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博士論文

AIRLINE NETWORK DESIGN IN RESPONSE TO PASSENGER DEMAND FLUCTUATIONS, COMPETITIVE DEMAND-SUPPLY INTERACTIONS AND INTERNATIONAL AIRLINE ALLIANCES

因應需求變動、競爭性供需互動與國際航空公司聯盟
之航空網路設計研究

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Airline Network Design in Response to Passenger Demand Fluctuations, Competitive Demand-Supply Interactions and International Airline Alliances

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Abstract

One of the most important problems airlines encounter is the design of their air service networks. The extreme complexity of designing an airline network is due largely to the need for transportation facilities to meet passenger demands efficiently. Analyses on passenger demand patterns, passenger choice behavior and airline market shares are of priority concern in the planning and design of an airline network. In previous studies of airline network design, passenger demand pattern is assumed to be exogenous, and demand is assumed to be inelastic. In such airline network design studies, the reliability and performance results of network designs, apart from short-term demand fluctuations, are generally not evaluated. The uncertainties with regard to competitive interactions are rarely considered in previous game-theory-based models of airline competition and network design studies. Moreover, few studies have been devoted to constructing network models for studying the airline alliances.

This dissertation is composed of five research subjects in airline network design problems, including multiobjective programming with grey numbers towards airline network design, reliability evaluation for airline network design in response to passenger demand fluctuations, determining flight frequencies on an airline network with demand-supply interactions and competitive interactions in competitive environments, and airline network design for international airline code-share alliances.

This study first developed a multiobjective programming with grey-number-based demand inputs for designing an airline network aimed at minimizing both the airline operating costs and the passenger travel costs. Next, this study developed a reliability evaluation model based on chance-constrained stochastic programming and provided a fine-tuning process of flight frequencies to tackle the short-term demand fluctuations for designing an airline network. Furthermore, this study integrated airline network design and market share analysis into one model, aims to analyze the impact of flight frequency/airfare options on passenger choices and airline market shares, and to incorporate demand-supply interaction into network design models. A fuzzy-logic-based competitive interaction model was further developed to describe the uncertain competitive interactions and evaluate the equilibrium of airline competition. Finally, this study combined the airline network design model and market share model with the interactive multiobjective programming techniques to design both the integrated alliance-based network and alliance partner airlines' networks and analyze the impact of the code-share alliance network on market demand, airline profit, and passenger level of service.

The results of case studies verify that the models are practical and demonstrate that how multiobjective programming, reliability evaluation, competitive demand-supply interactions and alliance interactions might be considered in designing airline networks. The models proposed in this dissertation provide highly effective tools that enable planners to assess the impact of changes in passenger demands and competitive environments on network design performance by taking demand variability, competitive demand-supply interactions and airline alliance interactions into account. Results in each part of the study shed further light into operational planning, performance-related issues, airline competition and alliance issues in airline network design.

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CHAPTER 1

Introduction

There are five research subjects in this dissertation. They are multiobjective programming with grey numbers towards airline network design, reliability evaluation for airline network design in response to passenger demand fluctuations, determining flight frequencies on an airline network with demand-supply interactions and in response to competitive interactions, and airline network design for international airline code-share alliances. This chapter gives an overview of the motivation, problem statement, research objectives and approaches, and depicts the framework of this dissertation.

1.1 Motivation and problem statement

One of the most important problems airlines encounter is the design of their air service networks. The airline network design problem in this study is defined as follows: Given the capacities and operating costs of various types of aircraft, design an airline network and determine flight frequencies that satisfy demands and minimize total transportation costs or maximize total airline profits (Teodorovic et al., 1994; Jaillet et al., 1996; Hsu and Wen, 2000, 2002). Airline network design is heavily emphasized since these decisions affect the cost to airlines of providing flight services and the quality of services provided by them to passengers. Since passengers usually choose airlines on the basis of their service quality and airfares, these decisions further affect airlines' passenger demand and revenues. Moreover, the revenues generated as well as the passenger demand for any airline's flight services depend not only on its own but those of all other airlines' network designs and airfares in the same markets. Clearly, a profit-maximizing airline must consider the trade-off between the cost of providing service and the revenue generated when choosing its network design and airfares (Lederer, 1993).

The extreme complexity of designing an airline network is due largely to the need for transportation facilities to meet passenger demands efficiently (Teodorovic and Krcmar-Nozic, 1989; Hsu and Wen, 2000). Accurately estimating the passenger demand is of priority concern in the planning and design of an airline network. Analyses on passenger demand patterns, passenger choice behavior and airline market shares allow the planners to assess the impact of various strategic and operational options on the markets, and to estimate the profits associated with airline network planning. Moreover, airline alliances have made it possible for the airline industry to provide better quality, lower price, and more competitive service for passengers thereby inducing faster growth in passenger demands. Therefore, how to design an adaptive network in response to fluctuations in passenger demands and changes in airline industry structure under uncertain competitive environments becomes very important for airlines to enhance their performance and remain competitive.

