Optimal and Heuristic Approaches for Constrained Flight Planning under Weather Uncertainty

Florian Geißer[1] Guillaume Povéda[2] Felipe Trevizan[1]
Manon Bondouy[2] Florent Teichteil-Königsbuch[2] Sylvie Thiébaux[1]

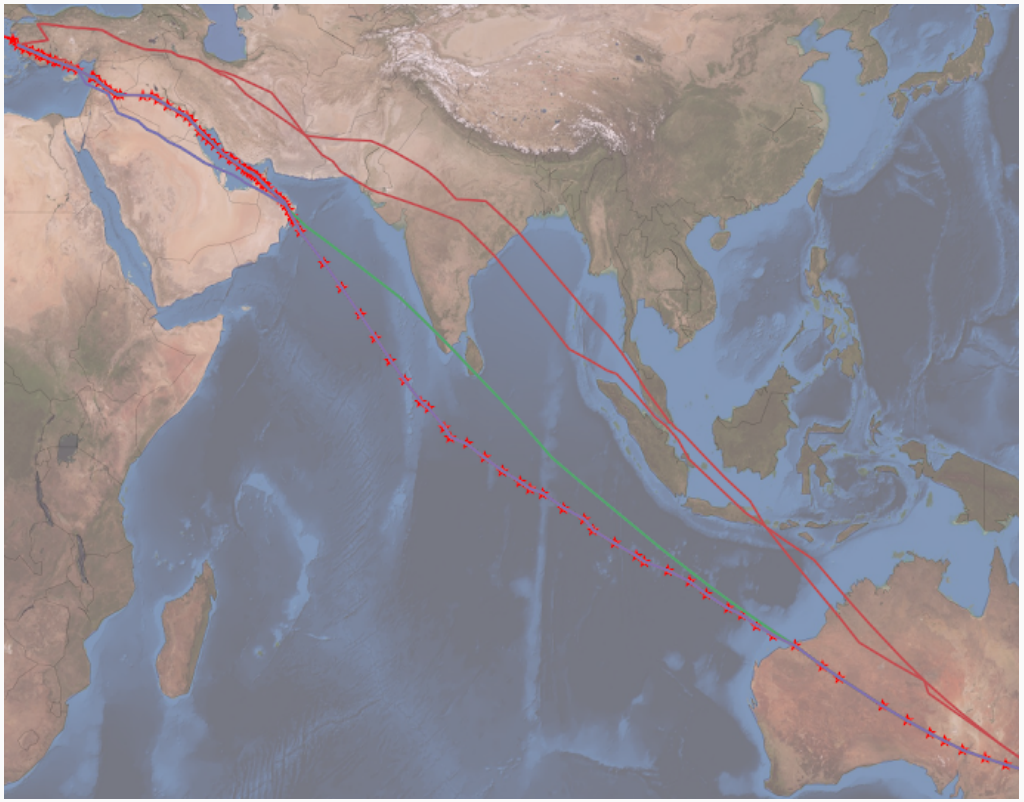
[1] Research School of Computer Science,
The Australian National University

[2] Airbus - Artificial Intelligence Research

Constrained Flight Planning under Weather Uncertainty

Flight Planning

Compute a flight plan for a given aircraft mission which minimises fuel consumption.



Constrained Flight Planning under Weather Uncertainty

- Convective activity indicates showers and thunderstorms
- Weather is inherently uncertain
- Can lead to significant delay in public air transport

Airline operations today are mainly based on deterministic weather forecasts and do not take uncertainty into account when optimising the flight trajectory.

Constrained Flight Planning under Weather Uncertainty

- In reality, a plan has to satisfy operational constraints
  - restrict expected travel time through convective areas
  - ensure expected arrival is in a given time window

Important

We consider constraints over expectations, which are different to hard constraints.

Constrained Flight Planning under Weather Uncertainty

- Ensure time and convection constraints $\Rightarrow$ Constrained
- Consider uncertain weather effects $\Rightarrow$ Stochastic
- Find a route minimizing fuel $\Rightarrow$ Shortest Path Problem

Constrained Flight Planning under Weather Uncertainty

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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

Stochastic Shortest Path Problem

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 a constant
    - e.g.: $\mathbb{E}[\text{duration}] \leq 300$ minutes

Constrained Stochastic Shortest Path Problem

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

Existing C-SSP planners are not applicable to our problem:

- i^2-dual: requires factored representation of the state space
- i-dual: requires a heuristic function for each cost function

Our paper presents a new algorithm for C-SSPs based on Column Generation.

