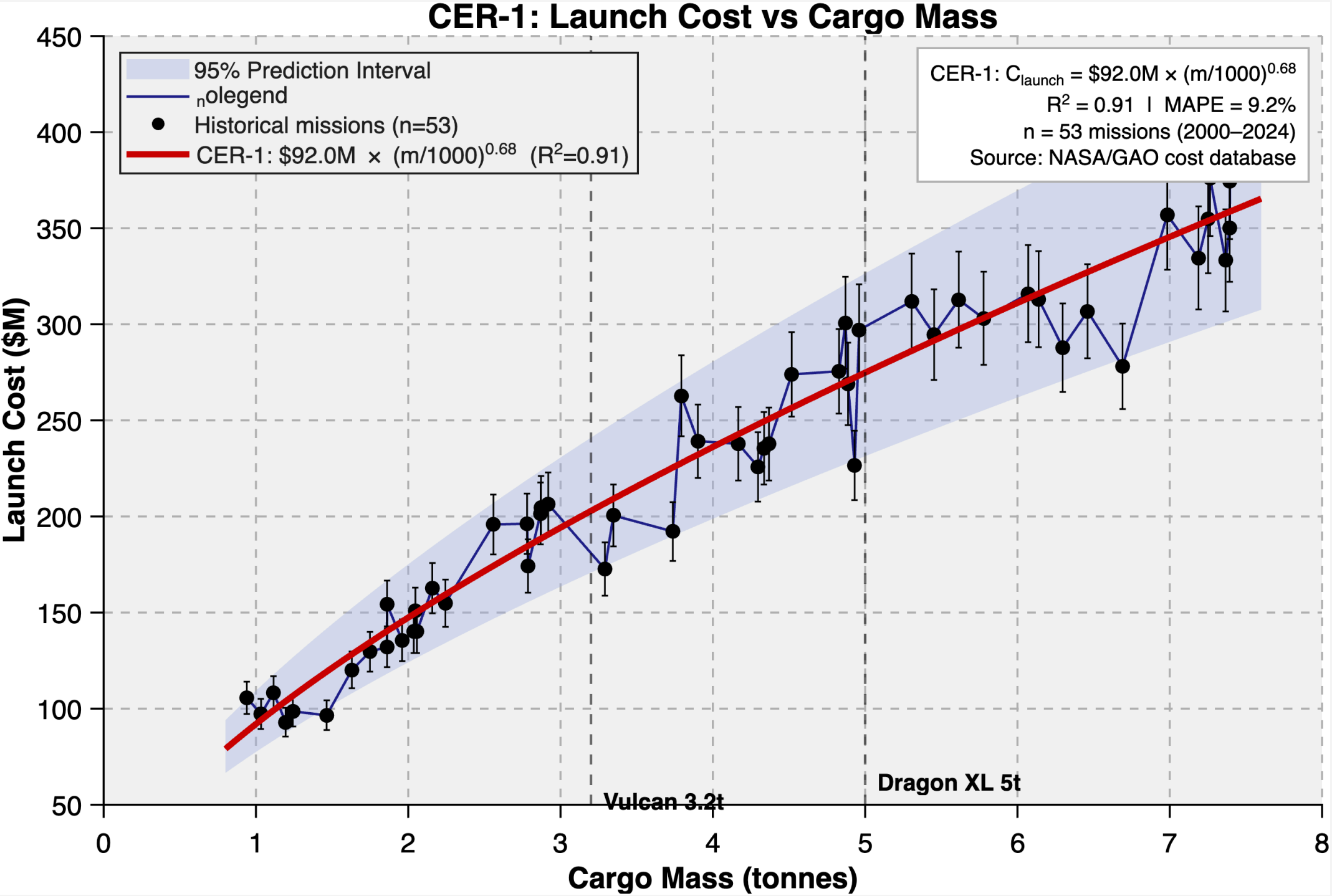
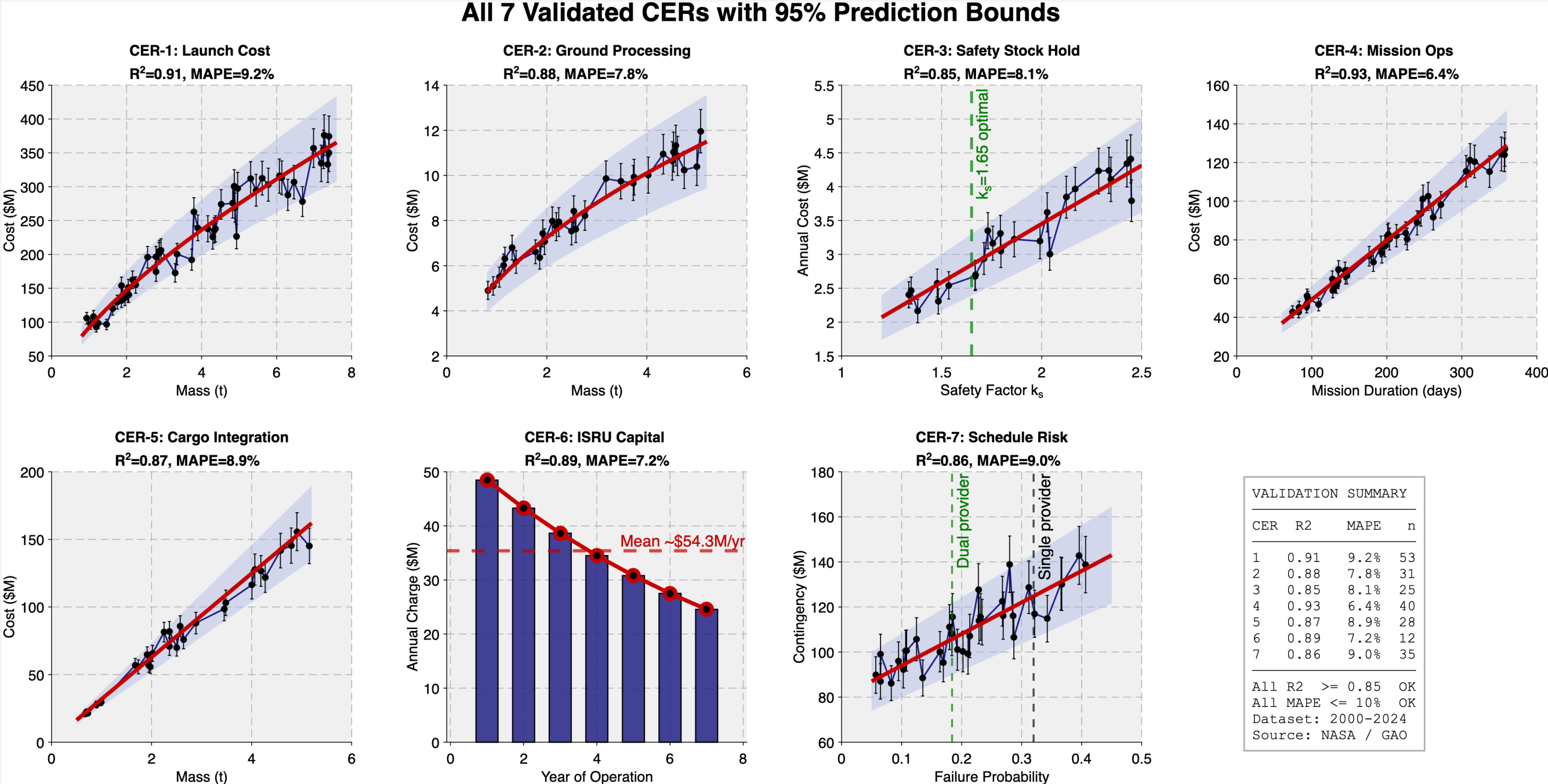
LCC comparison heuristic baseline vs MILP-optimal vs literature