The extent to which the economic cycle influences air transportation demand is quite apparent. For instance, an economic recession obviously impacts air traffic and, under such a circumstance, the airline industry more slowly recovers than other manufacturing or service industries. However, though the influence socioeconomic factors exert on air transportation demand is apparent, its extent is not yet certain enough to estimate. Moreover, passenger traffic between an origin-destination (OD) pair during a specific period fluctuates from time to time; the fluctuations are noted to be seasonal, monthly, weekly, or even daily. Season/off-season fluctuations occur and unexpected abnormal fluctuations influence future air passenger traffic.

There is a strong interaction between passenger demand and airline network design. On the demand-side, passengers concern themselves primarily with areas that influence their choices among different flights offered by different airlines such as route airfares, flight frequencies, nonstop flights, travel and layover times, and airlines' reputations and frequent-flyer programs. On the supply-side, airlines strive to generate the highest possible total profits, obtain higher load factors and gain the greatest possible market shares (Teodorovic and Krcmar-Nozic, 1989; Teodorovic et al., 1994). Airlines may use high flight frequencies or nonstop flights to attract passenger demand, but excess frequencies or nonstop flights may entail diseconomies of scale. Conversely, airlines may consolidate passenger flows from several city-pair routes, combining these individual routes into hub-and-spoke networks, and use larger aircraft and fewer nonstop flights. In doing so, the airlines may realize economies of flow concentration and perhaps achieve lower operating costs, thereby lowering average standard airfares and attracting more price-elastic passengers. However, these strategies may also raise passenger schedule delays and lose some time-sensitive passengers.

The interactions between passenger demand and airline network supply are of such significance as to necessitate using a system analysis approach to airline network design problems. Moreover, designing an airline network and determining the flight frequencies are more complex when there are several competing airlines making network and pricing decisions in the same OD market. Therefore, in a competitive environment, one airline must consider what its competitors' decisions are likely to be when determining flight frequencies and basic airfares on its own network (Dobson and Lederer, 1993).

Airline network design is fundamental to an airline's short-run operational planning such as flight scheduling, routing and pricing, since the proposed flight frequencies and basic airfares in the airline planning phase are usually used as bases for future operational planning. However, airline flight scheduling and routing policies usually continue and repeat daily over long periods (one or two seasons) to simplify flight operations and enhance customer familiarity. Furthermore, the output of operational planning represents one of the primary products of an airline and is certainly among the leading factors affecting a passenger's choice of a particular airline (Wells, 1993). Since flight frequencies and basic airfares proposed in the airline planning stage are bases for operational planning in later stages, a flexible flight frequency plan that can better respond to future passenger demand fluctuations and anticipated demand-supply interactions in competitive environments would be more appropriate for operational planning.

Previous studies focused mainly on airline network modeling and hub-location problems for hub-and-spoke airline networks (e.g., O'Kelly, 1986, 1987; Campbell, 1994, 1996; Aykin, 1995a; Jaillet et al., 1996). The models proposed in these studies concerned location-allocation *p*-hub median problems. Other studies on network models for air transportation have addressed the fleet assignment problem (e.g., Abara, 1989; Subramanian et al., 1994; Larke et al., 1996; Barnhart et al., 1998) and crew scheduling problem (e.g., Etschmaier and Mathaisal, 1985; Hoffman and Padberg, 1993; Stojovic et al., 1998). Most of this research developed deterministic programming models and addressed model improvements and algorithms to solve airline fleet assignment and crew scheduling problems.

Pertinent literature on airline network focuses mainly on airline network shape, flight frequency determination and aircraft choice (e.g., Swan, 1979; Teodorovic, 1983, 1986; Teodorovic and Krcmar-Nozic, 1989; Teodorovic et al., 1994). The authors considered flight frequency programming problems involving single airline networks from long-term perspectives and constructed problems using mathematical programming. However, the performance results of network designs, apart from passenger demand fluctuations, were generally not evaluated. In the published literature, passenger demand pattern is assumed to be exogenous, and demand is assumed to be inelastic, though passenger demand may be elastic to flight frequencies in a competitive environment.

Others have addressed airline competition in terms of game-theory-based approaches (Hansen, 1990; Hansen and Kanafani, 1990; Dobson and Lederer, 1993; Pels et al., 2000; Adler, 2001). Previous game-theory-based studies modeled interactions between competitors' decision-making processes while refining the definition of the game's airline players, introducing a set of restrictions on the set of actions available to them, and defining a simplified model of the payoff functions based on the restricted strategy set (e.g., Hansen, 1990; Hansen and Kanafani, 1990). In a competitive environment, the flight frequencies and airfares competing airlines offer in an OD-pair market are based on decisions that reflect their optimal strategies regarding not only the OD-pair market but their overall markets. Hence, when designing an airline network for a competitive environment, there are uncertainties resulting from lack of information with regard to competitors' strategies and behaviors. Nevertheless, the uncertainties were rarely considered in those game-theory-based models of airline competition and network design studies.

