Reliability and Cost Modeling of Reusable Launch Vehicles

Predicting, Preventing and Mitigating the Cost of Failure

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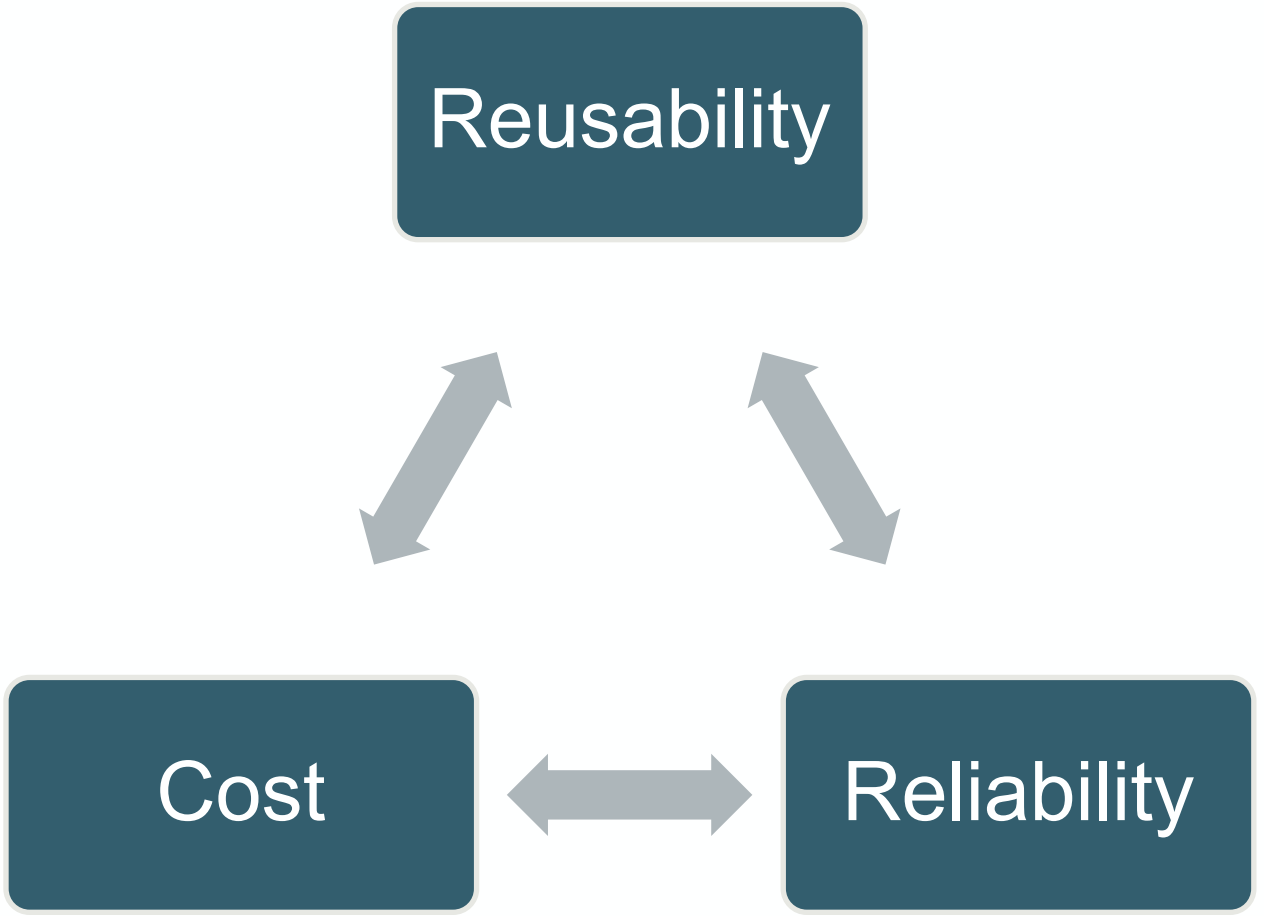
TABLE OF CONTENTS

