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

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Clean Sky 2

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Outline

1. **Background and Related Work**
2. **Problem Formulation**
3. **Methodology**
4. **Outcomes and Evaluation**
5. **Summary and Future Work**

Background and Related Work

Background

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

[1] IATA's Maintenance Cost Task Force. Airline Maintenance Cost Executive Commentary – An Exclusive Benchmark Analysis, 2015.

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

C-Check	M. Etschmaier, P. Franke, Long -Term Scheduling of Aircraft Overhauls, 1969 H. Bauer-Stampfli,Near Optimal Long-Term Scheduling of Aircraft Overhauls by Dynamic Programming, 1971 N. J. Boere, Air Canada Saves with Aircraft Maintenance Scheduling,1977
A-Check	T. A. Feo, J. F. Bard, Flight Scheduling and Maintenance Base Planning,1989 W. E. Moudani, F. Mora-Camino, A Dynamic Approach for Aircraft Assignment and Maintenance Scheduling by Airlines, 2000 C. Sriram, A. Haghani, An Optimization Model for Aircraft Maintenance Scheduling and Re-Assignment, 2003 ……

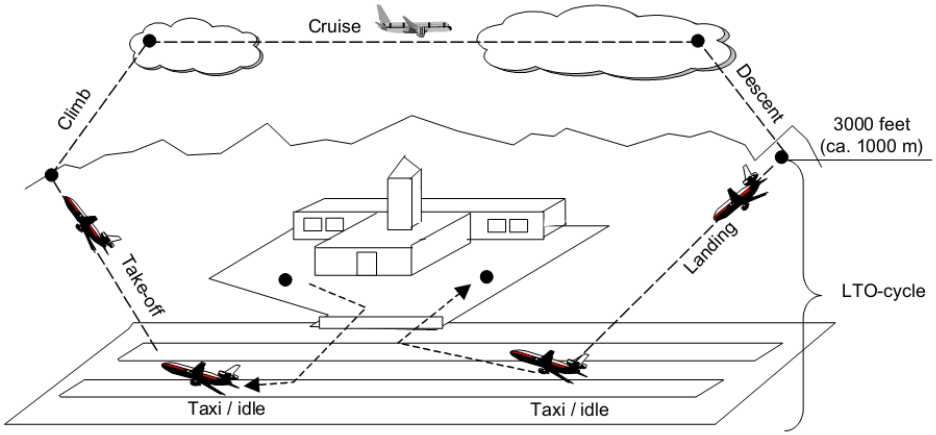
Problem Formulation

Problem Definition

Aircraft is aged by:

Calendar Day
(DY)

Flight Hour
(FH)



Flight Cycle [2]
(FC)

[2] K. Rypdal, 2000Aircraft emissions. In: Penman J, Kruger D, Galbally I, Hiraishi T, Nyenzi B, Emmanul S, Buendia L, Hoppaus R, Martinsen T, Meijer J, Miwa K, Tanabe K, editors. Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. Background paper, Japan: Institute for Global Environmental Strategies. 93102.

Problem Definition Cont.

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

0 DY
0 FH
0 FC

[3]

[3] Airbus A320 Maintenance Planning Document.

Problem Definition Cont.

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

120 DY
750 FH
750 FC

[3]

A-Check

[3] Airbus A320 Maintenance Planning Document.

Problem Definition Cont.