Airline alliances have changed the structure of the airline industry in the recent decade. A recent trend in international aviation markets is the emergence of airline alliance. Major air carriers have increasingly entered international alliances with foreign carriers as a means of extending the boundary of their networks and entering new markets so as to attract more passengers in an increasing competitive environment. One of the major benefits of international airline alliances for passengers is that the potential air service that alliances offer can facilitate them to travel between an expanded range of origin and destination points around the world while earning all miles for award. International alliances also allow airlines involved (i.e., alliance partners) to expand the reach of their networks and services to many parts of the world where it may not be economical to do so on their own or where there may be a lack authority to operate their own flights (Park, 1997; Park and Zhang, 1998; Park et al., 2001). According to the U.S. Department of Transportation (USDOT, 2000), alliance-based networks are the principal driving force behind price reductions and traffic gains, while the alliance network effect plays a key role in the evolving international aviation environment.

The alliances may provide opportunities for partner airlines to reduce cost by

The complementary alliance refers to a situation where two airlines link up their existing partial networks and build a new complementary network to feed traffic to each other. The parallel alliance refers to collaboration between two airlines competing, prior to their alliance, on the same routes of their networks.

In implementing an international airline code-share alliance, partner airlines tend to feed domestic traffic onto their alliance routes, while they may also re-route domestic flights through their alliance routes (Park and Zhang, 1998; Park et al., 2001). However, they may not always achieve the optimization on both individual and integrated networks, when they individually determine their airline networks under an international airline code-share alliance. Therefore, in the process of forming an alliance, airlines involved may seek a compromise between the alliance network optimization on an integrated basis and the airline network optimizations on individual bases.

However, few studies have been devoted to constructing network models for studying the airline alliances. Theoretical studies of airline alliances focused on analyzing the economic effects of alliances (Park, 1997; Park and Zhang, 1998; Brueckner, 2001; Park et al., 2001). Most studies of airline alliances had devoted effort to empirically investigating the effects of alliances (e.g., Youssef and Hansen, 1994; Hannegan and Mulvey, 1995; Oum et al., 1996; Zhang and Aldridge, 1997; Park and Zhang, 2000; Brueckner and Whalen, 2000). Moreover, most international airline routes have a few competitors. Thus, a code-share alliance between any two competing airlines on an international route may adversely affect the degree of competitions on the route. However, in forming an international airline alliance and designing alliance airlines' networks, the alliance partners might take competitive conditions they encounter into account. This study attempts to analyze international airline alliance while emphasizing on network design issues.

In sum, several important problems deserve further investigation while they are rarely theoretically formulated in airline network design literature. These include planning an airline network by considering the trade-off between satisfying the concerns of the airlines and those of the passengers, airline network design in response to passenger demand fluctuations, demand-supply interactions and competitive interactions in determining flight frequencies on an airline network under competitive conditions, and airline network design for international code-share alliances. This dissertation attempts to develop a series of models for dealing with these airline network design problems.

1.2 Research objectives

The purpose of this dissertation is to present a series of models, which plan an airline network by considering fluctuations in passenger demand and competitive demand-supply interactions, and design alliance-based networks proactively in the airline network planning stage. This dissertation is composed of five parts: multiobjective programming with grey numbers towards airline network design, reliability evaluation for airline network design in response to passenger demand fluctuations, determining flight frequencies on an airline network with demand-supply interactions and in response to competitive interactions, and airline network design for international airline code-share alliances.

In the first two parts of the dissertation, this study first incorporates fluctuations in passenger demand into designing an airline network. To tackle fluctuations in demand input in airline network programming models, the study uses random variables and grey numbers to account for the randomness of demand. In the first part of the study, a multiobjective programming with grey-number-based demand inputs is developed for designing an airline network aimed at minimizing both the airline operating costs and the passenger travel costs. In the second part of the study, a reliability evaluation approach based on a chance-constrained formulation is devised for assessing how well the results of an airline network design will work under future potential short-run normal/abnormal demand fluctuations; and then propose a fine-tuning method for redesigning the network in response to short-run demand fluctuations.

The third part of the study aims to develop a demand-supply interaction model for designing an airline network by explicitly taking into account demand-supply interactions between passenger demand and airline network design under competitive conditions. In this part of the study, a market share model based on passenger airline-flight choices is utilized to estimate airline market shares. The fourth part of the study further incorporates competing airlines' decisions and competitive interactions into determining flight frequencies on an airline network. This part of the study combines a fuzzy-logic-based competitive interaction model with the above demand-supply interaction approach, and aims to determine flight frequencies on an object airline's network by considering competitive interactions in the OD markets well in advance.

Furthermore, in the fifth part of the study, this study combines the market share model, the airline network design programming and the interactive multiobjective programming into one model to analyze international airline alliance while emphasizing on network design issues. In sum, the following research objectives are addressed in this study:

(i) Develop a multiobjective programming model with grey-number-based traffic inputs towards designing an airline network aimed at minimizing airline operating costs and passenger travel costs with various demand forecasts.

(ii) Establish a *post-design* reliability evaluation and an adjustment process to assess how well the results of an airline network design will work under future potential traffic fluctuations, and to fine-tune the flight frequencies on routes in response to short-run demand fluctuations.

(iii) Develop a systematic approach to analyze the demand-supply interactions in the airline network design by integrating a passenger choice submodel, an airline network design submodel, and a demand-supply interaction submodel; and then use an algorithm to solve the interaction problem.

