Optimal and Heuristic Approaches for Constrained Flight Planning under Weather Uncertainty

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Constrained Flight Planning under Weather Uncertainty

- Compute a flight plan for a given aircraft mission which minimises fuel consumption,
- underlying uncertain weather effects
- meets time and convection constraints

In other words: we want to solve a constrained stochastic shortest path problem (C-SSP)

Stochastic Shortest Path Problem

A Stochastic Shortest Path Problem $\mathbb{S}$ consists of:

- a set of states S
  - current position, speed, altitude ...
- a set of actions A
  - fly to waypoint, change altitude, change speed
- a cost function C
  - represents fuel consumption
- an initial state s_I and a set of goal states $S^\star$
  - departure and arrival airport
- a probabilistic transition function $P(s'|a, s)$
  - $\Rightarrow$ requires access to a weather forecast model
  - we use a black box model that computes state transitions

A solution for an SSP is a deterministic policy (mapping from states to actions) which minimizes costs.

Constrained Stochastic Shortest Path Problem

A constrained stochastic shortest path problem consists of:

- an SSP $\mathbb{S}$
- a set of constraints $\mathcal{C}$, where each constraint:
  - comes with a secondary cost function
  - bounds the expected cost of this function by some constant
    - e.g.: $\mathbb{E}[\text{duration}] \leq 300$ minutes

A solution for a C-SSP is a potentially stochastic policy which minimizes costs and satisfies constraints over expectation.

Contribution

- A C-SSP formulation of constrained flight planning under uncertainty
- A new algorithm for C-SSPs based on Column Generation
- An alternative approach that decomposes the problem into a 2D search and a greedy choice of altitude and speed from a set of heuristic strategies
- We evaluate on real flight routes with real weather data

Column Generation

Common approach for constrained deterministic shortest path problems based on linear programming.

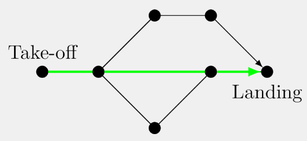
1. Solve the problem ignoring constraints
2. Evaluate constraints
3. Modify problem to improve the current solution

} repeat

$\Rightarrow$ adaptation of the primary cost function

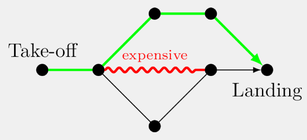
Column Generation – Solve the problem ignoring constraints

- We can use any SSP algorithm to solve this subproblem
- Computes a deterministic policy π with associated costs



Column Generation – Evaluate constraints on policy π

- If no constraint is violated and solution cannot be improved $\Rightarrow$ return solution
- Otherwise, modify current subproblem:
  - change problem such that π can not be optimal $\rightarrow$ original problem with shifted cost function
  - shifted costs explore different trade-offs between constraints and cost

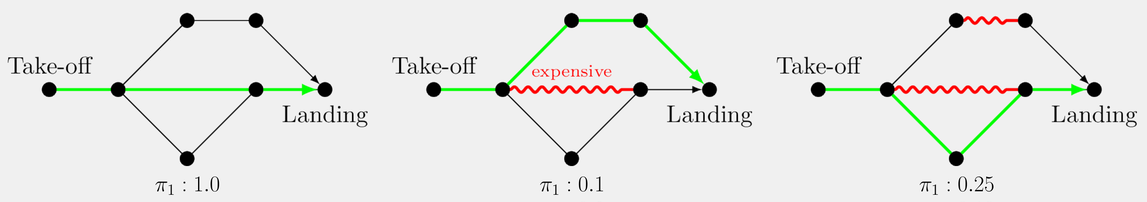


Column Generation

- Each policy corresponds to a column in the LP
- LP solver computes a solution to the LP:
  - solution is a convex combination of policies