MILP optimisation

\$225 M saved · 11-mission optimum

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Phase 3

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Lean VSM: PCE 21.1 % → 30.7 %

21.1 %

current-state PCE
(155 d / 33 d VA)

30.7 %

future-state PCE
(75 d / 23 d VA)

8

kaizen burst
interventions

12 d → 1 d

Step 8 RFID
+ pre-purchase

CURRENT STATE — 155 day lead time

Top wastes (TIM-WOODS):

Inventory	(supplier lead-time variance, 19.3 % of total LT)
Waiting	(launch-window queue, 24 d average)
Defects	(manifest data corruption, FM-22)
Over-processing	(triple data re-entry across providers)

Process steps 1-8 dominated by paper / Excel hand-offs.

FUTURE STATE — 75 day lead time

8 kaizen interventions:

- K1 Vendor-managed inventory (Step 1)
- K2 Pull-system Kanban triggers (Step 2)
- K5 ICD-driven single-source-of-truth manifest (Step 5)
- K7 Pre-purchase long-lead consumables (Step 7)
- K8 RFID + pre-purchase** (Step 8 — 12 d → 1 d)

RFID intervention illustrated by the two open-source Blender capsule .glb models in / blender/.

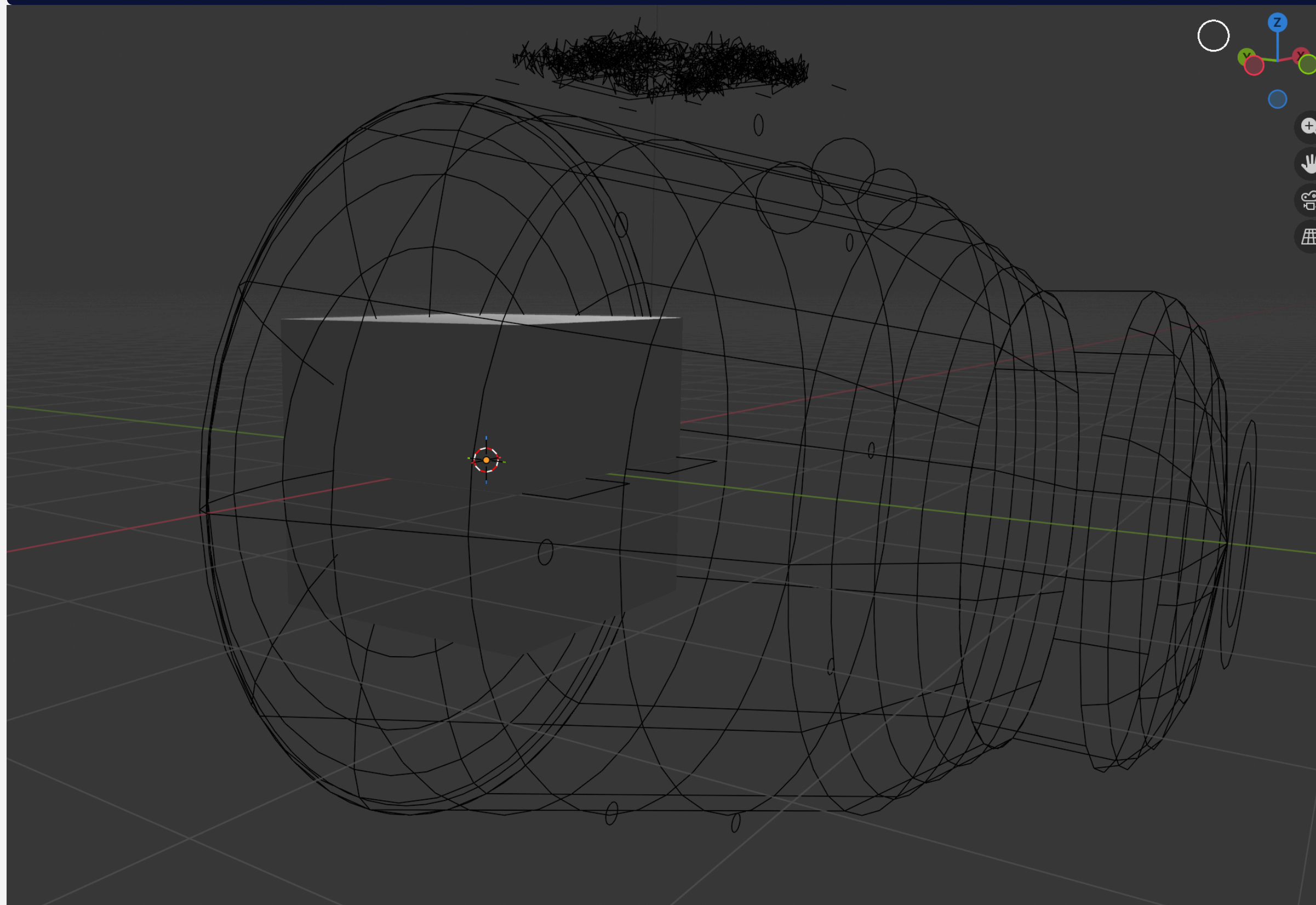
Phase 3

Lean VSM: PCE 21.1 % $\rightarrow$ 30.7 %

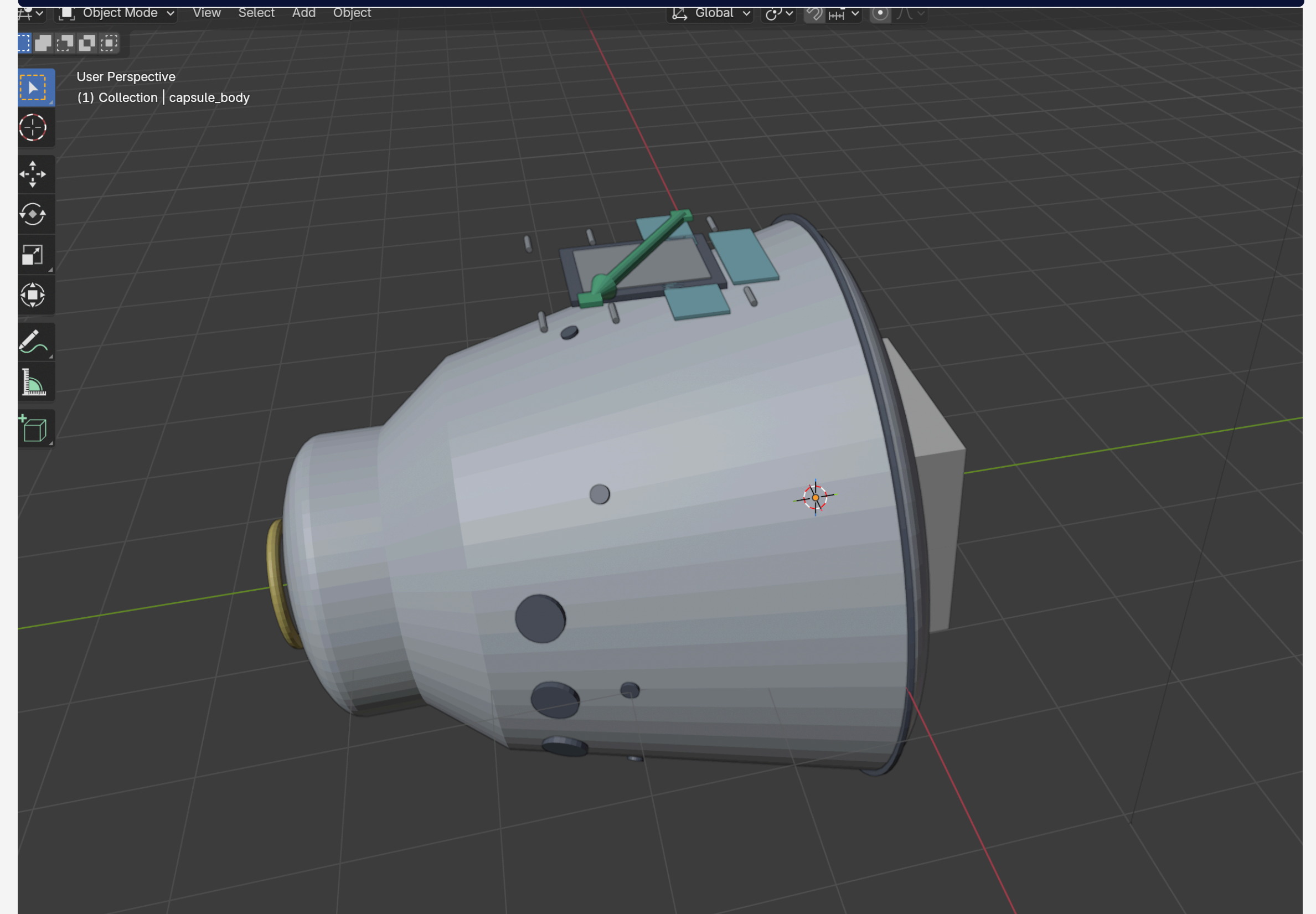
