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Tradespace Analysis and Exploration incorporating Reliability, Availability, Maintainability, and Cost

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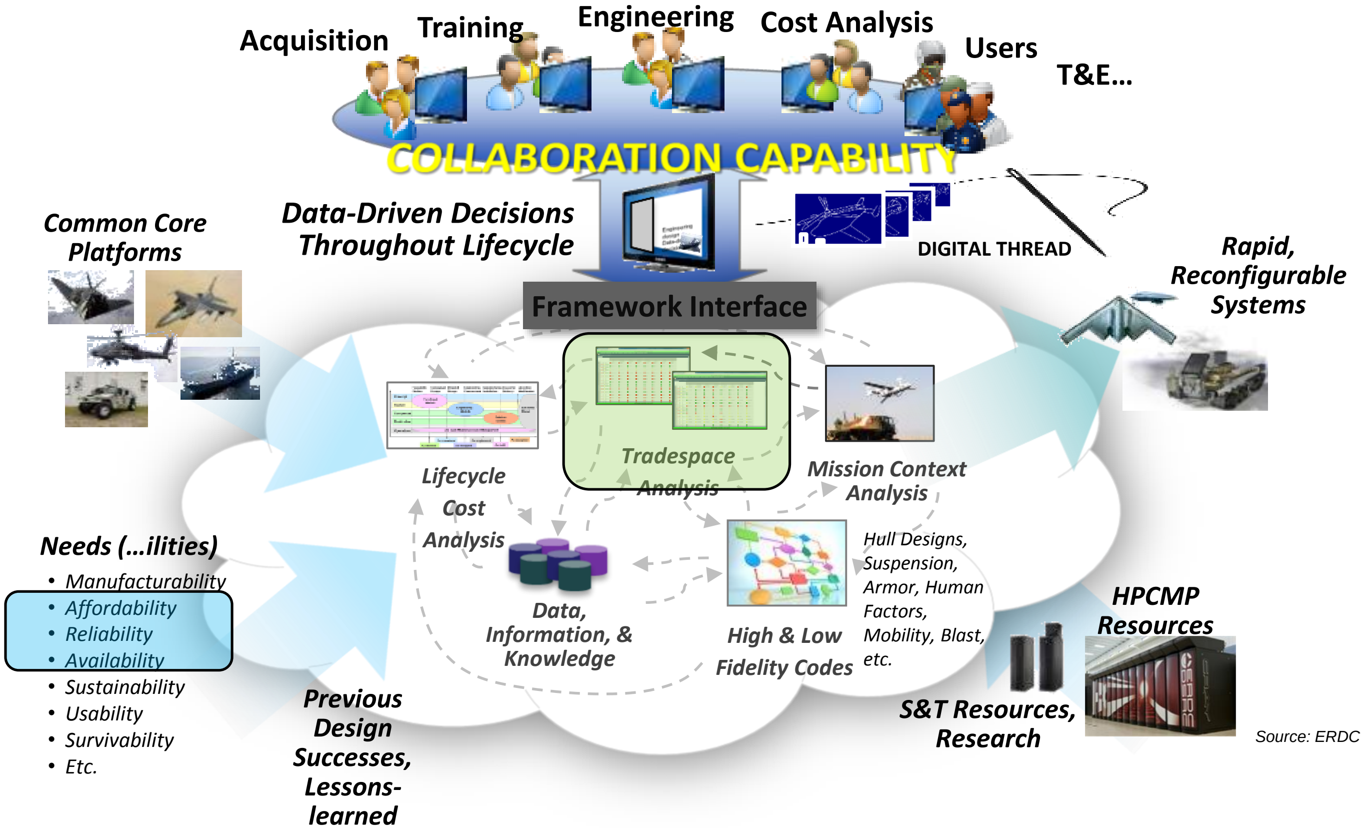
Background

- DOD Engineered Resilient Systems framework



Background (2)

- Tradespace exploration processes and accompanying tools
  - Provide intuitive environment to explore alternatives
  - Assess designs for feasibility in multiple contexts
  - Promising methodology to
    - Facilitate effective designer/stakeholder communication
    - Ensure final product with mutually agreed set of capabilities
    - Support systems engineering tradeoffs during acquisition lifecycle

