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Impact of service network topology on air transportation efficiency

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ABSTRACT

Each stakeholder in the air transportation system has a different perspective on the performance efficiency metrics, making analysis of system-wide design options very difficult. This paper uses topological structures of service networks to examine trade-offs between efficiency metrics established around the passenger, airline, and air navigation service provider perspectives. The findings indicate that the scale-free type topologies are preferred under most of the metrics. However, with enough density, random topologies become more appealing with its high robustness feature and performance comparable to scale-free.

1. Introduction

Modifying the national (and international) Air Transportation System (ATS) to meet future travel demand with greater efficiency is complicated by the myriad of stakeholder interests, including increased emphasis on noise and emissions reductions. Improving individual aircraft efficiencies and air traffic management (ATM) practices have been common approaches to satisfy increasing travel demand while reducing environmental impacts. While these efforts are important and appropriate, they may not be sufficient to satisfy the increasing air travel demand under constraints such as noise and emission restrictions. Other fundamental factors such as the Airline Service Route (ASR) network topology (network of airports interconnected by airline service), airline fleet mix and resource allocation (e.g., aircraft assignment on service routes) also have a profound impact on the system-wide performance of air transportation. However, these factors are often wide in scope and coupled in non-intuitive forms, making analysis as well as subsequent trade-off decisions extremely difficult.

The diversity in ATS stakeholder objective functions is also preventing formulation of an "ideal" ATS vision, exacerbating the challenges in its modification efforts (DeLaurentis, 2005). For the ATS to function, many components systems and resources must coordinate in unison. Aircraft, airports, command centers, and travel demand are all examples of ATS components. The authority to control these components is distributed among several stakeholders, such as passengers, airlines and regulators (federal/local government agencies) and the objective function between them may be mutual, competing or opposing (Manley and Sherry, 2009). For example, airlines provide transportation service between airports, and emphasize its economical effectiveness when deciding which airport pairs to connect. Besides economical effectiveness, passengers may also value travel time, number of connections or reliability when determining their demand, which may not coincide with what the airlines prefer. If there is a large mismatch between the passenger and airline preference in airport connectivity, the passenger can simply choose not to travel, or use a different airline. Since the airlines are primarily driven by profit supplied

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by passenger demand, the passenger utility will have a profound impact on the ASR network formulated by the airlines. Further, the passenger and airline preference in airport connectivity may also conflict with noise, emissions or capacity restrictions posed by interest of regulators like the Federal Aviation Administration.

The research objective of this paper is to quantify the trade-offs between stakeholder utilities and provide bounds on achievable ATS performance. This research does not aim to provide the ideal ATS configuration, but rather present policy makers with expected compromises (or cost) that will be required for the ATS to achieve a certain performance. The technical content of this paper describes a heuristic approach to analyze the trade-offs between several stakeholder-centered metrics in the ATS by employing the ASR network topology as a control variable. First, multiple ASR networks with incremental variation in topology characteristics are constructed by linking different airport pairs. Performance metrics based on the passenger, airline, and regulator perspectives then assess the ASR networks. The assessment results map the correlation between ASR network topology traits and performance metrics, but also reveal the trade-offs between the various performance metrics.

The remainder of the paper is organized as follows. Section 2provides a background on recent system-wide analysis efforts and network theory application on air transportation related research. Description on stakeholder centered ATS performance metrics and the network formulation algorithms form Section 3, followed by the corresponding trade-off study in Section 4. Section 5 summarizes the main conclusions of this study.

2. Background

This section reviews recent system-wide analysis efforts related to the ATS. Discussion also centers on the background and recent advancements in the network theory approach on ATS related analyses. The significant difference between previous research and those conducted by the authors of this paper lies in utilizing the Airline Service Route (ASR) network topology as the primary control variable to measure the trade-offs between stakeholder-centered performance metrics in the ATS.

2.1. Network theory background

Research established in the network theory community provided the basis for many of the modeling and analysis techniques discussed in this paper. Network theory is a study originating from graph theory investigating the structure and topology of networks with application in many domains including physics, mathematics, computer science, informatics, operations research sociology and biology. This field of study is especially useful for analyzing the complex structure of interactions and relationships that exist between components comprising the system of interest. For example, centrality measures like eigenvector centrality can quantify the relative importance of nodes and links within a network (Newman, 2004). Dependency analysis between the nodes can calculate the spreading process (e.g., social influence, disease, information) or cascading failures.

The random network model—studied extensively by Erdös and Rényi (1959)—has long been the classic and widely employed standard model used in network theory applications. In random networks, most nodes have the same number of links (termed degree), and the distribution of degree across all nodes follows a binominal distribution. However, this model has failed to predict topologies observed in many real networked systems, as documented in a wide array of application domains (Newman, 2003). Albert and Barabási (2002) recently developed the scale-free network model, an alternate to the random network model characterized by its power law degree distribution. Scale-free networks are similar to the airline hub-and-spoke service networks where few nodes with high degree (number of links) maintain much of the connectivity throughout the network. Using the scale-free model, Albert and Barabási were able to predict the evolution of real-world networks such as the Internet (network of routers) and World Wide Web (network of web sites). However, some more recent studies have opposed this view. For example, Doyle et al. (2005) concluded that the Internet is not constructed off the scale-free logic but instead through some global optimization principle, when considered with actual technological and economic considerations in addition to topology. Such opposed findings are, perhaps, a positive sign of the early development of the field.

2.2. ATS system-wide analysis

Classical ATS analysis research focused primarily on how the performance of individual system components (e.g. aircraft) influences ATS efficiency. For example, Babikian et al. (2002) employed energy usage and specific energy intensity—essentially aircraft-centric measures—as the performance metrics for analyzing the current and historical ATS. By using energy as part of the metric, the authors investigated the correlation between individual aircraft design parameters and transportation efficiency of the overall ATS. While it is important to assess and improve the technological aspect of individual ATS components, many other large scale, "system-wide" factors and issues also determine ATS performance. System-wide factors are large in scope, crossing over multiple domains and timescales. These factors include (but not limited to): ASR network topology, economic policy, airline fleet mixture and scheduling, distribution of new technology or infrastructure improvements, and the associated concepts of operations (DeLaurentis et al., 2008). For example, instead of individual aircraft metrics, Calderón-Meza et al. (2009) used fleet-level metrics to examine how changes in fleet operations affect ATS performance.