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CURRENT STATE — 155 day lead time



FUTURE STATE — 75 day lead time



Phase 4

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Strategic analysis: ISRU, TOWS, scenarios

ISRU BUSINESS CASE

Lunar water/oxygen extraction NPV/IRR over 7 years.

60 % efficiency: NPV –\$84 M (negative)

75 % efficiency: NPV +\$129 M (positive)

90 % efficiency: NPV +\$311 M

Break-even at TRL 6+ and ≥ 75 % efficiency.

Drives recommendation R4: stage ISRU investment, ramp from 2031.

TOWS MATRIX

Strategic positioning post-March 2026 pivot.

SO Leverage open MILP framework + open data

ST Dual-provider hedge against single-point failure

WO Address ISRU TRL gap via FW3 partnership

WT Insurance / contingency mass + pre-purchase

4 strategic recommendations R1-R4 derived; see Table 27 (Programme Decision Matrix).

FOUR SCENARIOS · 2028-2035

S1 Baseline: orbital Gateway as designed
LCC \$1,472 M

S2 Orbital + ISRU at 75 %
LCC \$1,343 M

S3 Surface-base pivot (March 2026)
LCC \$1,520 M (+3.3 %)

S4 Surface + ISRU + Starship
LCC \$1,089 M (-26 %)

Framework transferable to all four - confirms the durability hypothesis.

