On The Air Traffic Flow Management Rerouting Problem (ATFMRP)



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Objective

1. To give a brief introduction, background information and current trends/practices of the Air Traffic Flow Management.
2. To give a brief overview of the basic Air Traffic Flow Management Problem and methodologies for solving the problem.
3. To give an overview of the modeling and optimization of the ATFMP
4. To give a brief description of the Air Traffic Flow Management Rerouting Problem and insight on the proposed approach for solving the problem.

Outline

1. On the Air Traffic Flow Management- Overview
   - Introduction & Background Information
   - ATFM Current Practices & Methodologies
2. The Air Traffic Flow Management Problem
   - The Problem Statement, Overview of BATFMP Formulation
3. Insight on Proposed Approach to ATFMRP
4. References

Introduction

1. The air transportation industry, a key sector of any nation's economy, is one of the world's most important service industries.
2. This is as a result of the catalytic role it plays in most global economic activities which has significant impact on both local, national and international economies.
3. Oxford Economics report on the economic benefits from air transport in South Africa presented in 2011 noted that the aviation sector in South Africa contributes ZAR 50.9 billion (2.1%) to South African GDP through the direct contributions and ZAR 74.3 billion (3.1% of South African GDP) if the additional 'catalytic' benefits through tourism were added.
4. Over the past decade, the air traffic within and outside Africa as well as the aviation industry have witnessed a rapid growth as a result of the increased demand for airport and airspace resources due to the exponential increase in the number of users.

1. Moreover, flight delays and congestion problems abounds almost on daily basis as a result of capacity reductions in the system resources which is often associated with peak travel times or hours, bad weather conditions and other unforeseen factors that causes capacity reductions in the system resources.
2. The so called congestion in air transportation occurs when the demand for infrastructure exceeds capacity and this causes delays in the travel time".
3. But, the fact that congestion problems causes delays in travel time does not necessarily imply that all delays arises as a result of congestion since adverse weather conditions, en route problems, airline companies, airport and security procedures in a way are responsible to some of the delays.

1. Statistics shows that in the year 2007, approximately one out of every four flights in the United States was either delayed or canceled. Similar cases also exist in most of the European and African countries. These delays had an estimated annual direct cost of 2 billion impact on the economy. [2].
2. Also, "The Joint Economic Committee, US Senate (2008) has estimated that domestic flight delays or system delays cost passengers, airlines, and the US economy nothing less than 40 billion dollars in 2007.in the United States (US) in 2007 had a $31-40 billion impact on the economy.
3. Thus, the rapid growth in the air transportation industry have indeed placed excessive demand on the aviation system which in turn has serious impact on the nation's economy due to the significant costs incurred by airlines and passengers as a result of the flight delays.

Introduction

1. It has also been predicted that this increase in the air traffic and demand for air transportation will continue at an average growth rate of 4.7% over the next 20 years and this continued growth poses a great threat of more severe congestion in ATC and airport system which are currently being operated at full capacity[1].
2. The need for improvement in the management processes of the air traffic and traffic flow management procedures arises so as to meet up with the future demand for air transportation as well as accommodating the projected growth in the air traffic,
3. There is also the need for capacity enhancement of the systems resources as incremental changes in the physical capacity and current operations alone may not be able to meet up with the future demand for air transportation.

[1] The ATC and airport system capacity is also affected by the recent practice of hub and spoke system

Air Traffic Flow Management- Overview

1. Air Traffic Management (ATM) is a broader term that is used to represent the overall collection of management processes of the air traffic.
2. More precisely, it is the composite of services that are taken to ensures safe, efficient and expeditious movement of aircraft in the airspace. It comprises of two basic components namely Air Traffic Control (ATC) and Air Traffic Flow Management Problem (ATFM).
3. ATC refers to those processes that provide tactical separation services for conflict detection and avoidance while on the other hand, ATFM is set of strategic processes that reduce congestion problems and delays costs.
4. ATC generally controls individual aircraft; usually performed by human controllers with the aim of maintaining separation between aircraft while moving traffic as quickly as possible; the ATC actions are more tactical in nature and primarily address immediate safety concerns of airborne flights

Introduction

- **Air Traffic Flow Management (ATFM)** is the regulation of air traffic in order to avoid exceeding airport or flight sector capacity when handling traffic.
- A planning activity designed to address capacity-demand imbalances, which occur either when capacity is reduced or when demand is high, in order to protect **Air Traffic Control (ATC)** system from overloading. It tries to anticipate and prevent overload and limit resulting delays.
- ATFM is set of strategic processes that reduce congestion costs.
- The regulation is done by strategically modifying the departure times and trajectories of flights either by assigning ground holding delay, airborne holding together with any other control action that is deemed necessary. .

ATFM Objectives

- The objective is to match the capacity of the air transportation system with the demand for it in order to ensure that aircraft can flow through the airspace safely and efficiently.
- To avoid congestion and delays; to reduce their impact on airspace users as much as possible
- ATFM tries to resolve the capacity-demand imbalances, in a dynamic way by balancing the system. It tries to anticipate and prevent overload and limit resulting delays.

