Maintenance Scheduling of Fighter Aircraft Fleet with Multi-Objective Simulation-Optimization

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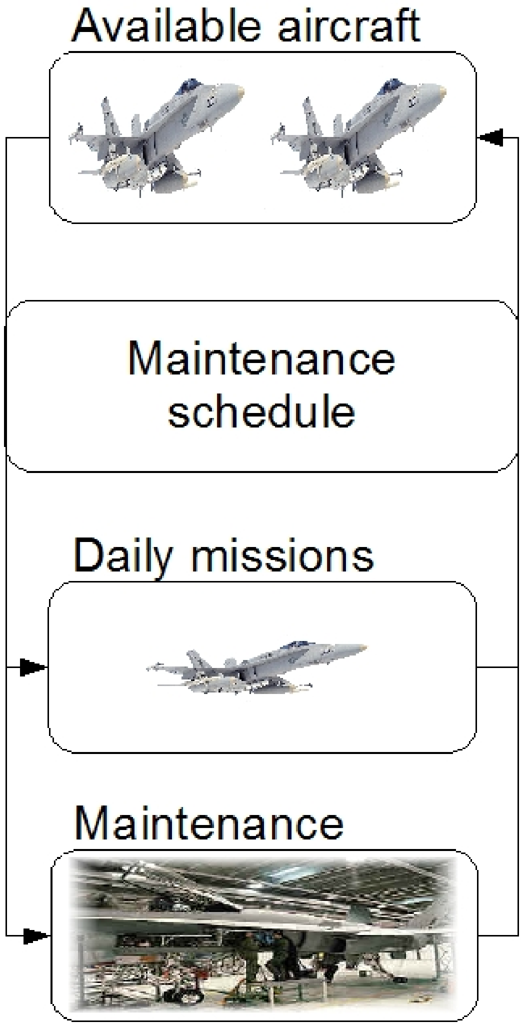
Maintenance scheduling of fighter aircraft fleet

- Extensive periodic maintenance
  - Ensuring
    - Flight safety
    - Performance
  - Normal conditions
  - Several maintenance levels
    - Durations
    - Feasible time window of maintenance ↔ Elapsed flight hours of an aircraft
- Maintenance scheduling
  - Aircraft availability guaranteed
  - Maintenance resources guaranteed
  - Planning period ≈ 1 year