Background (3)

- Majority of TSE research emphasizes tradeoffs between functional requirements
- Nonfunctional requirements such as reliability, availability, and maintainability which impact operation and support costs (O&S) considered less frequently
- Proposed strategy incorporates reliability engineering into tradespace exploration (TSE)
  - Develop subsystem-level reliability investment model to
    - Achieve savings over system lifecycle
    - Explore tradeoff between fleet size and average procurement unit cost (APUC)

Reliability Modeling

Cost & Availability Modeling

- Crow AMSAA model

  - Strategy to achieve desired level of reliability growth over series of developmental test cycles

  – Variety of failures discovered

    - Not all of equal severity or importance
    - Simplest method divides into two categories
      – A-mode – no corrective action taken
      – B-mode – corrective action taken

Model Assumptions

- B-mode failures
  - K – total number of failures (large unknown constant)
  - Each failure occurrence leads to system failure
    - Equivalent to series system
  - Failures discovered prior to end of testing cycle (T) subject to fix attempt by T

System failure rate and failure intensity

- As $K \to \infty$, expected failure intensity

$$\rho(T) = \lambda_A + \lambda_B\left((1 - \mu_d) + \frac{\mu_d}{1 + T}\right)$$

  - μ_d – Average success rate of corrective actions
  - λ_A – Rate of A-mode failures
  - $\sum_{i=1}^{K}(1 - d_i)\lambda_i$ – B-mode failure rate after corrective action
    - d_i – Fix effectiveness of i^{th} B-mode
  - $(\lambda_B - \sum_{i=1}^{K}\lambda_i)$ – unobserved B-mode failures

Reliability Investment

- Essential function failures (EFF) prevent fully mission capable (FMC) system

$$FMC = \prod_{i=1}^{n} (1 - EFF_i)$$

  - Similar to Crow's model of B-mode failures

- MTBEFF:= 1/expected failure intensity

$$M(T) \coloneqq \rho(T)^{-1}$$

Cost vs. Time

- Cost and time required to achieve MTBEFF

$$\gamma(T) = \frac{1}{CV^2}\left(C_0 T + \mu_b \ln(1+T)\right)$$

  - CV – Coefficient of variation in B-mode failures
  - C_0 – Cost to operate test, analyze, and fix (TAAF)
  - μ_b – Average value of cost increments incurred by corrective action

Subsystem MTBEFF as function of reliability investment

- Solving cost equation for time T_i and composing with MTBEFF provides direct relationship

$$M_i(T_i) = \lambda_{A,i} + \lambda_{B,i}\left(1 - \mu_{d,i} + \frac{C_{0,i}\mu_{d,i}}{\mu_{b,i}F^{-1}\left[\frac{C_{o,i}e^{\left(\frac{C_{0,i}+CV_i^2\gamma_i}{\mu_{b,i}}\right)}}{\mu_{b,i}}\right]}\right)^{-1}$$

- $F(W) = We^W$ - Lambert W-function

Maximizing availability through reliability investment

- Steady state availability of subsystem i

$$A_i(T_i) = \frac{M_i(T_i)}{M_i(T_i) + \mathrm{MTTR}_i}$$

  - MTTR_i - mean time to repair subsystem i
  - Treated as estimate of system or subsystem reliability

Availability and fleet size

- Average number of subsystem replacement over system lifecycle

$$P_i = \left\lfloor \frac{L}{M_i(T_i)} - \varepsilon \right\rfloor$$

- Average cost of initial subsystem *i* and replacements over system lifecycle

$$C_i = c_i * (1 + P_i)$$

- Average cost of *n* subsystem over system lifecycle

$$C_s = \sum_{i=1}^{n} C_i$$

Availability and fleet size (2)

- Number of systems that can be purchased and supported with budget B

$$\eta(\mathbf{T}) = \left\lfloor \frac{B - \sum_{i=1}^{n} \gamma_i(T_i)}{C_s} \right\rfloor$$

- $\mathbf{T}$ - Vector of subsystem reliability investments
- B - Total budget
- C_s - Cost of n subsystem over system lifecycle

