An Approximate Dynamic Programming (ADP) Approach for Aircraft Maintenance Scheduling

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2. Problem Formulation

3. Methodology

4. Outcomes and Evaluation

5. Summary and Future Work
Background and Related Work
# Background

<table>
<thead>
<tr>
<th>Maintenance Costs (51 Airlines)</th>
<th>Average (USD/Year)</th>
<th>Min (USD/Year)</th>
<th>Max (USD/Year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Per Airline</td>
<td>295M</td>
<td>0.95M</td>
<td>2.28B</td>
</tr>
<tr>
<td>Per Aircraft</td>
<td>3.6M</td>
<td>0.67M</td>
<td>9.3M</td>
</tr>
<tr>
<td>Per Flight Hour</td>
<td>1,087</td>
<td>287</td>
<td>2,841</td>
</tr>
<tr>
<td>Per Flight Cycle</td>
<td>2,681</td>
<td>465</td>
<td>11,937</td>
</tr>
</tbody>
</table>

Aircraft Maintenance Checks

- **A-Check**
  - General inspection of the interior/exterior

- **C-Check**
  - Detailed functional and operational systems checks, cleaning and servicing

- **D-Check or IL (sometimes merged with C-Checks)**
  - The exterior paint is stripped and large parts of the outer paneling are removed, uncovering the airframe, supporting structure and wings for inspection of most structurally significant items
## Related Work

<table>
<thead>
<tr>
<th>C-Check</th>
<th>M. Etschmaier, P. Franke, Long-Term Scheduling of Aircraft Overhauls, 1969</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H. Bauer-Stampfli, Near Optimal Long-Term Scheduling of Aircraft Overhauls by Dynamic Programming, 1971</td>
</tr>
<tr>
<td></td>
<td>N. J. Boere, Air Canada Saves with Aircraft Maintenance Scheduling, 1977</td>
</tr>
<tr>
<td></td>
<td>W. E. Moudani, F. Mora-Camino, A Dynamic Approach for Aircraft Assignment and Maintenance Scheduling by Airlines, 2000</td>
</tr>
<tr>
<td></td>
<td>……</td>
</tr>
<tr>
<td></td>
<td>……</td>
</tr>
</tbody>
</table>
Problem Formulation
Problem Definition

Aircraft is aged by:

Calendar Day (DY)

Flight Hour (FH)

Flight Cycle [2] (FC)

When is an aircraft scheduled C-check or A-check?

When is an aircraft scheduled C-check or A-check?

A-Check

120 DY
750 FH
750 FC

When is an aircraft scheduled C-check or A-check?

Maintenance Check and Duration [3]

A-Check:

<table>
<thead>
<tr>
<th></th>
<th>A-Check</th>
<th>A-Check</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 DY</td>
<td>120 DY</td>
<td>0 DY</td>
</tr>
<tr>
<td>0 FH</td>
<td>750 FH</td>
<td>0 FH</td>
</tr>
<tr>
<td>0 FC</td>
<td>750 FC</td>
<td>0 FC</td>
</tr>
</tbody>
</table>

1-2 day

C-Check:

<table>
<thead>
<tr>
<th></th>
<th>C-Check</th>
<th>C-Check</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 DY</td>
<td>730 DY</td>
<td>0 DY</td>
</tr>
<tr>
<td>0 FH</td>
<td>7500 FH</td>
<td>0 FH</td>
</tr>
<tr>
<td>0 FC</td>
<td>5000 FC</td>
<td>0 FC</td>
</tr>
</tbody>
</table>

1 to 4 weeks

Maintenance Constraints

- C-Check/A-Check Interval

- Hangar Capacity (Parallel C-/A-Check)
  - Maintenance Tools
  - Aircraft spare parts
  - Maintenance Engineers

- Commercial Peak Season
  - Weekends
  - Public Holidays
  - Summer
Objective and Decision Variable

Objective: Minimize the total unused FH of fleet

Decision Variables: Start dates of C-checks and A-checks
Methodology
Approximate Dynamic Programming
**Challenge:** Long computation time

**Solution:**

- Dynamic programming with forward induction
  - Divide a large problem to several small sub problems

