Decision Support for Optimal Runway Reconfiguration

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Runway configuration consists of the specification of active runways and the directions for take-off and landing at an airport. Airports typically have more than one configuration, and the reconfiguration process consists of switching from one configuration to another based on the changes in wind conditions, noise abatement procedures or traffic demand. This paper advances a decision support system that uses a queuing network model of the terminal area to determine the optimal time for reconfiguration to minimize arrival delays. The approach employs the Queuing Network Analyzer formulation, which provides corrections to the Markovian queuing approach to enable independent specification both the mean and variance of inter-arrival and service times. The parameters of the queuing network model are derived from an estimation methodology and the inter-aircraft arrival time distribution are derived from scheduled aircraft arrivals into the terminal area. Operation of the algorithm is demonstrated for the San Francisco Metroplex consisting of San Francisco airport, Oakland International Airport, and Mineta San Jose International Airport, and also the Los Angeles Metroplex consisting of Los Angeles International Airport, Bob Hope Burbank Airport, and John Wayne-Orange County Airport. The simulation results indicate that the proposed approach can provide actionable decisions in the presence of system uncertainties. Differences between the decisions made based on the two different queuing network formulations are given. An approach to derive robust reconfiguration decisions based on a trade-off between optimal mean and variance of the delay times is also illustrated.

Nomenclature

NAS
National Airspace System
SORM
System Oriented Runway Management
JPDO
Joint Planning and Development Office
RCM
Runway Configuration Management
CADRS
Combined Arrival/Departure Runway Scheduling
NextGen
Next Generation Air Transportation System
QNA
QNA Network Analyzer
M/M/1
Markovian queuing approach
n
number of nodes in the network
m
number of sever at node j (note \(m_j=1\) for the QNA model used for this study since at most only one aircraft can be at the same sever (location) at any time) (j=1, 2,..., n)
\(\Lambda_{0,j}\)
mean of external arrival rate to node j (j=1, 2,..., n)
\(c^2_{0,j}\)
variability parameter of the external arrival process to node j (squared coefficient of the variance of the arrival rate over the mean of the arrival rate) (j=1, 2,..., n)
\(\tau_j\)
mean of service time of node j (j=1, 2,..., n)
\(c^2_{s,j}\)
variability parameter of the service time distribution (squared coefficient of the variance of the service time over the mean of the service time) (j=1, 2,..., n)
Q
routing matrix with element \(q_{uid}\) denoting the proportion of aircraft completing service at node I, that go next to j. Note that \(q_{uid}\) is either 1 or 0 in the current study, since the

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network is formulated without any splits for the arrival traffic flows.

\[ \lambda_{w,i} \]
arrival flow rate at the \( i \) window before runway switch

\[ \lambda_{s,i} \]
arrival flow rate at the \( i \) window after runway switch is denoted as

\[ T_{w,i} \]
mean of the delay time (system time minus service time) for the arrival using a specified plan for the \( i \) window, occurring before runway reconfiguration

\[ T_{y,i} \]
Mean of the delay time using another plan for the \( i \) window, after runway reconfiguration.

\[ T_{w,rcm} \]
average delay time

Q-Gen Queuing Network Model Generator (Q-Gen).

SFO San Francisco International Airport

OAK Oakland International Airport

SJC Mineta San Jose International Airport

LAX Los Angeles International Airport

BUR Bob Hope Airport

SNA John Wayne-Orange County Airport

KSFO San Francisco Area Metroplex

KLAX Los Angeles Area Metroplex

I. Introduction

Runway configuration specifies active runways and the directions for take-off and landing at an airport. Runways are limited resources and a well planned and managed runway selection and usage is critical to the efficiency of both the airport and National Airspace System (NAS). Runway configuration management is the process by which an optimal airport arrival/departure traffic configuration is chosen to achieve the traffic flow objectives.