Average Procurement Unit Cost

- Simple subsystem level optimization model considering investment in reliability improvement

$$\min APUC(\mathbf{T}) = \min \left[\frac{\eta(\mathbf{T}) * C_s + \sum_{i=1}^{n} \gamma_i(T_i)}{\eta(\mathbf{T})} \right]$$

$$\text{such that } T_i > 0$$

  – Total cost = $\eta(\mathbf{T}) \times APUC$

Illustrations

Subsystem Parameters

- $n = 2$ subsystems
- $B = \$1{,}000{,}000{,}000$
- $L = 20{,}000$ flight hours per vehicle

Parameters	**Subsystem** $i = 1$	**Subsystem** $i = 2$
$M_{A,i}$ (initial A-mode failure MTBEFF)	1,000 Hours	500 Hours
$M_{B,i}$ (initial B-mode failure MTBEFF)	100 Hours	200 Hours
$C_{0,i}$ (Cost of operating TAAF)	$1,000,000	$8000,000
$\mu_{b,i}$ (Cost of corrective action during TAAF)	$5,000,000	$4,000,000
$\mu_{d,i}$ (B-mode fix effectiveness factor)	0.9	0.8
c_i (Subsystem replacement cost)	$200,000	$75,000
$MTTR_i$ (Mean time to repair)	24 Hours	36 Hours

