On The Air Traffic Flow Management Rerouting Problem (ATFMRP)

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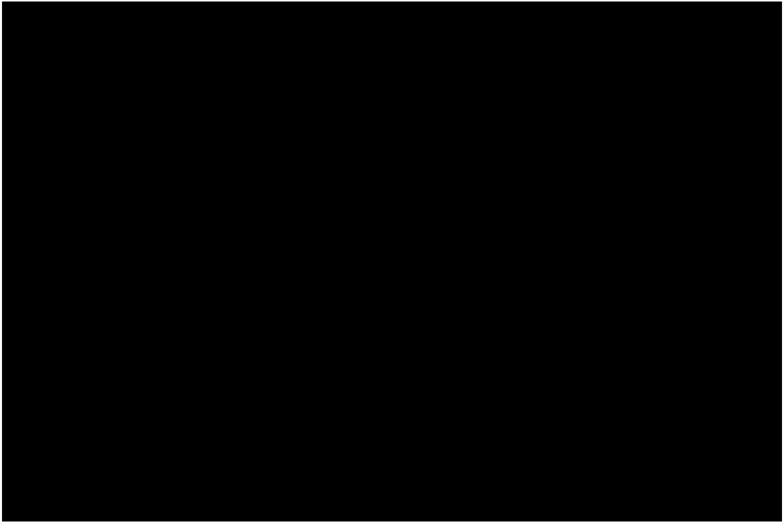
Outline

Introduction



1. **Air Traffic Flow Management Problem(ATFM)** is a set of strategic processes that reduce congestion problems and delays costs.
2. The fundamental challenge for ATFM arises when there is system disruption.
3. A major challenge encountered by air traffic managers is the problem of finding optimal scheduling strategies that mitigates congestion as well as minimizes delay costs when there is capacity reductions.
4. The problem of managing the air traffic so as to ensure safe and efficient flow of aircraft throughout the airspace is referred to as the **Air Traffic Flow Management Problem (ATFMP)**

The Big Question?

1. How best can this problem be formulated to include rerouting options (ATFMRP) and other modeling variation?
2. Since there is disruption in the system, the big question that arises is how to formulate the problem to account for the uncertainties that are inherent in the system.
3. Is it possible to develop a model that is computationally less expensive in terms of handling large instances of data when considering ATFMRP?

Methodologies for solving the ATFM Problem

1. The Air Traffic Flow Management Rerouting Problem can be formulated as a
   - Mixed Integer Programming Model
   - Multi-Commodity Network Flow Model
   - Single-Commodity Network Flow model (suitable for sparse network):
2. The multi-commodity network flow may not be applicable to Africa.
3. We are considering formulating the problem as a Single Commodity (Minimum Cost) Network Flow Model with Network Simplex Method as the solution method (with continuous iteration).

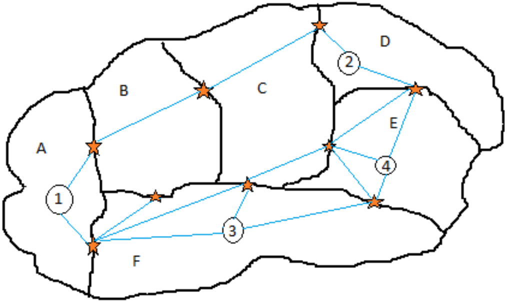


Figure: Illustrative Example: A geographical representation of an airspace

Problem Formulation & Setup

1. The airspace is divided into sectors with indication on the cross points
2. The airspace is transformed into graph network where the
   - Nodes represents airports or sectors
   - Sectors are transshipment nodes for which traffic flow
   - The edges are the possible routes from one sector to another
   - Each edge has corresponding travel time and the capacity of flights that is allowed at each time period.
3. Capacities of the airport/airspace vary with time

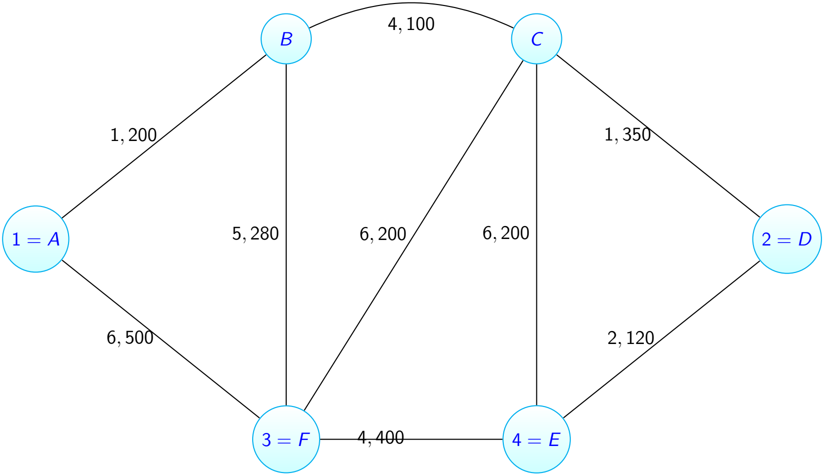


Figure: A graph representation of the airspace (Spatial Network)