Available aircraft

Maintenance schedule

Daily missions

Maintenance

Challenges in maintenance scheduling

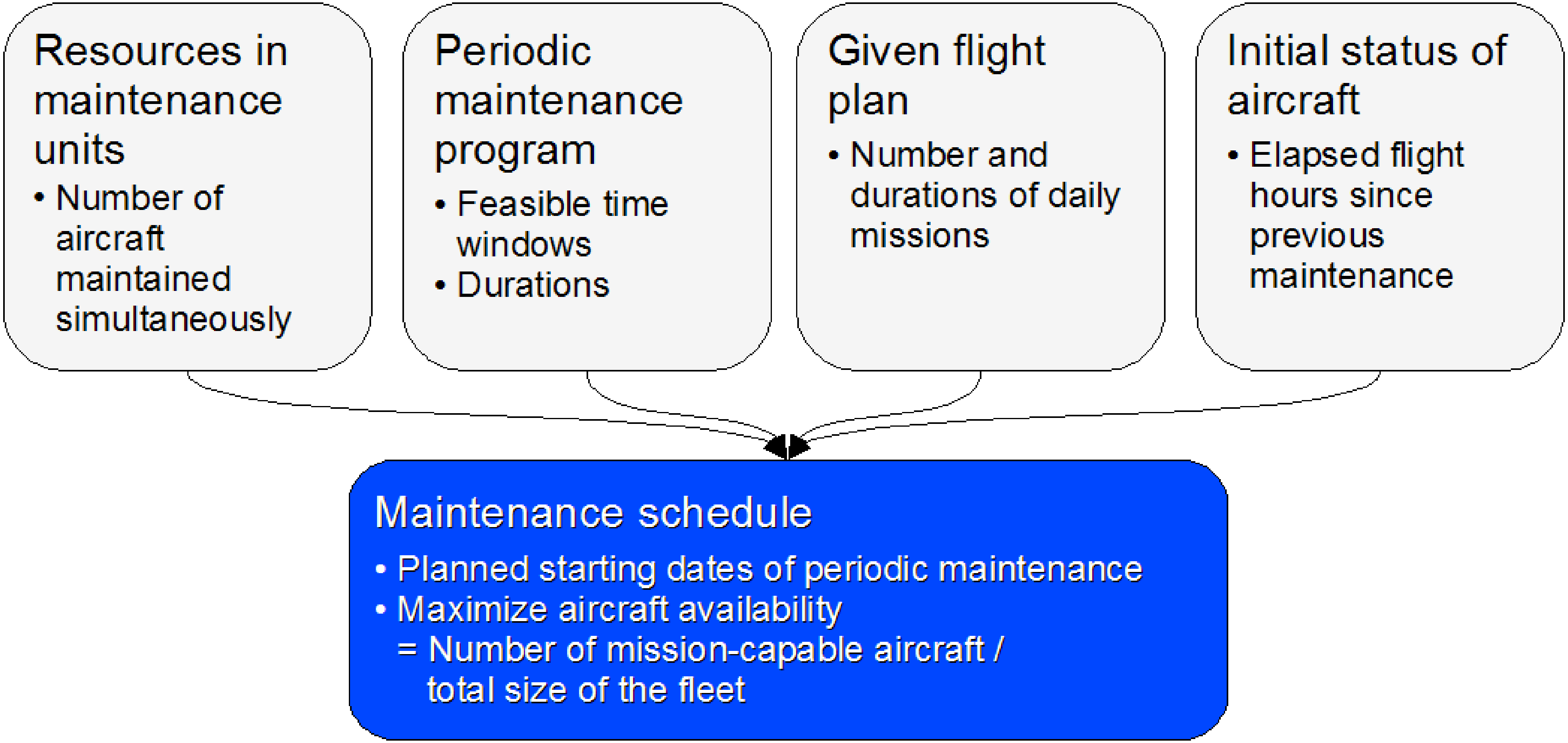
- Maintenance and usage coupled through complex nonlinear interactions – feedbacks
- Maintenance and usage entail uncertainties

⇒ Traditional scheduling formulations not suitable

Our multi-objective simulation-optimization approach

- Discrete-event simulation model for aircraft maintenance and usage (Mattila, Virtanen, and Raivio 2008)
- Optimization algorithm: Simulated annealing using probability of dominance
  ⇒ Non-dominated solutions
- Multi-attribute decision analysis model ⇒ Preferred solution
  - Preference programming (Salo and Hämäläinen 1992, 2001)