INTRODUCTION – State of the Space Launch Industry



INTRODUCTION – Main Challenges

Reusability

- Recovery Hardware
- Retrieval and Refurbishment Operations

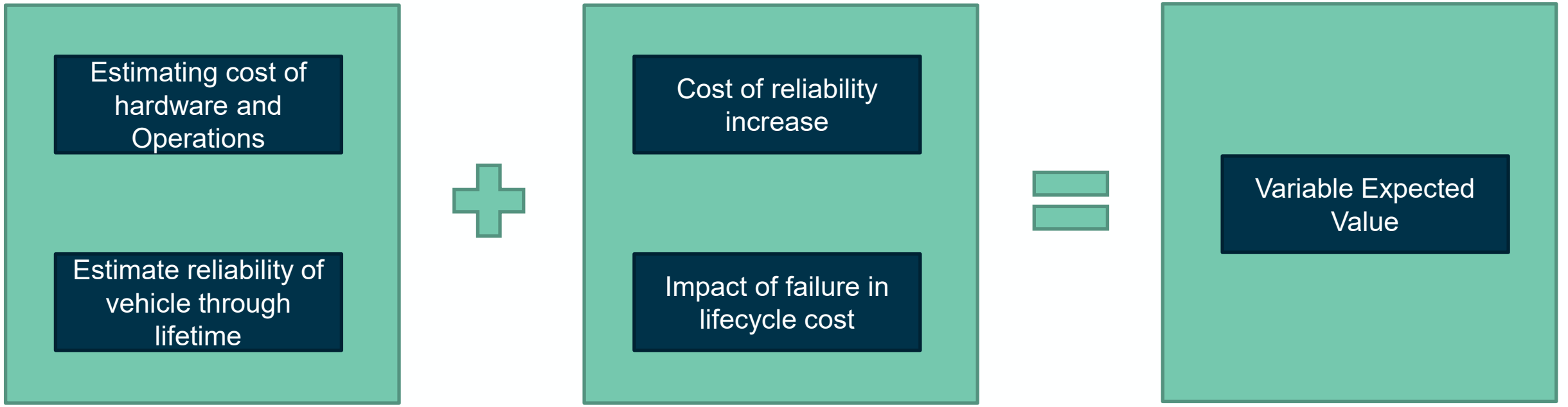
Reliability

- Reliability Decrease
- Aging Effect

Cost

- Reusable Hardware and Operations
- Reliability Increase
- Cost of Failure

INTRODUCTION – Model Synthesis

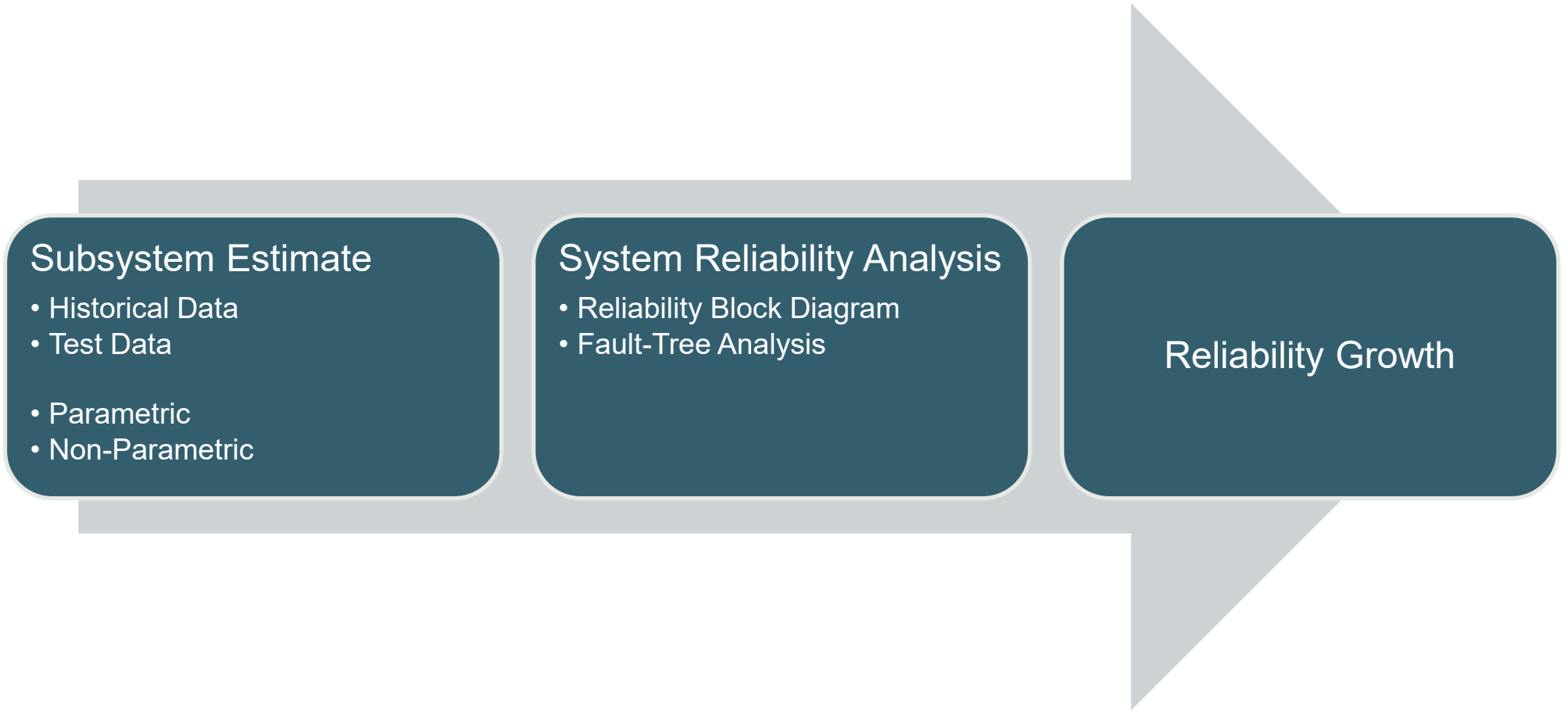


Classic modeling
- Cost model
- Reliability model

Intersection of cost and reliability
- New CERs
- Failure cost model

Product of linked model

RELIABILITY MODEL - Methodology



RELIABILITY MODEL – Propulsion System modeling requires further detail

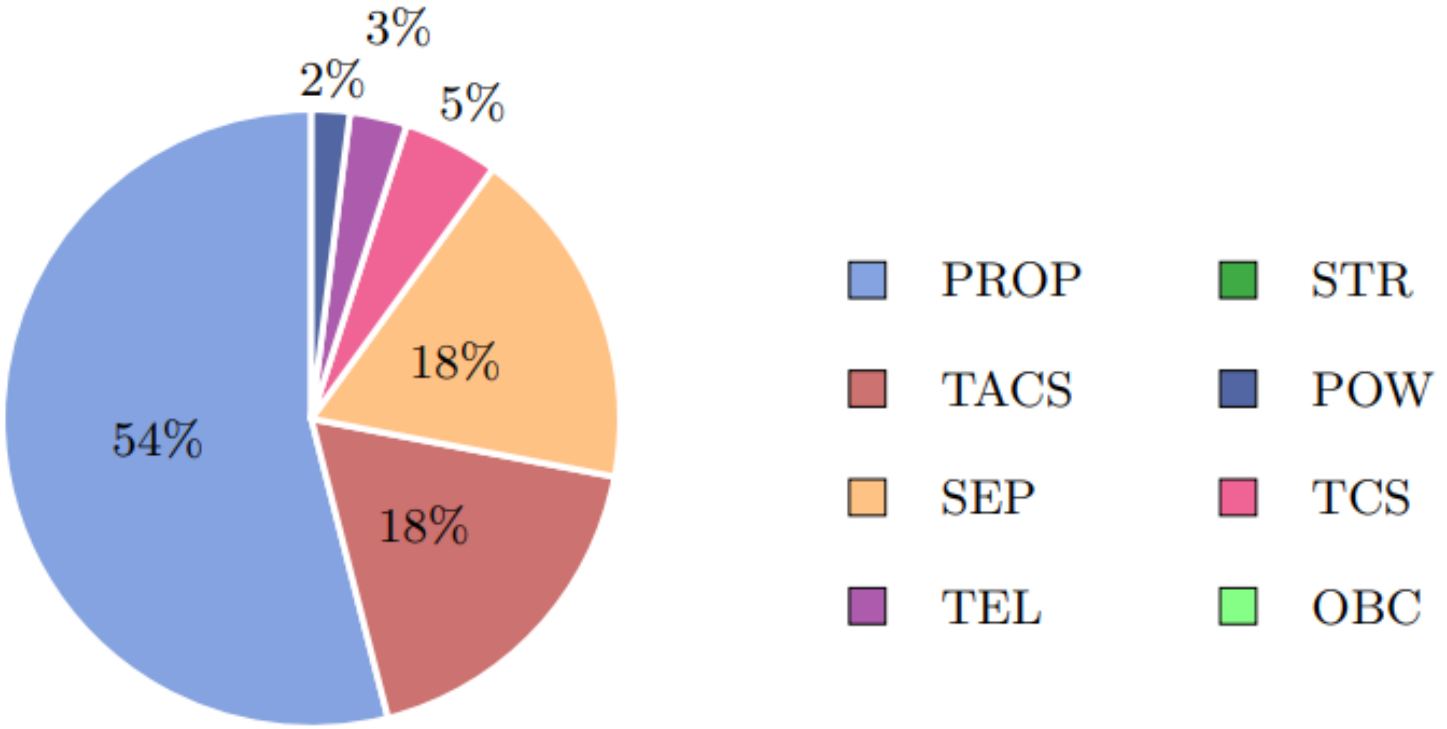
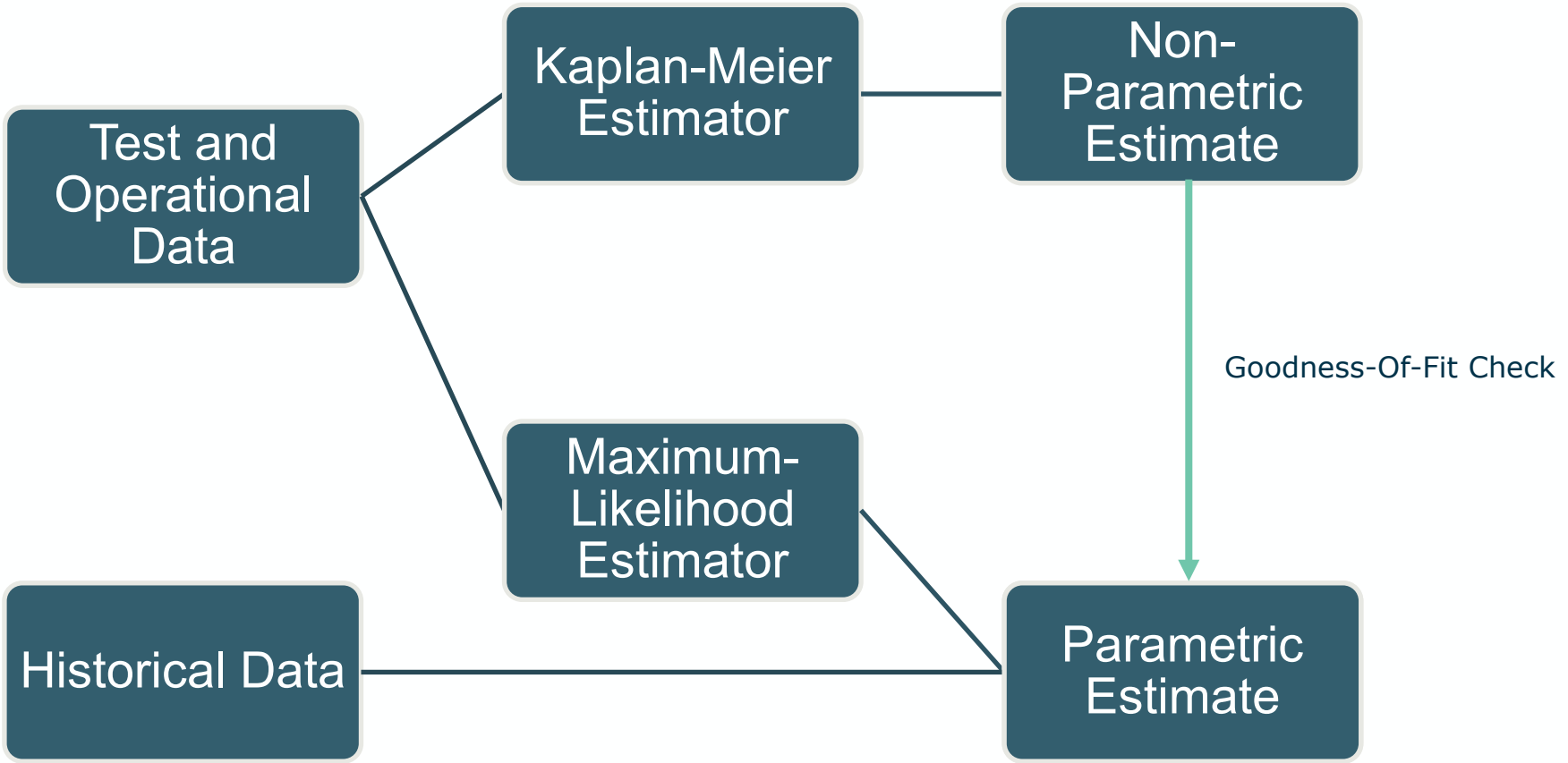


Fig. 1 - Launch failures in the past 15 years classified by subsystem [1].

- Propulsion System (PROP).
- Trajectory and Attitude Control System (TACS).
- Power Storage and Distribution System (POW).
- Telemetry (TEL).
- On-Board Computer (OBC).
- Thermal Control System (TCS).
- Structures (STR).
- Separation Systems (SEP).

RELIABILITY MODEL – Subsystem Estimate



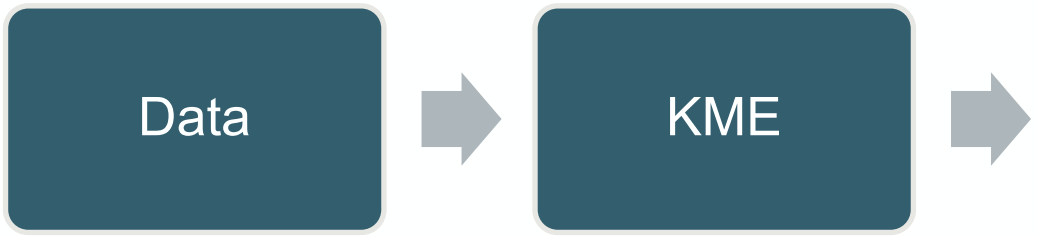
RELIABILITY MODEL – Subsystem Estimate
Merlin Engine Example

Flight Number	Number of Failures
1	3
5	1
6	1

Fig. 1 – Representation of a right-censored data set [2].

Flight Number	Number of Right-Censored Elements
1	154
2	160
3	20
4	40
5	19
6	19
7	10
10	10
11	20
12	10

RELIABILITY MODEL – Subsystem Estimate
Merlin Engine Example



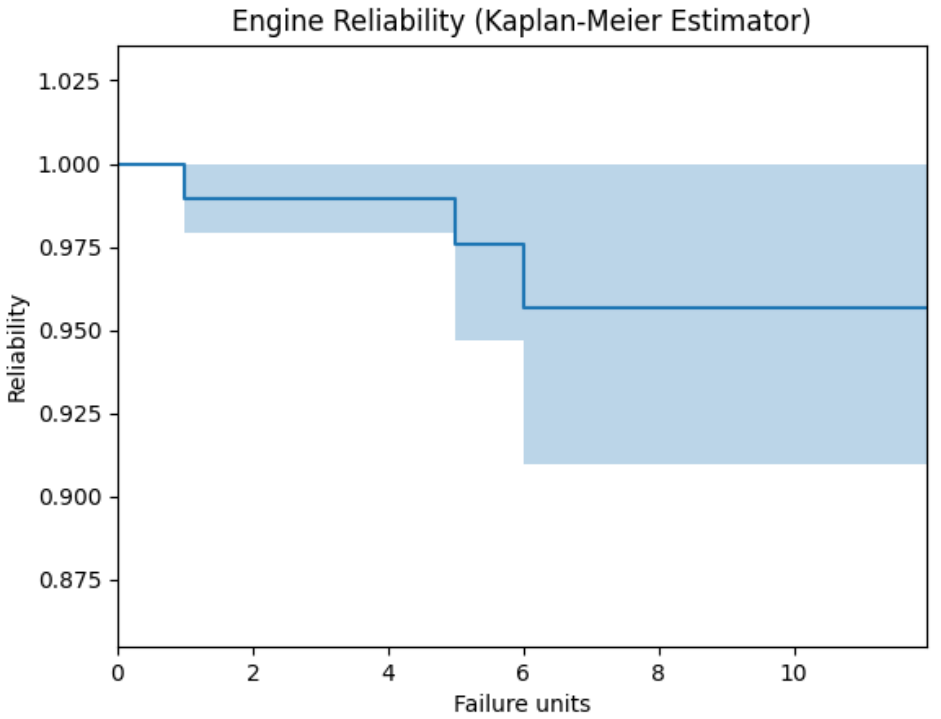
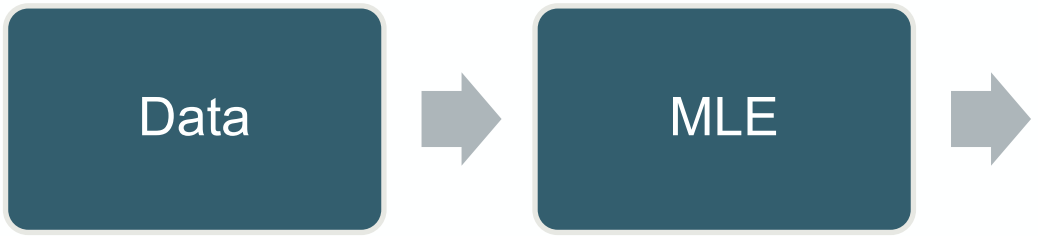


Fig. 3 – KME applied to Merlin Engine data.

