Optimal Cost Preventative Maintenance Scheduling for High Reliability Aerospace Systems

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Introduction

- **Highly Reliable Aerospace Systems Do not Fail Often** ***They are Designed that Way!***
- **Maintenance Options**
  - **May Allow to Fail in Service**
  - **Or, Perform Preventative Maintenance at Some Regular Service Interval**
- **Preventative Maintenance is Usually Cheaper than Replacement,** ***Much Cheaper***
- **How does one find the Interval that Optimally Balances the Cost Risk for Failure in Service, with the Cost Risk for PM?**

The Problem

- Highly Reliable Aerospace Systems that do not Fail Often Provide *very few if any* Failure Data
  - Classical Statistical Analyses Break Down with Very Few Event Data
  - Decision Makers *Very Nervous* Committing to a Preventative Maintenance Interval with Few Failure Data
- *It Gets Worse!*
  - What is the Basis for such a Decision?
  - There exists Uncertainty in the Statistical Results
  - The Wrong Decision could be *Career Limiting*

The Solution

- Must Select *Good* Figures of Merit for the Preventative Maintenance Interval Decision
  - Cost Based
  - Parameterized as a Function of Candidate PM Intervals
- Must Use Conditional Inferential Approach
  - Classical Statistics Break Down with Few Data
  - Conditional Methods Work Well with Few Data
  - Conditional Methods Allow Incorporation of Survivor Data (suspensions) Directly *with No Assumptions*
- *But,* For Real World Problems, Conditional Methods Rarely Produce Analytically Tractable Formulations
  - Explains Why Conditional Methods are Rarely Seen
  - *But,* Numerical Methods Developed in mid 1990's Can be Used with Conditional Approaches to Get Quantitative Results
  - Numerical Method: *Markov Chain Monte Carlo*

Example: US Coast Guard C130 Cockpit Cooling Turbine

- **Cooling Turbine Provides Cooling and Pressurization to the C130 Crew**
- **Failure in Service**
  - **Loss of Cooling, but More Important, Loss of Cabin Pressurization**
  - **Smoke, Loud, Crew Must Secure**
  - **Mission Compromised**
- **Costs**
  - **Replacement: *$30,000***
  - **Refurbishment: *$500***

The C130 PM Problem

- **60:1 Ratio, Replacement:Maintain**
- **Only Had Five Failure Data: 463, 538, 1652, 1673, and 2462 flight hours**
- **Only Had One Survivor Datum: 96 flight hours**
- **What PM Interval to Select?**
- **USCG Decision Makers *Paralyzed***