$\Rightarrow$ i.e. a probability distribution over deterministic policies

- guarantees minimum primary cost
- respects constraints over expectation

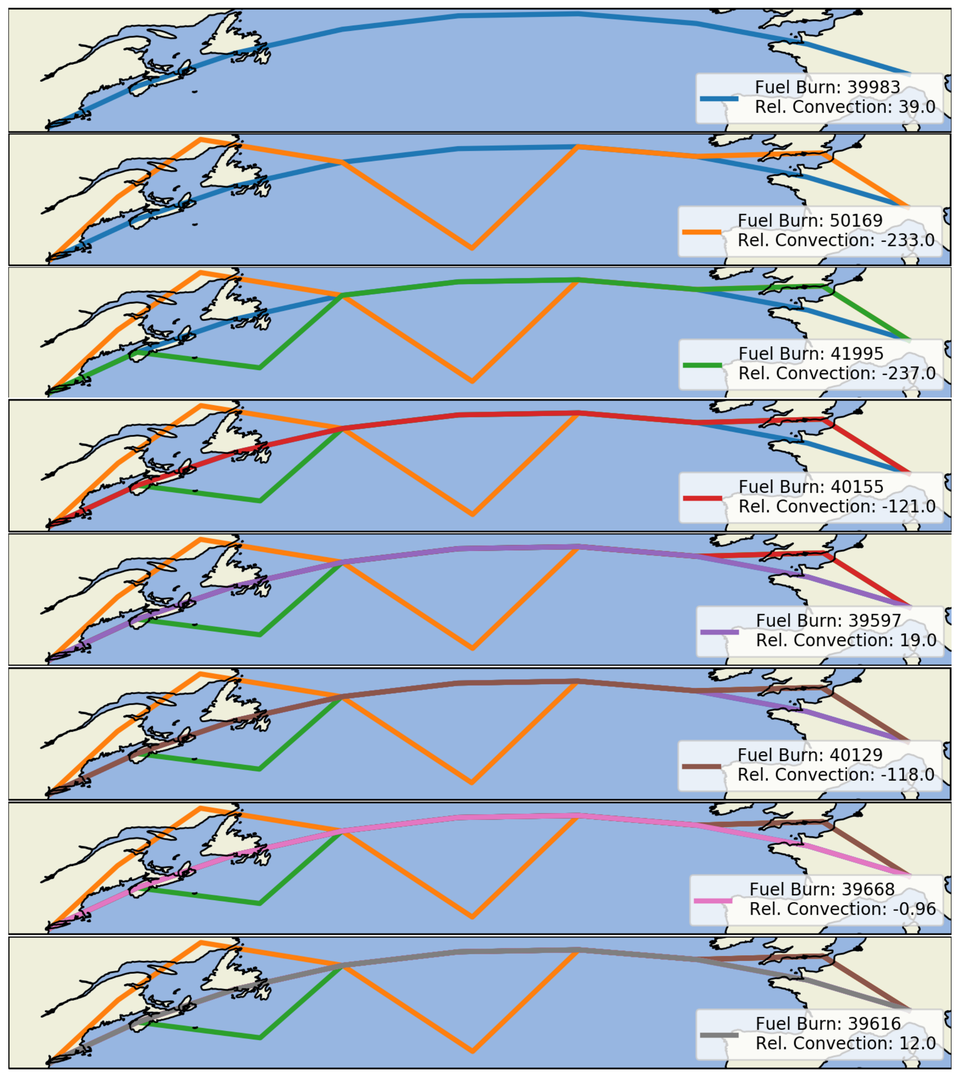


Stochastic and Deterministic Policies

- If required, we can select the best deterministic policy
- Deterministic policy is not guaranteed to satisfy constraints
- Finding an optimal deterministic policy is NP-complete

Alternative approach to Column Generation: Heuristic Decomposition based on Determinisation

Column Generation in Practice



Heuristic Decomposition

- Incorporate constraints in primary cost function via scalarisation
- Scalarisation: new cost function becomes a linear combination of primary and secondary cost functions
- Determinise: remove uncertain weather outcomes and use average travel time and fuel consumption for transitions
- Decompose the resulting problem in a 2D and a 3D problem
  - horizontal (2D) planning phase computes least cost path based on the earth surface
  - vertical (3D) planning phase assigns each node in the 2D plan an altitude and speed level

Empirical Evaluation

- Evaluate on real-world data set
- 3 short, medium, and long distance flights
- weather data from June 2018
- BADA aircraft performance model
- Time window constraints
- Convection constraints
- Focus on deterministic policies