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

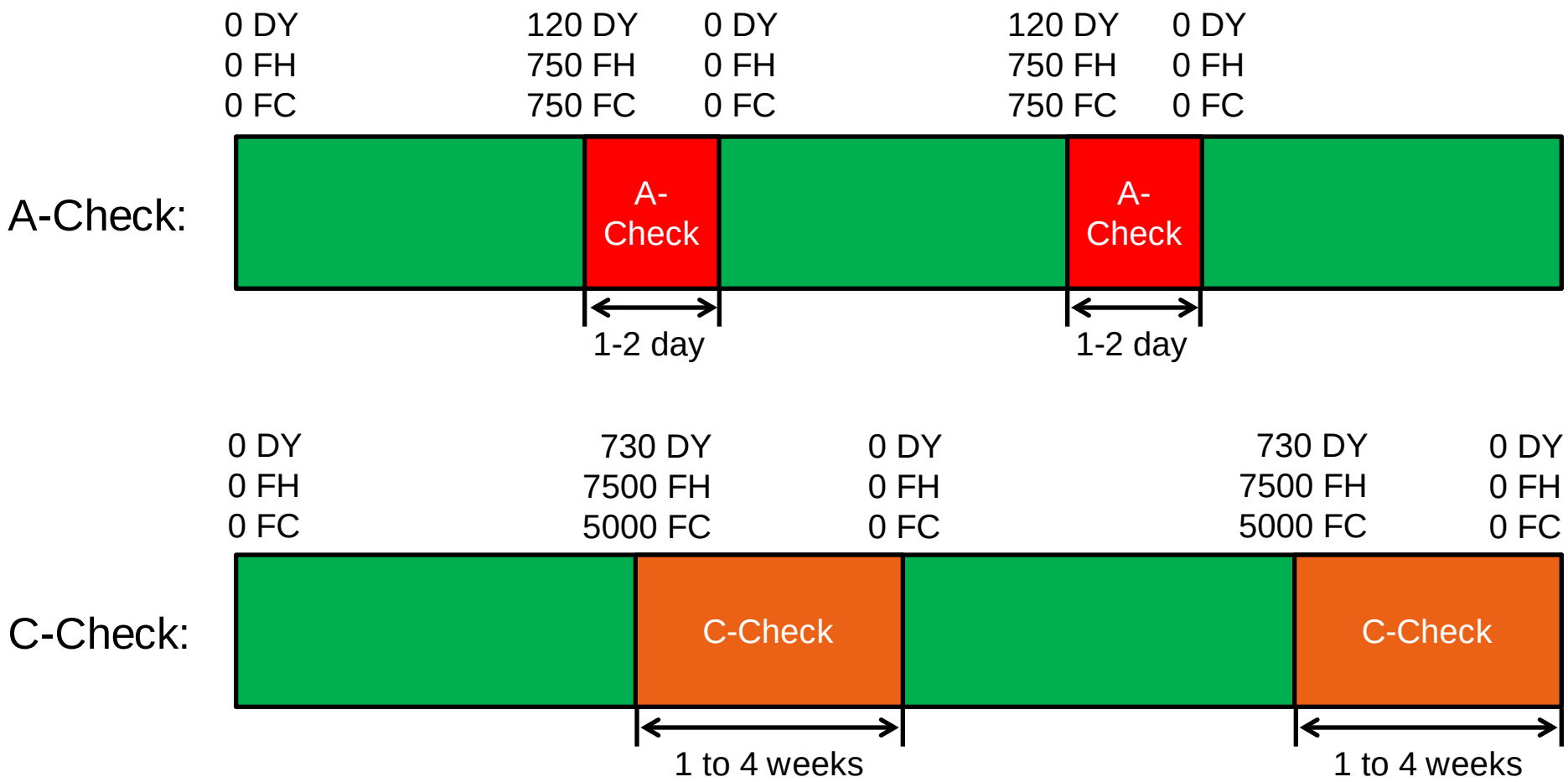
730 DY
7500 FH
5000 FC

[3]

C-Check

[3] Airbus A320 Maintenance Planning Document.

Maintenance Check and Duration [3]