Figures of Merit

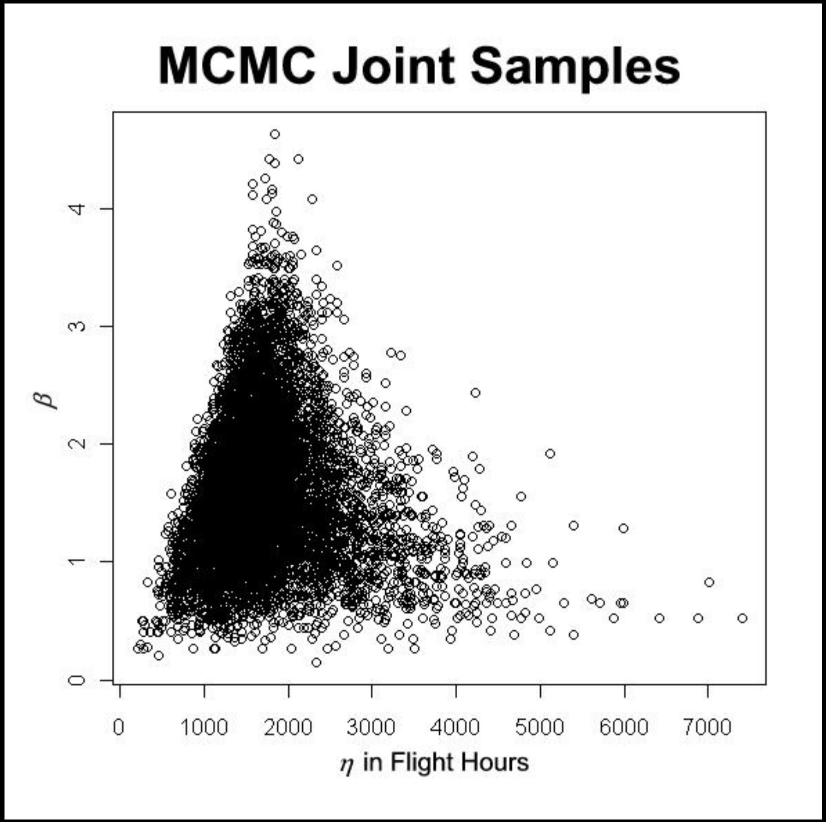
- USCG had No Idea what the Failure in Service Mode was Costing Them for the Fleet of C130's
  - Figure of Merit Based on This Cost for the Fleet per Flight Hour
  - C_{fis} – Cost per Flight Hour for Failures in Service
- Needed to Evaluate Costs for the Fleet of C130's using a Preventative Maintenance Interval – *Parameterized* as a function of Candidate PM Intervals
  - C_{tpm} – Cost per Flight Hour performing Preventative Maintenance at the Interval of *tpm* flight hours
  - CS_{tpm} – Cost Savings per Flight Hour of performing Preventative Maintenance at the Interval of *tpm* flight hours over Allowing Failures in Service

Methods

- **Used the Weibull Model for Failure and Survivor Data – Uncertain Parameters η and β**
- **Uncertainty Models for Figures of Merit Had Rather *Nasty Formulae***
  - $pd(C_{fis} \mid data) \propto \int_0^\infty \int_0^\infty \left(\left[\left(\frac{C_{rep}}{\eta} \right) * \Gamma\left(\frac{\beta - 1}{\beta} \right) \right] * pd\left(\eta, \beta \mid data \right) \right) d\eta d\beta$
  - $pd(C_{tpm} \mid data) \propto \int_0^\infty \int_0^\infty \left[\left(\frac{C_{rep}}{\eta} \right) * \left\{ \Gamma\left(\frac{\beta - 1}{\beta} \right) - \gamma\left(\frac{\beta - 1}{\beta}, \left(\frac{t_{pm}}{\eta} \right)^{\beta} \right) \right\} + \left(\frac{C_{pm}}{t_{pm}} \right) * e^{-\left(\frac{t_{pm}}{\eta} \right)^{\beta}} \right] * pd\left(\eta, \beta \mid data \right) d\eta d\beta$
  - $pd(CS_{tpm} \mid data) \propto \int_0^\infty \int_0^\infty \left[\left(\frac{C_{rep}}{\eta} \right) \gamma\left(\frac{\beta - 1}{\beta}, \left(\frac{t_{pm}}{\eta} \right)^{\beta} \right) - \left(\frac{C_{pm}}{t_{pm}} \right) * e^{-\left(\frac{t_{pm}}{\eta} \right)^{\beta}} \right] * pd\left(\eta, \beta \mid data \right) d\eta d\beta$
- **Used Numerical Methods (MCMC and MC) *Liberally***