Column Generation

Column Generation

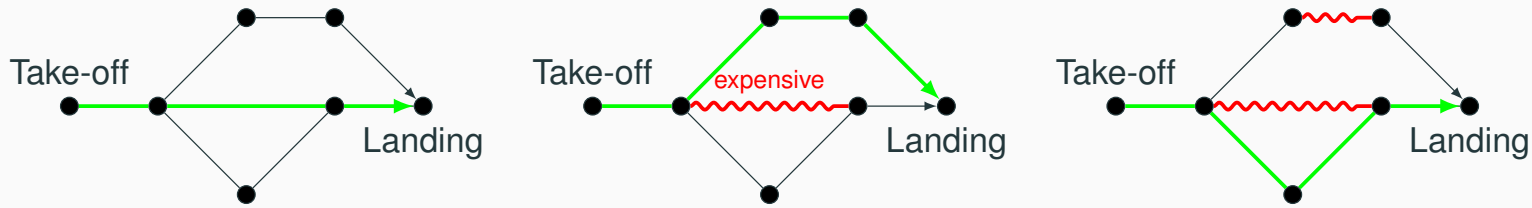
Common approach for constrained deterministic shortest path problems based on linear programming (LP).

We generalize Column Generation to the probabilistic case:

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

} repeat

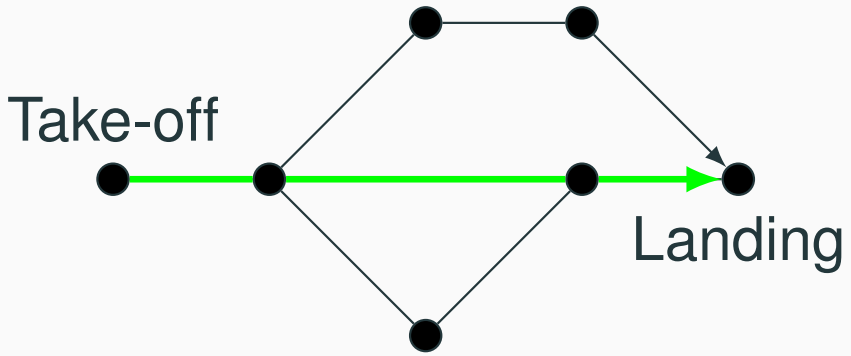
$\Rightarrow$ adaptation of the primary cost function



Column Generation

Solve the problem ignoring constraints:

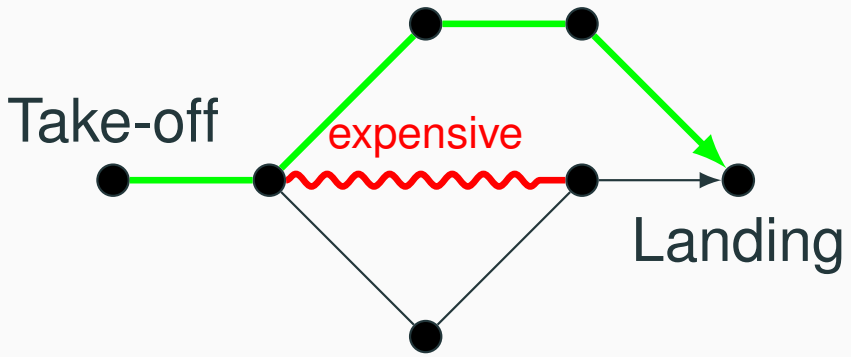
- we can use any SSP algorithm to solve this subproblem
- computes a deterministic policy π with associated costs



Column Generation

Evaluate constraints on policy π:

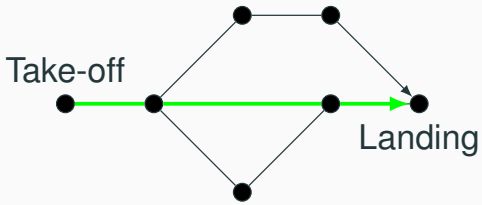
- if no constraint is violated and solution cannot be improved $\Rightarrow$ return solution
- otherwise, modify current subproblem:
  - change problem such that π can not be optimal
    $\rightarrow$ original problem with shifted cost function
  - shifted costs explore different trade-offs between constraints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