RELIABILITY MODEL – Subsystem Estimate
Merlin Engine Example



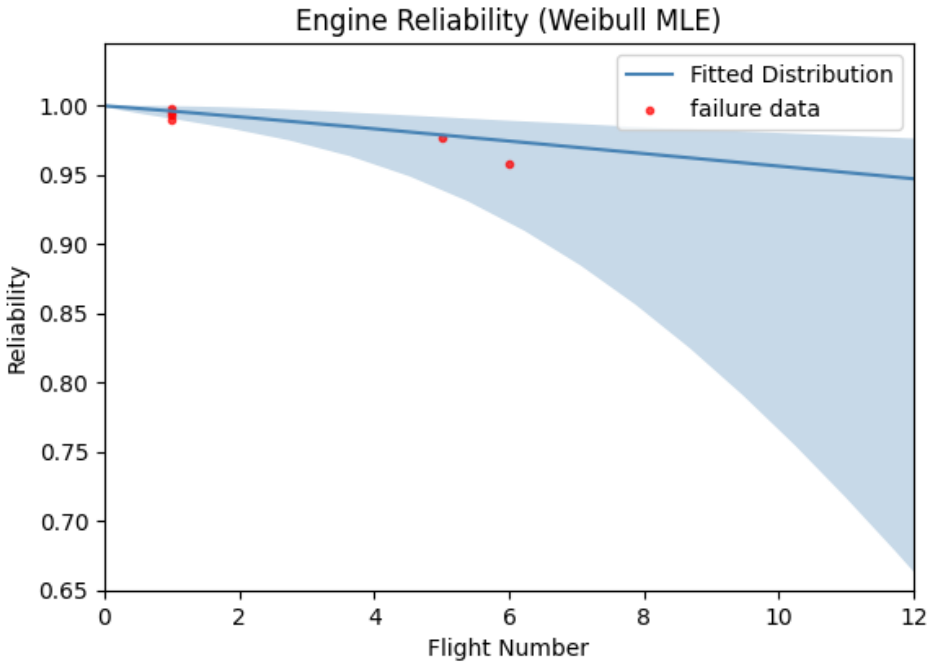


Fig. 4 – MLE applied to Merlin Engine data assuming Weibull distribution.

RELIABILITY MODEL – Subsystem Estimate
Merlin Engine Example

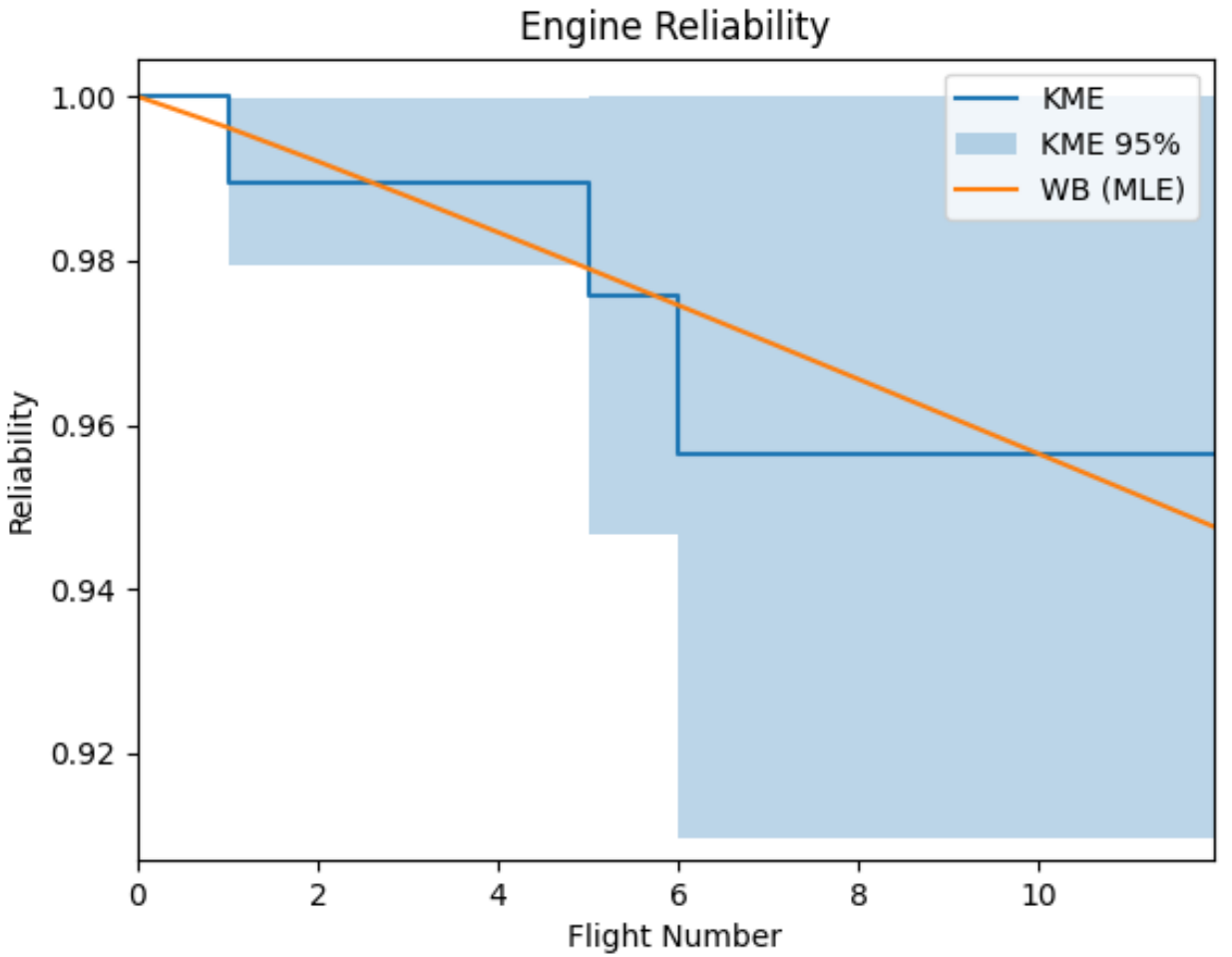
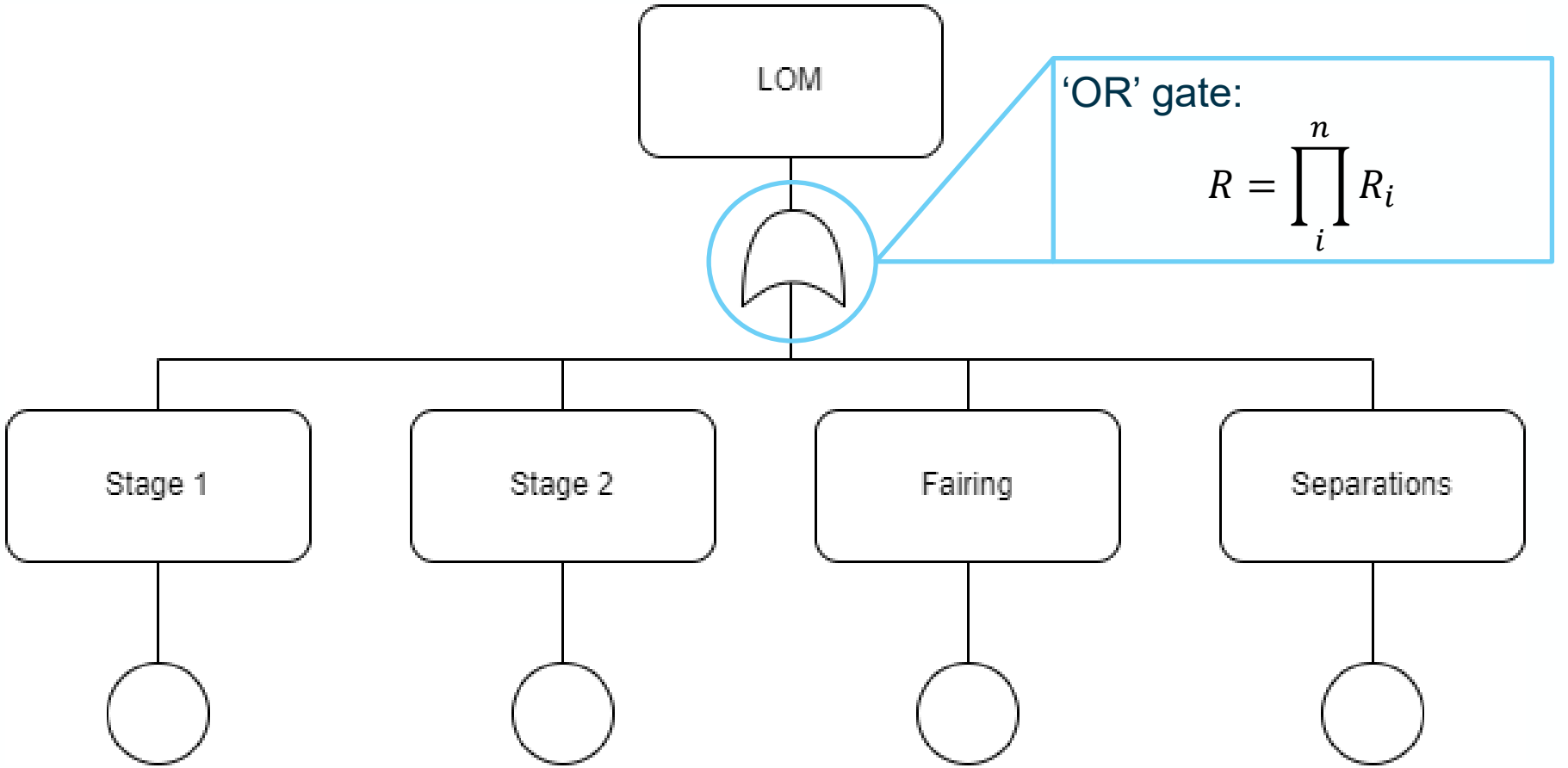
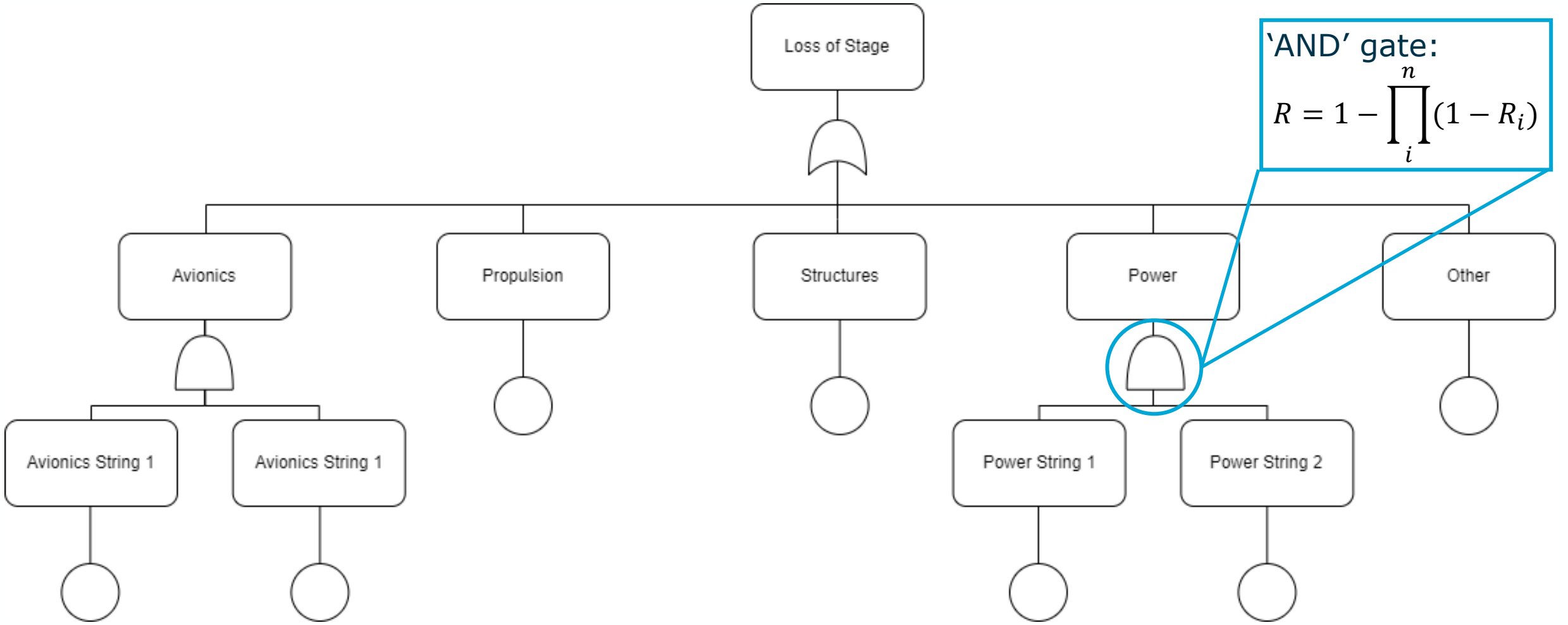


Fig. 5 – Goodness-of-fit verification of MLE Weibull with KME.

