RUNWAY CAPACITY OPTIMIZATION: AIRCRAFT SEQUENCING IN MIXED MODE OPERATION

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ABSTRACT

To meet future air transportation requirements, technology advancement has paved a way for the application of decision support systems to optimize strategic and tactical operations. This paper presents a simulation approach for the optimal sequencing of aircrafts on a single runway operating in a mixed mode (arrival and departure) and runway system capacity assessment using State Space Analysis. System dynamics are specified using the Coloured Petri Nets (CPN) formalism. The approach is capable of automating the decision activity (scheduling), analyzing different scenarios of scheduling policies and optimizing the runway capacity at any given time based on actual or dynamic traffic flow. It is aimed at validating not only the expected benefit of capacity and safety but also the benefits on efficiency from the air traffic controller's perspective.

Keywords: air traffic control, scheduling, coloured petri net, decision support system

1. INTRODUCTION

The increasing demand for air transportation services in recent times has called for the participation of the simulation community to provide and deploy solutions that would improve the current state of the industry. Specifically, efficient management of available infrastructure, for example, runways, taxiways, aprons etc in Air Traffic Management (ATM) has been a major concern in the industry. A challenging problem inherent to the air traffic flow management is how to maximize capacity given the available infrastructure in the face of growing demand.

The growth in air travel is outstripping the capacity of the airport and air traffic control (ATC) system, resulting in increasing congestion and delays. However, a misunderstanding of the poor utilization of the available infrastructure usually leads to greater investments in additional runways and extensive pavements for taxiways and aprons. In order to avoid this expensive approach, it is important to remove non-productive operations due to poor scheduling approaches. Thus, simulation models could help to analyze the operational efficiency of the current traffic control procedure and propose new viewpoints and decision support tools to address air traffic throughput.

Air traffic controllers have been able to maintain a safe and orderly flow of air traffic in a conservative manner. The use of traditional sequencing approaches mainly based on ICAO procedures (still using voice communications) hinders considerably the use of advanced decision support system (DSS). Though the traditional approach might seem to be a good one for scheduling landing and departure aircraft operations under low traffic conditions, this approach becomes inefficient during peak hours under a workload of a certain aircraft mix. A limiting feature of the sequencing pattern which in turn affects capacity is ATC regulation rules requiring a minimum safety separation between different types of aircrafts to avoid wake turbulence. Other factors influencing runway capacity include: air traffic control, characteristics of demand, environmental conditions and the layout and design of the runway system.

A number of different approaches have been employed by researchers for scheduling aircraft landings and departures in an effort to maximize runway capacity while minimizing delays. These approaches include: Queuing Models, Analytical Approaches and Computer Simulation. Bäuerle et al. (2007) presents a queuing model and a number of heuristic routing strategies to minimize the waiting time of arriving aircrafts (static) with one or two runways. Chandran and Balakrishnan (2007) use a dynamic programming algorithm to generate schedules of airport runway operations that are susceptible to perturbations. Several exact and heuristic optimization methods for scheduling arriving aircrafts and comparing these with integer programming formulations are given in Fahle et al. (2003). In Bolender et al. (2000), a number of scheduling strategies are analyzed in order to determine the most efficient means of scheduling aircraft when multiple runways are operational and the airport is operating at different utilization rates. Hu and Chen (2005) introduce the concept of receding horizon control (RHC) to the problem of arrival scheduling and sequencing in a dynamic environment. A multiple runway case of the static Aircraft Landing Problem is

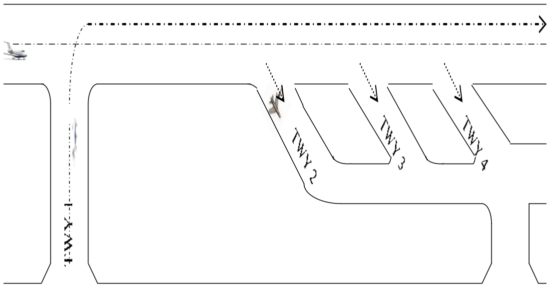


Figure 1: A Simple Runway

considered in Pinol and Beasley (2006), employing scatter search and population heuristic approaches.

Kovatcs et al (2005) developed a timed stochastic coloured petri net model of a single runway that analyzes the effect of the taxiway's availability on the runway capacity with respect to a given schedule. Some assumptions in this model cannot be adapted to practice.

Although airline business models help to understand the delay-capacity relationships, they do not provide accurate estimate of average delay except for simple situations, since they are used to evaluate best practices as a steady state solution when analyzing delay and throughput in the air traffic system. Not all models presented in the literature consider real aspects of aircraft landing and take off operations.