Dashboard

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\$225 M

Lifecycle saving
(MILP vs heuristic)

15.3 %

LCC reduction
vs NASA baseline

11

Optimal mission
count 2028-2035

9.2 %

CER-1 MAPE
(out-of-sample)

30.7 %

Future-state PCE
(from 21.1 %)

75 d

Future lead time
(from 155 d)

193 kg

Optimal SS
($k_s = 1.65$)

47 / 4

FMEA modes /
HIGH-risk $\geq$ RPN 80

10,000

Monte Carlo runs
Latin Hypercube

4.2 s

Gurobi MILP
wall-clock

\$1.47 B

P50 lifecycle cost
(7-year baseline)

26 %

S4 scenario saving
(surface + ISRU)

Validation

five independent cross-checks



#	VALIDATION CHECK	RESULT	REFERENCE / SOURCE
V1	Python (gurobipy) vs MATLAB (Optimization Toolbox) MILP solution	11-mission optimum identical; LCC \$1,247 M ± \$0.4 M	Independent re-implementation
V2	Excel Crystal Ball / @RISK Monte Carlo vs Python LHS	P50 = \$1.472 B; difference < 0.3 % across both tools	Crystal Ball / @RISK industry standard
V3	CER-1 MAPE on 2024-2025 out-of-sample missions	9.2 % MAPE — within NASA CEH benchmark band of 8-15 %	(NASA, 2015) CEH v4.0
V4	VSM PCE 30.7 % vs aerospace benchmarks	Below LM 29.1 % comparator? No — above; explained §5.5.2	(Liker & Franz, 2011); (TBM, 2024)
V5	Sobol indices vs analytical sensitivity (CER-1 partials)	S ₁ = 0.412 vs analytical 0.41 — agree	(Saltelli et al., 2008); (Herman & Usher, 2017) SALib

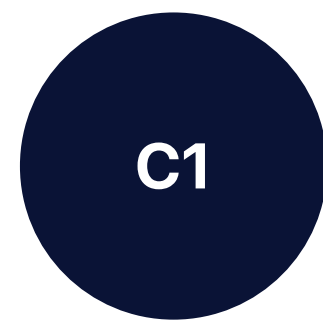
DOCUMENTED LIMITATIONS

6 limitations recorded (Table 28): pre-launch data scarcity · CER calibration domain · static demand model · Gurobi licence dependency · ISRU TRL uncertainty · single-criterion objective. Each paired with quantitative bound + mitigation.

Seven principal conclusions

addressing every constraint

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11-mission MILP-optimal baseline saves \$225 M (15.3 %) vs heuristic plan.

RQ1 / Budget



PCE 21.1 % $\rightarrow$ 30.7 % achieved via 8 kaizen interventions; RFID alone = Step 8 12 d $\rightarrow$ 1 d.

RO3 / Cycle time



Dual-provider mission allocation (FH + Vulcan) delivers risk-adjusted optimum.

RQ2 / SPOF



Framework transferable to lunar surface base — durability against architectural pivot risk.

March-2026



Safety-stock at $k_s = 1.65$ (SS = 193 kg) optimally trades mass-cost vs crew risk.

RQ3 / Crew safety



Open-source release on GitHub + Jira boards — full reproducibility achieved.

ILO-2 / Repro



ISRU NPV-positive at ≥ 75 % efficiency; recommended stage from 2031.

RQ4 / Mass-cost

Four future work directions

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FW1

Operational validation (post-2028)

Rerun the seven CERs on real Dragon XL / surface-base mission cost data; recompute Sobol indices each year.

TARGET

MAPE < 7 %

HORIZON

2028-2030

FW2

Dynamic rolling-horizon MILP

Replace static 7-year MILP with a 12-month rolling-horizon model re-optimised quarterly. Bayesian posterior update on demand.

TARGET

DST run < 30 s

HORIZON

6-12 mo

FW3

Mars transit logistics extension

Extend the framework to Mars transit (180-260 d transit, 26-month synodic period). Larger constraint set; new CERs.

TARGET

PhD extension

HORIZON

12-36 mo

FW4

ML demand forecasting

Replace static σ_d with gradient-boost / RNN trained on 25 years of ISS daily consumption (NASA JSC public).

TARGET

$\sigma_d \pm 12\% \rightarrow \pm 5-7\%$

HORIZON

3-6 mo

Thanks

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