Problem Formulation & Setup

1. Create a spatial network for any given information on flight schedules and routes.
2. Next, transform the spatial network into a time-space network with the nodes and edges representing vertex and arc respectively
3. The time horizon is divided into discrete time periods of equal length,
4. The different types of arcs as well as flows are specified

Outline

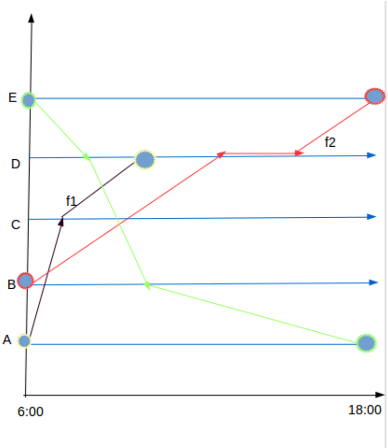


Figure: Illustration of a time-space network representation

Time-Space Network Representation of Datasets

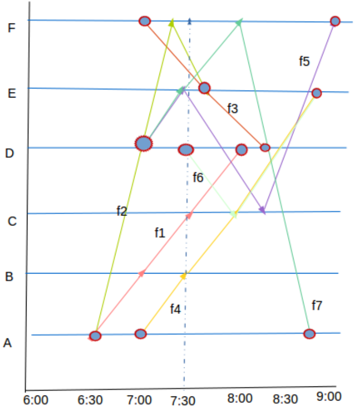


Figure: 7 flights, 4 airports and 6 sectors

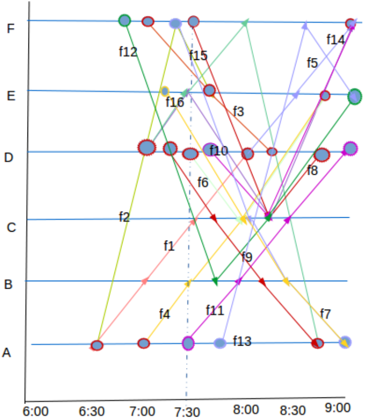


Figure: 16 flights, 4 airports and 6 sectors

The ATFM Rerouting Problem

1. Based on the given information, we assumed a system disruption at some time interval
2. The disruption can either be a route disruption or delay in the departure time
3. Next, we try to resolve the capacity imbalance in the system starting from the time interval the disruption occurs.
4. Rerouting takes place once there is a disruption
5. It is also possible reroute or delay a flight once the capacity is exceeded.

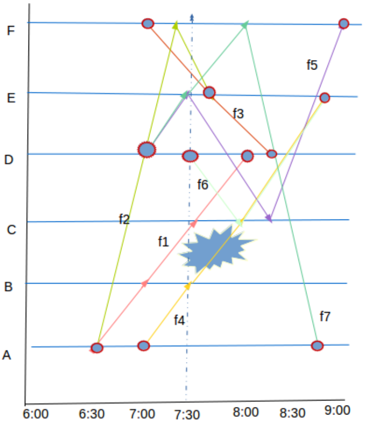


Figure: Illustrative Example: System Disruption

The ATFM Rerouting Problem

1. We proposed several approaches for incorporating the rerouting decision but only considered one in the implementation.
2. They include Dijkstra's algorithm, Sprague Grundy game approach, Enabled Search Methods (Neighbourhood and Tabu Search) with search moves (reroute or delay) etc
3. Constraint penalties and total cost incurred were also taken into consideration during the problem formulation.
4. A MATLAB data structure and code was created for the implementation of the artificially constructed flight schedule.

Outline

Neighbourhood Search Algorithm

1. Represent disruption as an increased arc cost.
2. Cost function
    - Delay time
    - Constraint penalties
3. Search for improved solution:
    1. Reroute disrupted flight:
        - Consider every possible alternative route.
        - Implement the highest saving move(route).
    2. Create a set of “affected” flights.
    3. For every “affected” flight:
        - Consider every possible alternative route:
        - Consider delays: 1 periods and 2 periods.
        - Implement highest saving move.
4. Repeat step 3 until no more savings are achieved.

Constructed Dataset

- Time Horizon - 02:30 hours ($6:30am - 9:00am$) discretized into 10 periods of 15 minutes each
- Flights $= 7$ and 16 flights respented as ($F1 - F16$)
- Sectors $= 6$ ($A - F$)
- Airports $= 4$ $(1 - 4)$
- The number of flight that can flow through an edge is either 1 or 2
- Disruption is assumed to occur on $F4$ route
- The scheduled route for each flight is defined
- Conflicts in travel times

Example Datasets

Flights	Etd	Origin	Sectors	Eta	Destination
F1	0	1(A)	ABCD	6	4(D)
F2	0	1(A)	AFE	5	5(E)
F3	2	6(F)	FCD	7	4(D)
F4	2	1(A)	ABCE	9	5(E)
F5	2	4(D)	DECF	10	6(F)
F6	4	4(D)	DCE	9	5(A)
F7	2	4(D)	DEFA	9	1(A)

Table 1: Flight Schedule for the small schedule.