ATFM Challenges

1. The fundamental challenge for ATFM arises when the system is disrupted. That is when there is fluctuating weather conditions, equipment outages and demand surges. These disruptions are highly unpredictable and cause significant capacity-demand imbalances. In particular, adverse weather conditions frequently cause temporary and substantial reductions in airspace and airport capacity.
2. The number of flights departing or arriving from a certain airport as well as the number of aircraft's traversing in a particular sector of the airspace are functions of several variables which include *the number of runways available, ATC capacity, airspace restrictions and restrictions as to which aircraft can follow an aircraft of a given class*.
3. One of the major challenge encountered by air traffic managers is the problem of finding optimal scheduling strategies that minimizes delay costs.

Background Info

Hence, the need to come up with good and optimal scheduling ATFM strategies that not only mitigates congestion problems but also minimizes delay costs while satisfying the airport and en route airspace capacity constraints

Background Info

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)**

Background Info

Approaches for solving the ATFMP problem are classified into three major categories; **long, medium and short term goals/approaches.**

Air Traffic Flow Management- Overview

1. **Long-term approaches** (usually 5-10 years) tries to solve the ATFMP by increasing the capacity which includes construction of new airports and additional runways, improvement of traffic control techniques and introduction of new technologies.
2. **Medium-term approaches** (6months - 2years) can be seen as economic and administrative measures taken into consideration in order to solve the ATFMP which includes modifying the traffic flow patterns via temporary redistribution; flight diversion to off-peak times; or regulation of the rate of departure and arrival via imposition of time-varying fees in order to mitigate the congestion problems.
3. **Short-term approaches** (done on a daily basis and with a planning horizon of at most 6-12 hours) are those actions that are efficiently applied to control the air traffic flow so as to best match the demand with available capacity over time and across the various components of the ATC and airports network.

Air Traffic Flow Management- Overview

1. **Short-term approaches** mitigates congestion problems that arises as a result of weather disturbances or unpredictable disruptions in the shortest possible times.
2. The current practices in most airspace management unit are based on these short term goals. Moreover, most optimization models in theory that addresses ATFMP focuses more on the short term goal
3. Our interest in mainly on the modeling and optimization of the Air Traffic Flow Management Rerouting Problem

ATFM-Current Practices

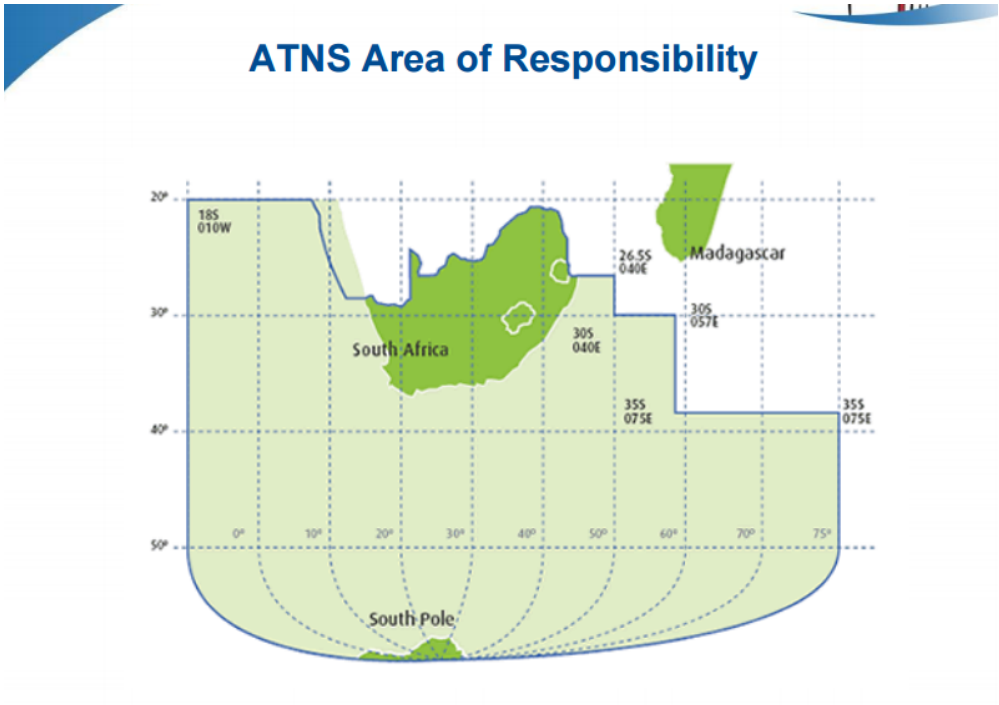
- In the United States, there is an arm of the Federal Aviation Administration (FAA) that is in charge of the air traffic for the entire United States airspace. They balance air traffic demand with system capacity in the National Airspace System (NAS) and are committed to managing the NAS in a safe, efficient, and cohesive manner.
- In South Africa, the Central Airspace Management Unit (CAMU) is responsible for the management of air traffic flow and capacity management within South African airspace in collaboration with the South Africa Air Traffic & Navigation Services (ATNS), the sole commercial provider of air traffic, navigation and associated services and responsible for air traffic control
- CAMU is mainly responsible for the airspace capacity management; slot allocation; flexible use of airspace, and re-routing of traffic affected by adverse weather or restricted airspace using different basic and advanced ATFM techniques.