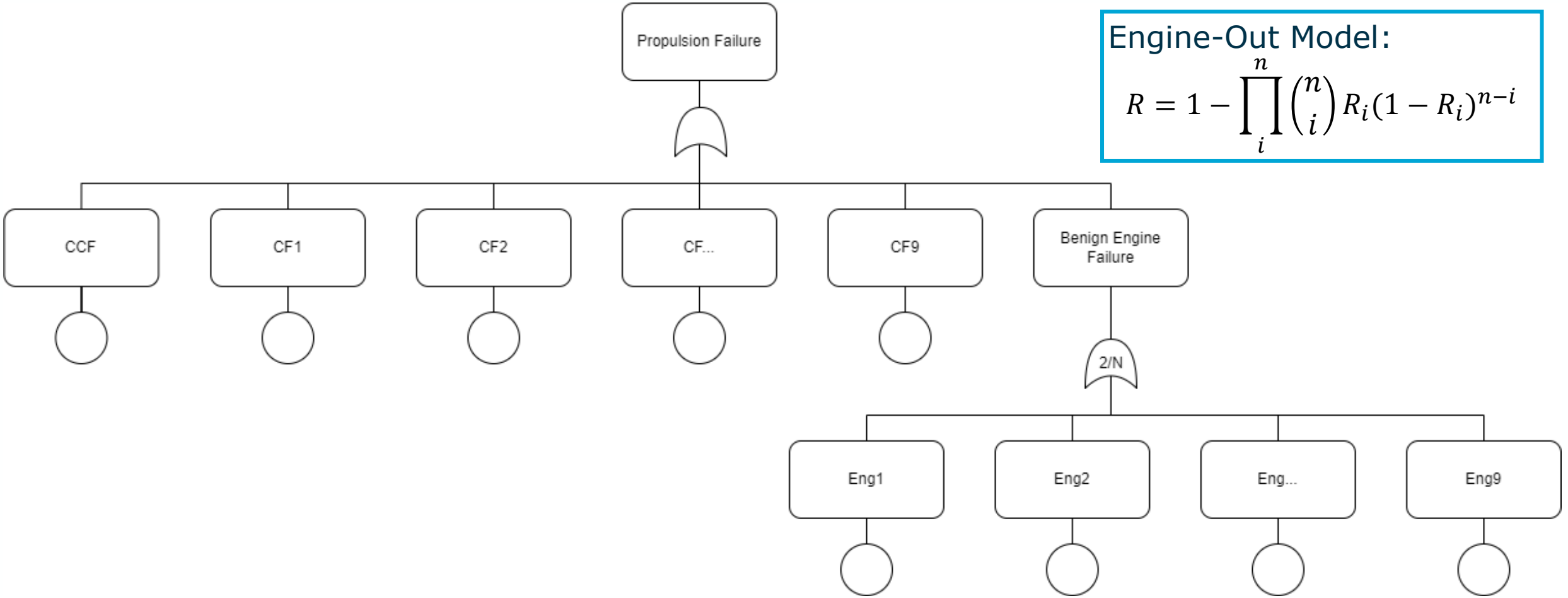
RELIABILITY MODEL – System Estimate
Fault Tree Analysis Top Level



RELIABILITY MODEL – System Estimate
Fault Tree Analysis Subsystem Level



RELIABILITY MODEL – System Estimate
FTA Propulsion System



Engine-Out Model:

$$R = 1 - \prod_{i}^{n} \binom{n}{i} R_i (1 - R_i)^{n-i}$$

RELIABILITY MODEL – Reliability Increase Strategies

Increased Testing	• Crow-AMSAA Reliability Growth Model; • Counting Method;
Redundancy	• Simple Redundancy; • Engine-Out Capability;
Derating	• Operating an item at a stress lower than its rated design value;
Quality Increase	• Use of components with higher reliability.

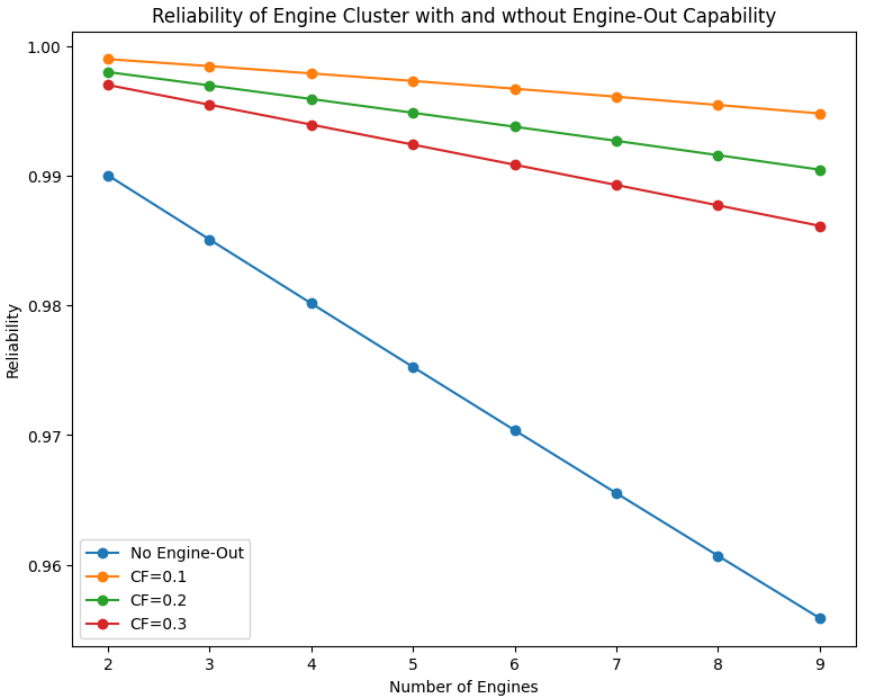
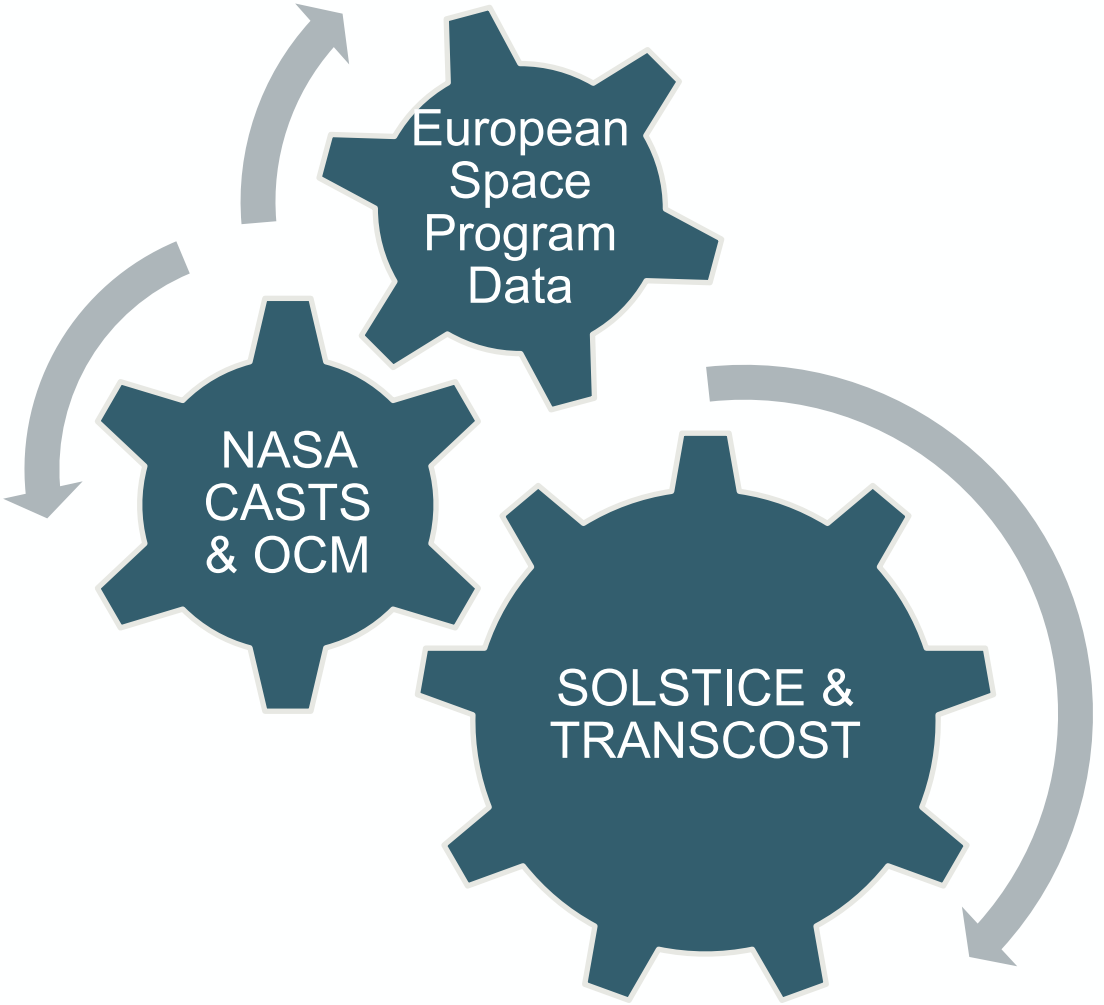
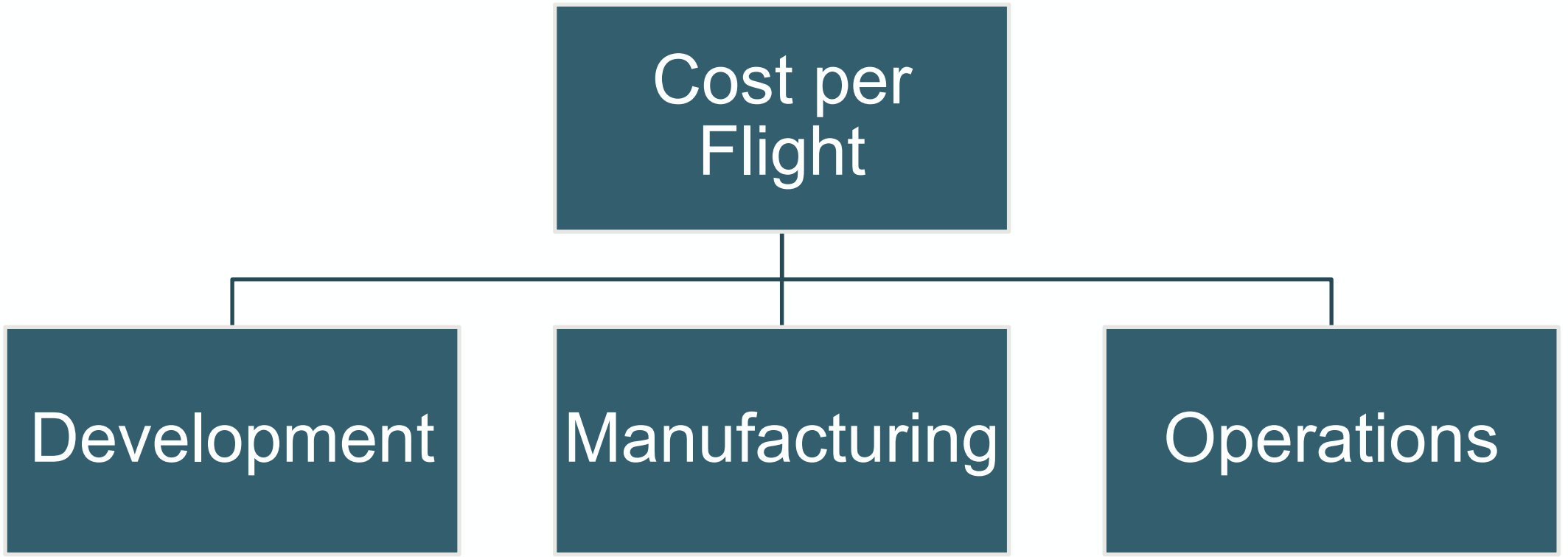


Fig. 6 – Reliability increase due to engine-out capability.