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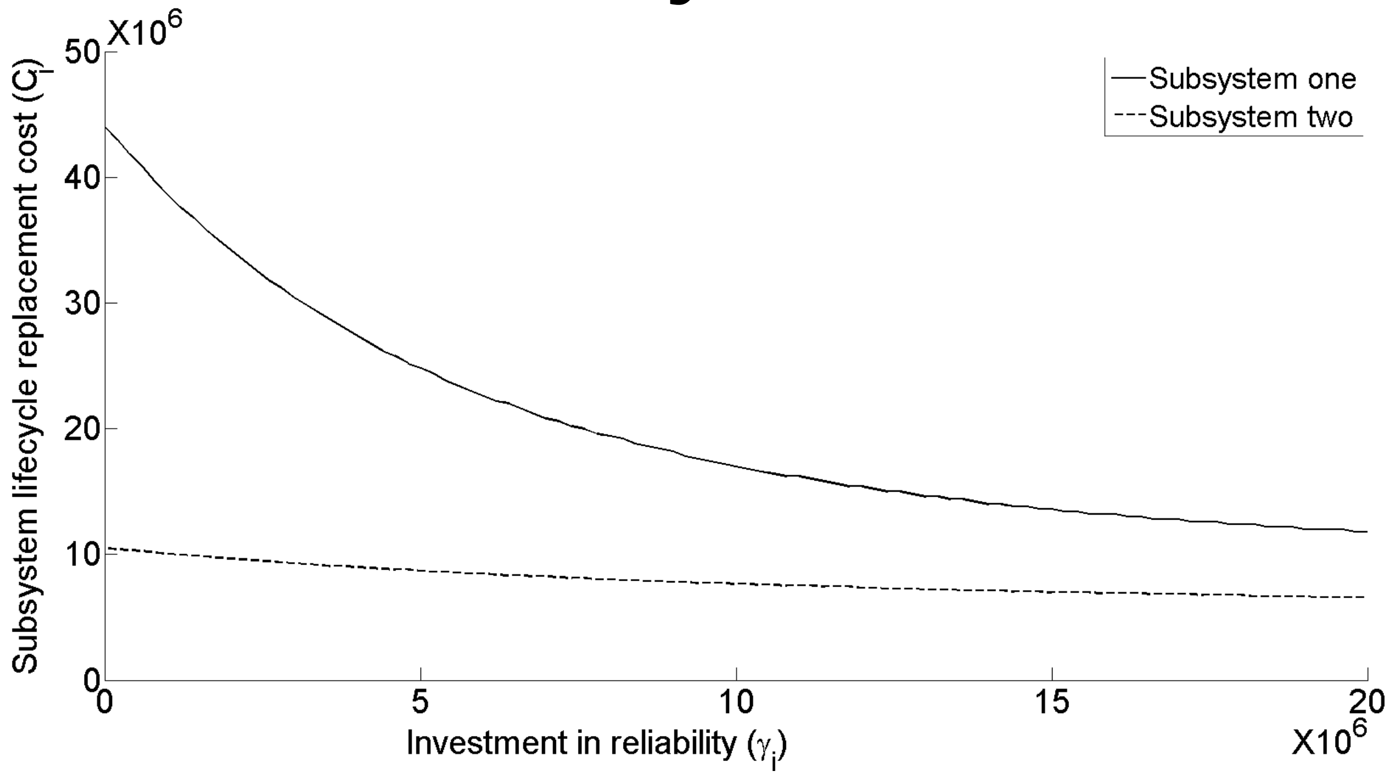
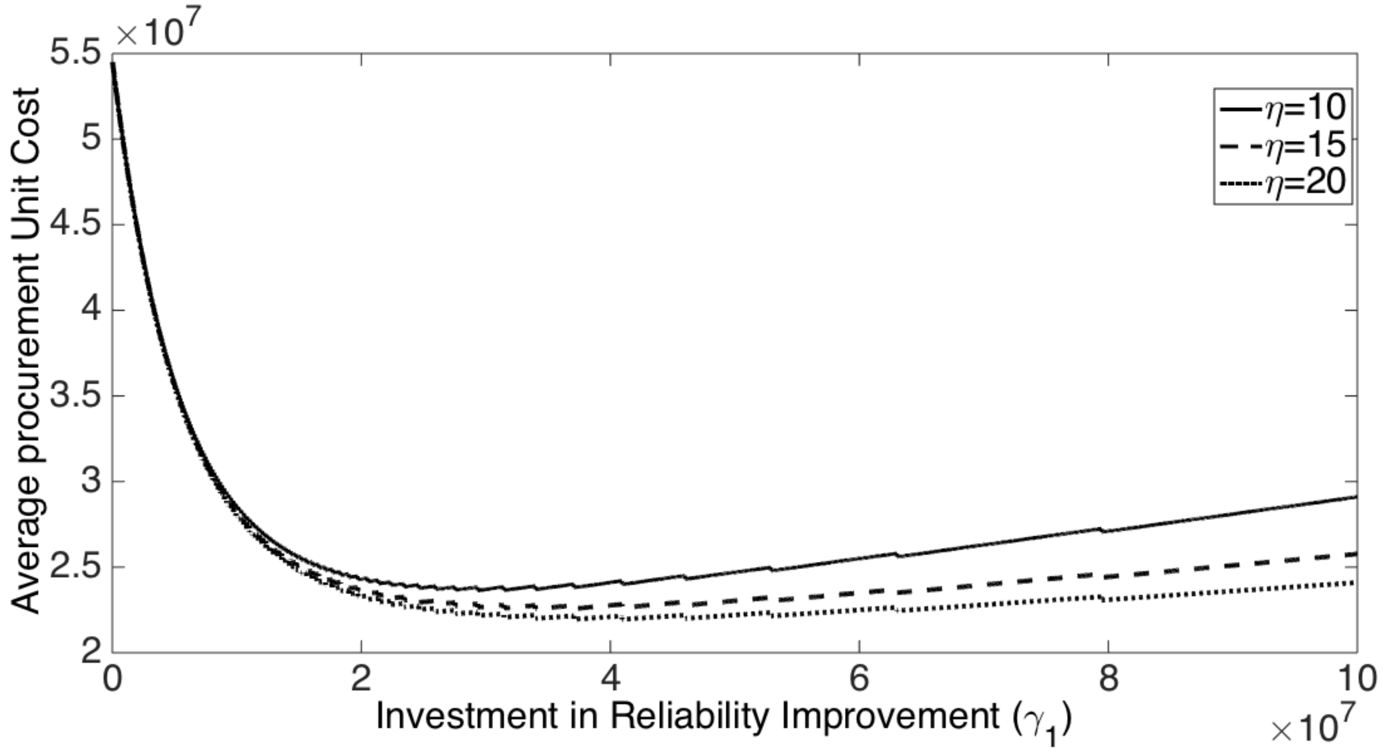
Impact of reliability investment on lifecycle cost