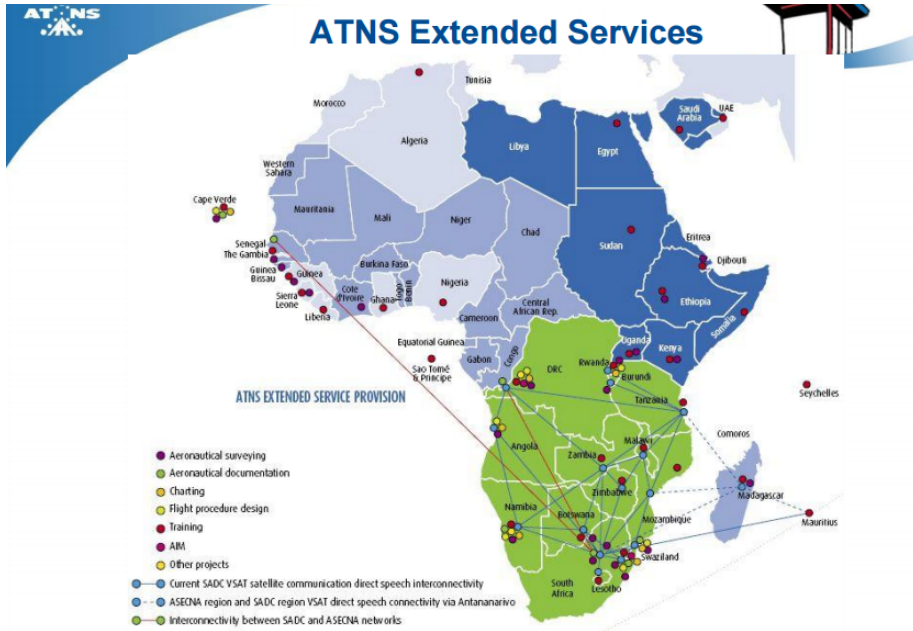
ATFM-Current Practices

1. Ground Delay Programme was the first to implement by FAA & ATCSCC since the problem of airport congestion basically occur in USA via national ground holding policy using a computerized procedure in order to select appropriate ground-holds.
2. To ensure safe and efficient traffic flow management, CAMU already have different ATFM techniques like Ground Stops, Ground delay Programmes and Airspace Flow Programmes [2] as well as ATFM tools like Airport Flow Tool (AFT), Airspace Management Tool (AMT), Thales's ATFM solution (FLOWCAT) AND CAMU WEB etc. for traffic management decision making which can either be strategic, pre-tactical or tactical flow management decision.

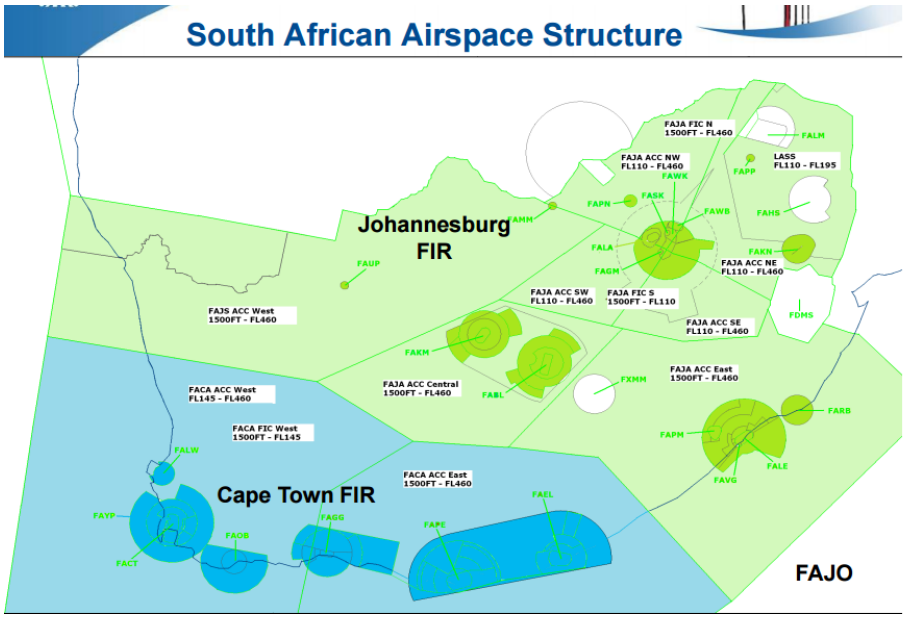
[2] Ground Holding, Airborne Holding, Flight Cancellation, Rerouting, Swapping, Miles & Minutes-in-Trail (MIT & MINIT), Traffic Sequencing Programmes, Speed Control and other control actions.

1. In particular, FLOWCAT developed by Thales with the support of Metron is a system that optimizes the use of available airspace and airport resources by balancing load and capacity in order to reduce delays, alleviate congestion and streamline the workload of air traffic controllers
2. The procedure involves the use of a Flight Schedule Monitor software to assign arrival slots to aircraft based on the available capacity and flight arrival times adding delay in sequential order until demand equals capacity.