Runway configurations are selected based on factors such as runway length for arrival and departure, tail wind and crosswind components, runway physical conditions, land and short operations, arrival runway instrument landing system (ILS) category versus visibility and ceiling, noise-favored/noise constrained runways, runway interactions such as wake turbulence spacing, converging and intersecting runways, taxi choke points, safety of flight issues such as the risk of runway incursions, adequate separation to provide for missed approaches. A runway reconfiguration will be required to accommodate the changes of these factors as well as to improve the overall air traffic efficiency.

NASA’s System Oriented Runway Management (SORM) is an operational layer between surface operations and airspace management that seeks to address Joint Planning and Development Office (JPDO) objectives OI-0331 and OI-03394, which deal with integrated arrival/departure, and surface operations and traffic management. The purpose of SORM program is to provide enhanced runway management capabilities, by defining procedures for runway configuration selection and the orchestration of traffic across runway configurations. SORM program is composed of two procedural concepts: Runway Configuration Management (RCM), which is the process of designing active runways, monitoring the active runway configuration for suitability given the current conditions, and predicating future configuration changes; whereas Combined Arrival/Departure Runway Scheduling (CADRS) is the process of assigning arrival and departure runways based on airport and NAS goals.

An assessment given in Reference 3, which included a survey of 15 air traffic control towers serving high-demand airports and five Terminal Radar Approach Controls, concluded that there was little automation used in the runway management process. Although air traffic controllers have done an excellent job of managing runways based on experience and “rules of thumb”, the air traffic flow on runways and in the terminal area are becoming more complex. In the NextGen, it is expected that enhancements will be made in communication, navigation, and weather prediction, as well as traffic flow management. These comprehensive set of procedures will make the system more stable and predictable, and will allow for future optimization in the NextGen. However, these benefits will be realized only if the runway configuration decisions can be based on these myriad information components in an efficient manner. SORM, as an element of enhanced traffic flow management, focuses on a systematic approach for runway management, that serves to promote efficiency for the NAS and provides assistance to air traffic personnel in the runway management decision making process.
An automation tool to facilitate the runway management has been reported in the references such as in 8-10. However, complexity and stochasticity of the complex airspace and runway environment were not included in those early research efforts. Additionally, although several automation tools have been developed under the NextGen program, the problem of determining the optimal time to switch from one runway configuration to another has not been previously discussed. The present paper advances an approach for determining the time instant for reconfiguration based on stochastic models of the terminal airspace and the runways.

The development of a decision support system for determining the optimal time to switch from one runway configuration to another within a prescribed window, so as to minimize the overall delay in the system is discussed in this paper. It is assumed here that a time window has been specified for runway reconfiguration, and the remaining decision is the selection of the time instant within this window at which the reconfiguration should be initiated. In order to derive this decision, the traffic patterns in the terminal area are abstracted as a queuing network. The mean and variance of the delay times in the network are derived through Queuing Network Analyzer\textsuperscript{16}, for several possible reconfiguration times. The optimal reconfiguration time is then chosen to minimize the delay time.

Queuing network models capture the stochastic nature of the traffic flow through the queuing parameters such as the inter-arrival time distribution and service time distribution. Several recent research studies have shown that these models are suitable for modeling the traffic flows in both the airspace and the terminal areas\textsuperscript{11-13}. This abstraction allows the computation of system times and delay times along the existing routes, and along the routes after reconfiguration. The queuing network models of the terminal area configurations, together with the statistical characteristics of the arrival flow rates are derived from radar track data.

The remainder of the paper is organized as follows. Section II presents the formulation of the optimal runway reconfiguration problem. Section III presents case study results for San Francisco Area Metroplex. Case study results for Los Angeles Area Metroplex are presented in Section IV. Conclusions from the present research are summarized in Section VI.