(iv) Develop a systematic approach with fuzzy-logic-based competitive interaction to determine airline networks by taking into account competitors' decisions and competitive interactions in individual OD markets well in advance.

(v) Develop a network design procedure using interactive multiobjective programming techniques to design an optimal integrated alliance-based network and two alliance partner airlines' networks by considering bargaining interactions between two partner-airlines.

(vi) Apply the proposed models in case studies to confirm their accuracy and capability to provide high flexibility in decision-making for airlines to design their networks in competitive and uncertain environments.

1.3 Study approach

In the first part of the study, this study first applies grey models to forecast passenger traffic inputs. The passenger traffic is further regarded as a grey number with upper and lower limits, to capture the extents of variations in passenger traffic evolution trends. Then, these forecasted, grey-number-based, passenger traffics between all OD pairs are used as input parameters for multiobjective programming models towards determining flight frequencies on an airline network. The multiobjective programming method is applied for determining flight frequencies on an airline network by minimizing both airline operating costs and passenger travel costs. Furthermore, a Pareto-optimality method is applied herein for solving the mutiobjective programming problem. Instead of a complete optimal solution, the Pareto optimality is available to multiobjective programming. The Pareto optimality is the solution where no objective can be reached without simultaneously worsening at least one of the remaining objectives (Cohon, 1978). This study applies the e-constraint method and compromise programming method to solve the Pareto optimal solutions for this multiobjective programming problem. The compromise solution is a Pareto optimal solution which has the shortest geometrical distance from the ideal point (Yu and Lietmann, 1974). The trade-off rates between objective functions are also calculated. In this manner, a variety of frequency plans with different levels of demand forecasts for routes can be generated from Pareto optimal solutions.

If the short-term passenger traffics between OD pairs are considered to be random parameters in airline network design programming, then the random parameters may turn the programming problem into a stochastic programming problem. Chance-constrained (probabilistic constrained) stochastic programming provides a means of considering the constraints with random parameters (Charnes and Cooper, 1959). The programming model is well-known and involves fixing certain reliability levels for random constraints. The second part of the study further devises a reliability evaluation approach based on a chance-constrained formulation to tackle stochastic characteristics of the input parameter in airline network design programming. This study presents a two-stage process to tackle the randomness of traffic input data for designing an airline network in the airline network-planning phase. Deterministic airline network program is first used to determine average weekly/monthly route flight frequencies, and then the reliability of the proposed flight frequencies is evaluated under fluctuating monthly OD demand, using the chance-constrained formulation. The reliability evaluation method is then devised for assessing how well the results of an airline network design will work under future potential short-run normal/abnormal traffic fluctuations; and then propose a fine-tuning method for redesigning the network in response to short-run demand fluctuations. Instead of reconstructing the whole network, this dynamic adjustment procedure merely refines flight frequencies for some local routes/OD-pairs sustaining severe fluctuations while maintaining overall global network design objectives.

In the third part of the dissertation, this study integrates airline network design and market share analysis into one model, and aims to analyze the impact of flight frequency/airfare options on passenger choices and airline market shares, and to incorporate demand-supply interaction into network design. Previous studies have focused on competitive airline network modeling and scheduling in a hub-and-spoke system with exogenous OD demand (Dobson and Lederer, 1993; Adler, 2001); while they constructed demand models as logit-based functions of frequency, service quality, and route prices. In contrast to those logit-based models, this study develops an analytical passenger airline-flight choice model for estimating airline-route market shares from long-term perspectives. And, OD market demands are made endogenous as functions of socioeconomic variables and flight frequencies, while the OD demand functions are formulated by using grey systematic forecasting. Passengers' airline-flight choices are assumed to depend on perceived line-haul travel time costs, schedule delay costs, and airfares on various airlines' route flights. The model treats different individuals' values of time as random variables. The model also takes the long-term customer benefits of frequent-flyer membership on individual passengers' choice into account. The model aggregates individual passengers' airline-flight choices to estimate the market shares for the object airline's routes by integrating the joint probability density functions of the value of time and frequent-flyer-membership valuation. This part of the study has three features: (1) the demand submodel estimates the market shares for all routes of the object airline network and predicts market demands for all OD pairs; (2) the supply submodel determines optimal flight frequencies and basic airfares on individual routes of the object airline network by maximizing the airline's total profit; (3) the demand-supply interactions on the flight frequency programming are analyzed by integrating demand and supply submodels, and using an algorithm to solve the interaction problem.