ATNS Area of Responsibility
18S 010W
26.5S 040E
Madagascar
30S 057E
30S 040E
South Africa
35S 075E
35S 075E
South Pole
20°
30°
40°
50°
0°
10°
20°
30°
40°
50°
60°
70°
75°

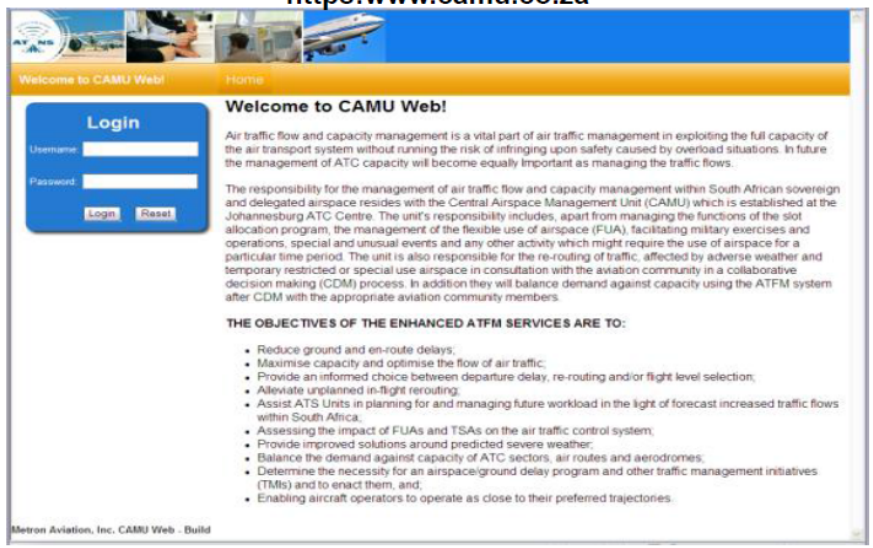

ATNS Extended Services
ATNS EXTENDED SERVICE PROVISION
Aeronautical surveying
Aeronautical documentation
Charting
Flight procedure design
Training
AIM
Other projects
Current SADC VSAT satellite communication direct speech interconnectivity
ASECNA region and SADC region VSAT direct speech connectivity via Antananarivo
Interconnectivity between SADC and ASECNA networks
Tunisia
Morocco
Algeria
Libya
Egypt
Saudi Arabia
UAE
Western Sahara
Mauritania
Mali
Niger
Chad
Sudan
Eritrea
Djibouti
Cape Verde
Senegal
The Gambia
Guinea Bissau
Guinea
Burkina Faso
Sierra Leone
Liberia
Cote d'Ivoire
Ghana
Togo
Benin
Nigeria
Cameroon
Central African Rep.
Ethiopia
Somalia
Equatorial Guinea
Gabon
Sao Tomé & Principe
Congo
DRC
Uganda
Kenya
Rwanda
Burundi
Tanzania
Seychelles
Angola
Zambia
Malawi
Comoros
Zimbabwe
Namibia
Botswana
Mozambique
Madagascar
Mauritius
Swaziland
South Africa
Lesotho