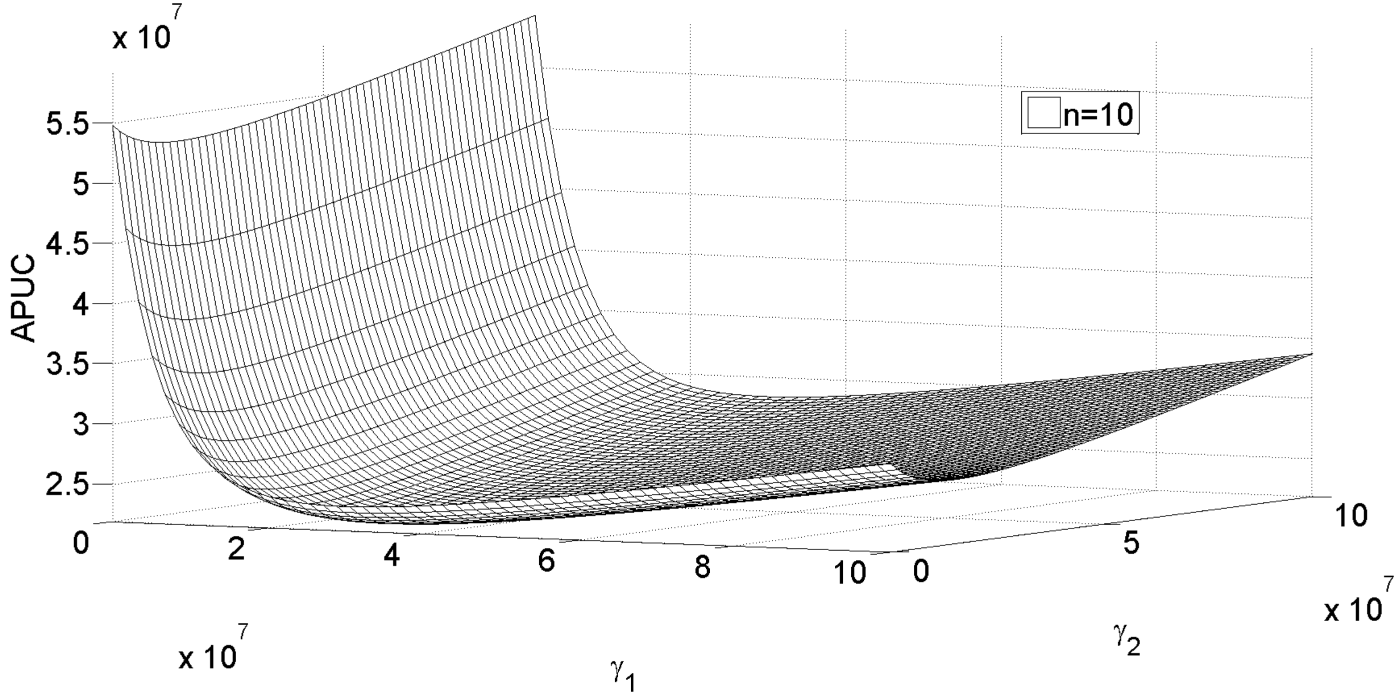
Investment in subsystem one could achieve greater part replacement cost savings over system lifecycle