II. Formulation of the Optimal Runway Reconfiguration Problem

The objective of the reconfiguration algorithm is to determine an optimal time instant within a specified reconfiguration time window that leads to the minimum arrival delay time. The routes in the terminal area for the two runway configurations in the Metroplex are abstracted from radar tracking data using a software package available at Optimal Synthesis Inc, termed the Queuing Network Model Generator (Q-Gen). The parameters of the queue models are derived using a Bayesian estimation methodology\textsuperscript{14}. The inter-aircraft arrival time distribution is also derived from the radar track data. These data components are then used to determine the optimal time instant for runway reconfiguration. Queuing Network Analyzer (QNA) Formulation

The simplest queuing model is the single-server Markov queue or the so called the M/M/1 queue\textsuperscript{15}. The M/M/1 model requires the arrivals to be Poisson processes and service times to have exponential distributions. This indirectly implies that the mean and variance of the inter-arrival and service time distributions cannot be independently specified. However, in practical queuing situations, it is desirable to employ distinct values for the mean and variance of both these times. The QNA formulation\textsuperscript{16} provides corrections to the Markovian queuing approach to enable independent specification both the mean and variance of the inter-arrival and service times. The QNA approach can be used to model non-Markov queuing networks.

The major formulas for QNA are summarized next. When compared with equations in Reference 16, the following equations have been tailored to the network being modeled. The present work does not include flow split parameters in the formulation. Specifically: $m_j=1$, $\gamma_j = 1$. This is valid because air traffics that come from the same departure airport but goes to different destinations have been formulated as distinct routes. Additionally $\nu_{ij} = 0$ is the same as the parameters chosen in Reference 16.

1. The traffic-rate equation in matrix notation is

$$L = (I - Q^T)^{-1} L_0$$  \hspace{1cm} (1)

where $I$ is an $n$ by $n$ identity matrix, $L_0 = [\lambda_{0,1}, \lambda_{0,2}, \cdots, \lambda_{0,n}]^T$ is the vector of the external arrival rates, and $L = [\lambda_1, \lambda_2, \cdots, \lambda_n]^T$ is the vector of the total traffic flow rate at all the nodes.

2. The traffic utilization equation for each node is obtained from
\[ \rho_j = \frac{L_j}{\mu_j} \quad (j = 1, 2, \ldots, n) \]  

Note that the network becomes unstable if for any node, \( \rho_j \) approaches unity over a finite time duration.

3. The traffic variability equation in matrix-vector notation is

\[ C_a^2 = (I - B^T)a \]  

where \( C_{a,j}^2 \), the \( j \)th element of \( C_a^2 \), yields the variability parameters for the internal flow at node \( j \), \( a \) and \( B \) are constants depending on the input data and their elements are calculated from:

\[ a_j = 1 + \omega_j \left( p_{ij} c_{a,j}^2 - 1 \right) + \sum_{i=1}^{n} p_{ij} \left( 1 - q_{ij} \right) + q_{ij} \rho_j^2 x_j \]  

\[ b_{ij} = \omega_j p_{ij} q_{ij} (1 - \rho_j^2) \]  

The equations to solve for these parameters are:

\[ p_{ij} = \frac{\lambda_{ij}}{\lambda_j} \]  

which denotes the proportion of arrivals to node \( j \) from node \( i \), and

\[ \lambda_{ij} = \lambda_i q_{ij} \]  

is the arrival rate to node \( j \) from node \( i \). Additionally,

\[ x_i = 1 + \left\{ \max \{ c_{a,j}^2, 0.2 \} - 1 \right\} \]  

\[ \omega_j = \left[ 1 + 4(1 - \rho_j)^2 (\nu_j - 1) \right]^{-1} \]  

and

\[ \nu_j = \left[ \sum_{i=0}^{n} P_{ij}^2 \right]^{-1} \]  

4. The delay time for each node is computed from

\[ EW_j = \tau_j \rho_j (1 - \rho_j) (c_{a,j}^2 + c_{s,j}^2) g_j / 2 \]  

where \( g \) is defined as

\[ g(\rho, c_a^2, c_s^2) = \begin{cases} 2(1-\rho)(1+c_s^2) & , c_a^2 < 1 \\ 1 & , c_a^2 \geq 1 \end{cases} \]  

Notice for the M/M/1 model, the delay time for each node is computed from

\[ EW_j = \tau_j \rho_j (1 - \rho_j) \]  