- Define proper planning stage
  - 1 stage = 1 calendar day

- Define state of problem for decision making
  - State = \{DY/FH/FC since last C-Check/A-check\}
**Multi-Dimensional Action Vector**

**Challenge:** Computationally expensive to evaluate all actions  
**Solution:** Define Aircraft (A-/C-) Check Priority

<table>
<thead>
<tr>
<th>C-Check</th>
<th>A-Check:</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/C 1: 0.5</td>
<td>A/C 1: 0.6</td>
</tr>
<tr>
<td>A/C 2: 0.9</td>
<td>A/C 2: 0.2</td>
</tr>
<tr>
<td>A/C 3: 0.7</td>
<td>A/C 3: 0.9</td>
</tr>
<tr>
<td>A/C 4: 0.8</td>
<td>A/C 4: 0.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>C-Check</th>
<th>A-Check:</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/C 2: 0.9</td>
<td>A/C 3: 0.9</td>
</tr>
<tr>
<td>A/C 4: 0.8</td>
<td>A/C 1: 0.6</td>
</tr>
<tr>
<td>A/C 3: 0.7</td>
<td>A/C 4: 0.5</td>
</tr>
<tr>
<td>A/C 1: 0.5</td>
<td>A/C 2: 0.2</td>
</tr>
</tbody>
</table>

C-Check Priority: A/C 2, A/C 4, A/C 3, A/C 1  
A-Check Priority: A/C 3, A/C 1, A/C 4, A/C 2
Multi-Dimensional State Variable

Example: No check, 1 C-check, 1 A-check

<table>
<thead>
<tr>
<th>Day</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>......</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outcomes</td>
<td>1</td>
<td>3</td>
<td>9</td>
<td>27</td>
<td>......</td>
<td>$3^n$</td>
</tr>
</tbody>
</table>

Impossible to evaluate all actions and save all outcomes!
Multi-Dimensional State Variable

**Challenge:** Difficult for discretization and large outcome space

**Solution:** Define utilization threshold for making decision

Sort utilization: \( \{u_{c,1}, u_{c,2}, u_{c,3}, \ldots (u_{c,i} > u_{c,i+1})\}, \{u_{a,1}, u_{a,2}, u_{a,3}, \ldots (u_{a,i} > u_{a,i+1})\} \)

Is there C-check/A-check slot?

Generate Utilization Threshold: \([U_c, U_a] = g(\text{Features})\)

If \(u_{c,1} \geq U_c\), allocate C-check
If \(u_{a,1} \geq U_a\), allocate A-check

Significantly reduce the search states!
Policy Function (PF)

- Define the rule that determines a decision at a state
- Introducing policy function reduces the number of search states
- Policy function generates the C-check/A-check utilization threshold: $[U_c, U_a] = g(\text{Features})$

- Features:
  - Mean utilization of fleet
  - Standard deviation of utilization
  - Current available C-check/A-check block
  - The coming commercial peak when no C-/A-check is allowed
Policy Iteration

- Find the optimal policy to make optimal decision
- Policy iteration requires many simulation runs to find the optimal coefficient of policy function
- Each simulation run simulates the decision given by policy function and step forward through time
- After the coefficients are found, the policy function can be used to make decision and respond to changes of input in seconds.
Policy Iteration Cont.

Formulation of Policy Function:

\[ U_c = 1 - (k_{c,1}x_{c,1} + k_{c,2}x_{c,2} + k_{c,3}x_{c,3} + k_{c,4}x_{c,4} + \ldots) \]
\[ U_a = 1 - (k_{a,1}x_{a,1} + k_{a,2}x_{a,2} + k_{a,3}x_{a,3} + k_{a,4}x_{a,4} + \ldots) \]

\( x_{c,1}, x_{c,2}, x_{c,3}, \ldots \) are the features related to C-check
\( x_{a,1}, x_{a,2}, x_{a,3}, \ldots \) are the features related to A-check

Machine Learning:

C - Check: \[ k_{c,i} = k_{c,i} - \alpha_c \frac{\partial F}{\partial k_{c,i}} \]
A - Check: \[ k_{a,i} = k_{a,i} - \alpha_a \frac{\partial F}{\partial k_{a,i}} \]

\( F \) — objective function; \( \alpha_c / \alpha_a \) — learning rates for C-check/A-check
Work Flow of Policy Iteration