In order to accommodate future air traffic needs, a "paradigm shift" supported by the state-of-the-art and innovative technologies is required (SESAR, 2005 and its equivalent NGATS). The SESAR (Single European Sky ATM Research Programme) project, currently in the development phase is aimed at developing new generation air traffic management system capable of ensuring the safety and fluidity of air transport worldwide over the next 30 years. New communication requirements consist of a data link to automate the air traffic control system for scheduling aircrafts with less human intervention. Thus, some of these new technology advancements have paved a way for the application of simulation in the air transportation industry.

The primary objective of the research introduced in this paper is to develop a simulation model to automate and optimize the scheduling decision activity of air traffic controllers when prioritizing the next landing or departure operation while maintaining a high safety level (ie. wake turbulences), reducing costs and minimizing environmental hazards. Thus, an approach based on a simulation model that describes the system dynamics developed in CPN Tools is presented. Though simulation allows the modeller to visualize and understand how the system works, as a decision support tool it is only capable of reporting or exploring a small number of scenarios. The implemented approach is capable of automating the decision activity (scheduling), by analyzing different scenarios of scheduling policies and optimizing the runway capacity at any given time based on actual traffic flow. It is aimed at validating not only the expected benefit of capacity and safety but also the benefits on efficiency from the air traffic controllers' perspective.

The paper is organized as follows: Section 2 describes the air traffic flow problem and modes of operation; Section 3 presents the CPN model and the benefits obtained by using Coloured Petri Nets as a modelling formalism for logistic systems; Section 4 presents the scheduling strategies employed; Section 5 describes the results obtained while Section 6 gives a summary of the paper and ideas for future research.

2. THE PROBLEM

Given a set of aircraft fleet mix competing for landing or take off operation on a single runway, the optimization problem can be simplified to find an automatic optimal scheduling policy and to allocate landing or take off times during heavy traffic flow. The objective is to maximize the runway capacity such that: only one aircraft can occupy the runway at a time, the minimum separation requirement between aircrafts is met, and the precedence of arrivals over departures. Other objective that will be considered is: minimizing delays whilst in air and on land in terms of fuel consumption and environmental hazards. Figure 1 shows the layout of a simple runway.

The aircraft fleet mix can be modelled as a three weight classes based on the maximum take off weight capacity (Chandran B. and Hamsa B., 2007). They are classified as: heavy (H), medium (M) and light (L). The minimum time-based separation requirement matrix between the different classes of aircrafts using the same runway as presented in Martinez J.C et al. (2001) is shown in table 1. The separation time ensures that the runway will be free when a trailing aircraft is scheduled to touch down or enter the runway. This is a measure to avoid collisions and wake turbulence in air and on the runway. With this, only one aircraft would be able to occupy the runway at a particular point in time. This goes a long way in reducing runway capacity. Another striking feature that influences runway capacity is the number of available exit taxiways for aircrafts. It brings about variation in runway occupancy time (ROT) for the different aircraft classes. The average ROT and touch down time for the aircraft categories according to the approach speed is given in table 2 (Martinez J.C et al., 2001). In practice, arrivals are generally given absolute priority over departures. Departures are released when suitable gaps occur in the arrival stream. The runway is said to be under-utilized if it is operating in a segregated mode (Ashford N. 1992). Runway capacity can be substantially increased with mixed operations.

During arrival or departure, a controller directs each aircraft. Upon approaching an airport at which a landing is to be made, the pilot is required to make contact with a controller so that separation of all aircrafts can be provided. If the path is clear, the controller directs the pilot to the runway; if the airport is busy, the aircraft is fitted into a traffic pattern with other aircraft waiting to land - a holding area away from the runway called Terminal Control Area (or Terminal Manoeuvring Area, TMA). This is an area where the aircrafts hold until the control units are ready to position them into an approach sequence to land. When the runway becomes available, the waiting aircraft is directed to the Instrument Landing System (ILS). Several aircrafts can be on the ILS at the same time, several miles apart. The aerodrome controller directs the plane to the proper runway and then informs the pilot about conditions at the airport, such as weather, speed and direction of wind, and visibility. The procedure is reversed for departures. The controller directs the aircraft waiting on taxiway for instructions to enter the runway and then informs the pilot about conditions at the airport. The controller also issues runway clearance for the pilot to take off. Once in the air, the aircraft is guided out of the airport's airspace by the controller.