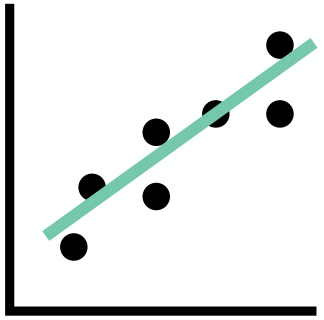
COST MODEL – Cost Estimating Tools



COST MODEL - Methodology



COST MODEL – T1 Equivalence Method



$$C = a \cdot M^b$$
$$\log(C) = \log(a) + b \cdot \log(M)$$

C-Cost

M-Mass

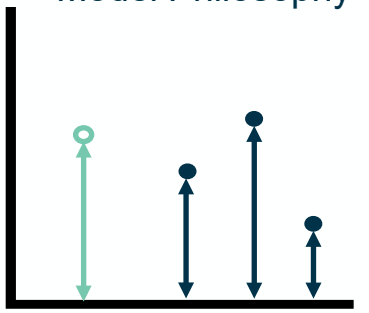
a, b-Regression Coefficients

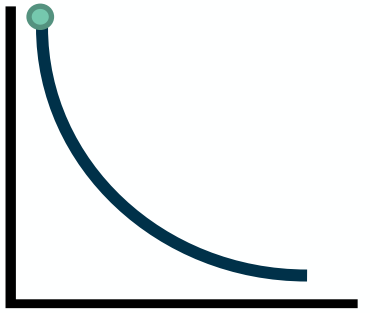
First Unit Estimate

Development Costs

Manufacturing Costs

Model Philosophy



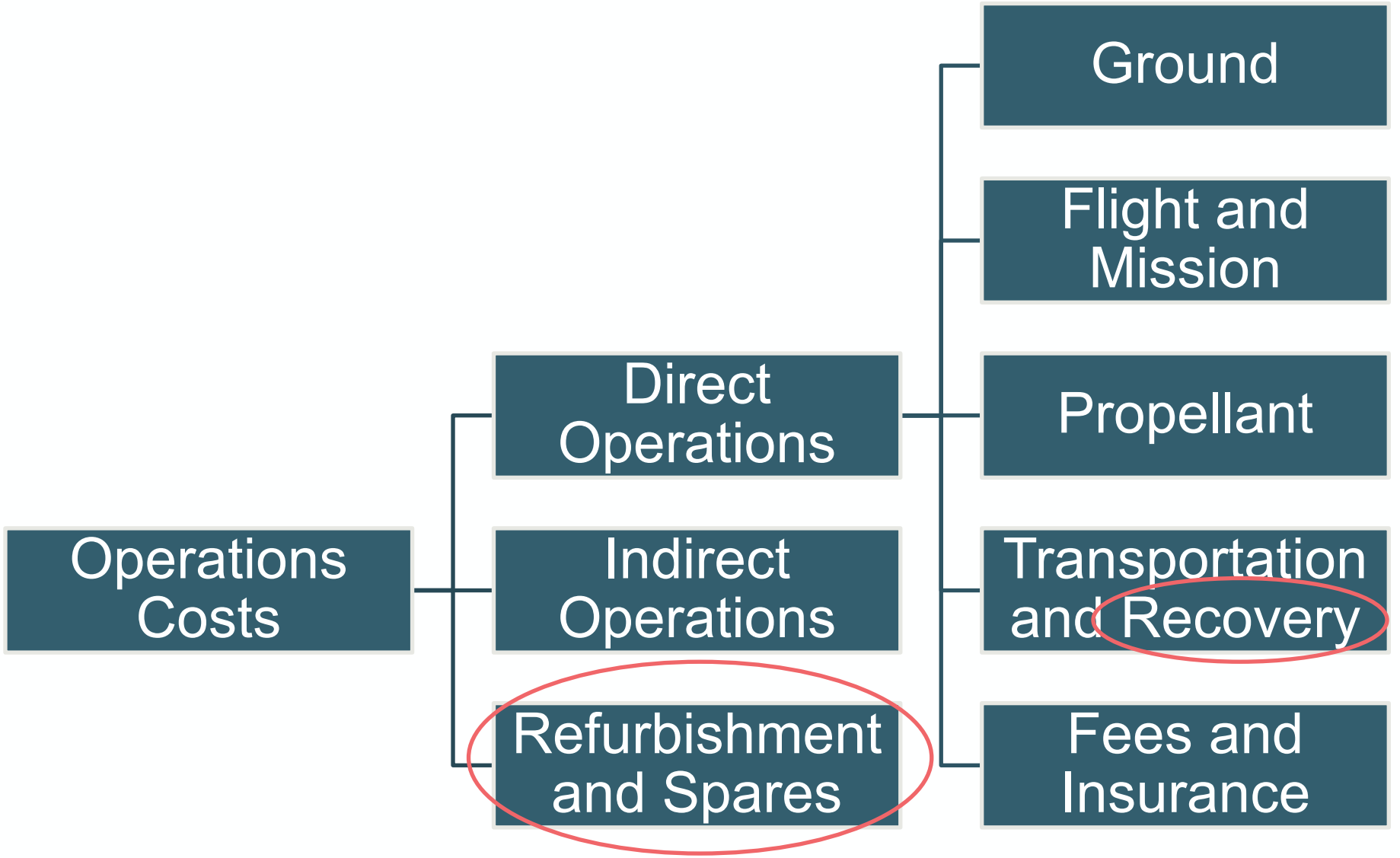


Crawford learning curve:

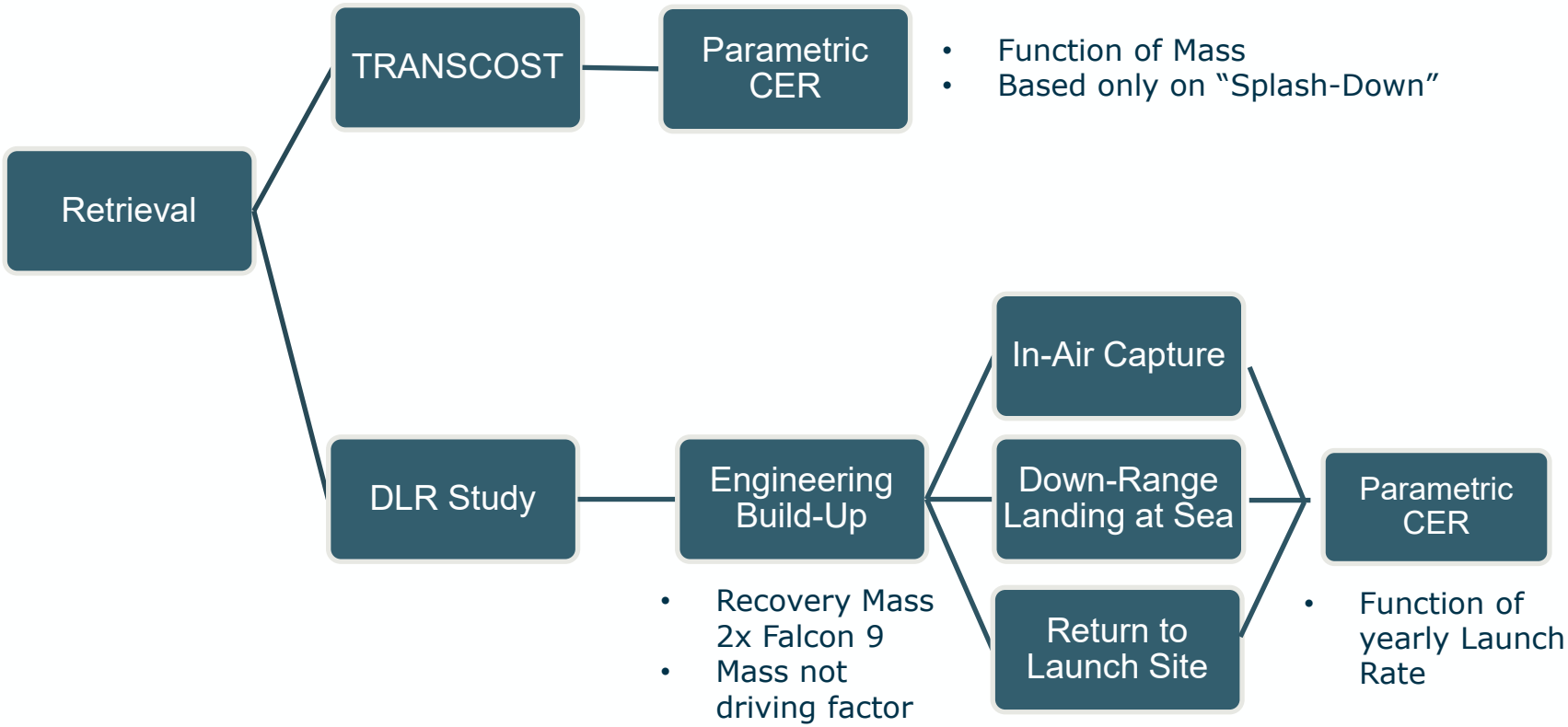
$$MAN_i = T_1 \cdot i^{\frac{\log(p)}{\log(2)}}$$

Integration and Testing Factor (I&T)

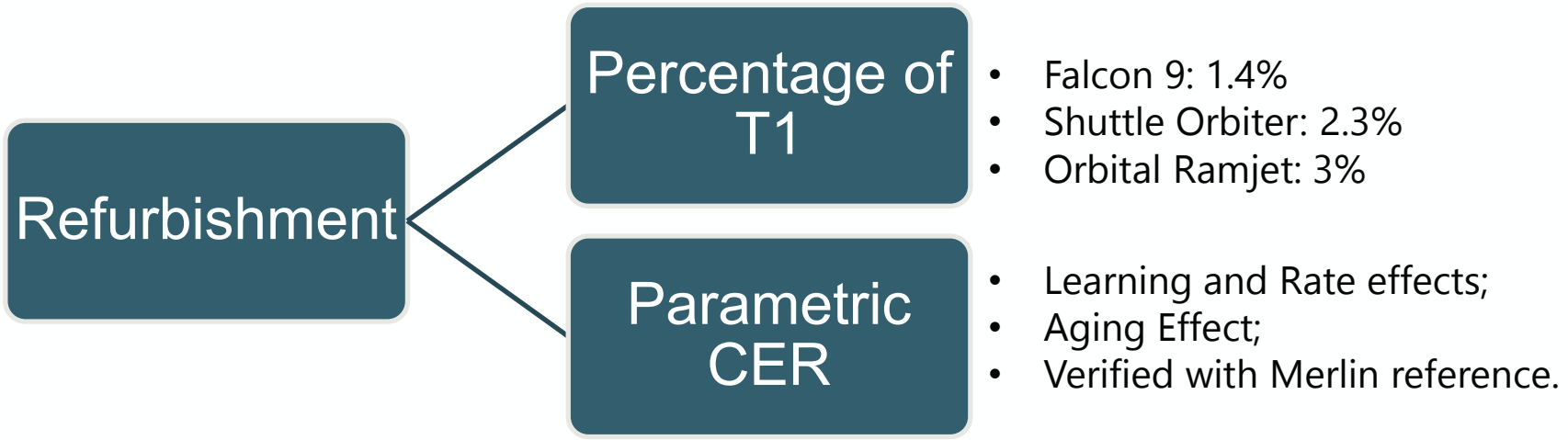
COST MODEL – Cost of Operations



COST MODEL – Cost of Retrieval



COST MODEL – Cost of Refurbishment



- Falcon 9: 1.4%
- Shuttle Orbiter: 2.3%
- Orbital Ramjet: 3%

- Learning and Rate effects;
- Aging Effect;
- Verified with Merlin reference.