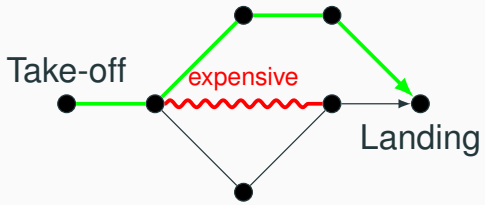
Column Generation

- 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

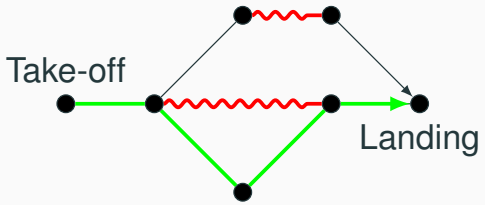


$\pi_1 : 1.0$



$\pi_1 : 0.1$

$\pi_2 : 0.9$



$\pi_1 : 0.25$

$\pi_2 : 0.10$

$\pi_3 : 0.65$

Stochastic and Deterministic Policies

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

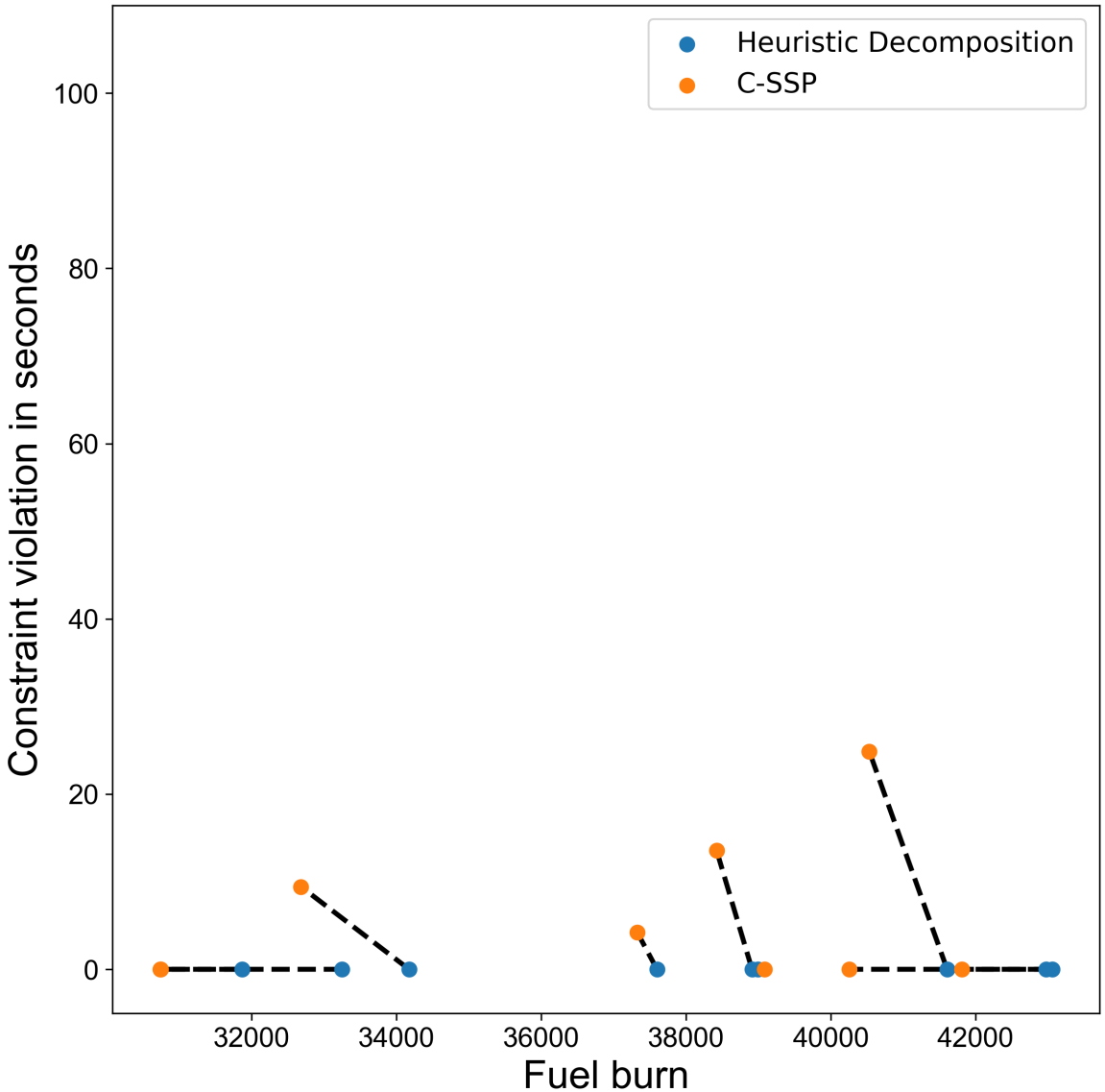
Alternative approach to Column Generation:
Heuristic Decomposition based on Determinisation

More details in the paper.