ATFM-Current Practices

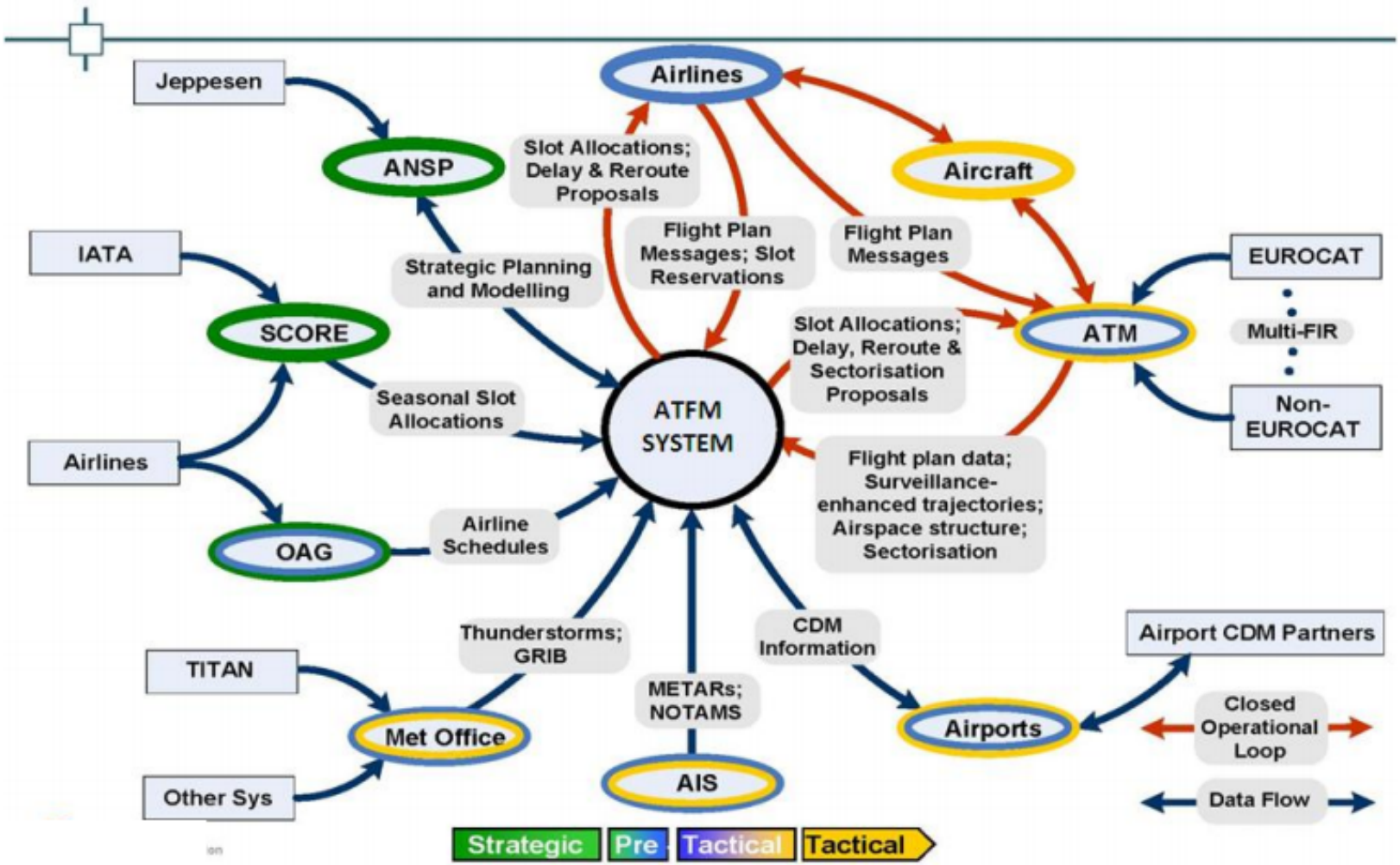


CAMU WEB

https:www.camu.co.za

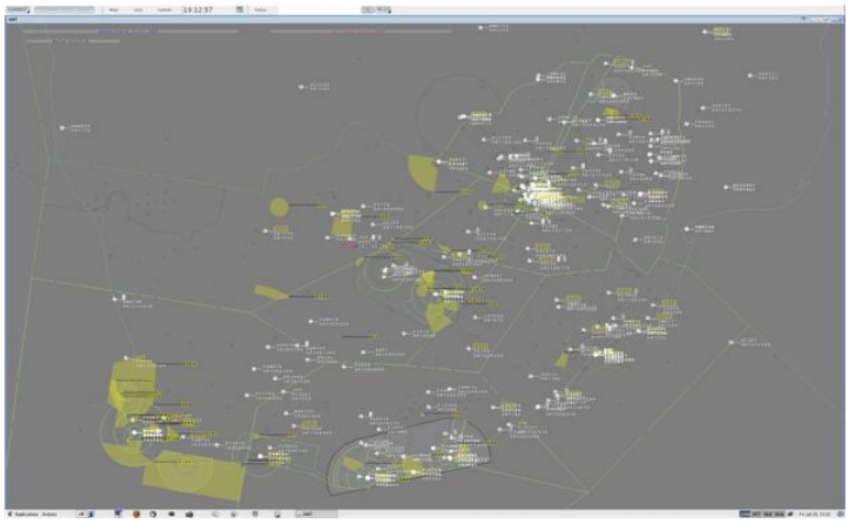


Data Exchange through the ATFM Phases

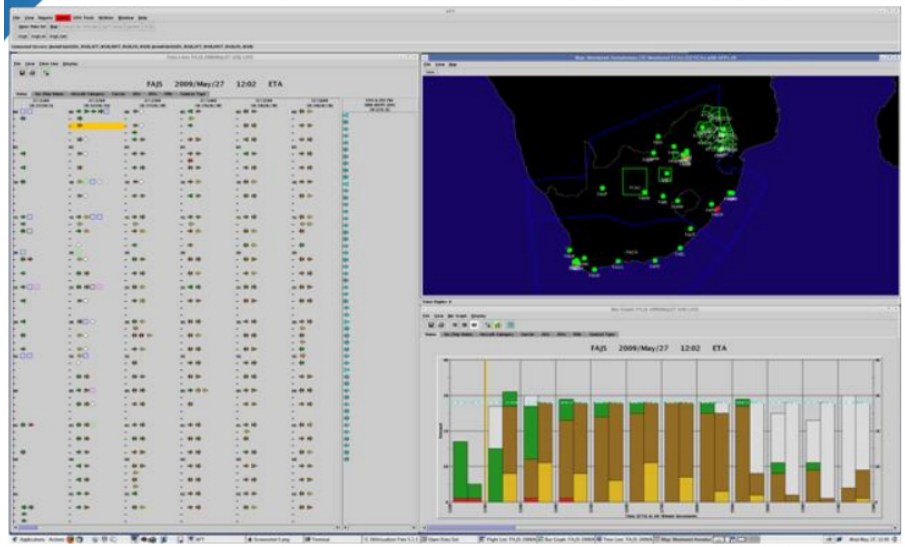


ATFM-Current Practices

AIRSPACE MANAGEMENT TOOL (AMT)



AIRPORT FLOW TOOL (AFT)



1. The research literature dealing on Air Traffic Flow Management is quite much as there are a lot of existing models in literature that addresses the demand management, congestion problems as well as air traffic delay.
2. Approaches for solving ATFM includes Single Airport Ground Holding Problem **(SAGHP)**, Multiple Airport Ground Holding Problem **(MAGHP)**, **ATFM**, Air Traffic Flow Management Rerouting Problem **(ATFMRP)**, ATFMRP with **Uncertainty**.
3. SAGHP and MAGHP are categorized as Ground Holding Approaches while ATFM, ATFMRP are categorized as Air Traffic Flow Management Approaches with En-route Capacities.
4. Models that addresses ATFM are broadly classified into Prescriptive and Descriptive Models which are further categorized mathematically as Deterministic vs Stochastic Models, Static vs Dynamic Models.