The delay time for the total network is the summation of the delay time of each node, thus

\[ T_w = \sum_{j=1}^{n} EW_j \]  

5. The variance of delay time for each node is computed from

\[ Var(W_j) = (EW_j)^2 c_w^2 \]  

where

\[ c_w^2 = \frac{c_D^2 + (1 - \sigma)}{\sigma} \]  

with
\[ c_D^2 = 2\rho - 1 + 4(1 - \rho)d_s^3 / 3(c_s^2 + 1)^2 \]  
\[ \sigma = \rho + (c_s^2 - 1)\rho(1 - \rho)h \]

for which

\[ d_s^3 = \begin{cases} 
3c_s^2(1 + c_s^2), & c_s^2 \geq 1 \\
(2c_s^2 + 1)(c_s^2 + 1), & c_s^2 < 1 
\end{cases} \]

\[ h(\rho, c_a^2, c_s^2) = \begin{cases} 
1 + c_a^2 + \rho c_a^2, & c_a^2 < 1 \\
1 + \rho(c_a^2 - 1) + \rho^2(4c_a^2 + c_s^2), & c_a^2 \geq 1 
\end{cases} \]

Note for M/M/1 model, the variance of delay time for each node is computed from

\[ Var(W_j) = \frac{\rho_j}{(1 - \rho_j)^2} \]

The variance of the delay time for the total network is simply the summation of the variance of the delay time of each node:

\[ Var(W) = \sum_{j=1}^{n} Var(W_j) \]

The reconfiguration window is assumed to be specified in \( m \) integer multiples of 15 minutes in the present research, with the statistics of external arrival rate specified in 15-minutes intervals. The objective is to find an optimal time for runway reconfiguration that minimizes the average delay time \( T_{w_{rcm}} \), defined as

\[ T_{w_{rcm}} = \frac{\sum_{j=1}^{k} T_{w,j} + \sum_{i=k+1}^{m} T_{s,j}}{m} \]

In Eq.(23), \( T_{w,j} \) is the mean of the delay time (system time minus the service time) for arrivals using a specified plan for the \( i^{th} \) window, occurring before runway reconfiguration, and \( T_{s,j} \) is the mean of the delay time using another plan for the \( i^{th} \) window, after runway reconfiguration. The index \( k \) that provides the minimum \( T_{w_{rcm}} \) over the \( m \) options of switch times is the optimal switch time.

\section*{III. Case Studies for the San Francisco Metroplex}

In this section, the developed runway reconfiguration methodology is applied at the San Francisco Metroplex, which includes San Francisco airport (SFO), Oakland International Airport (OAK), and Mineta San Jose International Airport (SJC). The arrival-departure routes in the KSFO Metroplex according to the West Plan configuration is shown in Figure 1 and the arrival-departure routes according to the South East Plan configuration is shown in Figure 2.

For the present study, only the arrival air traffic has been included in the network model. The radar track data on October 2, 2010 and on January 25, 2010 was used to generate the configuration information for the West Plan and the South East Plan. Ten arrival routes for the West Plan and 9 arrivals routes for the South East Plan configuration have been identified. These routes are shown in Figure 3 and Figure 4. Note these routes begin about 50 nautical miles from the center of the Metroplex. These routes were assembled by Q-Gen using the “Digital Terminal Procedures” data and radar track data. The Instrument Approach Procedures (IAP)\textsuperscript{17} and Standard Terminal Arrivals (STAR)\textsuperscript{18} provided guidelines to build these routes, whereas the radar tracking record on October 2, 2010, and the radar tracking record on January 25, 2010 were used to generate the final routes for the West Plan and the South East Plan respectively.

On October 2, 2010, San Francisco Metroplex used the West Plan configuration, for which SFO used Runways 28L and 28R for arrivals, OAK used Runway 29 for arrivals, and SJC used Runway 30R for arrivals. On January 25,
2010, San Francisco Metroplex used the South East plan configuration, for which SFO used Runways 19L and 19R for arrivals, OAK used Runway 11 for arrivals, and SJC used Runway 12R for arrivals. The Q-Gen software is used to partition the routes into servers, each of which are laid out at a distance of about 3 nautical miles, which is the FAA mandated separation standard in the terminal area.