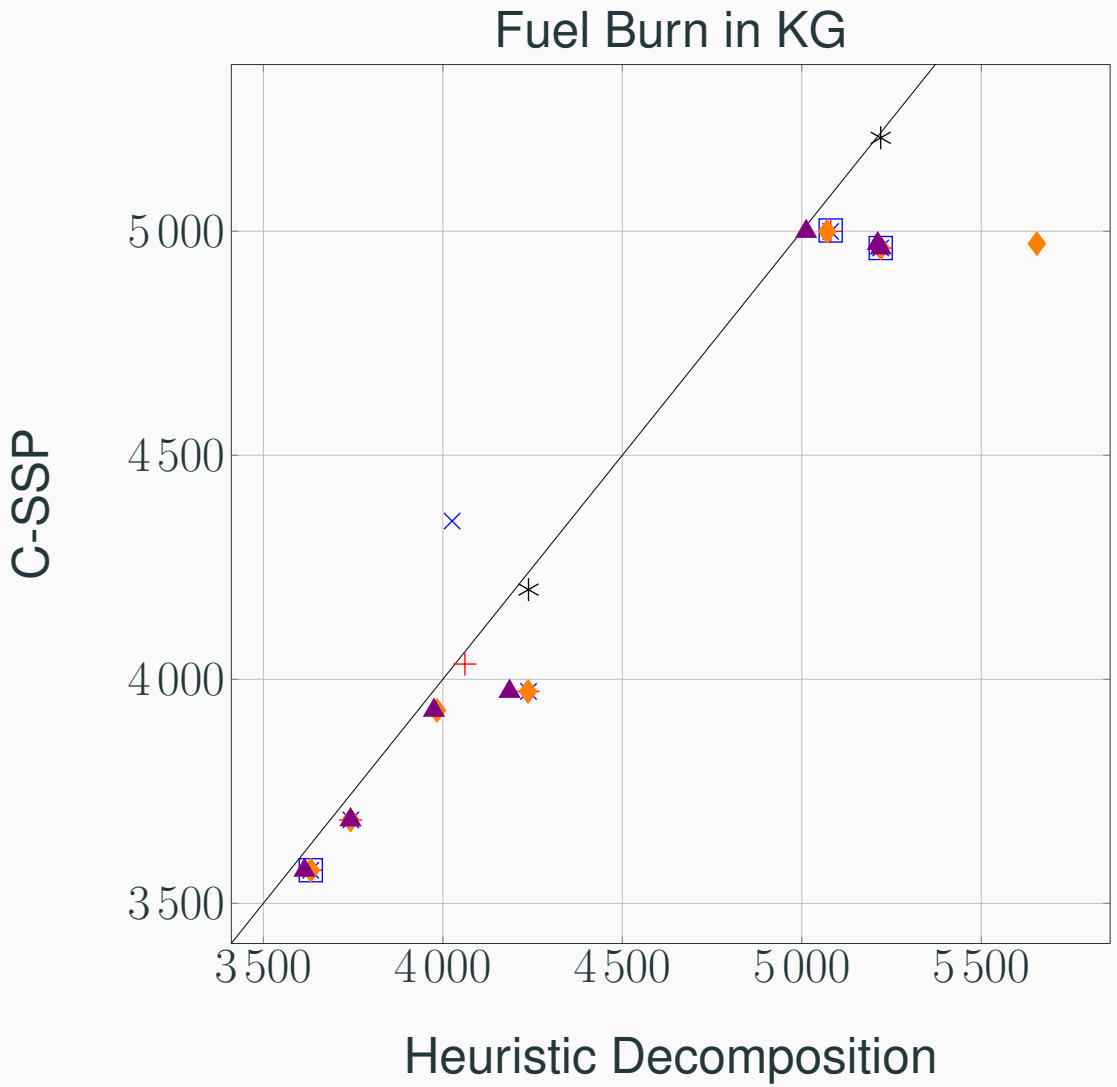
Empirical Evaluation

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

Empirical Evaluation - Time Constraints



Empirical Evaluation - Convection Constraints



Further Details in the paper.

Or: visit us in the poster session!