Bayesian Component Reliability Estimation: an F-35 Case Study

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F-35 is a complex aircraft...

**Conventional Take-Off and Landing (CTOL)**
- In-Flight Refueling Door (Boom)
- Internal 25mm 4-Barrel Gatling Gun

**Carrier Variant (CV)**
- Probe and Drogue Refueling (Basket)
- Strengthened Landing Gear and Tailhook
- Centerline Gun Pod with 25mm Gun

**Short Take-Off and Vertical Landing (STOVL)**
- Probe and Drogue Refueling (Basket)
- Lift Fan
- Roll Posts

**3-Bearing Swivel Nozzle**

DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.
Estimating Component Reliability is essential for Operations and Sustainment

Reliability estimates drive:
- Spares purchases
- Program budgeting
- Cost estimation
- Readiness

<table>
<thead>
<tr>
<th>Air Vehicle Systems</th>
<th># components within category</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWR &amp; THERMAL MGMTSYS (PTMS)</td>
<td>88</td>
</tr>
<tr>
<td>270VDC GENERATION AND DIST</td>
<td>28</td>
</tr>
<tr>
<td>CONTROL PANELS</td>
<td>26</td>
</tr>
<tr>
<td>SENSORS, WPNS BAY, ENG BAY</td>
<td>46</td>
</tr>
<tr>
<td>CONTROL SURFACES</td>
<td>49</td>
</tr>
<tr>
<td>FUEL SYSTEM</td>
<td>141</td>
</tr>
<tr>
<td>ICE DETECTION</td>
<td>5</td>
</tr>
<tr>
<td>LANDING GEAR</td>
<td>261</td>
</tr>
<tr>
<td>LIGHTING</td>
<td>31</td>
</tr>
<tr>
<td>IMU &amp; IEU</td>
<td>16</td>
</tr>
<tr>
<td>OXYGEN GEN</td>
<td>7</td>
</tr>
<tr>
<td>HELMET AND DATA PROCESSORS</td>
<td>52</td>
</tr>
<tr>
<td>PHM AIR VEHICLE</td>
<td>7</td>
</tr>
<tr>
<td>VEHICLE SYS PROCESSING (VSP)</td>
<td>16</td>
</tr>
<tr>
<td>CNI SYSTEM</td>
<td>70</td>
</tr>
<tr>
<td>STANDARD PRACTICES, STRUCTURES</td>
<td>38</td>
</tr>
<tr>
<td>DOORS &amp; COVERS</td>
<td>330</td>
</tr>
<tr>
<td>FRAME, BULKHEADS</td>
<td>113</td>
</tr>
<tr>
<td>STABILIZERS, RUDDER</td>
<td>40</td>
</tr>
<tr>
<td>CANOPY</td>
<td>27</td>
</tr>
<tr>
<td>STRUCTURE, FARINGS, FLAPS</td>
<td>92</td>
</tr>
<tr>
<td>PROPULSION AIRCRAFT INTERFACE</td>
<td>9</td>
</tr>
<tr>
<td>THROTTLE</td>
<td>6</td>
</tr>
<tr>
<td>DOOR ACTUATORS (STOVL ONLY)</td>
<td>49</td>
</tr>
<tr>
<td>RADAR SYSTEM</td>
<td>149</td>
</tr>
<tr>
<td>EJECTION SEAT, SYSTEM</td>
<td>34</td>
</tr>
<tr>
<td>ELECTRONIC WARFARE</td>
<td>81</td>
</tr>
</tbody>
</table>

Over 2,000 parts
What comprises F-35 Costs per Flying Hour?

- Manpower (operations & maintenance)
- Fuel, Expendables
- Maintenance
  - Depot level repair and other maintenance costs
  - Air Vehicle component removals for repair/replacement
  - Engine modules removals for repair/replacement
- Support, Training
- System Improvements

*Note: IDA logo watermark.*
What comprises F-35 Costs per Flying Hour?

\[ CPFH_{Total} = \sum_{i=1}^{n} \frac{\text{[Replacement or Repair Cost]}_i \times \text{(num failures)}_i}{\text{Total Flight Hours}} \]

 CPFH = Cost per Flight Hour  MFHBR = Mean Flight Hours Between Removals

Depot level repair and other maintenance costs

Manpower (operations & maintenance)  Fuel, Expendables  Maintenance  Support, Training  System Improvements
What comprises F-35 Costs per Flying Hour?

CPFH\textsubscript{Total} = \sum_{i=1}^{n} \frac{[\text{Replacement or Repair Cost}]_i}{\text{MFHBR}_i}

Accurate component Reliability estimates are essential for cost estimation

CPFH = Cost per Flight Hour \quad MFHBR = \text{Mean Flight Hours Between Removals}
Data is often scarce for reliability estimation

Early in a Program we only have *Engineering Estimates* for component reliability (also when a new variant/configuration begins flying)

Later, sufficient failures have occurred, flying hours accumulated, to begin estimating reliability for each component.
Component Reliability Estimates – Many methods

Three Cases

Many failures (N>20)

\[
MFHBR_i = \frac{Total \ Flight \ Hours}{N_i}
\]

(assume failure times follow an Exponential Distribution)

Do we use:
- \( FH/N \) (ignore uncertainty)?
- Report a weighted average?
  - E.g., \( 0.3(FH/N) + 0.7 \text{Engineer Est.} \)

Few failures (1 < N < 20)

\[
MFHBR_i = MFHBR_i^{\text{Engineer Est.}}
\]

What if \( FH >> MFHBR_i^{\text{Engineer Est.}} \)?

- Do we use the:
  - lower CI bound?
  - set equal to FH?
  - engineering est.?