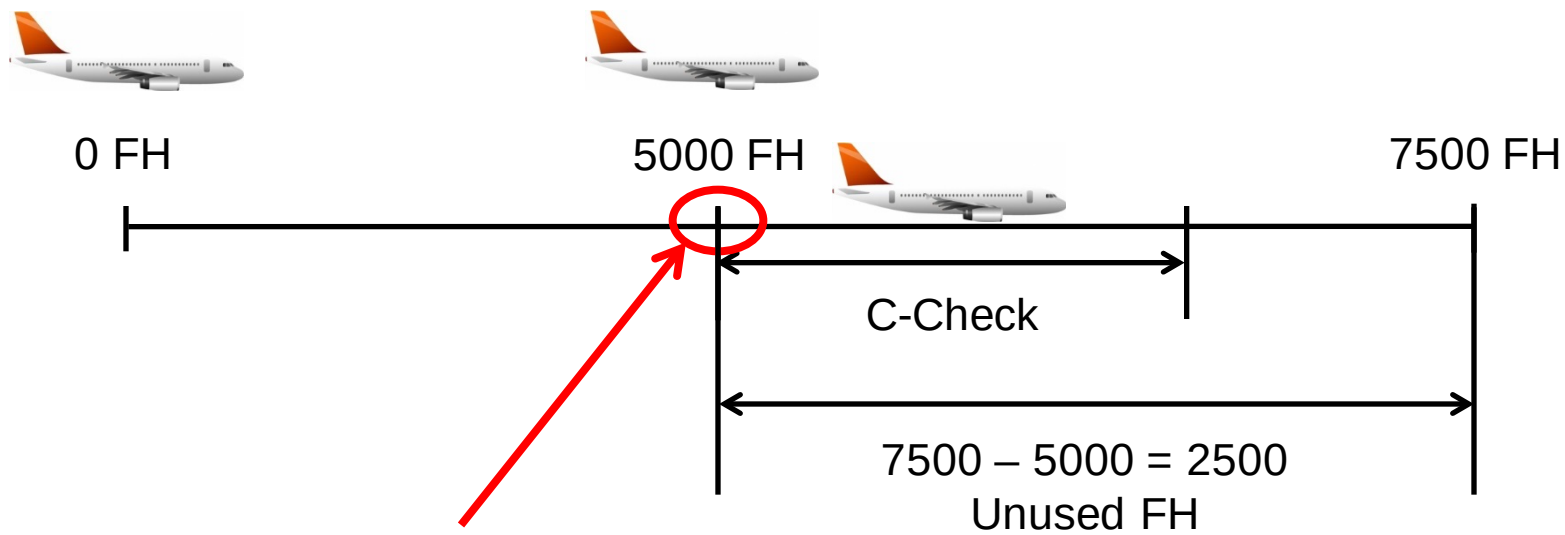
[3] Airbus A320 Maintenance Planning Document.

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

Integer Decision Variables

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

C-Check	A-Check:
A/C 1: 0.5	A/C 1: 0.6
A/C 2: 0.9	A/C 2: 0.2
A/C 3: 0.7	A/C 3: 0.9
A/C 4: 0.8	A/C 4: 0.5

Sort Utilization →

C-Check	A-Check:
A/C 2: 0.9	A/C 3: 0.9
A/C 4: 0.8	A/C 1: 0.6