- **Prescriptive models** are those models that can be classified according to the time horizon of the flow management application they address which includes Demand Management, Airport Capacity Allocation Models, Airspace Capacity Allocation Models and Airline Response.
- **Descriptive models** are those models that aim to analyze or predict the key characteristics of the air transportation industry which includes Airspace and Airport models.
- **Deterministic vs Stochastic Models**. The distinguishing factor between them is whether the capacities of the system are assumed deterministic or probabilistic.
- **Static vs Dynamic Models**. The distinguishing factor is whether or not the solutions are updated dynamically during the day.

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Problem Statement

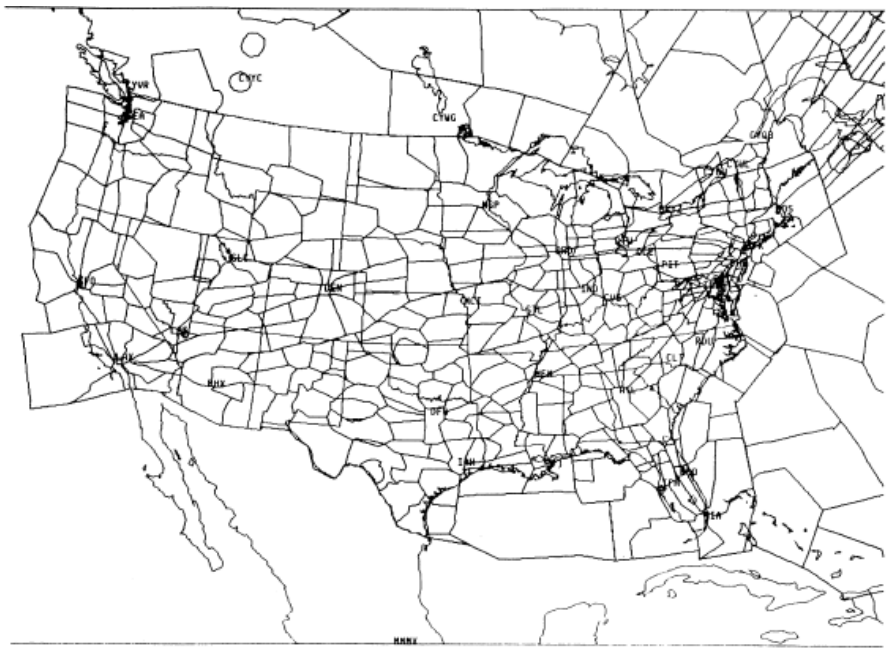
- Given an airspace system, consisting of a set of airports, airways, and sectors, each with its own capacity for each time period, t, over a time horizon of T periods, and given flights schedules through the airspace system during T, we want to find good and optimal scheduling ATFM strategies that not only mitigates congestion problems but also minimizes delay costs while satisfying the airport and en route airspace capacity constraints

Objective

- The proposed model has to decide the amount of ground and airborne delays to be assigned to the flights in a way that all the capacity constraints are satisfied while minimizing a function of the associated cost of the total delay assigned taken into consideration all other possible control actions for ATFMP.

BATFMP- Starting Point

- The Airspace is divided into sectors
- Each flight passes through adjacent sectors while en route to its destination
- The number of airplanes that may fly within a sector at a given time is limited. This restriction is referred to as en route sector capacities
- The limit is dependent on the number that the air traffic controller can manage at one time, the geographic location and the weather conditions.



- The O-D can be represented as sequence of sectors flown by an aircraft. The O-D route is predetermined if rerouting is not part of the control actions.

BATFMP- Starting Point

- The assumption for the basic ATFMP is that the time is discrete, the demand and capacity are deterministic, no rerouting and flight continuation is allowed.
- More precisely, the O-D route for BATFMP is just a predefined route for each flight and the sectors in a flight's path is predetermined.
- Identify the input data sets include set of flights, set of airports, set of sectors, set of time periods and set of continued flights, set of origin-destination pairs etc.
- Also, identify the parameters which includes the departure and arrival airport for each flight, the scheduled departure and arrival time for each flight

BATFMP Starting Point

- The departure and arrival capacity of airport at time t, the sector capacity at time t,
- The turnaround time of an airplane after each flight, minimum number of time units of that a flight will spend in a sector,
- The costs of holding flights on ground and in air for one unit of time, other associated costs (if any), the set of feasible times for flight to arrive at a particular sector.
- The Decision Variables for the basic ATFMP include flight-sector variable, ground and air borne delay variable.
- Decide what the objective of the model should look like and the possible constraints.
- Decide how to formulate the problem and the optimization techniques that will be used in solving the problem.
- The assumptions have to depicts the current ATFM practices and what is obtainable in real-life scenario.