1. Initial fleet data
2. Generate initial coefficient for policy function
3. Make C-check and A-check decisions from day 1 to day $n$
4. Are the partial derivative of all coefficients of PF 0?
   - Yes: Stop and return the C-check and A-check schedule
   - No: Tune the coefficients of policy function
Outcomes and Evaluation
Case study (Jan 2011 – Dec 2015)

- Test Fleet: 39 aircraft of A320 family
- C-Check Interval: 7500 FH / 5000 FC / 730 Days
  A-Check Interval: 750 FH / 750 FC / 120 Days
- C-Check Tolerance: 750 FH / 500 FC / 60 DY
  A-Check Tolerance: 75 FH / 75 FC / 12 DY
- No C-check is allowed from Dec 18th - Jan 7th, the weeks before and after Easter and Jun 1st – Sep 30th. No A-check on weekend and public holidays
- 3 slots available for C-checks, 1 slot for A-check

Selected Features

• C-Check:
  ▪ The coming commercial peak season when no C-check is allowed ($x_{c,1}$)
  ▪ Current available C-check block ($x_{c,2}$)
  ▪ Standard deviation of utilization ($x_{c,3}$)
  ▪ Constant ($x_{c,4}$)

• A-Check:
  ▪ The coming bank holiday when no A-check is allowed ($x_{a,1}$)
  ▪ Standard deviation of utilization ($x_{a,2}$)
  ▪ Constant ($x_{a,3}$)

Note: all the features are normalized between 0 and 1.
Coefficients of Policy Function

Policy Function:

\[
\begin{align*}
U_c &= 1 - (k_{c,1}x_{c,1} + k_{c,2}x_{c,2} + k_{c,3}x_{c,3} + k_{c,4}x_{c,4}) \\
U_a &= 1 - (k_{a,1}x_{a,1} + k_{a,2}x_{a,2} + k_{a,3}x_{a,3})
\end{align*}
\]

**Coefficient**

- \(k_{c,1}\) (Length of commercial peak season)
- \(k_{c,2}\) (Length of remaining C-check block)
- \(k_{c,3}\) (Standard deviation of C-check utilization)
- \(k_{c,4}\) (Constant)
- \(k_{a,1}\) (Length of public holiday or weekend)
- \(k_{a,2}\) (Standard deviation of A-check utilization)
- \(k_{a,3}\) (Constant)
# Optimized vs. Airline Schedule

<table>
<thead>
<tr>
<th>Jan 1st 2011 - Dec 31st 2015</th>
<th>C-Check</th>
<th></th>
<th>A-Check</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average FH</td>
<td>Total C-Checks</td>
<td>Average FH</td>
<td>Total A-Checks</td>
</tr>
<tr>
<td>Airline</td>
<td>6644.5</td>
<td>108</td>
<td>689</td>
<td>1054</td>
</tr>
<tr>
<td>1-stage ADP</td>
<td>6686.9</td>
<td>102</td>
<td>682.2</td>
<td>1043</td>
</tr>
<tr>
<td>n-stage ADP</td>
<td>6900.0</td>
<td>95</td>
<td>728.9</td>
<td>972</td>
</tr>
</tbody>
</table>

- Reduce 13 C-checks
- Reduce 82 A-checks
- Lower maintenance costs
- Higher aircraft utilization
Utilization Distribution (C-Check)

Aircraft Utilization Distribution Under
Original C-Check Schedule

Expected Aircraft Utilization Distribution Under
Optimized C-Check Schedule (ADP)

Desired Utilization
Utilization Distribution (A-Check)

Aircraft Utilization Distribution Under Original A-Check Schedule

Expected Aircraft Utilization Distribution Under Optimized A-Check Schedule (ADP)
Summary and Future Work
Summary

- Define C-check/A-check priority to simplify the action vector.
- Use policy function to reduce search states.
- Both C-checks and A-checks are optimized in one step.
Future Work

• Calculation of workload associated with the schedule:
  • Workload capacity control

• Introduction of uncertainty (stochastic modelling):
  • Elapse times
  • Aircraft FH & FC

• Line maintenance planning:
  • Optimize the sequence of line maintenance
  • Allocate workforce
Acknowledgment

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http://www.airmes-project.eu/
Thank you!

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