A/C 3: 0.7	A/C 4: 0.5
A/C 1: 0.5	A/C 2: 0.2

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

Day	0	1	2	3	……	n
Outcomes	1	3	9	27		3^n

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:

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

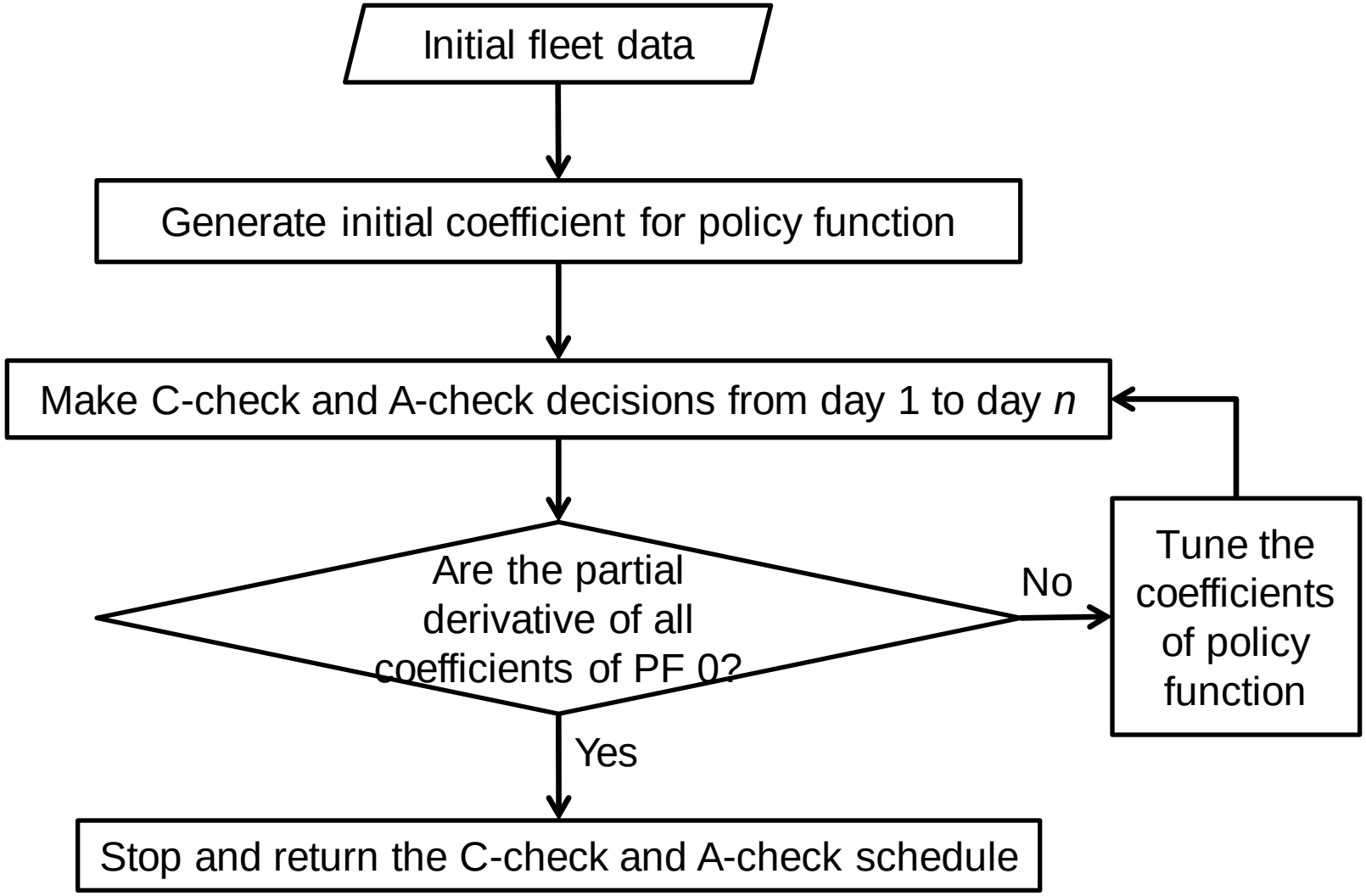
$x_{c,1}$, $x_{c,2}$, $x_{c,3}$, … are the features related to C-check
$x_{a,1}$, $x_{a,2}$, $x_{a,3}$, … are the features related to A-check