Table 1: Minimum Time between Successive Arrivals and Departures (seconds)

Leading Plane	Trailing Plane					
	Heavy		Medium		Light	
Heavy	96	60	120	90	144	120
Medium	72	60	72	60	96	90
Light	72	60	72	60	72	60

Table 2: Runway Occupancy and Touch Down Times

Aircraft Type	Runway Occupancy Time		Touch Down Time
	Landing	Departure	Landing
Heavy	55	38	60
Medium	50	43	65
Light	45	50	70

3. THE CPN MODEL

CPNs are well known for their capability in simulating and analyzing discrete-event system (Jensen K. 1997). In this section a CPN model is illustrated to determine the scheduling strategies, expected landing and take-off time, runway capacity assessment, total fuel consumption and air quality factor index.

CPN has been chosen as the modelling formalism due to its ability to describe the complete structure of a system together with its behaviour and the information about the system state (Narciso M. and Piera M.A, 2001) through the use of a functional programming language. PN is a bipartite directed graph describing the structure of a discrete event system, while the dynamics of the system is described by the execution of the PN. A PN is coloured if the tokens are distinguishable. The main CPN components are: state vectors, arc expressions and guards, colour sets, places and transitions. See [(Jensen K. 1997), (Narciso M. and Piera M.A, 2001)] for the description of these terms and tutorial on CPN.

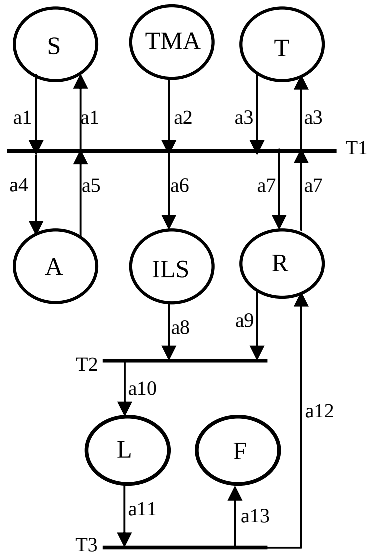
To model the air traffic flow operations as a discrete event system, it is necessary to define events that are relevant. CPN allows the representation of a system in a compact structure with few places and transitions. The model is implemented in CPN Tools software developed and maintained by the CPN Group, University of Aarhus, Denmark for validation and verification purposes. It is then transferred to another CPN simulator tool developed at the Universitat Autonoma de Barcelona, Spain for evaluating the state space (See section 4). Figures 2 and 3 shows the CPN model of arrivals and departures respectively. The model consists of 13 place nodes and 5 transitions (T1, T2, T3, T4 and T5) that describe the system dynamics. The meanings are given in table 4, 5 and 6.

The model has 2 parts; one for the arrivals and the other for departures, competing for the shared resource (Runway). The information enclosed in TMA node consists of 4-tuples (aircraft type, average runway occupancy time, fuel consumption rate per second and time) describing aircrafts waiting in the TMA to be positioned at the ILS for landing. Place node TW represents the aircrafts waiting to take off. Place node S contains the matrix of minimum separation time for landing and take off. Other measures used to determine delays are: total fuel consumption rate and a weighted air quality index. The fuel consumption rate measured in litres/secs is used to estimate the total delay for aircrafts in holding trajectory while the weighted air quality index is a penalty for departing aircrafts' delay. The values are given in table 3.

Transition T1 is an event that positions arriving aircrafts from the TMA on the ILS while maintaining the minimum separation time. The sequence in which the aircrafts are placed in the ILS is independent of the aircraft type. Transition T4 places the aircrafts waiting to depart at the apron for take off while Transitions T2, T3, T5 are events describing touch down, exit from the runway and aircraft take off respectively. The time is kept at zero for aircrafts in the TMA and taxiway. This is to measure the effect of continuous demand on the runway capacity during heavy traffic flow.

Table 3: Fuel Consumption and Weighted Air Quality Index

Aircraft Type	Fuel Consumption (/secs)	Air Quality Index
	Landing	Departure
Heavy	4	60
Medium	2	40
Light	1	20