Manual planning



Resources in maintenance units
- Number of aircraft maintained simultaneously

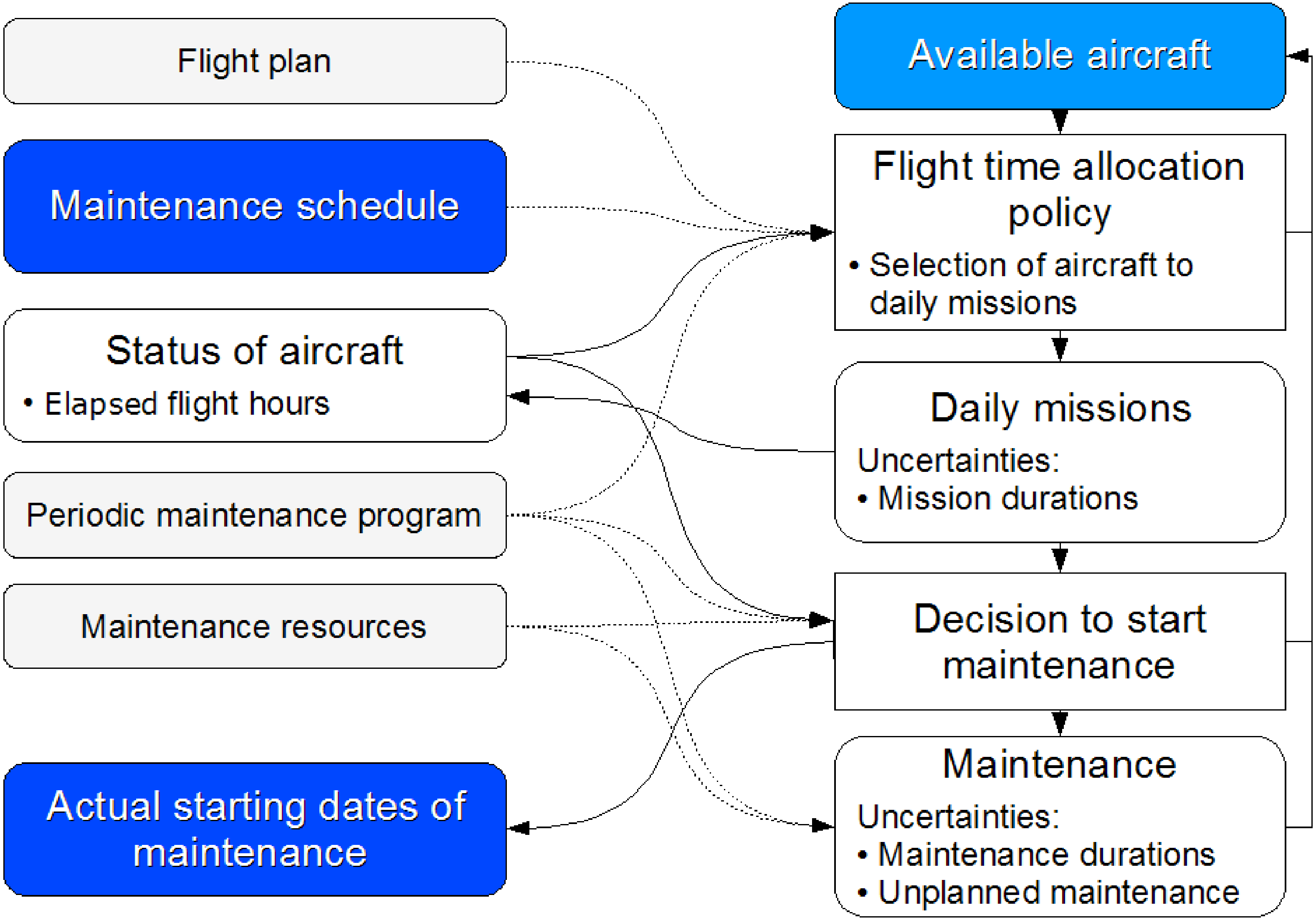
Periodic maintenance program
- Feasible time windows
- Durations