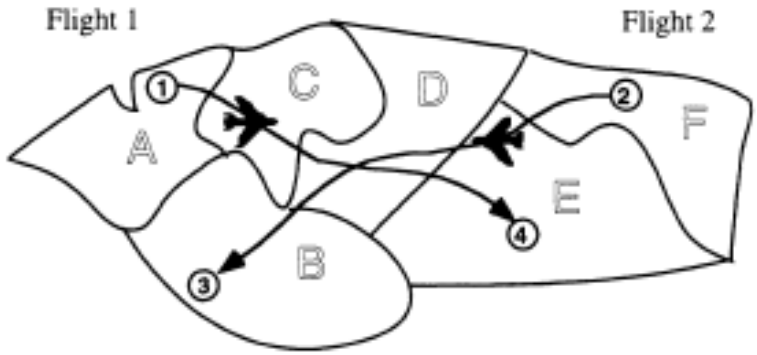
Decision Variables

$$w^j_{f,t} = \begin{cases} 1, & \text{if flight } f \text{ arrives at sector } j \textbf{ by} \text{ time } t \\ 0, & \text{otherwise} \end{cases}$$

Objective Function

$$Min \sum_{f \in F} \left(c^g_f g_f + c^a_f a_f \right) \quad g_f \text{ and } a_f \text{ are ground and air delay}$$

- Definition with **by** rather than **at** and the transformation from $u^j_{f,t}$ to $w^j_{f,t}$ i.e. $u^j_{f,t} = w^j_{f,t} - w^j_{f,t-1}$ and $w^j_{f,t} = \sum_{t' \leq t} u^j_{f,t'}$ are critical for models excellent performance.



- It is a variant of the standard flight-sector variable

$$u^j_{f,t} = \begin{cases} 1 & \text{if } f \text{ arrives at } j \textbf{ at } t \\ 0 & \text{otherwise} \end{cases}$$

- $P_1 = (1, A, C, D, E, 4)$ & $P_2 = (2, F, E, D, B, 3)$
- $w^1_{1,t} = 1,\ w^A_{1,t} = 1,\ w^C_{1,t} = 1,\ w^D_{1,t} = w^E_{1,t} = w^4_{1,t} = 0$
- $w^2_{2,t} = 1,\ w^F_{2,t} = 1,\ w^E_{2,t} = 1,\ w^D_{2,t} = w^B_{2,t} = w^3_{2,t} = 0$

BATFMP: Illustrative Example

Flight	Gcost	Acost	SDep	ADep	SArr	AAr	GD	AD
1. M-P-Go	400	20000	1	1	3	3	0	0
2. Go-Ca	600	30000	4	4	5	5	0	0
3. P-Be-Ba	800	40000	3	3	5*	5	0	0
4. Go-Co-Ba	1000	50000	3	3	5*	5	0	0
1. M-P-Go	400	20000	1	1	3	3	0	0
2. Go-Ca	600	30000	4	4	5	5	0	0
3. P-Be-Ba	800	40000	3	4	5*	6	1	0
4. Go-Co-Ba	1000	50000	3	3	5*	5	0	0
Arr Cap= 2; Obj = 0 & Cost = 0; Arr Cap= 1; Obj = 800 & Cost = 800								

Table: Results with Arrival Capacity = 2 and 1 respectively at all times

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Insight on Proposed Approach to ATFMRP

1. Our goal is to develop a model for the ATFMRP that will be extended to incorporate most of the variations but we will restrict ourselves to what is obtainable within African region, in particular, Southern Africa.
2. ATFMRP is more complicated in the sense that aside assigning ground holding and airborne delay, flights may be rerouted through a different path in order to reach its destination if the current route passes through a region that is unusable due to bad weather conditions that causes drastic fluctuations in the available airspace or some other factors.
3. These rerouting decisions are handled through the experience of the air traffic managers using technologically designed systems and software and not through a formal optimization model.

Insight on Proposed Approach to ATFMRP

1. Bertsimas et.al highlighted two possible approaches to incorporate rerouting decisions namely sector and path approach.
2. The path approach first defines the set of possible routes that flight f may fly while the sector approach decides at each sector in its route, which sector to enter next.
3. Thus, the sector approach first defines the set of sectors that flight f can enter immediately after exiting sector j as well as the set of sectors that flight f can enter immediately before entering sector j.
4. There are few works in literature that considers rerouting of flights as one of the control options in ATFM.

