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Comparison of alternative route selection strategies based on simulation optimization

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Abstract Air traffic flow management (ATFM) is a collaborative process between the airspace provider and the airspace users. The result of the collaboration should be an outcome that maximizes the utility of the system without excessively penalizing any of the agents. This paper develops a discrete-event simulation model which consists of aggregate departure/arrival airports, flight routes, and sectors for evaluating the alternative collaborative route selection strategy. Given the different perspectives from air traffic control center (ACC) and airlines, eight performance-metrics and five alternative route selection strategies represent the past, current and proposed air traffic flow management operations that were evaluated. The Monte Carlo method combined with the Optimal Computing Budget Allocation (OCBA) simulation optimization technique is employed to assess the performance of different strategies. A case study of the upper air routes in central and southern China shows that the proposed model can be readily implemented to simulate different kinds of air traffic flow management strategies and predict the effect of changes on the airspace system. It also shows that the proposed alternative collaborative route selection strategy is an effective way in alleviating the en-route traffic congestion.

1. Introduction

With the rapid development of civil aviation in China, the air traffic congestion problem has created an urgent need for upgrading the air traffic flow management mode. According to the Chinese civil aviation developed statistical bulletin,[1] the on-time performance rate for flights declined to 69.09% in 2014. The Chinese air transportation system is heading toward a severe crisis and will face many challenges. In order to alleviate the stress of air traffic operation, civil aviation administration of China (CAAC) started the project known

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as the collaborative decision making-air traffic flow management (CDM-ATFM) system, and completed the construction of the first phase in 2014. Currently, the primary collaborative departure management system has been set up to balance the demand and capacity in airports by regional traffic management centers (RTMC). However, RTMC and airlines do not have any shared impact assessment tools, but the responsibility for solving major air traffic congestion still falls upon the RTMC. Thus, improving the decision making process and alleviating the flight delay problem have become research focus in China.

Many scholars have conducted extensive research on the subject of ATFM for decades, and these works can be divided into two major types: (1) optimization; and (2) simulation.

Optimization is generally designed to model the air traffic system by means of mathematical formulations or expressions. Most of the research takes a centralized perspective, attempting to develop integral programming models.[2–5] Bertsimas and Patterson[6,7] proposed an integer programming model that covers all the phases of each flight with a broad range of ATFM intervention options including ground and airborne delay, speed control, and rerouting. Kotnyek and Richetta[8] proposed two static-stochastic models for the ground holding problem (GHP) that exercise control on groups of flights instead of individual flights under the CDM paradigm. Lulli and Odoni[9] presented a deterministic model which designs flow management strategies involving combinations of ground and airborne holding. Agustin et al.[10,11] presented a framework for modeling multistage mixed 0–1 problems for ATFM with rerouting. They also considered several types of objective functions and allowed for flight cancelation and rerouting. Sherali et al.[12] proposed a model that selects among alternative flight plans for the affected flights while integrating a slot exchange mechanism. One limitation of these works is that only one objective function can be employed by each model, such as the total system delay time or delay cost. If more goals are considered, the issue will become the multi-objective optimization which is an intractable problem. Moreover, the shortcomings of an optimization model which lacks feedback and dynamics make it difficult to accurately reflect the interactive procedure between Air Traffic Control Centers (ACCs) and airlines.

Simulation is designed to imitate the operation of air transportation system over time, and to clarify what would happen in a given situation. Most of the research is presented by considering an approach or algorithm based on some sophisticated simulation system. Campell et al.[13] modeled the information sharing and collaboration in weather-induced schedule disruptions by the intelligent agent-based model for policy analysis of collaborative traffic flow management (IMPACT). Wanke et al.[14] studied the probabilistic airspace congestion management method based on the demand prediction function of Enhanced Traffic Management System (ETMS). Wolfe et al.[15] developed a collaborative traffic flow management simulation model with Bramhs to study the route assignment procedure. Ramamoorthy et al.[16] proposed a trajectory-based probabilistic traffic flow management approach by the Probabilistic NAS Platform (PNP) which is a real-time probabilistic traffic flow management evaluation system. Tumer and Agogino[17,18] tested a multi-agent algorithm for traffic flow management by future air traffic control concepts evaluation tool (FACET) which is a simulation and analysis tool for exploration, development and evaluation of advanced air traffic management concepts. Calderon-Meza and Sherry[19] studied the effects on the NAS of adaptable route selection behavior of airlines based on current and historical performance information by FACET. These works are mainly based on a maturity simulation system lacking extensible interfaces. It is too difficult to combine new strategies with required metrics. Also the computational cost that accompanies the nation-wide simulation is expensive and often unacceptable. Hence, a simpler and efficient model with an intermediate level of stochastic features would be preferred for studying the ATFM problem.

Thus, the objective of this paper was to develop a discrete-event simulation model for evaluating the alternative collaborative route selection strategy. The simulation model with the outcomes of collaborative strategy could provide the ACCs and airlines with suggestions in advance to aid in ATFM decision-making. The rest of the paper is organized as follows: Section 2 introduces the construction of airspace system model with stochastic capacity and uncertain demand. A collaborative route selection strategy with other four practical route strategies is also defined in this section for comparison. In addition, 8 performance metrics and a flight delay model are presented to help airlines make route selection decisions for themselves. In Section 3, OCBA is combined with our simulation optimization to dramatically improve the efficiency of Monte Carlo simulation. In Section 4, a special case in Central and Southern China is considered as an example for strategy comparison and analysis. The discrete-event model is developed in Arena software, and the OCBA algorithm is written in the C++ programming language. Finally, Section 5 summarizes our main findings and discusses several directions for future work.

2. Model and route selection strategies

2.1. Airspace modeling

Our airspace network model consists of two aggregate departure/arrival airports, flight routes and sectors. The aggregate airports are equivalent to the “virtual” airports and act as source and destination nodes in the airspace network model. The directional aircraft flow will transit from the aggregate departure airports to the aggregate arrival airports along flight routes passing through several sectors. In the real world, the aggregate airports are described as different airports that are not necessarily collocated but include some flights scheduled to travel though a common route segment. The combination of en-route sectors represents a route segment in which a flight may pass through according to the schedule. Also, each en-route sector is modeled as a multi-server queue, and the server’s number represents the capacity limitation of each sector which is defined as the number of aircraft that can fly in the sector simultaneously in accordance with the current air traffic control rules (CCAR-93TM-R4, air traffic control rules).[20] Thus, different sectors should have different transit times with some stochastic deviation. In order to include the pre-departure uncertainty, en-route traversal time uncertainty, and en-route capacity uncertainty, a method that combines capacity uncertainty with demand uncertainty is presented and applied to construct the airspace model.