Machine Learning:

$$\text{C} - \text{Check:} \quad k_{c,i} = k_{c,i} - \alpha_c \frac{\partial F}{\partial k_{c,i}}$$
$$\text{A} - \text{Check:} \quad k_{a,i} = k_{a,i} - \alpha_a \frac{\partial F}{\partial k_{a,i}}$$

F — objective function; α_c/ α_a — learning rates for C-check/A-check

Work Flow of Policy Iteration



Outcomes and Evaluation

Case study (Jan 2011 – Dec 2015)

[4]

- 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

[4] https://flyawaysimulation.com/downloads/files/3972/fsx-airbus-industrie-house-a320/

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:

$$U_c = 1 - (k_{c,1}x_{c,1} + k_{c,2}x_{c,2} + k_{c,3}x_{c,3} + k_{c,4}x_{c,4})$$
$$U_a = 1 - (k_{a,1}x_{a,1} + k_{a,2}x_{a,2} + k_{a,3}x_{a,3})$$

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)

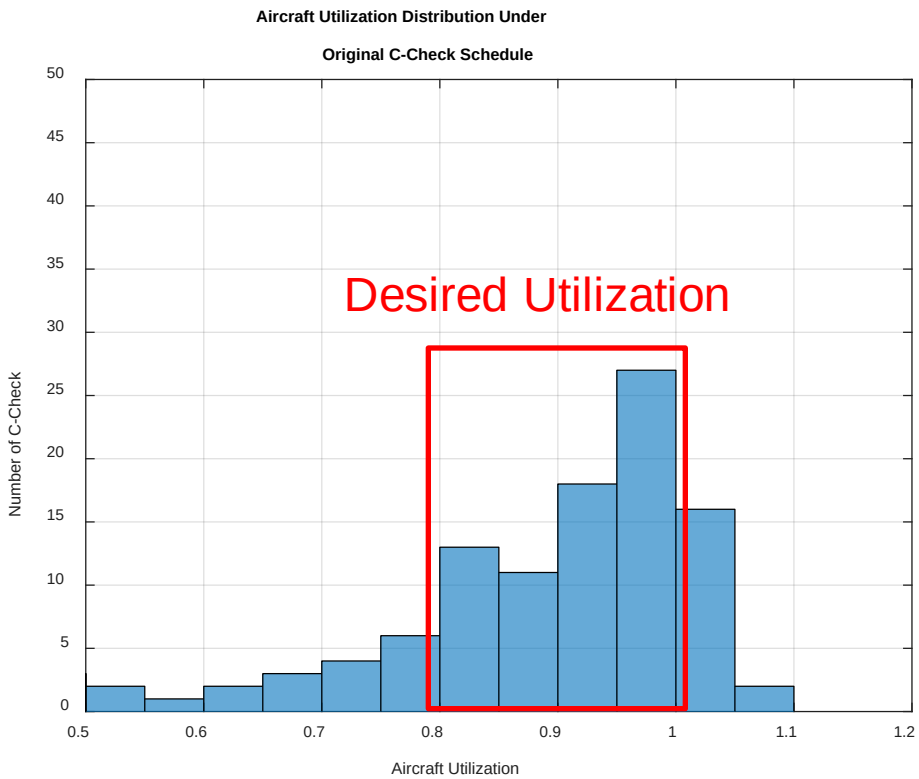
Optimized vs. Airline Schedule

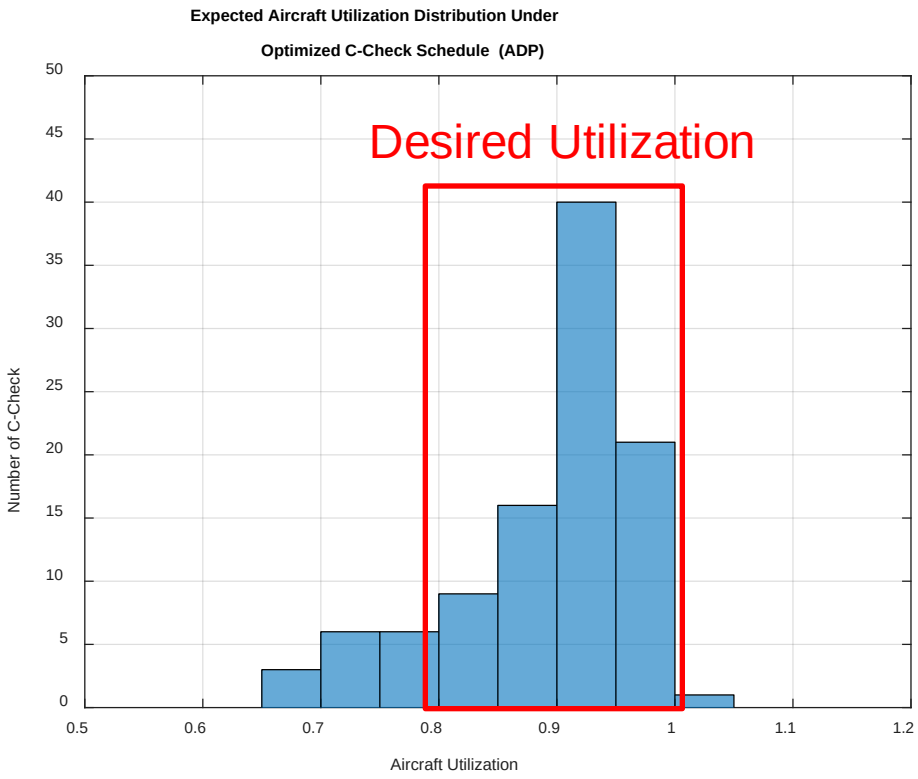
Jan 1st 2011 - Dec 31st 2015	C-Check		A-Check	
	Average FH	Total C-Checks	Average FH	Total A-Checks
Airline	6644.5	108	689	1054
1-stage ADP	6686.9	102	682.2	1043
n-stage ADP	6900.0	95	728.9	972