For the West Plan, 10 arrival routes were included as shown in Figure 3, consisting of:
1) Route 0 PYE to RW28R(SFO)
2) Route 1 PYE to RW28L(SFO)
3) Route 2 ANJEE to RW28L(SFO)
4) Route 3 MOD to RW28R(SFO)
5) Route 4 KARNN to RW29(OAK)
6) Route 5 STIKM to RW29(OAK)
7) Route 6 WP-14 to RW28L(SFO)
8) Route 7 WP-21 to RW29(OAK)
9) Route 8 WP-22 to RW30R(SJC)
10) Route 9 WP-24 to RW30R(SJC)

For the South East Plan, 9 arrival routes were included as shown in Figure 4, consisting of:

1) Route 0 PYE to RW19L(SFO)
2) Route 1 MOD to RW19L(SFO)
3) Route 2 ANJEE to RW19R(SFO)
4) Route 3 WP-1 to RW19R(SFO)
5) Route 4 STIKM to RW11(OAK)
6) Route 5 WP-6 to RW11(OAK)
7) Route 6 KARNN to RW11(OAK)
8) Route 7 WP-17 to RW12R(SJC)
9) Route 8 WP-18 to RW12R(SJC)

Note that a corresponding matrix should be constructed that can map the arrival flows that are planned to fly into the West Plan to the entry flow that will fly into the South East Plan after the reconfiguration. For the current study, this matrix is built by assuming that the arrival traffic will not change the destination airport. For example, it is assumed that traffic along Route 3 in the West Plan (MOD to 28R) will fly into Route 1 of South East Plan (MOD to 19L). For Route 0 (PYE to 28R) and Route 1 (PYE to 28L) in the West Plan, both traffic will fly along Route 0 of South East Plan (PYE to 19L).

Figure 3 Queuing Network Model of the San Francisco Metroplex - West Plan
The arrival rates into the 10 routes at the San Francisco Area Metroplex on Oct. 2, 2012 from 9AM to 11AM are shown in Figure 5. The inter-arrival time are obtained from a Bayesian estimation approach based on the historical radar track data. Note that the arrival rate is the inverse of the inter-arrival time. The average transition time for each sever of the West Plan and the South East Plan are shown in Figure 6 and Figure 7, respectively. The minimum mean delay time for each reconfiguration times using both M/M/1 and QNA are given in Figure 8 and the standard deviation of the delay time for each reconfiguration time using both M/M/1 and QNA are shown in Figure 9, leading to the optimal switch time to be after 2 hours. Since the delays are decreasing with respect to the switch time, it is intuitively clear that the reconfiguration from the West Plan to the South Plan should be made as late as possible within the specified reconfiguration window.

A second situation illustrated in this paper is to determine the optimal switch time for the reconfiguration in the time window between 11AM to 12:30 PM. The mean and standard deviation of the delay time for each switch time computed using the QNA approach are shown in Figure 10 and Figure 11. Figure 10 shows that reconfiguration at 75 minutes results in the least mean arrival delays. However from minimizing the standard deviation in arrival delays, the optimal switch time should be near 90 minutes.

Figure 5. Arrival Rates into the San Francisco Area Metroplex (9 AM-11 AM)
delays, the optimal reconfiguration time should be as late in the given time window as possible. Since smaller standard deviations imply more predictable process, this example illustrates that a tradeoff may exist between these two factors. The decision maker can choose to relatively weight these two factors to create a risk-hedged runway reconfiguration decision.