No Failures to date (N=0)

\[
MFHBR_i = MFHBR_i^{\text{Engineer Est.}}
\]

Alternatively we can use a Bayesian approach

(sliding scale weighted average)

\( N = \text{number of failures; FH = Flight Hours} \)
Bayesian statistics combine “prior” knowledge with observed data to produce an estimate

Example for Component X:
• Engineering Estimate MFHBR = 990 hours
• Flight Hours flown to date: 40,000 hours
• Observed 2 Failures…. traditional methods estimate:
• MFHBR = 40,000 / 2 = 20,000 hours

What’s the best number to use for MFHBR? 990 or 20,000?
Average the two? (~10,500?)
Weigh one more than the other? Which one?
Bayesian approach to estimating Reliability

- **Likelihood Distribution**: Exponential ($\lambda$)
  - $MFHBR = \frac{1}{\lambda} = \frac{Total\ Flight\ Hours}{n}$

- **Prior Distribution**: Gamma ($\alpha, \beta$)
  - We can use the engineering estimates to solve for $\alpha$ and $\beta$.
  - Inv. Gamma mean = $MFHBR_{Engineer\ Est}$
  - Inv. Gamma std. = $MFHBR_{Engineer\ Est} \times p$

- **Posterior Distribution**: Gamma ($\alpha', \beta'$)
  - $\alpha' = N + \alpha$
  - $\beta' = Total\ Flight\ hours + \beta$

$p$ = the “confidence” we place in the prior information. We used a $p = 1.5$. 
Bayesian statistics combine “prior” knowledge with observed data to produce an estimate

Example for Component X:

- Engineering Estimate \( \text{MFHBR} = 990 \text{ hours} \) (yellow “prior” below)
- Flight Hours flown to date: 40,000 hours
- Observed 2 Failures…. traditional methods estimate:
- \( \text{MFHBR} = \frac{40,000}{2} = 20,000 \text{ hours} \) (blue “likelihood” below)
Bayesian statistics combine “prior” knowledge with observed data to produce an estimate

Example for Component X:
• Engineering Estimate MFHBR = 990 hours (yellow “prior” below)
• Flight Hours flown to date: 40,000 hours
• Observed 2 Failures…. traditional methods estimate:
• MFHBR = 40,000 / 2 = 20,000 hours (blue “likelihood” below)

We’re showing our trust in the Engineering Estimates with the narrow width of the prior

The final estimate is influenced significantly by the Engineering Estimate because
1. few data (failures) exist,
2. we chose a narrow distribution for the prior
With more failure data available, the final estimate is less influenced by the MAC value.

Example for Component Y:

- MAC/SPUD estimates the MFHBR = 990 hours (yellow prior below)
- Flight Hours flown to date: 40,000
- Observed 10 Failures, so, traditional methods estimate:
  - MFHBR = 40,000 / 10 = 4,000 hours (blue “likelihood” below)

**Graph:**
- MFHBR from engineering estimates
- MFHBR est. from data alone

**Legend:**
- Posterior Median/Mean (best estimate of “true” reliability)
A robust methodology for all cases

- Bayesian method appropriately moves MFHBR estimate towards the traditional result as the available data increases
- The approach also automatically handles cases where N=0 (something not satisfactorily handled with traditional approaches)
A frequent debate: How do we estimate MFHBR for a new configuration?

Example for Component Z:

<table>
<thead>
<tr>
<th></th>
<th>Older Lots (anticipated improvement)</th>
<th>New Lots</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engineering Estimate</td>
<td>900</td>
<td>900</td>
</tr>
<tr>
<td>Flight hours</td>
<td>20,000</td>
<td>10,000</td>
</tr>
<tr>
<td>Failures observed</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>MFHBR</td>
<td>4,000</td>
<td>3,338? (95% Lower bound)</td>
</tr>
</tbody>
</table>

- Bayesian method provides an ideal (and defensible) calculation method for this case
- MFHBR for Older Lots serves as the new prior estimate for the New Lots calculation
  - Appropriately using the available data as a starting point, but allowing the available New data to dictate how much the final estimate is moved
- Bayesian results for New Lots: MFHBR = 7,576
Distributed Aperture System Sensors’ reliability show the benefit of the Bayesian approach.
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Only one failure observed; point estimate is highly uncertain

Bayesian estimate uses previous Lot estimate as starting point – much better reliability estimate

Cases with lots of data (failures), estimates are the same
Distributed Aperture System Sensors’ reliability show the benefit of the Bayesian approach

Only a lower bound can be estimated – and is more pessimistic than the Bayesian point estimate

Sensor #3 saw 11 failures in older Lots, and zero failures in New Lots
Distributed Aperture System Sensors’ reliability show the benefit of the Bayesian approach

Traditional method is highly uncertain (2 failures), but suggest a degradation in performance.

Bayesian method is a properly weighted average between Engineering Estimate and Traditional.

Point estimates reflect the fact that there is no real difference in performance.
What comprises F-35 Costs per Flying Hour?

- **Manpower** (operations & maintenance)
- **Fuel, Expendables**
- **Maintenance**
- **Support, Training**
- **System Improvements**

- **Depot level repair and other maintenance costs**
- **Air Vehicle component removals for repair/replacement**
- **Engine modules removals for repair/replacement**
Bayesian Reliability results in a more informed estimate of maintenance costs


New Estimate (uses IDA-Bayesian method for Reliability)

Maintenance Costs ($)
Conclusion

Bayesian methods provide a means to combine available knowledge of reliability with operational data to estimate component reliability, resulting in a more informed estimate of F -35 maintenance costs.

- Updated from early engineering estimates
- Updated from previous system/variant data
- Handles cases with few data (even no failures!)