Given flight plan
- Number and durations of daily missions

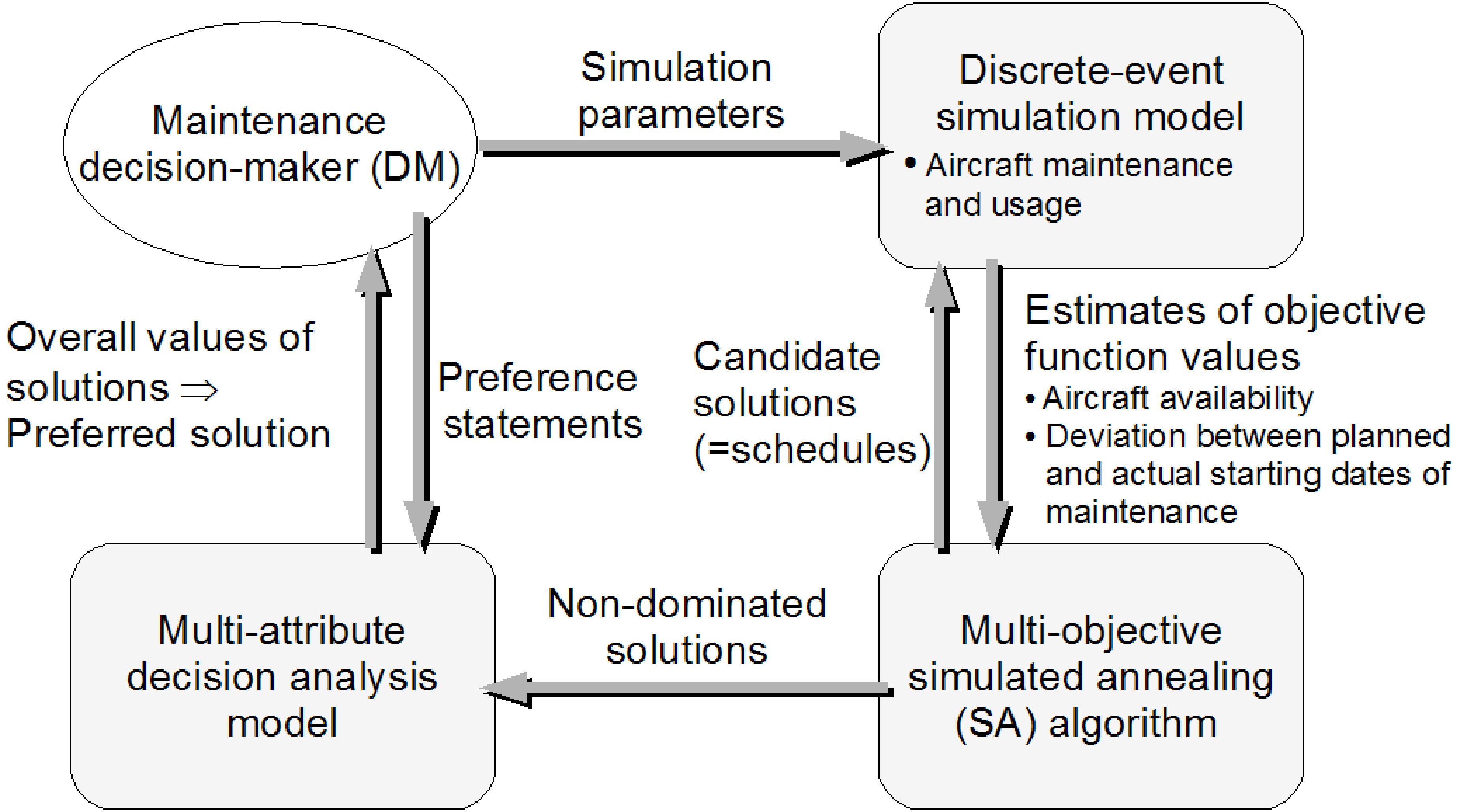
Initial status of aircraft
- Elapsed flight hours since previous maintenance

Maintenance schedule
- Planned starting dates of periodic maintenance
- Maximize aircraft availability
  = Number of mission-capable aircraft / total size of the fleet

Implementation of the schedule



The multi-objective simulation-optimization approach



Maintenance decision-maker (DM)

Simulation parameters

Discrete-event simulation model

- Aircraft maintenance and usage

Overall values of solutions ⇒ Preferred solution

Preference statements

Candidate solutions (=schedules)

Estimates of objective function values

- Aircraft availability
- Deviation between planned and actual starting dates of maintenance

Multi-attribute decision analysis model

Non-dominated solutions

Multi-objective simulated annealing (SA) algorithm

Generation of non-dominated solutions

- Existing algorithms for multi-objective simulation-optimization
  - Multi-objective evolutionary algorithms (EAs) (e.g., Lee et al. 2008; Goh and Tan 2009)
    - E.g. ranking of solutions based on probability of dominance (Hughes 2001)
  - Population-based simulated annealing (SA), weighted objectives (Gutjahr 2005)
- Justification for using SA
  - Outperformed EAs in single-objective versions of the scheduling problem (Mattila and Virtanen 2006)
  - Success of multi-objective SA algorithms in deterministic settings (Smith et al. 2008; Bandyobadhyay et al. 2008)
- The multi-objective SA algorithm for maintenance scheduling
  - Performance of a solution based on probability of dominance
  - Outperformed population-based SA (Gutjahr 2005)