Furthermore, in a competitive environment, one airline must consider what its competitors' decisions are likely to be when determining flight frequencies and basic airfares on its own network. The fourth part of the study further combines a competitive interaction model with the above demand-supply interaction approach, aims to determine airline networks by taking into account competitors' decisions and competitive interactions in individual OD markets well in advance. Herein, the flight frequency programming on an airline network in response to competitive interactions is stated as one of optimization problems in the medium-term airline network-planning phase. Knowledge of competitors' strategy choices is usually indeterminate owing to the lack of information on how those competitors make their network decisions, since competing airlines offering services to any OD pair may not have the same size networks in a competitive environment. Facing the uncertainties and indeterminacy involved in airline competition, the fuzzy logic tools might be applied to describe the competitive interactions and further evaluate the equilibrium of airline competition. Therefore, this part of the study attempts to develop a fuzzy-logic-based competitive interaction model to describe frequency and airfare interactions between two competing airlines on individual OD pairs in uncertain competitive environments. While not radically departing from theories developed in previous studies on airline competition, the fuzzy rules of our model will be made on the basis of pertinent game theoretical knowledge and empirical evidence concerning airline competition (e.g., Hansen, 1990; Hansen and Kanafani, 1990; Pels et al., 2000). An algorithm consisting of an iterative scheme that integrates the airline network programming model, market share model and the fuzzy-logic-based competition model is developed to determine flight frequencies on an airline network in response to competitive interactions.

In the fifth part of this dissertation, this study analyzes international airline code-share alliance while emphasizing on network design issues by integrating the airline network design model, market share model, and multiobjective programming technique into one model. This study aims to design both the optimal integrated alliance-based network and partner airlines' networks when they enter an international alliance. The model analyzes the impact of the code-share alliance network on market demands, alliance partner airlines' costs as well as profits, and passengers' level of services. The bargaining interactions between alliance partner airlines are also taken into considerations. An interactive airline network design procedure is developed to determine alliance partners' airline networks accounting for the bargaining interaction process in an international alliance agreement.

This study develops a single airline network design model, an integrated alliance network design model. The integrated alliance network design model and two alliance airlines' network design models can be combined into a two-level hierarchical programming process, in which the upper level is the integrated alliance network model and the lower level are two single alliance airlines' network models. Furthermore, the bargaining interactions between two partner-airlines and various objective functions among partner airlines under the alliance negotiations are taken into considerations. This study uses interactive multiobjective programming techniques to solve the two-level programming model for alliance airlines in competitive environments. The reference point method (Wierzbiciki, 1980; 1982) with achievement scalarizing programming is used for solving our problem. When individual airlines' decision-makers specify reference points for their objective functions, optimization of the corresponding achievement scalarizing function provides the Pareto optimal solutions close to the decision-makers' reference points or better than that if the reference points are attainable. The decision-makers compare the current Pareto optimal solutions proposed from the achievement scalarizing function with those proposed from their single airline network design models. Then, the decision-makers either choose these current Pareto optimal solutions or modify the reference points of one or more objective functions in order to find satisfying solutions. The reference levels can be changed interactively by alliance airlines' decision-makers due to learning or improved understanding during the solution process, and hence, yields satisfying solutions.

1.4 Framework of the dissertation

The relationships among different research subjects in this dissertation are shown in Figure 1.1. Figure 1.1 depicts differences in the relative complexity, problem size

Figure 1.1. The relationships among various research subjects in this dissertation

and time scale on decision-making among various research subjects in this dissertation.

The airline network design model is the basic model in this study. This study first incorporates grey multiobjective programming into designing an airline network to tackle the extents of variations in passenger demand (Chapter 3). Next, a reliability evaluation model based on a chance-constrained stochastic programming is developed to deal with the short-term demand fluctuations for designing an airline network (Chapter 4). Furthermore, this study develops a demand-supply interaction model by integrating airline network design model and passenger airline-flight choice model to determine flight frequencies and basic airfares on an airline network by taking into account demand-supply interactions in the phase of long-term airline network-planning (Chapter 5). This study further combines a fuzzy-logic-based competitive interaction model with the demand-supply interaction model to determine flight frequencies on an object airline network in response to medium-term competitive frequency/airfare interactions among competing airlines (Chapter 6). Finally, in designing an alliance-based network, this study integrates individual alliance-partners' airline network models and the integrated alliance network model into a two-level hierarchical multiobjective programming model (Chapter 7). An interactive multiobjective programming technique is used to solve the alliance network model by considering bargaining interactions between two partner-airlines in competitive environments.

The framework of this dissertation is also shown in Figure 1.2. Figure 1.2 depicts the content of each part of the study and the approaches of submodels within the model developed in each part. The rest of this dissertation is organized as follows. Chapter 2 reviews relevant literature in airline network modeling with regard to hubbing, airline network routing, flight frequency determination, and research methods on airline competition and alliance. Chapter 3 presents grey models for forecasting passenger demand and a multiobjective programming model for determining flight frequencies on an airline network. The airline network design problem is formulated as a multiobjective programming by minimizing both the airline operating costs and the passenger travel costs. Then, the e-constraint method is applied to solve the Pareto optimal solutions for the multiobjective programming problem.

Chapter 4 uses chance-constrained stochastic programming to formulate the airline network programming problem by taking the short-term passenger demand fluctuations into account. This chapter develops a reliability evaluation approach based on a chance-constrained formulation for airline network design problem, and proposes a fine-tuning process of flight frequencies for redesigning the network in response to short-run demand fluctuations.

