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Analysis of Air Transportation Network Delays Using Stochastic Modeling

Abstract

We model the air traffic of 10 airports (each w/1 gate) with a closed Jackson queuing network using various service rates at each node and various network designs. The modeling of an air traffic network using stochastic inputs is not commonly studied. The network assumes exponential service rates at each node. We expect to see higher service rates cause less congestion. We also expect that a well-connected network of airports will have less congestion than a network with only a few connections between nodes. Results, conclusions, and ideas for further research are presented.

Introduction

The study of airport network delays is not a new problem. Ample research has been conducted using models of various sorts to build the most efficient airports, aircrafts, and flight schedules. However, most of these models are deterministic in nature. They assume a 100% guaranteed probability of events in the model occurring. Few researchers have investigated a stochastic approach to solving this network problem, yet the events within an airport network model are largely probabilistic when studied closely. For instance, aircraft do not always take off on time, do not always fly the most direct route, and seldom know exactly how long they will taxi before takeoff. An airport network model based on stochastic inputs might provide more insightful results than the current literature.

Literature Review

Existing research in this area is either focused on the theory of closed Jackson networks or the deterministic analysis of air traffic delays. There is no available research focused on the utilization of Jackson networks in air traffic analysis to our knowledge.

Gross (2008) explains the mechanics of Jackson networks with in-depth calculations and examples mainly focused on reliability and telephone service. Both closed and open Jackson networks are analyzed in this text, but none is specifically focused on air transportation. Yao (1989) describes an optimization algorithm that chooses Jackson network parameters with the lowest cost, where cost is defined by the user. He utilizes a combination of deterministic and stochastic approaches to present optimal solutions to Jackson network problems. However, there is no focus on air transportation or the complexities of air travel.

The study of Jackson networks is typically focused on either open or closed networks. That is, either all customers stay within the network or customers enter and exit the network according to a defined process. Down (1997) presents a Jackson network that considers a mixture of the two earlier defined types. He evaluates the stability of such a network and concludes that calculations can be as

reliable as those developed for the open Jackson network. The idea of a mixed Jackson network has many applications in air transportation, but no research has been conducted in this area to date.

Couluris (2008) designed a model that takes a variety of inputs specifically catered to the air traffic industry and outputs several performance metrics and summary statistics regarding airport surface traffic. Though probabilistic inputs appear to be considered in the model, the solutions are based on multiple simulations and there is no utilization of Jackson network analysis. Closed-form solutions are not easily applicable in such a model. Levy (2009) presents a similar model focused on airport surface holding patterns. But again, the model is based on repetitive simulation and does not employ a simple, analytical solution base. Luong (2004) presents the use of Jackson networks in resource allocation models. The model is specifically focused on manpower allocation in engineering fields. Though this use of Jackson networks is new and innovative, it still does not explore their relation to air transportation and the complexities within.

Methodology

We apply our methodology to five airport networks with each node having one runway. We first present Figure 1 that shows the number of airports (5) and each airport ID.

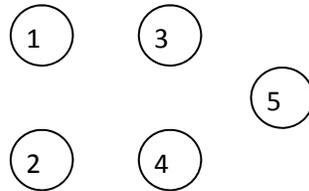


Figure 1: Airports and airport ID's

We then present the five different airport networks in Figure 2. The topologies were selected randomly, since there are infinite variations of air traffic networks in practice today. The airport networks contain the same five airport nodes as shown in Figure 1. The arrows portray the bi-directional ability of travel from one airport to another. Note the variations in the topography of each network.

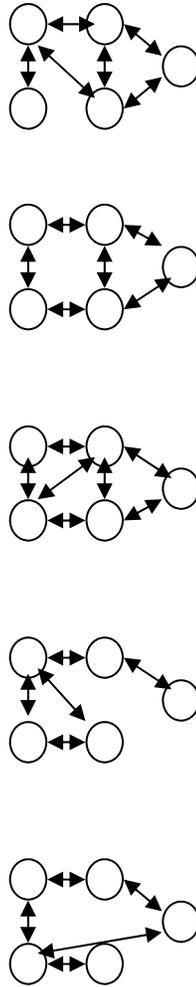


Figure 2: Five network topographies

The objective of the methodology is to determine the average wait times and queue lengths on each runway, given that there are 5 runways and 15 airplanes within the network. The only factor that varies between each network is the topology. The average service rate of each odd-numbered airport runway is 10/hr and the average service rate of each even-numbered airport runway is 20/hr. We assume that the service times are distributed exponentially. And we assume that the probability that a plane will fly from one airport to another given its allowable network topology is equally split among the available arcs. For instance, the first network topology has three outgoing arcs from airport #1. The probability of a plane headed for each of those three airports from airport #1 is 0.33.

The assumption of exponentially distributed service times allow us to solve for performance metrics utilizing the design of a closed Jackson network. We reserve the detailed equations for another paper. However, the reader should note that the Jackson network allows for the computation of analytical solutions that do not require simulation. This is a huge benefit to any analyst. If small enough, solutions to a Jackson network can be calculated by hand on the back of a notepad. Large networks can be solved with very few computational resources. Unfortunately, the Jackson networks require the

assumption of exponential service times that are not usually realistic. Research is being conducted to utilize the benefit of this assumption in contexts that do not have exponential service times.

We use an Excel-based software program called QTSPPlus (Gross, Shortle, 2008) to solve for the performance metrics of average queue length and average wait time. The software exploits the assumptions and benefits of the Jackson network to calculate results.