The multi-objective SA algorithm

- Structure similar to basic SA
- Modifications for multi-objective simulation-optimization
  - Performance of solution $x \leftrightarrow$

    Probability: Solution x dominates members y of non-dominated set S
    - Probability wrt objective i: $P(x \text{ dom } y \text{ wrt objective } i)$
    - Probability wrt solution y: $P(x \text{ dom } y) = \prod_i P(x \text{ dom } y \text{ wrt objective } i)$

    $\Rightarrow$ Performance of $x = \sum_{y \in S} P(x \text{ dom } y)$
  - Maintaining non-dominated set S
    - Fixed number of solutions with highest performance included

Selection of the preferred non-dominated solution

- Use of preference information in multi-objective simulation-optimization
  - Transformation into a single objective
    - Utility function & a ranking and selection method (Butler, Morrice, and Mullarkey 2001)
    - Value function & a response surface method (Rosen, Harmonosky, and Traband 2007)

- Our decision analysis approach
  - Post-optimization analysis
  - Preference programming and interval techniques (Salo and Hämäläinen 1992, 2001)

⇒Considers uncertainty both in objective function values and DM's preference statements

- Quan et al. (2007): Use of intervals in an EA ⇒ Preferred subsets of non-dominated solutions in a deterministic setting

The multi-attribute decision analysis model

Additive presentation of DM's preference for solution x

$$V(x) = w_A v_A(x) + w_D v_D(x)$$

v_A, v_D Objective function values for Availability and Deviation → single attribute values

w_A, w_D Weights

Simulation model ⇒ Confidence intervals of objective function values

→ Single attribute value intervals:

$$[\underline{v}_A(x), \overline{v}_A(x)]$$

$$[\underline{v}_D(x), \overline{v}_D(x)]$$

DM ⇒ Incomplete preference statements

→ Weight intervals:

$$[\underline{w}_A, \overline{w}_A]$$

$$[\underline{w}_D, \overline{w}_D]$$

Overall value interval of a solution

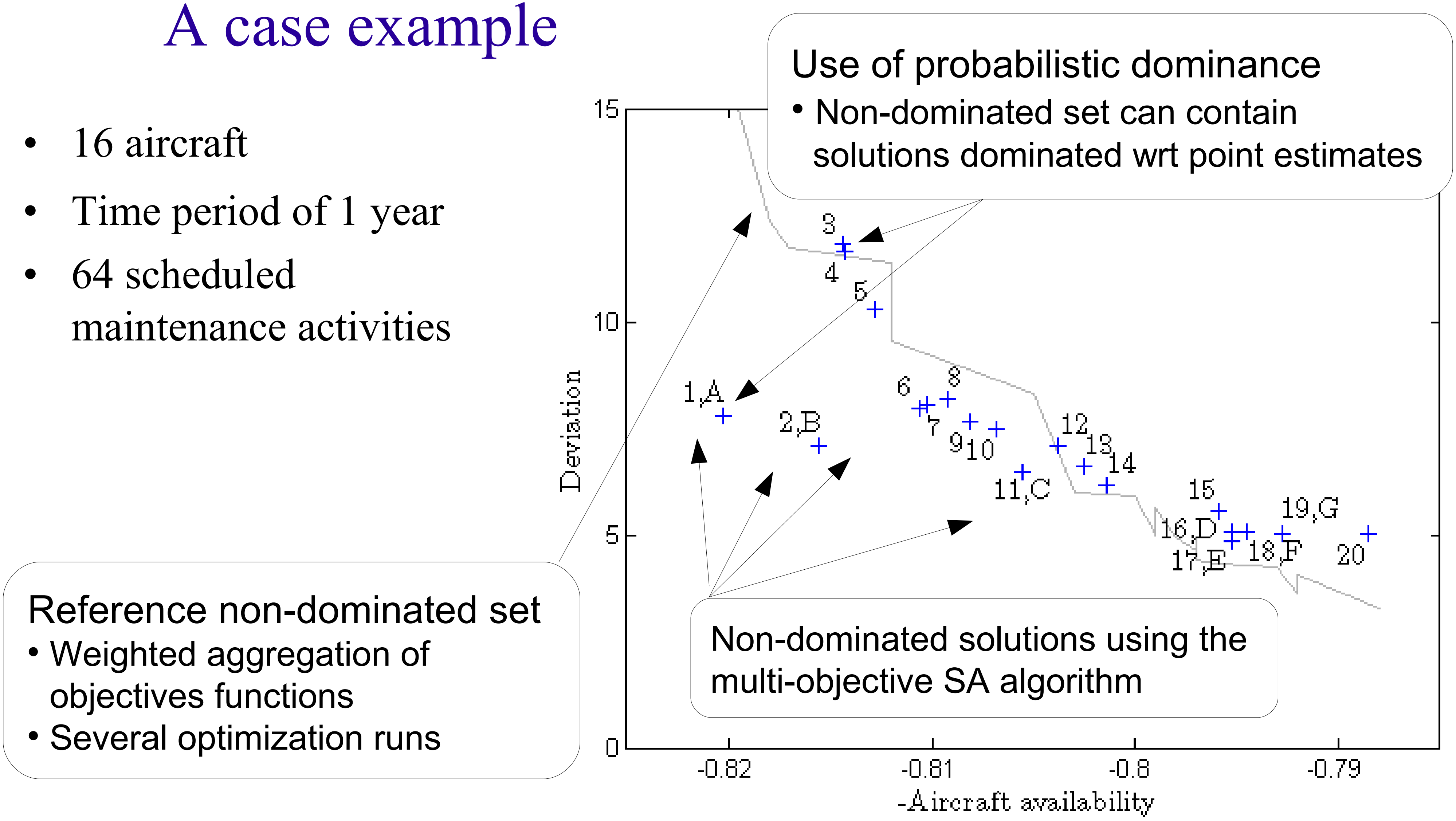
$$\begin{cases} \underline{V}(x) = \min\limits_{w_A, w_D} w_A \underline{v}_A(x) + w_D \underline{v}_D(x) \\ \overline{V}(x) = \max\limits_{w_A, w_D} w_A \overline{v}_A(x) + w_D \overline{v}_D(x) \end{cases}$$

Comparison of non-dominated solutions

- Dominance concepts
  - Absolute dominance:
    Value intervals do not overlap
  - Pairwise dominance:
    Value intervals do not overlap for any feasible combinations of weights
- If single dominating (=preferred) solution does not exist
  - More precise preference information ⇒ narrows weight intervals
  - Additional simulation ⇒ narrows single attribute value intervals
  - Decision rules, e.g., *maximin*, *maximax*, *central values*