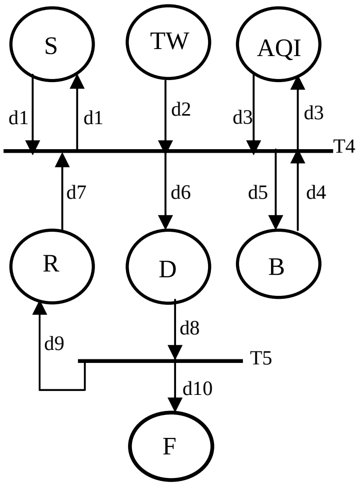


Figure 3: CPN Model of Departing Aircrafts

Figure 2: CPN Model of Arriving Aircrafts

Table 4: Colour Description

Colour	Definition	Colour Description
X,Y	int 1..3	Aircraft type, Leading aircraft
L	int	Landing/take off occupancy time
Lt	int	Computed touch down time for scheduled landing aircrafts
C	int 1..4	Fuel consumption (litres/secs)
T, S	int	Time at the TMA/Taxiway, Separation time
T1, T2	int	Cumulative separation times, Runway utilization time
To, Ts	int	Cumulative occupancy time, Estimated scheduled time
T3, Tt	int	Time at touch down, Touch down time for aircrafts on the ILS
O, I	int	Operation identifier; landing or departure, integer
U, Q	int	Cumulative fuel consumption, Cumulative air quality index
Sm	Product Y, X, S	Safety Matrix
Tm	Product X, L, C, T	Landing aircrafts information waiting in the TMA
Td	Product X, Tt	Touch down information
Sc	Product Y, T1	Cumulative separation
Is	Product X, L, C, Lt, Tt	Aircrafts on the ILS
Ri	Product I, T2, U, Q, I, To	Runway information
La	Product X, L, T3, Tt, U, Q, I, To	Landing aircrafts occupying the runway
Tw	Product X, T	Departing aircraft information waiting on the taxiway
Aq	Product X, L, Q	Air quality information
Da	Product X, L, Ts, Q, U, To	Departing aircrafts occupying the runway
Fs	Product X, O, Ts	Scheduled aircrafts

Table 5: Colour Petri Net Place Description

Place	Colour	Description
A, B	Sc	Cumulative separation for arrival and departure respectively
AQI	Aq	Represents air quality information
D	Da	Departing aircrafts occupying the runway
F	Fs	Scheduled aircrafts – final state
ILS	Is	Represents aircrafts positioned on the ILS
L	La	Landing aircrafts occupying the runway
R	Ri	Runway information
S	Sm	Represents safety matrix
T	Td	Describes the touch down time for arriving aircrafts
TMA	Tm	Represents arriving aircrafts in holding trajectory
TW	Tw	Represents departing aircrafts waiting on the taxiway

Table 6: Arc Expression

Arc	Expression
a1, a2	1’(y, x, s), 1’(x, l, c, t)
a3, a4	1’(x, tt), 1’(x, M(tt, t + s, t2 - tt))
a5, a6	1’(y, t1), 1’(x, l, c, M(tt, t + s, t2 - tt) + tt, tt)
a7, a8	1’(1, t2, u, q, 0, to), 1’(x, l, c, lt, tt)
a9	1’(1, t2, u, q, 0, to)
a10	if (lt >= t2) then 1’(x, l, lt, tt, u + c * (lt - tt), q, 0, to + l) else 1’(x, l, t2, tt, u + c * (lt - tt), q, 1, to + l)
a11, a12	1’(x, l, t3, tt, u, q, i, to), 1’(1, l + t3, u, q, i, to)
a13	1’(x, 1, t3 - tt)
d1, d2	1’(y, x, s), 1’(x ,t)
d3, d4	1’(x, l, q1), 1'(y, t1)
d5, d6	1’(x, M(tt, t + s, t2 - tt)), 1’(x, l, M(t, t2, t1 + s), q + l * tt, u, to + q1)
d7, d8	1’(1, t2, u, q, 0, to), 1’(x, l, ts, q, u, to)
d9, d10	1’(1, ts + l, u, q, 0, to), 1’(x, 2, ts)
M	fun M(x ,y, z: INT) = (if x >= y andalso x >=z then x else if y >= x andalso y >= z then y else z);

Table 7: Scheduling Solution

Place Node	R	F
Final State	1'(1,1443,6936,0,0,940)	1'(1,1,192) + 1'(1,1,96) + 1'(1,2,1405) + 1'(1,2,60) + 1'(2,1,312) + 1'(2,1,384) + 1'(2,1,456) + 1'(2,2,1075) + 1'(2,2,1285) + 1'(2,2,1345) + 1'(3,1,552) + 1'(3,1,624) + 1'(3,1,696) + 1'(3,1,768) + 1'(3,1,840) + 1'(3,2,1015) + 1'(3,2,1165) + 1'(3,2,1225) + 1'(3,2,571) + 1'(3,2,955)

Key: F - (aircraft type, operation identifier, scheduled time)
Aircraft type: 1 – light, 2 – medium, 3 – heavy
Operation identifier: 1 – landing, 2 – departure

4. SCHEDULING STRATEGY

State Space analysis permits the evaluation of a wide range of options leading to better decision making: it permits the comparison of various alternatives depending on the actors involved; it allows timely policy and real time decisions to be made. However, the amount of nodes generated can grow to computationally prohibited size when applied to real systems. The CPN simulator tool is used to generate and explore the coverability tree.