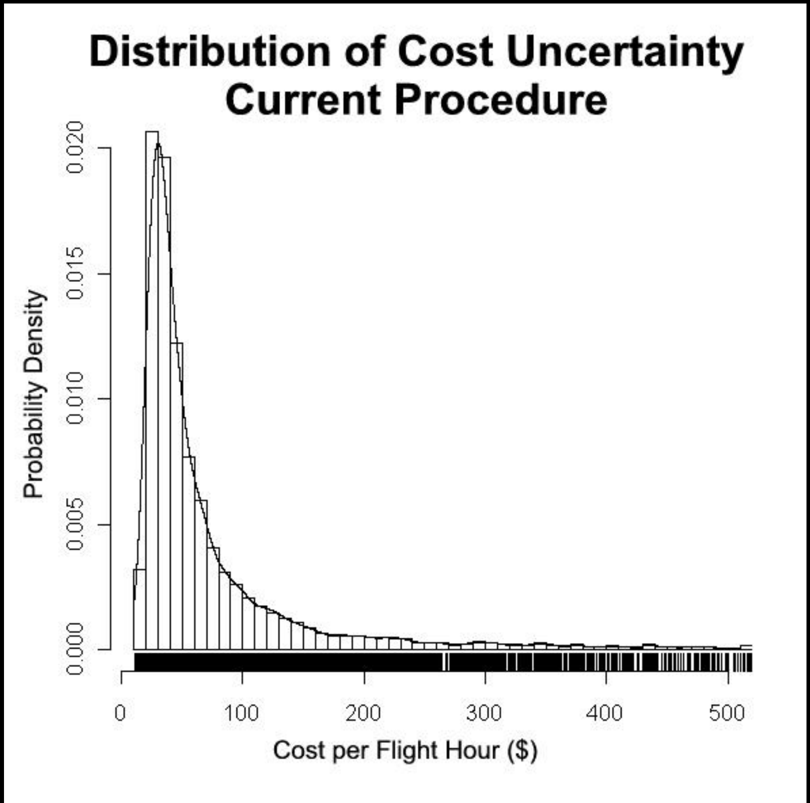
Results

- **Used MCMC to Sample Joint Uncertainty Model for Weibull Parameters Based Solely on the Data –**
  pd(η,β |data)
- **Non-Intuitive *Porkchop* Looking Distribution**
  - **Lots of Outliers – Good!**
  - **Correlations Not Describable Using any Recognized Models**



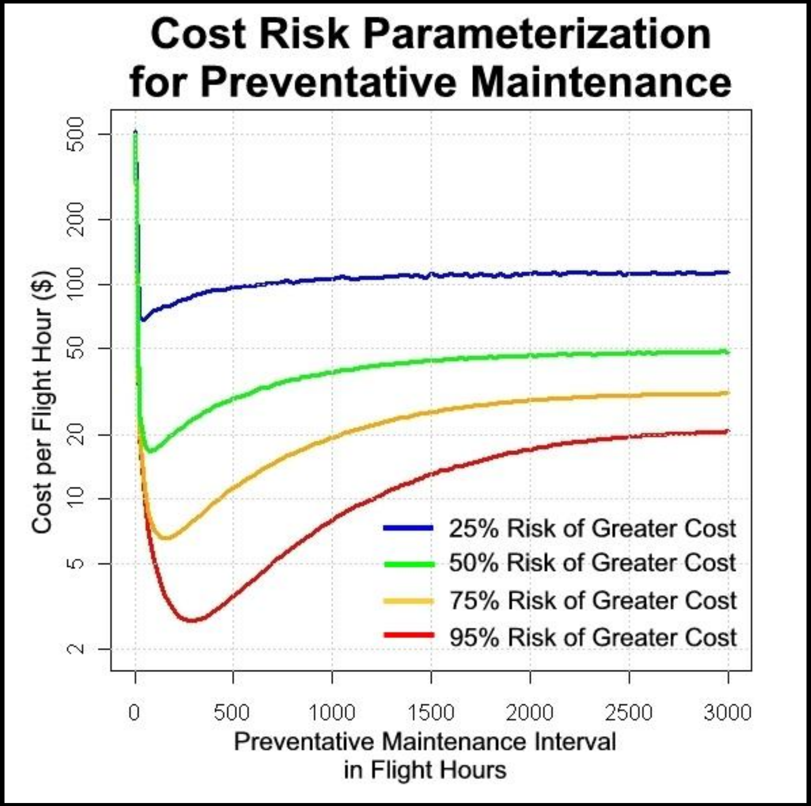
Cost Uncertainty of Allowing Failure in Service