Sensitivity of APUC to reliability investment



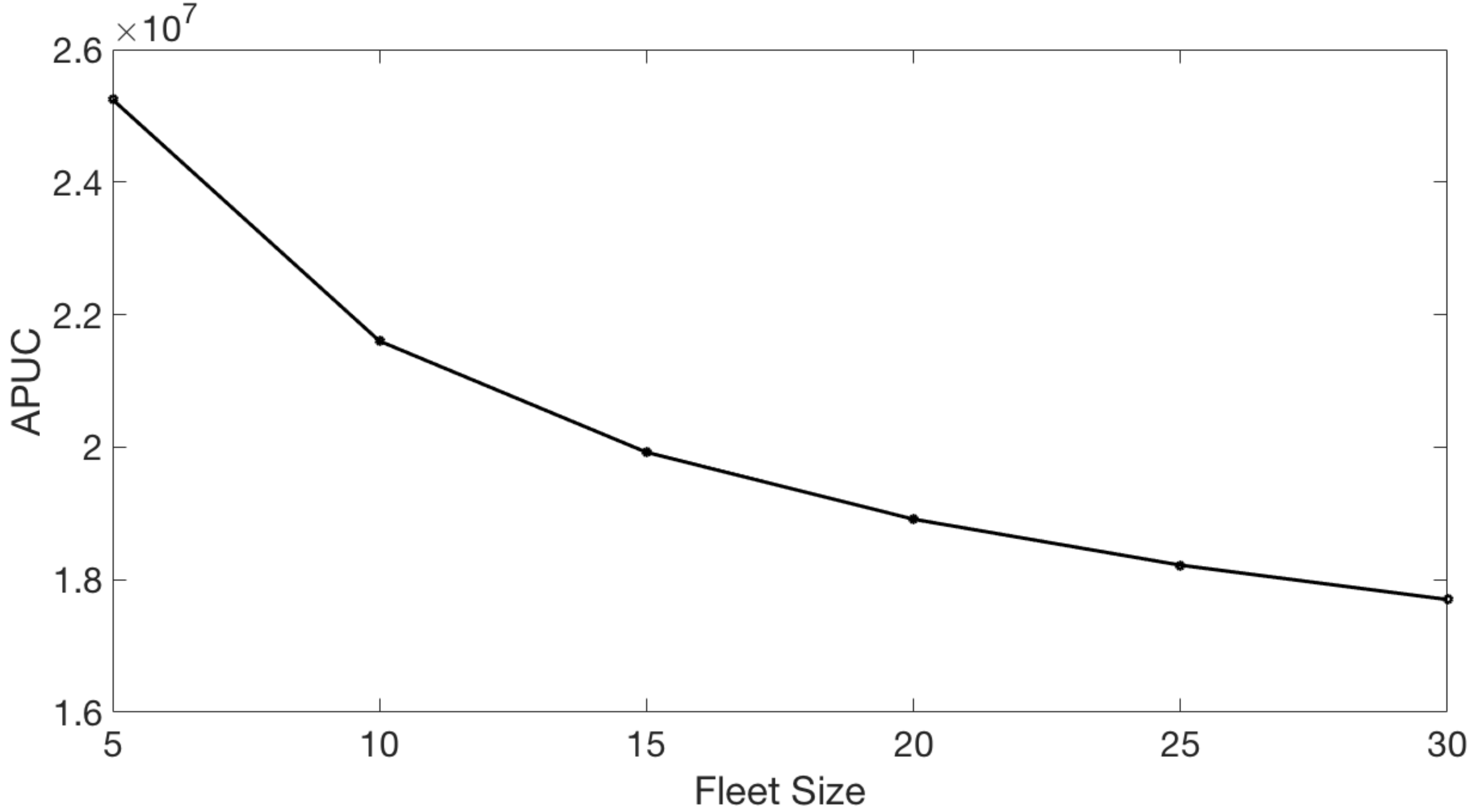
APUC decreases initially, but gradually increases as larger investments leads to little reduction in subsystem lifecycle cost