Example Datasets

Flights	Etd	Origin	Sectors	Eta	Destination
F8	4	1(A)	ABCD	9	4(D)
F9	3	1(A)	AFE	9	5(E)
F10	5	6(F)	FCD	10	4(D)
F11	4	1(A)	ABCE	10	5(E)
F12	1	4(D)	DECF	10	6(F)
F13	5	4(D)	DCE	10	5(A)
F14	6	4(D)	DEFA	10	1(A)
F15	3	4(D)	DEFA	10	1(A)
F16	3	4(D)	DEFA	10	1(A)

Table 2: Additional flight schedule to the small schedule(large schedule)

1. For the small schedule, F4 was the only rerouted flight from 1-2-3-5 to 1-2-6-5. Total delay increased by 15 minutes.
2. For the large schedule, flight 4 (F4) was rerouted from 1-2-3-5 to 1-2-6-5. Also, flight 8 (F8) departure time delayed by 30 minutes (2 times period).
3. For each test case, 4 capacities constraints were exceeded.

F	1	2	3	4	5	6	7
DT	0	0	30	30	30	60	30
AT	90	75	105	135	150	135	135
OA	1	1	6	1	4	4	4
DA	4	5	4	5	6	5	1
RO	1	1	6	1	4	4	4
	2	6	3	2	5	3	5
	3	5	4	3	3	5	6
	4	0	0	5	6	0	1
	0	0	0	0	0	0	0
	0	0	0	0	0	0	0

Table 3: Flight Schedule for the small schedule before rerouting.

F	1	2	3	4	5	6	7
DT	0	0	30	30	30	60	30
AT	90	75	105	135	150	135	135
OA	1	1	6	1	4	4	4
DA	4	5	4	5	6	5	1
RO	1	1	6	1	4	4	4
	2	6	3	2	5	3	5
	3	5	4	6	3	5	6
	4	0	0	5	6	0	1
	0	0	0	0	0	0	0
	0	0	0	0	0	0	0

Table 4: Flight Schedule for the small schedule after rerouting.

F	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
DT	0	0	30	30	30	60	30	60	45	75	60	15	45	90	45	45
AT	90	75	105	135	150	135	135	135	135	150	150	150	150	150	150	150
OA	1	1	6	1	4	4	4	6	4	4	1	6	1	4	6	5
DA	4	5	4	5	6	5	1	4	1	6	4	5	5	6	1	1
RO	1	1	6	1	4	4	4	6	4	4	1	6	1	4	6	5
	2	6	3	2	5	3	5	3	3	3	2	2	6	5	3	3
	3	5	4	3	3	5	6	4	2	6	3	3	5	6	2	2
	4	0	0	5	6	0	1	0	1	0	4	5	0	0	1	1
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 5: Flight Schedule for the large schedule before rerouting.

Implementation & Results

F	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
DT	0	0	30	30	30	60	30	90	45	75	60	15	45	90	45	45
AT	90	75	105	135	150	135	135	165	135	150	150	150	150	150	150	150
OA	1	1	6	1	4	4	4	6	4	4	1	6	1	4	6	5
DA	4	5	4	5	6	5	1	4	1	6	4	5	5	6	1	1
RO	1	1	6	1	4	4	4	6	4	4	1	6	1	4	6	5
	2	6	3	2	5	3	5	3	3	3	2	2	6	5	3	3
	3	5	4	6	3	5	6	4	2	6	3	3	5	6	2	2
	4	0	0	5	6	0	1	0	1	0	4	5	0	0	1	1
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 6: Flight Schedule for the large schedule after rerouting.

Outline

Conclusion

1. The algorithm reroutes the affected flight and thereafter improves the solution for the two example datasets.
2. Our neighbourhood search algorithm is:
   - a fast and effective method.
   - practical and applicable in an industrial setting.
3. The search could in future be guided using a Tabu Search strategy to get even better results.

- Thanks to MISG 2016 organizers for such a wonderful opportunity to be part of this year's workshop.
- Thanks to the industry representative and moderators for their meaningful contributions and assistance.
- Thanks to the group members for taking up the challenge of solving such a complex problem.

Outline

- Bertsimas, D., Gughelmo Lulli, S., Amedeo Odoni: The Air Traffic Flow Management Problem. An Integer Optimization Approach.
- Bertsimas, D., Stock, S.: The Air Traffic Management Problem with Enroute Capacities. Operations Research 46, 406-422, (1998).
- Bertsimas, D., Stock Patterson, S.: The Traffic Flow Management Rerouting Problem in Air Traffic Control: A Dynamic Network Flow Approach. Transportation Science 34, 239-255 (2000).
- Helme, M.: Reducing air traffic delay in a space-time network. In: IEEE International Conference on Systems, Man and Cybernetics, vol. 1, pp. 236-242 (1992).