- **Full Distribution Per Flight Hour, Per Bird -** C_{fis}
- **Based Solely on The Data**
- **Most Likely Cost per Bird per Flight Hour -** ***$34/flight hour***
- **Note Appreciable Uncertainty out Beyond $100/flight hour**



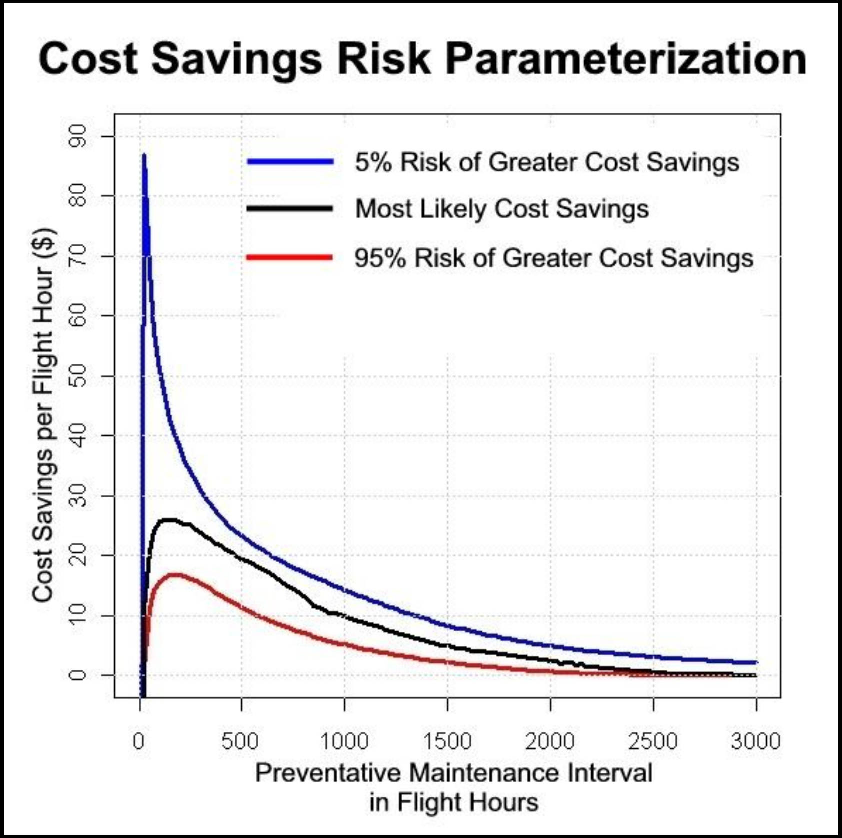
Cost Risks Using a PM Interval - Parameterized

- **Full Distributions Per Flight Hour, Per Bird - C_{tpm}**
- **Based Solely on The Data, Parameterized as a function of PM Interval in flight hours**
- **Notice *Dips* at all Risk Levels between about 100 and 450 flight hours**



Cost Savings Risks Using a PM Interval - Parameterized

- Full Distributions Per Flight Hour, Per Bird - CS_{tpm}
- Based Solely on The Data, Parameterized as a function of PM Interval in flight hours
- Plotted Only 5th, Most Likely, and 95th percentile Cost Savings Risks
- Peaks all between 100 and 450 flight hours
- At *tpm* = 250 hours, 95% Certain, based on the data, that USCG can ***SAVE*** at least $17 per flight hour per bird



Conclusions

- Conditional Inferential Methods combined with Markov Chain Monte Carlo numerical Methods Provide *Useable* Quantified Figures of Merit
- USCG Decision Makers were *Comfortable* with the Results and Made *Immediate* Decision

  Despite having only Five Data!
- Approach can be Directly Applied to any Highly Reliable Aerospace System with Fixed Costs for Replacement and Refurbishment
- Approach can be Easily Extended when Refurbishment Costs Vary
- Welcome Contact about Your Problem