Reduce 13 C-checks
Reduce 82 A-checks

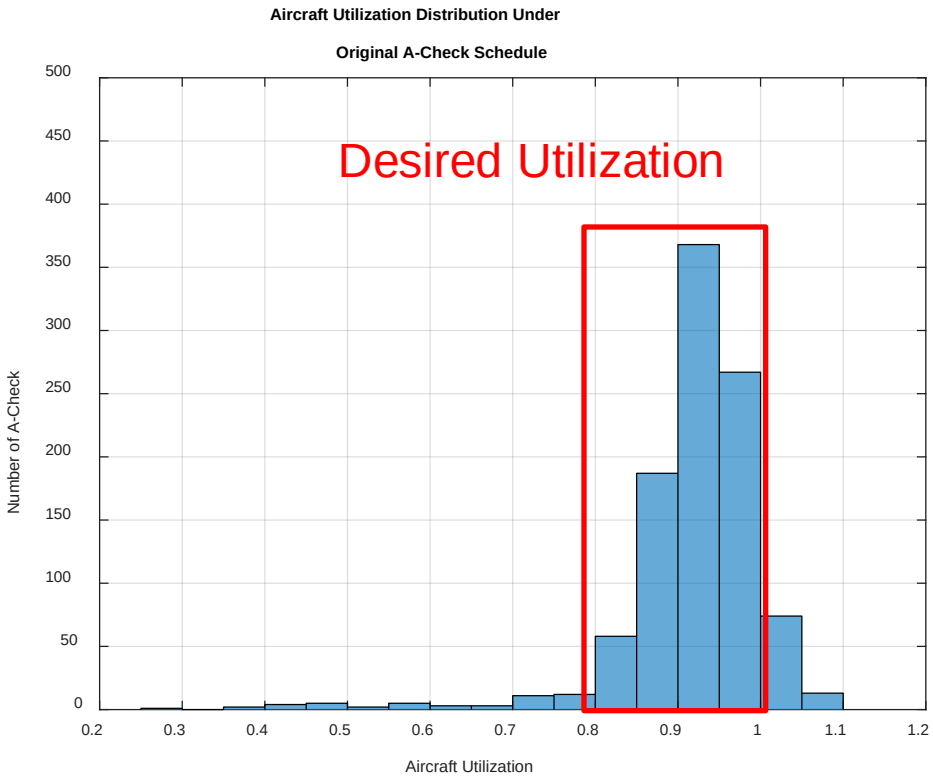
} Lower maintenance costs
Higher aircraft utilization

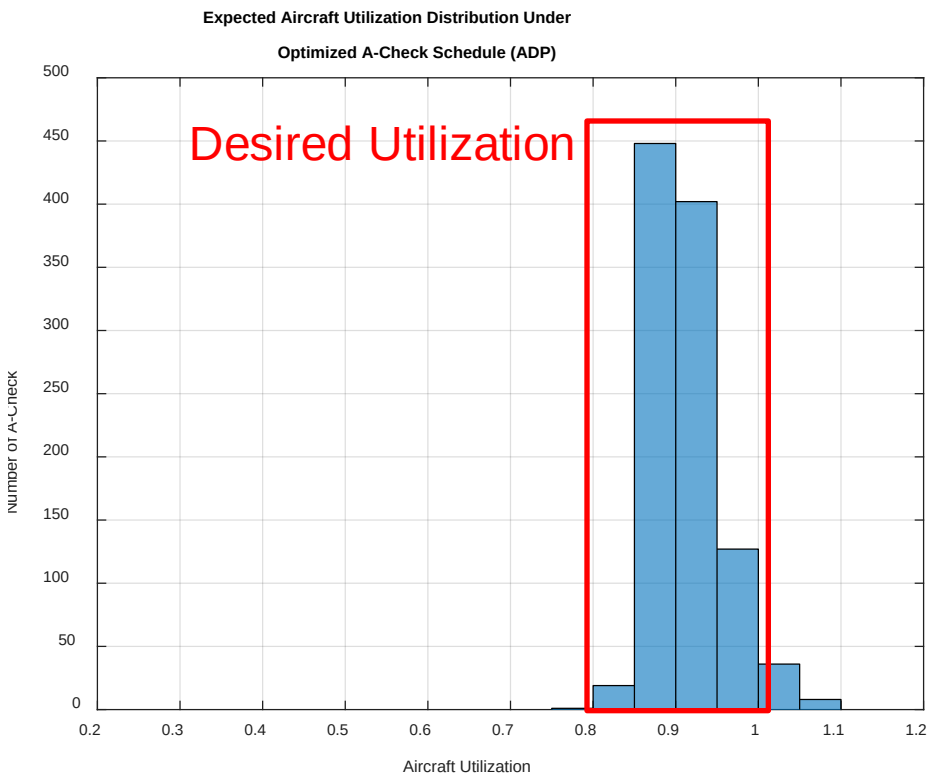
Utilization Distribution (C-Check)





Utilization Distribution (A-Check)





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

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