COST MODEL – Cost of Failure

Failure Cost: 2-5 times CpF

1. Flight/Vehicle Replacement
2. Increase in Insurance Rates
3. Failure Investigation
4. Implementation of Modifications
5. Cost of Downtime

COST MODEL – Cost of Failure

Vehicle/Flight Replacement

- Manufacturing Costs
- Operation Costs
- Re-Flight Guarantee (RFG)

COST MODEL – Cost of Failure

Increase in Insurance Rates

- Insurance Policy
- Insurance Rates
- Time to Recover

COST MODEL – Cost of Failure

Failure Investigation

- Investigation Duration
- Board size (Head Count)
- Worker Costs per Year

COST MODEL – Cost of Failure

Implementation of Modifications

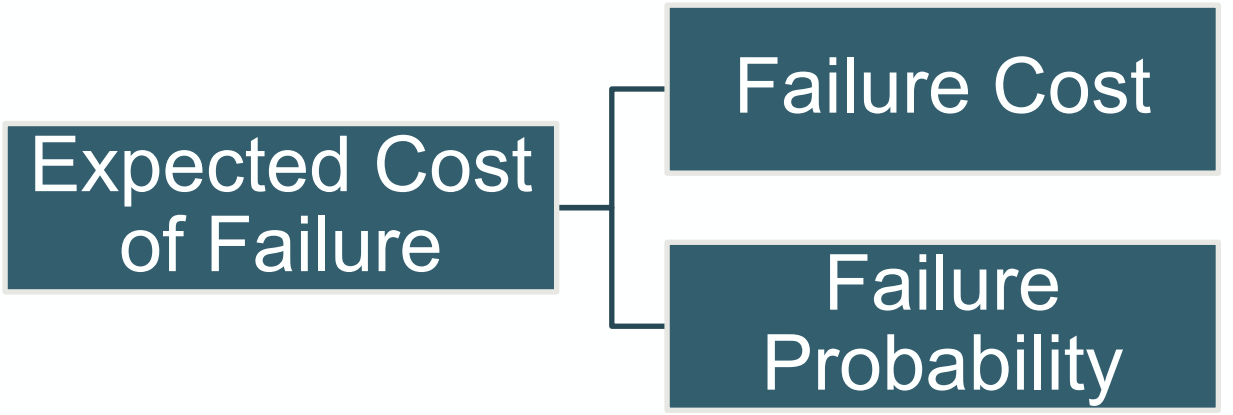
- Subsystem (type and T1)
- Level of Modification

COST MODEL – Cost of Failure

Cost of Downtime

- Duration
- Launch Rate
- Profit Margin
- Mass in Storage
- Characteristics of Facilities

COMBINED MODEL – Expected Cost of Failure



$$C_F = C_f \cdot (1 - R)$$

C_F - Expected Cost of Failure

C_f - Failure Cost

R - Reliability

COMBINED MODEL – Expected Cost of Failure

Finding: Recovery failures do not lead to downtime or formal failure investigation.

$$C_F = \sum C_{f\,i} \cdot P_i$$

P_1-Probability of Mission Failure

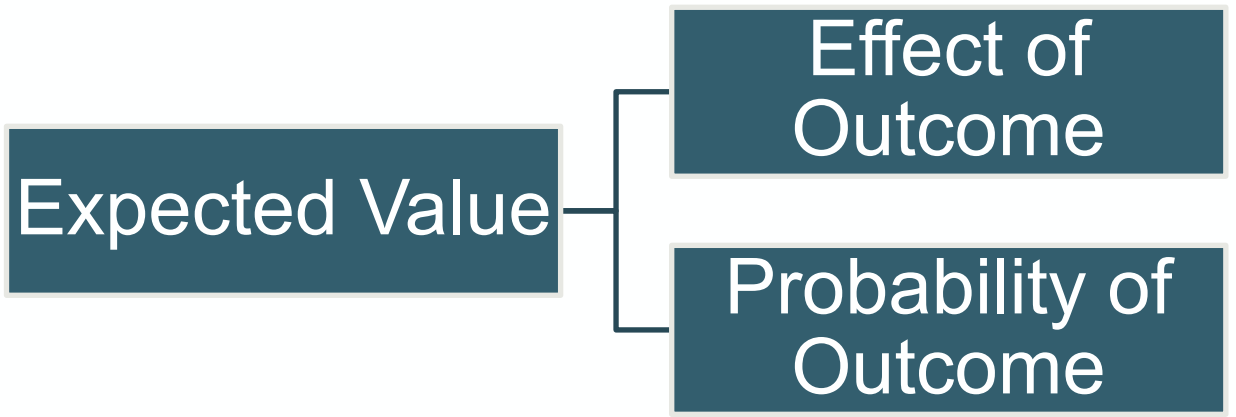
P_2-Probability of First Stage not Surviving

COMBINED MODEL – Expected Value

$$EV = \sum U_i \cdot P_i$$

U_i-Outcomes

P_i-Probability of Outcome



COMBINED MODEL – Expected Value
Standard Case

$$EV = \sum U_i \cdot P_i$$

Simple Case:

	Profit	RFG	Insurance Premium	Replace Vehicle	Relaunch Payload	Insurance Increase	Failure Investigation	Modifications	Downtime
Total Success	✓								
Ascent Failure	✓			✓			✓	✓	✓
Landing Failure	✓			✓				✓	

COMBINED MODEL – Expected Value
Re-Flight Guarantee

$$EV = \sum U_i \cdot P_i$$

RFG Case:

	Profit	RFG	Insurance Premium	Replace Vehicle	Relaunch Payload	Insurance Increase	Failure Investigation	Modifications	Downtime
Total Success	✔	✔							
Ascent Failure	✔	✔		✔	✔		✔	✔	✔
Landing Failure	✔	✔		✔				✔	

COMBINED MODEL – Expected Value
Insured Launch Vehicle

$$EV = \sum U_i \cdot P_i$$

Insured Case:

	Profit	RFG	Insurance Premium	Replace Vehicle	Relaunch Payload	Insurance Increase	Failure Investigation	Modifications	Downtime
Total Success	✔		✔						
Ascent Failure	✔		✔			✔	✔	✔	✔
Landing Failure	✔		✔			✔		✔	

COMBINED MODEL – Expected Value
RFG & Insurance

$$EV = \sum U_i \cdot P_i$$

RFG & Insured Case:

	Profit	RFG	Insurance Premium	Replace Vehicle	Relaunch Payload	Insurance Increase	Failure Investigation	Modifications	Downtime
Total Success	✔	✔	✔						
Ascent Failure	✔	✔	✔		✔	✔	✔	✔	✔
Landing Failure	✔	✔	✔			✔		✔	

RESULTS - Reliability

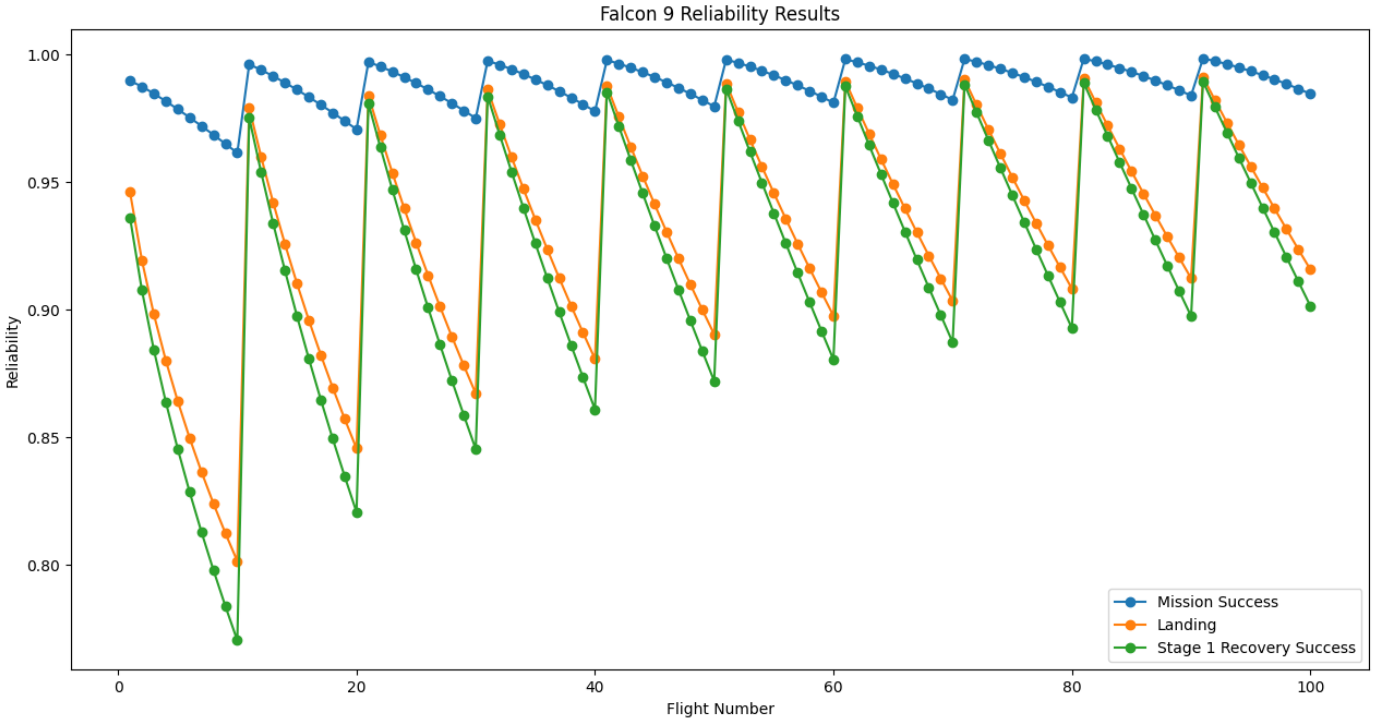


Fig. 8 – Reliability life-cycle results for Falcon 9.