Impact of subsystem reliability investment on APUC



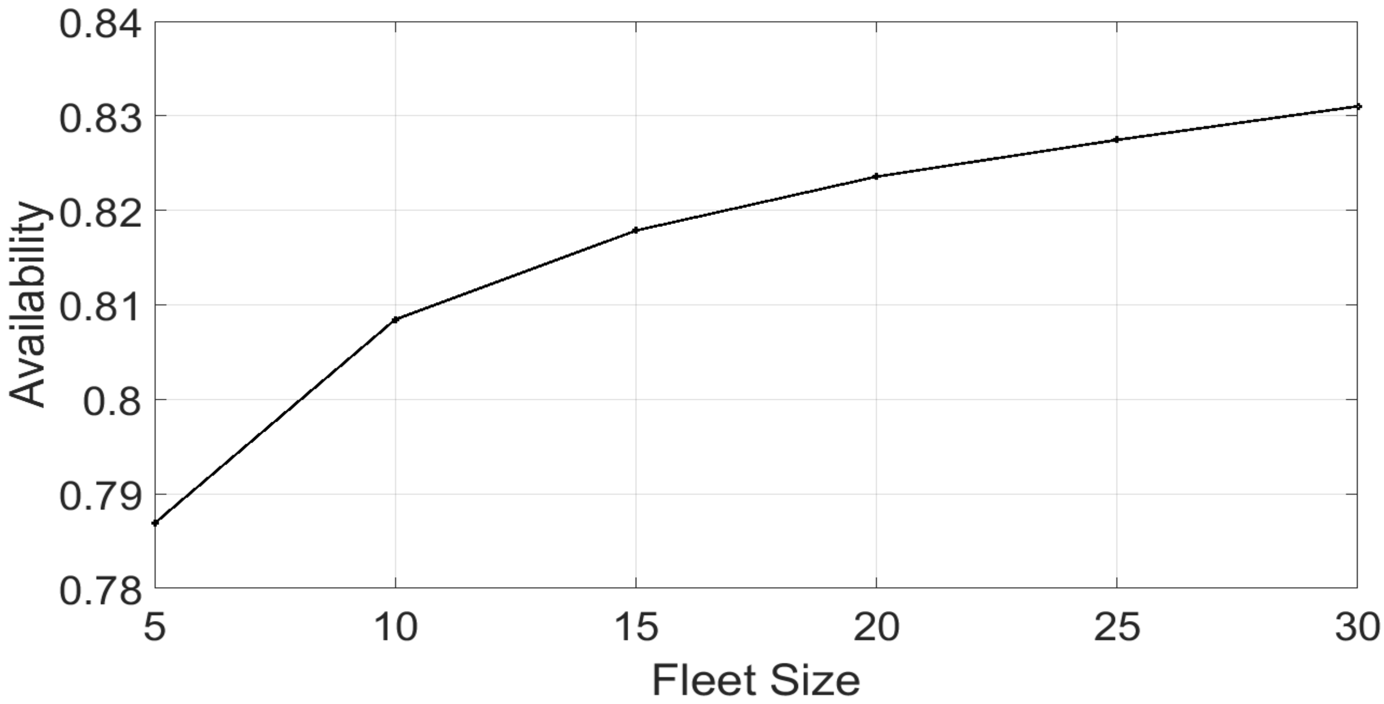
Optimal subsystem reliability investment strategy possesses unique minimum

Impact of fleet size on optimal APUC



Economy of scale decreases APUC as fleet size increases

Impact of fleet size on optimal availability



Increasing fleet size increases reliability investment and subsequently availability

Impact of fleet size on various parameters

η	APUC (10^6)	γ_1 (10^6)	γ_2 (10^6)	Unit cost (10^6)	Total Cost(10^6)	Availability
5	25.25	22.35	8.13	19.15	126.23	0.7869
10	21.60	29.34	15.66	17.10	216.00	0.8084
15	19.92	33.98	21.11	16.25	298.84	0.8179
20	18.91	40.95	24.81	15.63	378.26	0.8236
25	18.22	40.95	29.54	15.40	455.49	0.8275
30	17.71	46.00	33.52	15.05	531.02	0.8310
100	15.62	46.00	48.49	14.68	1562.00	0.8376
1000	13.79	79.45	93.15	13.63	1379.76	0.8422

Increasing fleet size decreases APUC and unit cost but increases reliability investment and total cost

Summary, Conclusions, Future research, and Acknowledgement

Summary and Conclusions

- Combine reliability engineering and TSE
  - Strategy to consider investment over long term
- Studies linking reliability investment and APUC could promote
  - Compromise between performance and non-functional reliability and affordability attributes
  - Reduce lifecycle cost and enhance affordability
  - Improve fleet availability
  - Identify trade off between fleet size, availability, and cost

Future Research

- Greater realism in cost modeling
- Validation through application to rotary wing aircraft in government databases
- Combine methodology with CATE and NDARC to enable rotorcraft TSE considering reliability and availability

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