Chapter 5 focuses on developing a model for determining flight frequencies on an airline network by taking into account competitors' decisions and competitive interactions in individual OD-pair markets of the airline network well in advance. The model is composed of three submodels, which includes an airline flight frequency programming model, a passenger choice model, and a demand-supply competitive interaction model. The flight frequency programming model determines flight frequencies and basic airfares on individual routes of an airline network by maximizing the airline's total profit. The passenger choice submodel estimates the market shares for all routes of the object airline network and predicts market demands for all OD pairs. The demand-supply interactions on the flight frequency programming are analyzed by integrating demand and supply submodels, and using an algorithm to solve the interaction problem.

Chapter 6 further develops a fuzzy-logic-based airline competitive interaction model to describe the competitive frequency/airfare interactions between two competing airlines. Then, an algorithm consisting of an iterative scheme that integrates the airline network programming model, market share model and the competitive interaction model is developed to determine flight frequencies on an airline network in response to competitive interactions.

Chapter 7 combines the single airline network model and integrated alliance network design model into a two-level hierarchical programming problem for designing the code-share alliance-based network. Then, interactive multiobjective programming techniques are used in this chapter to solve the two-level programming problem for alliance airlines in competitive environments. Since the international airline alliances are in competitive markets, the demand-supply interactions under competitive conditions are also taken into consideration in the interactive alliance network design procedure. Case studies are provided in each of Chapters 3 to 7 to illustrate the application of the models and to demonstrate the proposed models' effectiveness. The final chapter (Chapter 8) presents the summary, conclusions, and the future research of this dissertation.

Figure 1.2. The framework of this dissertation

CHAPTER 2

Literature Review

The following literature review briefly discusses airline network modeling with regard to airline hubbing, airline network routing, flight frequency determination, and research methods on airline network. Studies on airline competition and alliance are also discussed.

2.1 Airline network modeling

There is a vast literature on airline network modeling with a variety of issues. Studies related to airline hubbing, network routing, airline economic issues, and flight frequency determination will be reviewed here.

2.1.1 Hub-location problem for airline network design

2.1.2 Economic issues of airline networks

2.1.3 Flight frequency determination and aircraft choice

2.2 Airline competition

2.3 Airline alliance

CHAPTER 3

Multiobjective Programming with Grey Numbers towards Airline Network Design

CHAPTER 4

Reliability Evaluation for Airline Network Design in Response to Fluctuation in Passenger Demand

CHAPTER 5

Determining Flight Frequencies on an Airline Network with Demand-Supply Interactions

CHAPTER 6

Determining Flight Frequencies on an Airline Network in Response to Competitive Interactions

CHAPTER 7

Airline Network Design for International Airline Code-Share Alliances

CHAPTER 8

Conclusions

This dissertation developed a series of models for investigating five important research subjects in airline network design problems. These include multiobjective programming with grey numbers towards airline network design, reliability evaluation for airline network design in response to passenger demand fluctuations, determining flight frequencies on an airline network with demand-supply interactions and in response to competitive interactions in competitive environments, and airline network design for international airline code-share alliances. This chapter provides a summary of the key findings of each part of the dissertation, and highlights extensions for future research in this field.

8.1 Research summary

Since the extreme complexity of designing an airline network is due largely to the need for transportation facilities to meet passenger demands efficiently, analyses on passenger demand patterns, passenger choice behavior and airline market shares are of priority concern in the planning and design of an airline network. In previous studies of airline network design, passenger demand pattern is assumed to be exogenous, and demand is assumed to be inelastic. In such airline network design studies, the reliability and performance results of network designs, apart from short-term demand fluctuations, are generally not evaluated. The uncertainties with regard to competitive interactions are rarely considered in previous game-theory-based models of airline competition and network design studies. Moreover, few studies have been devoted to constructing network models for studying the airline alliances. This dissertation aims to develop a series of models for dealing with these airline network design problems.

This study first developed a multiobjective programming with grey-number-based demand inputs for designing an airline network aimed at minimizing both the airline operating costs and the passenger travel costs. Next, this study developed a reliability evaluation model based on chance-constrained stochastic programming and provided a fine-tuning process of flight frequencies to tackle the short-term demand fluctuations for designing an airline network. Furthermore, this study integrated airline network design and market share analysis into one model, aimed to analyze the impact of flight frequency/airfare options on passenger choices and airline market shares, and incorporated demand-supply interaction into network design models. A fuzzy-logic-based competitive interaction model was further developed to describe the uncertain competitive interactions and evaluate the equilibrium of airline competition. Finally, this study combined the airline network design model and market share model with the interactive multiobjective programming techniques to design both the integrated alliance-based network and alliance partner airlines' networks and analyze the impact of the code-share alliance network on market demand, airline profit, and passenger level of service. The major results of each part of the study are listed as follows:

Part I: *Multiobjective programming with grey numbers towards airline network design*

(1) Grey time-series models were developed to forecast the airline's city-pair traffic and to estimate their upper and lower limits to capture the extents of variations in future trends. A group of optimal frequency plans on routes of airline networks with various grey-number-based demand forecasts were determined by applying multiobjective programming.

(2) The groups of solutions not only provided flexibility in decision-making with two different objectives, but also showed the trade-off rates and the marginal rates of substitution between two objectives that minimize the total airline costs and/or the passenger travel costs.