Element	Average Reliability
Mission Success	0.9881
Landing Success	0.9298
First Stage Recovery	0.9190

RESULTS – Cost per Flight

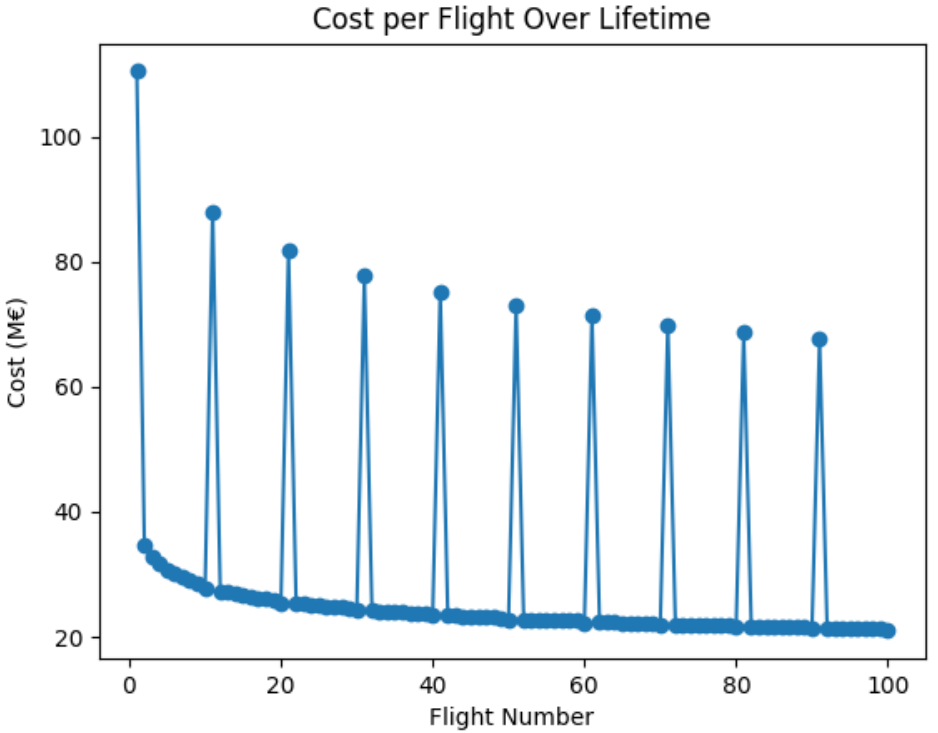


Fig. 9 – Life-cycle Cost per Flight results for Falcon 9.

Flight Type	Average Cost (2021 M€)	Average Cost (2021 M$)
New Launcher	78.3	92.6
Launch w/ Reused Booster	23.8	28.1
Total	29.3	34.65

RESULTS – Failure Cost

- Expectation from literature: 2-5 times the CpF;
- Result for Falcon 9: 17 times the CpF.

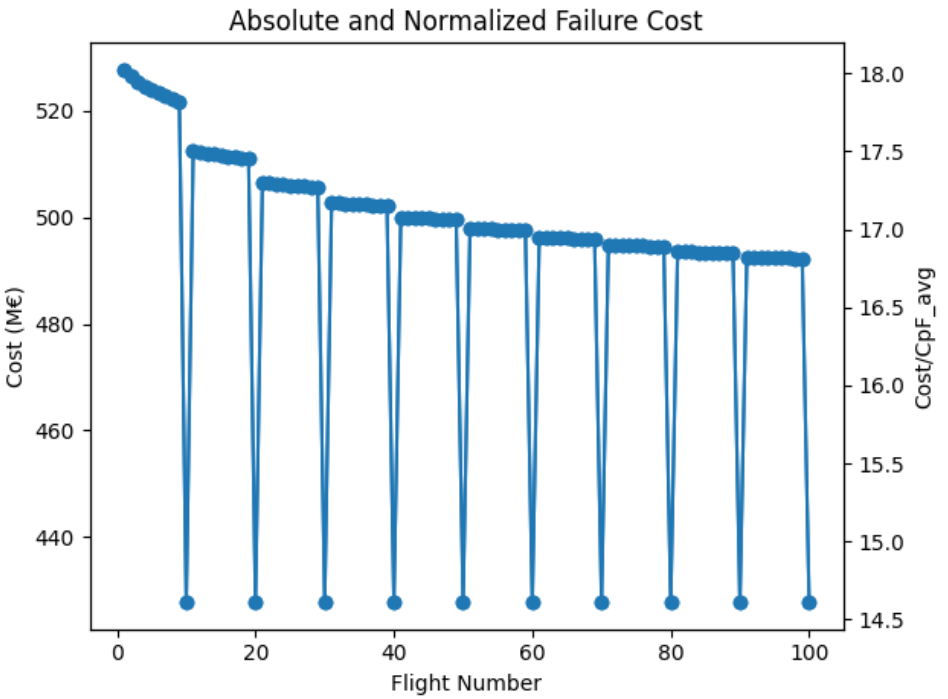


Fig. 10 – Failure cost results for Falcon 9.

RESULTS – Expected Cost of Failure

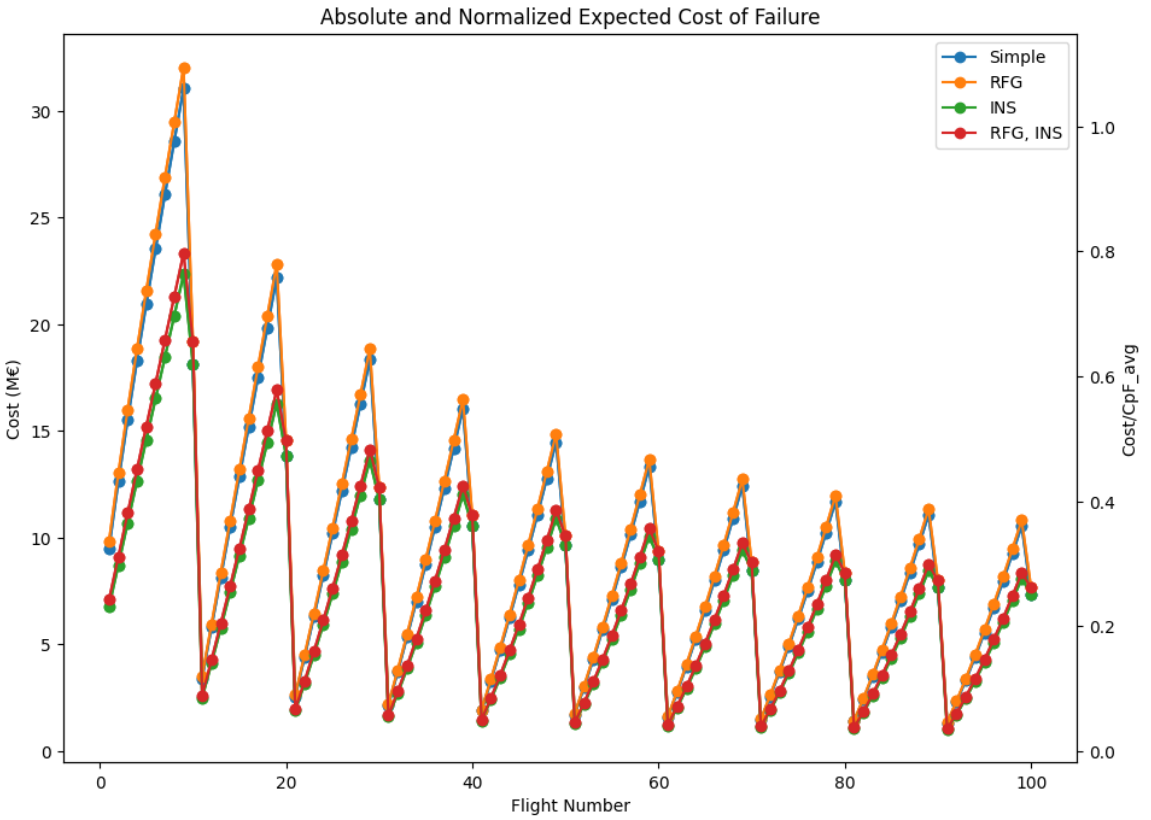


Fig. 11 – Expected Cost of Failure cost results for Falcon 9.

Case	$C_{F_{avg}}$ (M€)	$C_{F_{avg}}/CpF_{avg}$ (%)
Simple	9.4	32.1%
RFG	9.7	33%
INS	7.2	24.4%
RFG+INS	7.4	25.4%

RESULTS – Expected Value

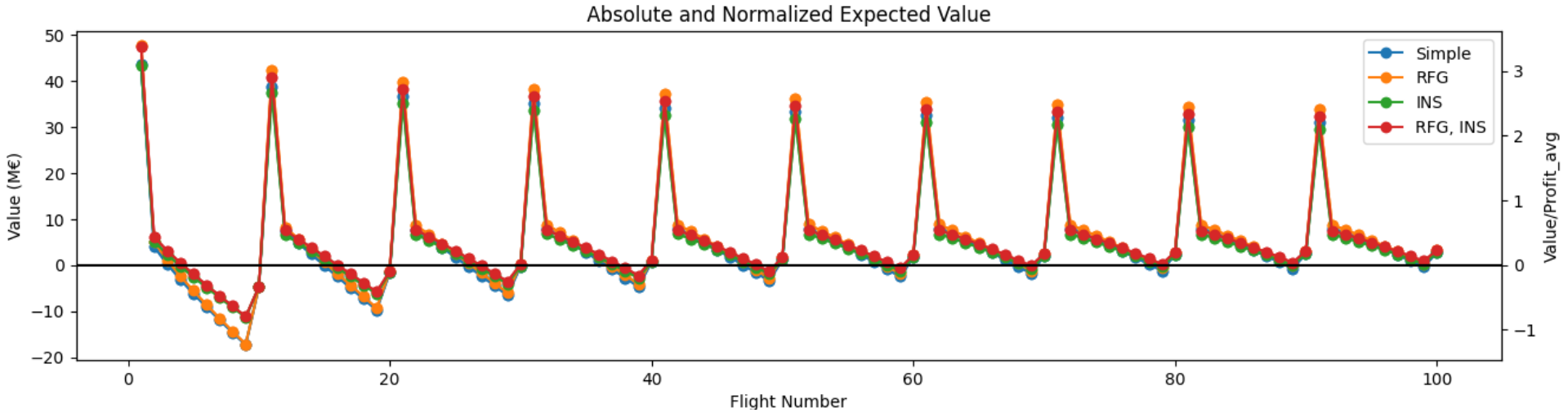


Fig. 12a – Falcon 9 Expected Value results 9 (constant profit).