Results

We calculated four performance metrics at each airport node for each network topology. These metrics were the average arrival rate per airport, the average utilization of each airport, the average number of planes at the airport, and the average time each plane spent at each airport. See the graphs in Figure 3.

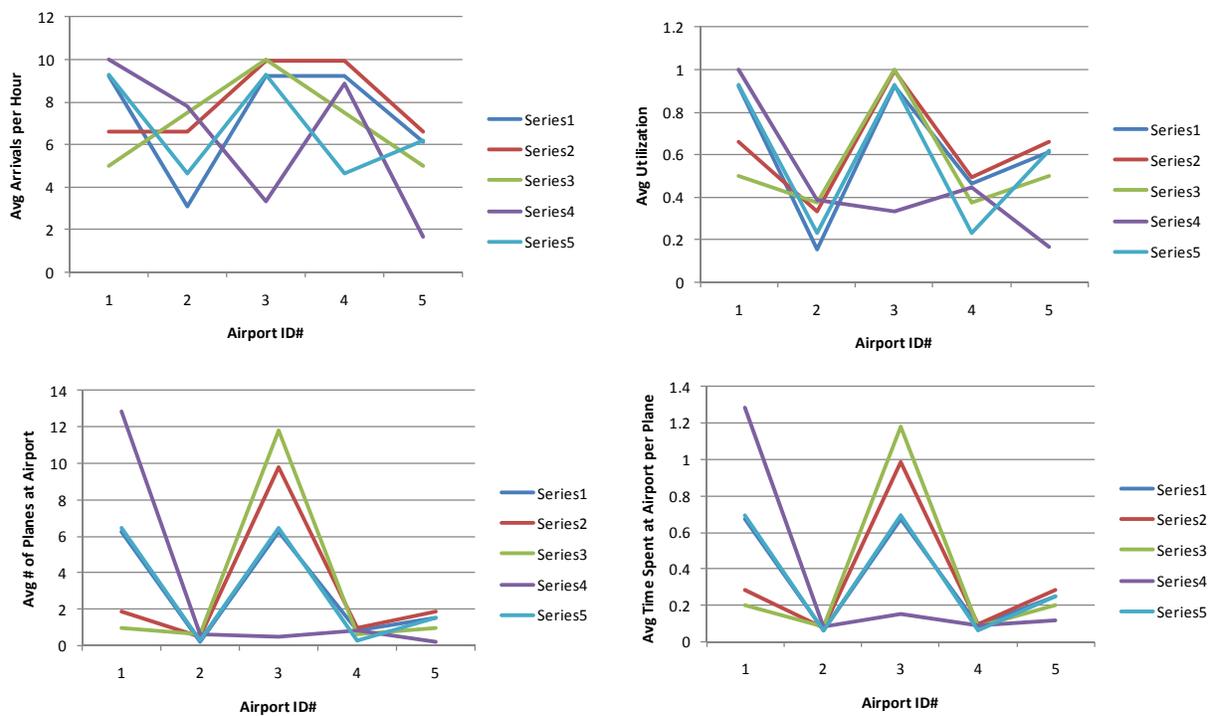


Figure 3: Performance metrics at each airport node

The results portray some definite patterns. Nodes 1, 3, and 4 all have the highest arrival rate. Nodes 1, 3, and 5 are utilized the heaviest. Nodes 1 and 3 have the most number of planes at the airport and the highest time spent at the airport per plane. A natural extension of these conclusions is that node 3 is the “busiest” airport. Looking back at the five topologies, we note that node 3 is always in the center of the network and always has 2-3 bidirectional arcs connected to it. Node 1 is relatively “busy” as well. Nodes 1 and 3 are both along critical paths that relay transit from node 5 and node 2 in almost every scenario. This means that most planes must transit through node 1 or node 3 to get to node 2 from node 5.

On the contrary, nodes 2, 4, and 5 do not appear congested and also aren't utilized very much. Looking back at the topologies once again, we note that these nodes generally have the least number of arcs connected to them and do not usually fall on critical paths. We should also note that nodes 1,3, and 5 have a much slower service rate than nodes 2 and 4. That could be the predominant reason for the evident congestion or lack thereof.

Conclusions

Though this basic analysis did not produce any groundbreaking results, it did introduce and validate the use of Jackson networks in air transportation systems. If the assumption of exponential service times can be accepted, this simple, analytical approach to congestion studies can provide thorough results easily. None of the results in this analysis appeared far-fetched or outlandish. The analysis was conducted in a basic spreadsheet program in less than one hour. And the results provided enough insight for an air traffic network engineer to make changes or improvements to the flight network.

However, the analysis is far from perfect. First, improvements should be made to the network topologies to represent more common air traffic networks, including the hub and spoke as well as more common peer-to-peer designs. More nodes should be added to further validate the use of Jackson network assumptions in real-world analysis. There exists research that attempts to relieve Jackson network analysis of the exponential service time assumption. Such models should also be used in the air traffic analysis to see if there are any inherent advantages in one over the other. The closed form results of this analysis should be compared to simulated results. Also, the analysis assumes that all nodes are equidistant from each other, an assumption that is far from realistic. Further research can be dedicated to adapting this model to include assumptions that are more realistic. Additional nodes can be added to consider aircraft maintenance, hi-jacking, and even unintended stops. The ability to expand this research is virtually endless.

References

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