(3) From the Pareto optimal boundaries with trade-off rates, it can be found that if the decision-makers decide to choose solutions with higher operating economies and want to lower one more unit of airline's operating cost, they must simultaneously worsen larger amount of the service levels.

(4) The results also showed that the overall substitution rates between passengers' traveling costs and airline's operating costs with high traffic surpassed those associated with lower traffic.

(5) The results obtained form groups of Pareto optimal solutions corresponded with different objectives and fulfilled various traffic levels, thereby determining different groups of flight frequency plans. The compromise solutions were reasonable by comparing them with the actual frequencies shown on CI's existing time table.

(6) The case study not only demonstrated that the optimal solutions of the designed networks yield promising results, but also verified that the multiobjective

programming models are practical in airline network design.

Part II: *Reliability evaluation for airline network design in response to fluctuation in passenger demand*

(1) The reliability evaluation method evaluates the reliabilities of proposed monthly flight frequencies on individual OD pairs on condition that normal/abnormal fluctuations occur on it.

(2) The probabilities of normal and abnormal state occurrences and the probabilities of their durations were analyzed, and the reliabilities for individual OD pairs during the planned year were estimated.

(3) *A priori* adjustment of flight frequencies was developed by tuning flight frequencies on only parts of routes with severe traffic fluctuations while still maintaining overall airline network design objectives.

(4) From the results of the case study, it can be found that a lower dispersion of monthly OD traffic values implies higher reliability of the proposed monthly OD flight frequencies. In the test airline network, most OD pairs did not exhibit severe enough monthly traffic fluctuations to evoke unreliability; the proposed monthly flight frequencies for these pairs were therefore assessed to be highly reliable.

(5) In the case study, relatively low reliability value OD pairs were detected by the reliability evaluation when those OD pairs had severe enough monthly traffic fluctuations to evoke unreliability.

(6) The results also showed that not only the flight adjustment costs on unreliable OD pairs were less than expected losses, but also the total cost of the adjusted airline

network was less than the total costs of the original airline network design when no adjustments were performed.

(7) The flight frequency adjustment method may benefit the airline and its passengers and provide flexibility in decision-making for determining responsive flight frequency plans on OD pairs with severe fluctuations.

Part III: *Determining flight frequencies on an airline network with demand-supply interactions*

(1) The model proposed in this part of the study consists of two submodels, including a passenger airline-flight choice model and an airline flight frequency programming model.

(2) The market shares for each OD pair in an airline's route network were estimated by aggregating individual passengers' airline-flight choices formulated in the demand submodel, while passengers' choices are considered functions of perceived line-haul travel time cost, schedule delay cost, and airfare of various airlines' route flights. Values of travel time and FFlyer airfare-discount factors were considered and treated as correlated random variables with covariance between them.

(3) Airline flight frequency programming problem with demand-supply interactions was solved using an algorithm consisting of an iterative scheme that integrates the demand and supply submodels.

(4) Though the results of the proposed market-share submodel in the case study slightly underestimated the market shares for most of those test OD pairs, the low percentage errors indicated that the market-share submodel was accurate enough

to estimate airlines' route market shares.

(5) Convergence in the demand-supply interaction results was achieved after six rounds. It was found that when the flight-frequency elasticity for all city-pair routes was smaller than 1, convergence of the demand-supply interaction occurred.

(6) The determined flight frequencies with demand-supply convergence were more accurate than those with initially given market shares. The results of this example were shown to be reasonable by comparing the solutions obtained from our models with actual CI's flight frequencies.

(7) The results demonstrated how demand-supply interactions might be considered well in advance in flight frequency programming problem for an airline network. Restated, by taking into account demand-supply interactions, the results of the proposed flight frequency programming on an airline network are practicable for decision-making in airline network-planning during the long-term planning periods.

Part IV: *Determining flight frequencies on an airline network in response to competitive interactions*

(1) The model proposed in this part of the study consists of three submodels, including an airline market share model, an airline flight frequency programming model, and a fuzzy-logic-based competitive interaction model.

(2) The airline market share model was formulated as functions of flight frequency shares and relative airline airfares on OD-pairs. The passenger demands as well as airline market shares for all OD pairs were used as input parameters to

the airline flight frequency programming model.

(3) The competitive interaction model, based on fuzzy logic tools, was developed to estimate competitors' reactions. Two propositions based on theoretical findings from published literature were made to build an approximate reasoning algorithm consisting of fuzzy IF-THEN rules.

(4) Airline flight frequency programming problems with anticipated competitive interactions were solved using an algorithm consisting of an iterative scheme that integrates the three submodels.

(5) In the estimation process for the proposed market share model, a very good fit between the estimated models and historical data was found in the case study. According to the model estimation results, the relationship between airline market share and airline airfare is elastic.

(6) Three cases with different load factor values were included in the case study, and convergence in competitive interaction results was achieved in all cases. The results were also shown to be reasonable by comparing the solutions obtained with the actual CI's market shares and route flight frequencies.

(7) The results demonstrated how anticipated airline competitive interactions might be considered well in advance in airline flight frequency programming problems.