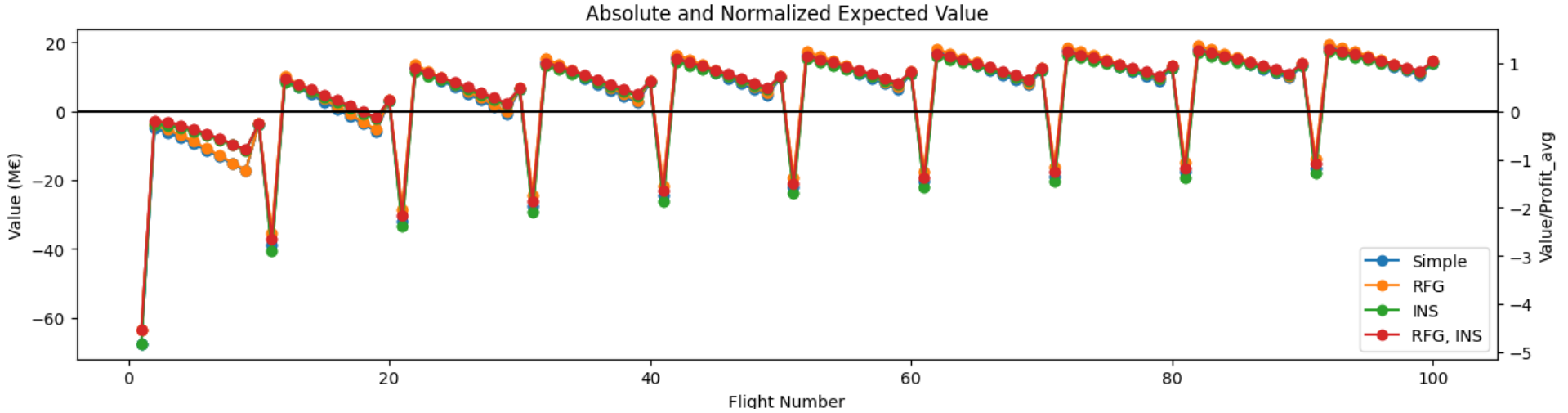


Fig. 12b – Falcon 9 Expected Value results 9 (fixed price).

RESULTS – Expected Value

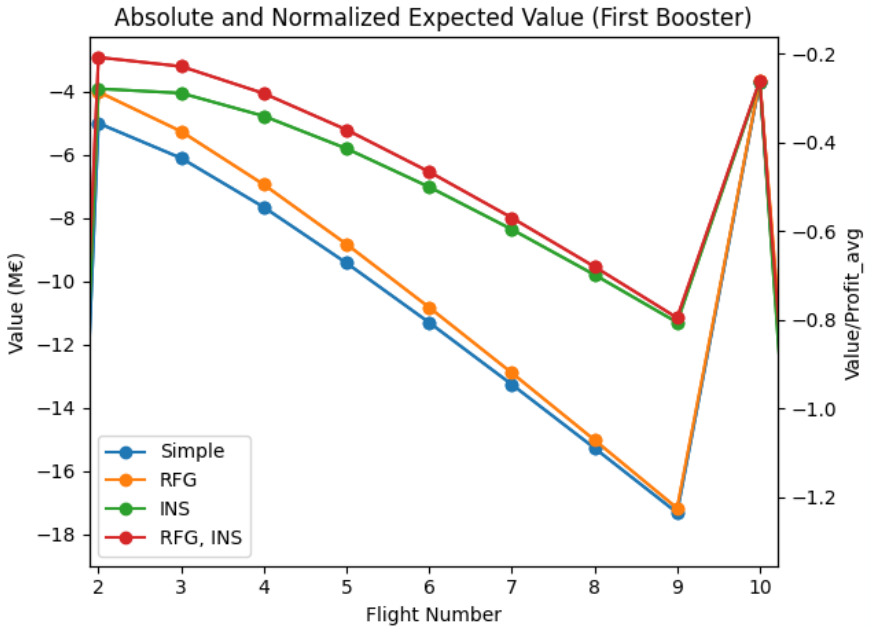


Fig. 13a – Falcon 9 Expected Value (first booster).

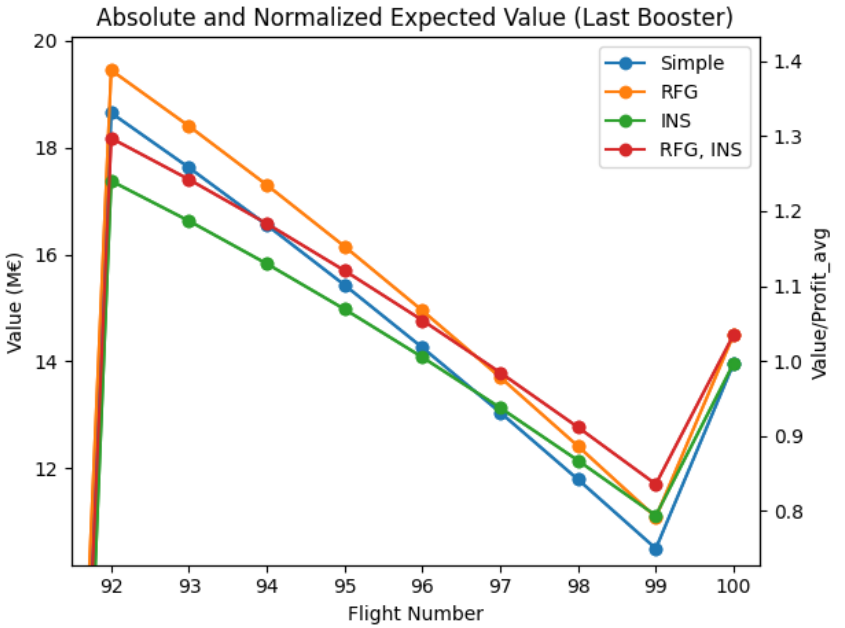


Fig. 13b – Falcon 9 Expected Value (last booster).

RESULTS – Expected Value

Case	EV_{avg} (M€)	$EV_{avg}/(Profit)_{avg}$ (%)
Simple	4.6	32.8%
RFG	5.5	39%
INS	5.0	35.7%
RFG+INS	5.8	41.4%
Maximum Value	6.2	44.3%

RFG: Re-Flight Guarantee

INS: Insurance

RESULTS – Expendable Case

	LpY =20 Profit = 48%	LpY = 10 Profit = 48%	LpY = 10 Profit = 8%
PpF	96.9 M€	86.3 M€	63 M€
EV/Profit	92.6%	82.6%	30%

ALTERNATIVE USE-CASE - Methodology

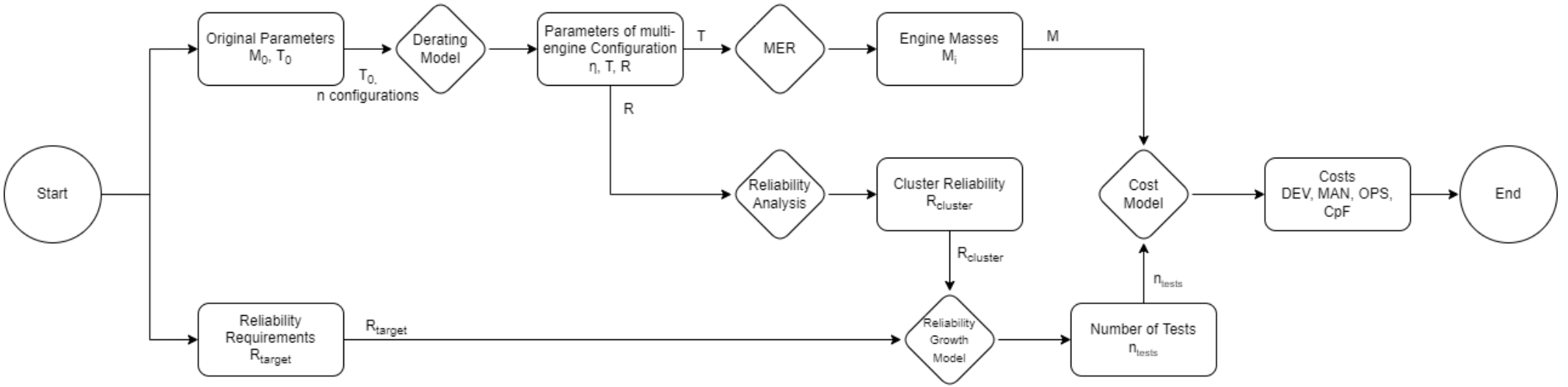
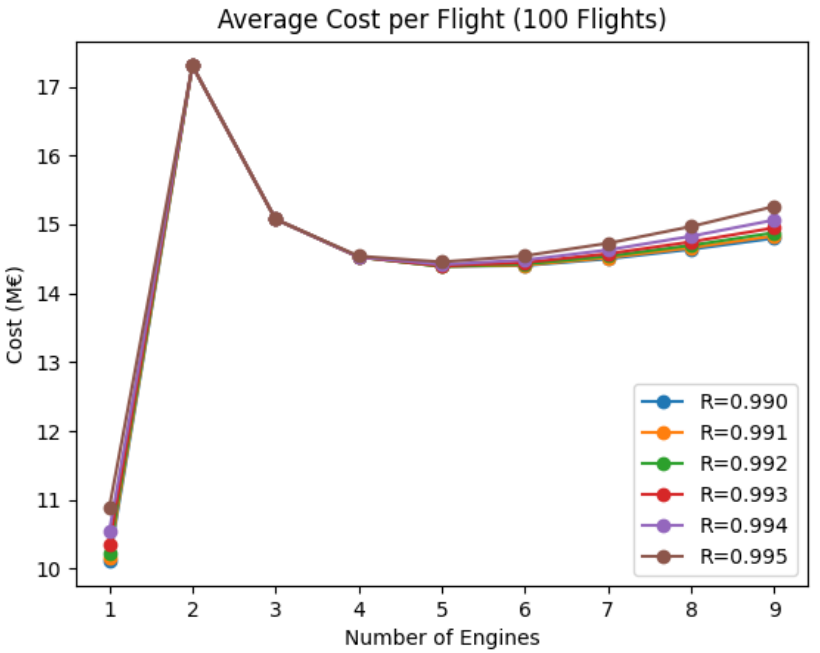


Fig. 14 – Multi-stage problem solving methodology.

ALTERNATIVE USE-CASE - Results

Fig. 15a – Expendable Vehicle results.



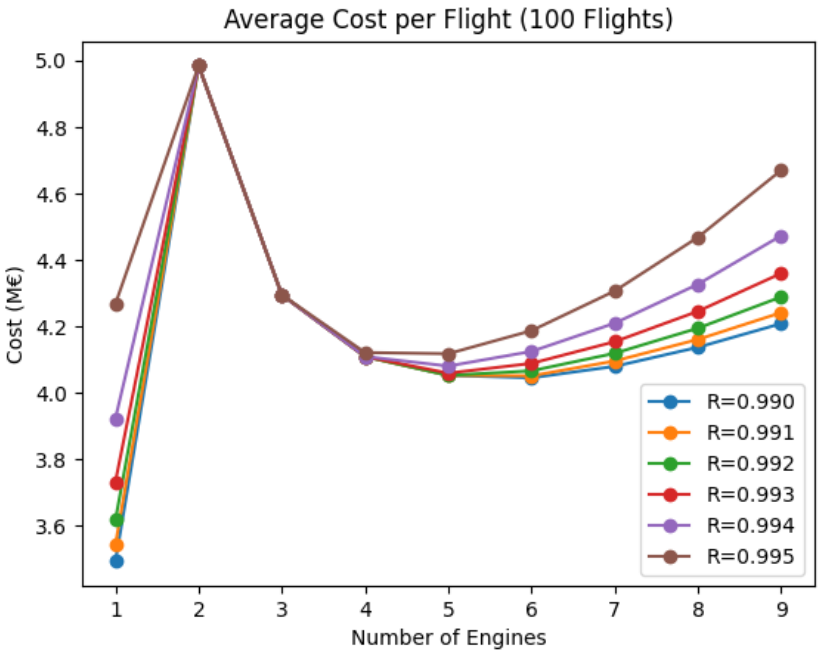


Fig. 15b – Reusable Vehicle results.

Additional findings:

- Engine commonality with upper stage beneficial in reusable case;
- Heavier original engines yield better results

CONCLUSIONS

- Combination of tools;
- Development of new CERs;
- Failure incorporated as a cost figure;
- Accounting for cost of Reliability increase;
- New variable for MDO: Value
- Range of applications: From design to insurance

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