A case example

- 16 aircraft
- Time period of 1 year
- 64 scheduled maintenance activities



Use of probabilistic dominance

- Non-dominated set can contain solutions dominated wrt point estimates

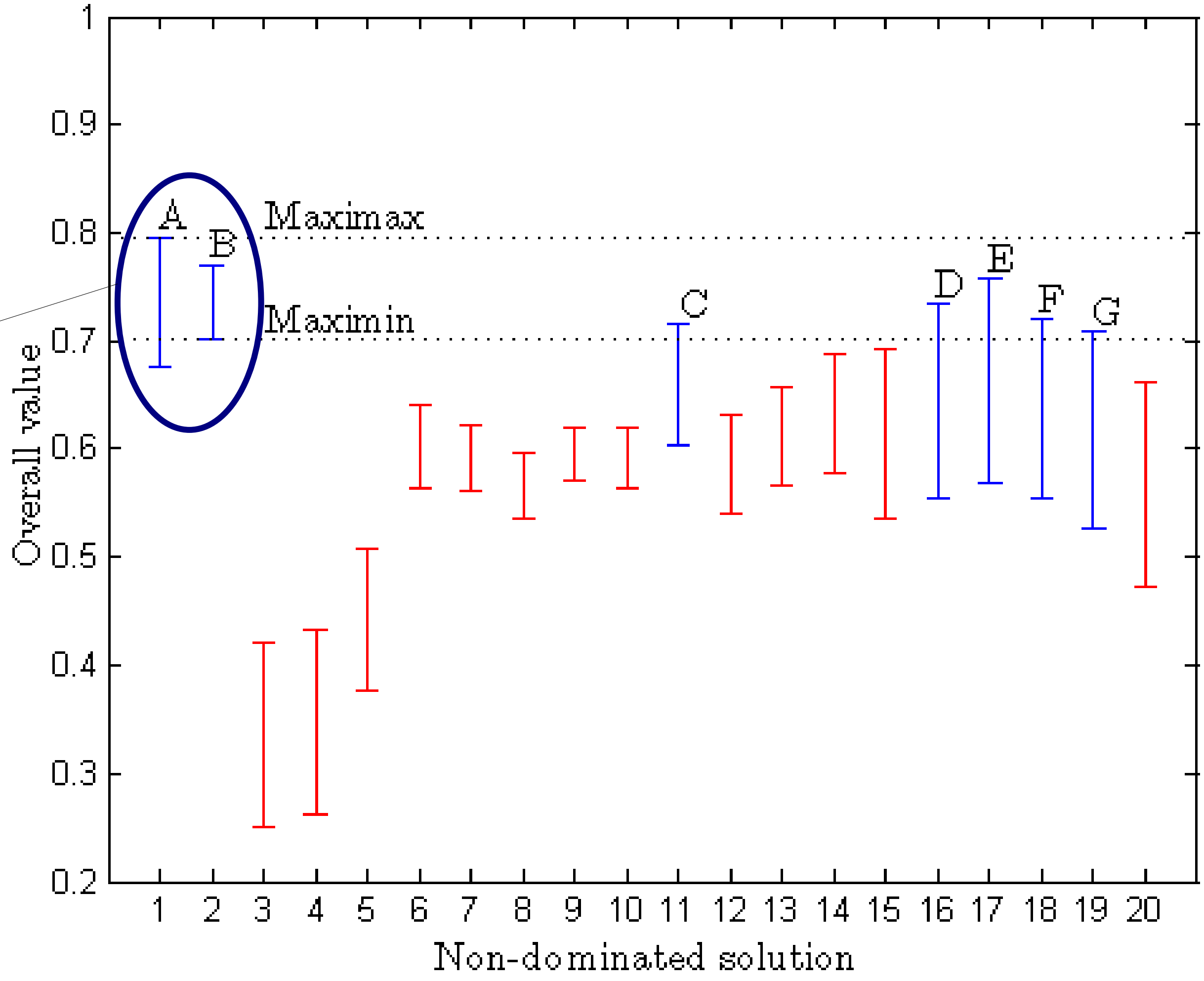
Reference non-dominated set

- Weighted aggregation of objectives functions
- Several optimization runs

Non-dominated solutions using the multi-objective SA algorithm

Overall value intervals

- 13 solutions absolutely dominated
- 7 solutions remain, A...G
- Use of decision rules
  - Maximax:
    A has highest upper bound
  - Maximin:
    B has highest lower bound



Conclusions

- The multi-objective simulation-optimization approach
  - The multi-objective simulated annealing algorithm utilizing probability of dominance
  - The multi-criteria decision analysis model utilizing preference programming
- Application in a complex maintenance scheduling problem
  - Being implemented as a decision-support tool
- Future research on multi-objective simulation-optimization algorithms
  - Use of preference information
  - Efficient allocation of computational effort

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