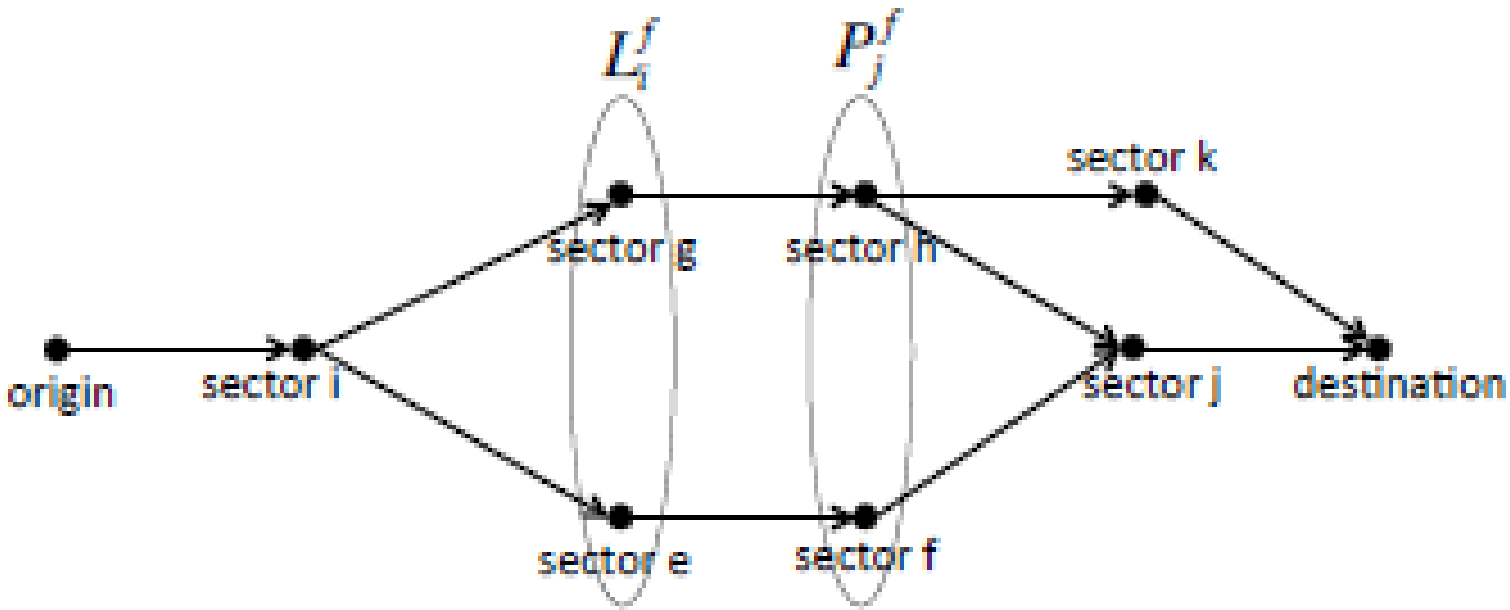


Figure: Illustration of possible routes from one origin to a destination airport.

New Decision Variables- Path Approach

Let R_f be the set of possible routes that flight f may choose. For the BATFMP, $R_f = P_f$. We note that $P(f,1)$ and $P(f,N_f)$ remains the same.

$$w_{f,t}^{jr} = \begin{cases} 1, & \text{if flight } f \text{ arrives at sector } j \textbf{ by} \text{ time } t \text{ along route } r \\ 0, & \text{otherwise} \end{cases}$$

We can rewrite the first decision variables in terms of the new ones i.e.

$$w_{f,t}^{j} = \sum_{r \in R_f} w_{f,t}^{jr}$$

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New Decision Variables- Sector Approach

Let $\mathcal{N}_{f,j}$ be the set of sectors that flight f can enter immediately after exiting sector j and $\mathcal{P}_{f,j}$ be the set of sectors that flight f can enter immediately before entering sector j. We note that $P(f,1)$ and $P(f,N_f)$ are the beginning and ending sector for a given flight f over all routes if we define $S_{f,j}$ to be the set of sectors that can be flown by a flight including the departure and arrival airport.

$$w_{f,t}^{jj'} = \begin{cases} 1, & \text{if flight } f \text{ arrives at sector } j' \text{ from sector } j \textbf{ by} \text{ time } t \\ 0, & \text{otherwise} \end{cases}$$

We can rewrite the first decision variables in terms of the new ones i.e.

$$w_{f,t}^{j} = \sum_{j' \in N_{f,j}} w_{f,t}^{jj'}$$

Modeling Variations

- The basic ATFMP can be easily extended in many directions taking into account several variations of the model. The variations include

1. **Aspect of Fairness in assigning delays to flight**
2. **Rerouting of Aircraft**
3. **Flight Cancellation Priorities**
4. **Dependency between Arrival and Departure Capacities**
5. **Bank of Flights**
6. **Hub Connectivity and Multiple Connections**
7. **Interaction with airlines**
8. **Dynamic Updating of Decisions**
9. **Incorporating Capacity uncertainty i.e Stochastic Modeling**
10. **Trying other search techniques and make comparison with the established IP model**

The Big Question?

1. How best can this problem be formulated to include rerouting options and other modeling variation? More precisely, how best can one formulate this problem to depict the current practice in South Africa?
2. Since we already know that the system is disrupted when there is fluctuating weather conditions, equipment outages and demand surges and these disruptions are highly unpredictable and cause significant capacity-demand imbalances, temporary and substantial reductions in airspace and airport capacity.
3. The big question that arises is how to extend the deterministic environment of this formulation to a probabilistic environment in order to account for the uncertainties that are inherent in the system.
4. Is it possible to develop a model that is computationally less expensive in terms of handling large instances of data when considering ATFMRP?

Thank You, Comments & Questions



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