Each time a new state is generated, the markings are checked against the previous states on the same path. If the new marking has been generated previously, it is labelled as “old”. The tool will not explore enabled transitions associated with this new state. However, a new state is labelled as “dead end” if there is no enabled transition. The tree is further explored if the same state has not been generated until the final state is established. In addition, a new state is not generated for a node where there is a successive increment of tokens. A symbol “ω” is introduced to stop the further expansion of the path. A simple example of the CT for a Petri net is presented in figure 4.

The underlying idea is to transform a scheduling problem to a search problem, that is, to obtain a path from a certain system state to a desired goal state in a tree structure that represents the problem state. CPN formalism provides an easy way to introduce new restrictions to reduce the size of the state space under acceptable computational time: restricting the search space by eliminating some possibilities that will not lead to a feasible solution and specification of constraints on events firing. The tool allows the modeller to specify the final state required or desired to be reached.

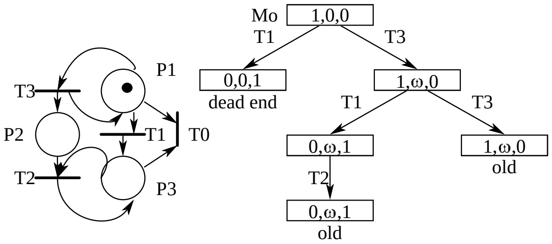


Figure 4: PN Coverability Tree Example

Though the state space is used to determine the various scheduling strategies, a number of other strategies that supports the state space to drive the system to optimal are implemented in the model. These include:

1. Runway utilization is kept open for arriving and departing aircrafts. This is to allow the state space explore all the possible scheduling policies that are obtainable for aircrafts waiting in queue. Several possibilities exist: all arriving aircrafts can be scheduled before the departing ones; arrivals can be scheduled after departures, two departures can be scheduled to take off after every arrival and vice versa.
2. An aircraft is scheduled to land if and only if the runway will be free at touch down and the minimum separation time between the leading and trailing aircraft is adhered to.
3. A departing aircraft is authorized to take off if the ROT is less than or equal to the time a trailing aircraft will touch down. This is to avoid collisions and wake turbulence on the runway.
4. The further expansion of nodes on a path is disabled if the touch down time or a take off time of a trailing aircraft is greater than the time a leading aircraft will leave the runway. This is a restriction to eliminate the search for infeasible solutions as wake turbulence and land side accidents are bound to occur.

A scheduling policy is considered optimal if it has the best sequence of events that maximizes the runway capacity while fulfilling the security and minimum delay requirements. The model allows the formulation of different objective functions according to the preference of the actors involved. For instance, an airline may be more interested in the scheduling policy that minimizes the total fuel consumption of her aircraft whilst in queue.

5. RESULTS

The model is driven by an aircraft mix index of 50% H; 30% M; 20% L; for both landing and departure. The aircraft mix can be easily modified to reflect any other mix according to aircraft flows at any point in time.

The preferred measure is the saturation runway capacity; the maximum number of aircraft that can be handled during a given period under conditions of continuous demand, expressed in operations (i.e. arrivals, departures) per hour.

The scheduling policy that leads to a feasible solution with the estimated landing and take off time is given in table 7. The total time for the operation is given as 1443 seconds while the total fuel consumption is 6936 litres.

The maximum runway capacity under this mix is evaluated as 50 operations per hour (20/1443*3600) and the runway will be occupied two-thirds of an hour (50*940/20 = 2350 seconds). The results presented validate the capability of the runway for handling aircraft flows when operating in mixed mode.

6. CONCLUSIONS

Runway capacity analysis is undertaken for two purposes; to measure the capability of the runway for handling aircraft flows and continuous demand and to estimate delays experienced in the system at different levels of demand. The study has dealt with the two objectives with delays measured by fuel consumption of arriving aircrafts in air and air quality index of departing aircrafts on the land side.

Further research work will focus on simultaneously allocating taxiways to each aircraft with the scheduled time and rescheduling or re-feeding landed aircrafts into the system for subsequent departure. With this, the runway capacity can be improved since aircraft occupancy time differs according to the aircraft type and allocated runway.

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