![Figure 6 Average Transition Time of West Plan](image_url)

![Figure 7 Average Transition Time of South Plan](image_url)

![Figure 8 Mean Delay Time (Starting from 9 AM)](image_url)

![Figure 9 Delay Time Standard Deviations (Starting from 9 AM)](image_url)
IV. Case Studies for the Los Angeles Area Metroplex

In this section, the proposed flow control methodology is applied at the Los Angeles Metroplex, which includes Los Angeles International Airport (LAX), Bob Hope Airport (BUR), and John Wayne-Orange County Airport (SNA). Eleven routes of the West Plan are shown in Figure 12, consisting of:

1) Route 0, WP-29 to RW08 (BUR)
2) Route 1, WP-42 to WP-35 (SNA)
3) Route 2, WP-42 to RW08 (BUR)
4) Route 3, WP-43 to RW24R (LAX)
5) Route 4, WP-43 to RW25L (LAX)
6) Route 5, WP-39 to WP-35 (SNA)
7) Route 6, WP-42 to RW24R (LAX)
8) Route 7, WP-45 to RW25L (LAX)
9) Route 8, WP-46 to RW25L (LAX)
10) Route 9, WP-46 to RW24R (LAX)
11) Route 10, WP-42R to RW25L (LAX)

Eleven routes of East Plan are shown in Figure 13, consisting of:

1) Route 0, WP-2 to RW06R (LAX)
2) Route 1, WP-2 to RW07L (LAX)
3) Route 2, OCN to RW06R (LAX)
4) Route 3, OCN to RW07L (LAX)
5) Route 4, WP-5 to RW07L (LAX)
6) Route 5, WP-15 to WP-23 (SNA)
7) Route 6, WP-21 to RW06R (LAX)
8) Route 7, WP-21 to RW07L (LAX)
9) Route 8, WP-21 to RW08 (BUR)
10) Route 9, WP-21 to WP-23 (SNA)
11) Route 10, WP-22 to RW08 (BUR)
The arrival rates along the 11 routes into the Los Angeles Area Metroplex on January 2, 2010 from 9 AM to 11 AM are shown in Figure 14. The average transition time for each sever of the West Plan and the East Plan are shown in Figure 15 and Figure 16, respectively. The minimum mean delay time for each reconfiguration times using the QNA approach are given in Figure 17 and the standard deviation of the delay time for each switch time using the QNA approach are shown in Figure 18. Figure 17 shows that the optimal reconfiguration time should be as early in the time window as possible. In the present case, since the traffic aggregation time is 15 minutes, reconfiguration should be initiated at the first sample instance of 15 minutes.
Figure 14 Arrival Rates into the Los Angeles Area Metroplex (9AM-11AM)

Figure 15 Average Transition Time for the West Plan

Figure 16 Average Transition Time for the South Plan
V. Decision Support Software for Terminal Area and Surface Traffic Control

An integrated software package has been developed based on the algorithm reported in this paper. The overall software package consists of three main modules: Queuing network-Generator, QUEuing network parameter ESTimator (QUEST), and Decision Support System for SORM (DS3). Q-Gen module provides a GUI that accepts inputs from the user and displays the information related to real-time traffic display. The Q-Gen module also plays the role of a communication server through which QUEST and DS3 communicate with the user and relay information required to run each module. The overall architecture of the software package is illustrated in Figure 19.

The user builds the queuing network for the terminal area, together with the stochastic parameters using the traffic flow data. Next, the arrival rates along all the routes are used in conjunction with the specification of a reconfiguration time window are used to determine the optimal reconfiguration time. A sample GUI is given in Figure 20.
VI. Conclusions

This paper discussed the development of an algorithm for computing optimal runway reconfiguration time to minimize arrival delays in the terminal area. The approach employs a queuing network formulation of traffic flow to estimate the traffic delays. Stochastic parameters of the queuing network such as arrival rate distribution and service time distributions are derived from radar track data using a Bayesian estimation scheme. A one-dimensional minimization algorithm is used to determine the optimal reconfiguration time.

The proposed methodology was illustrated for both San Francisco metroplex, and the Los Angeles metroplex. It is shown that depending on the traffic flows, the methodology appears to choose physically plausible reconfiguration times.

The current runway reconfiguration methodology only considered the arrival traffic flows. Analysis of the methodology including the departure and surface traffic flows will be of future interest.

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References