(8) The proposed models provided an analytical tool for airlines to evaluate the impacts of their flight frequency and airfare adjustment strategies in competitive environments, and also provided a useful device for iteratively identifying the competitive convergence.

Part V: *Airline network design for international airline code-share alliances*

(1) An interactive airline network design procedure for determining international code-share alliance-based networks was developed by taking alliance performance and bargaining interactions between alliance partner airlines into considerations.

(2) The models proposed in this part of the study included a single airline network programming model in profit-maximizing programming form and an integrated alliance network design model in multiobjective programming form.

(3) The focus was put on maximizing total profits, maximizing the total number of passenger carried and minimizing the total passenger schedule delays when designing the integrated alliance network.

(4) The reference point method was used to solve the two-level hierarchical multiobjective programming model allowing for bargaining interactions between alliance partners in competitive environments.

(5) In analyzing the satisfactory solutions obtained from the interactive multiobjective programming procedures, it can be found that alliance partners all earned more profits under alliance conditions than under the pre-alliance conditions.

(6) Under complementary alliance conditions, both EVA and Continental increased their flight frequencies after the alliance. The increases in EVA's and Continental's flight frequencies will gain them more market shares in complementary-alliance OD pairs as well as in relevant complementary-alliance links.

(7) Under parallel-alliance conditions, the alliance partners might produce less output if their market shares are relatively low. Airlines are more likely to join the

parallel-alliance for markets where they have large market shares.

(8) The results were shown to be reasonable by comparing with the actual EVA's, ANA's and Continental's time tables. The results demonstrated how network design models and interactive multiobjective programming models might be applied for designing alliance airlines' networks proactively and planning airline code-share alliances.

(9) The proposed models not only provided a useful device for alliance airlines to iteratively evaluate their alliance performance and also provided a planning tool for designing their alliance-based networks under the code-share alliance negotiations.

In sum, the models proposed in this dissertation provided highly effective tools that enable planners to assess the impact of changes in passenger demands and competitive environments on airline network design performance by taking demand variability, competitive demand-supply interactions and airline alliance interactions into account. Results in each part of the study shed further light into operational planning, performance-related issues, airline competition and alliance issues in airline network design.

APPENDIX

Grey Models for Forecasting OD-pair Traffic

In grey models, there is a group of difference equations with variations in the structure along with time rather than being general difference equations. A GM series is defined as a time series in which the number of data points of the series must be more than or equal to four (Deng et al., 1988). Although applying the data from the original series to construct GM models would be unnecessary, the data must be taken at equal intervals and in consecutive order without bypassing any data (Deng et al., 1988). A condition which should be satisfied to establish a GM is that the potency of the series must be more than four. Furthermore, assumptions regarding statistical distribution of data are unnecessary when applying the grey theory. Accumulated generating operation (AGO), an important feature of grey models, focuses largely on reducing the randomness of data. In fact, functions derived from AGO formulations of original series are always well-fitted to exponential functions (Deng, 1985). As mentioned in Section 1.2, Deng emphasized that nonnegative smooth discrete functions can be transformed into a sequence with the approximate exponential law. A detailed derivation of the grey exponential law can be found in Deng et al. (1988). Grey forecasting models have been recently used in many applications (e.g. Deng et al., 1988; Sun, 1991; Chen and Tien, 1996; 1997; Tien and Chen, 1997; 1998; Hsu and Wen, 1997; 1998). According to the results of Hsu and Wen (1997, 1998), the accuracy of forecasted results by applying grey models yields more precise forecasts than conventional statistical models such as the ARIMA and multiple regression models.

For generalization, we first introduce the general form of the grey model, GM(*h*,N), where *h* stands for the *h*-th order derivative of AGO-series of dependent variables, and N stands for N variables (i.e., one dependent variable and N-1 independent variables) in the differential equation in the model. GM(*h*,N) is defined as a linear differential equation (Deng, 1986; Chen and Tien, 1996; Tien and Chen, 1998):

(A.1)

where Y is the dependent variable; X_1, X_2, …, X_{N-1} are independent variables; $Y^{(1)}(k)$, $X_1^{(1)}(k)$, …, $X_{N-1}^{(1)}(k)$ are their AGO-series, respectively (we will show AGO formulation later, see Eqn.(14)), and a_1, a_2, …, a_h and b_1, b_2, …, b_{N-1} are parameters.

Grey models are commonly represented in the form of first-order derivatives or as polynomial expressions (i.e., *h*=0), e.g., GM(1,1), GM(1,N) or GM(0,N); where GM(1,1) is a time-series forecasting model, GM(1,N) is a polyfactor system forecasting model and GM(0,N) is a smoothed polynomial interpolation (Deng, 1986). Furthermore, the *h*-order differential equation can be used to represent continuous dynamic systems (Chen and Tien, 1996). Chen and Tien (1996) and Tien and Chen (1998) extended GM(2,2) to be a deterministic grey dynamic model DGDM(2,2,1) for forecasting series in dynamic and changeable systems.

A-1. Grey time-series model－GM(1,1) models

A-2. Grey systematic models－GM(1,N) models

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