O.R. Applications

Interactive multiobjective programming in airline network design for international airline code-share alliance

Yuh-Horng Wen, Chaug-Ing Hsu *

Department of Transportation Technology and Management, National Chiao Tung University, Hsinchu 30010, Taiwan, ROC

Abstract

This study presents an interactive airline network design procedure to facilitate bargaining interactions necessitated by international code-share alliance agreements. Code sharing involves partner airlines individually maximizing their own profits, while mutually considering overall profitability, traffic gains, and quality benefits for the markets in which they cooperate with their partners. This study uses a reference point method to solve the interactive multiobjective programming model, to support the bargaining interactions between two partner-airlines in an alliance negotiation. The impact of the code-share alliance network on market demand, alliance partners' costs and profits, and levels of service are also discussed. A case study demonstrates the feasibility of applying the proposed models and elucidates how interactive multiobjective programming models may be applied to determine flight frequencies for airline code-share alliance networks. The results of this study provide ways by which alliance airlines can evaluate iteratively the output and profits of the alliance members under code-share alliance agreements.
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1. Introduction

The emergence of airline code-share alliances has characterized international aviation markets recently, when airlines' strategies have moved aggressively to expand market share and to hold down costs (Wells, 1993). Major air carriers have increasingly entered international alliances with foreign carriers to extend their networks and access new markets so as to attract more passengers in a competitive environment (Park, 1997; Park and Zhang, 1998; Park et al., 2001). Following Mockler (1999) and Morasch (2000), alliance is

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* Corresponding author. Tel.: +886 3 573 1672; fax: +886 3 572 0844.
  E-mail address: cihsu@cc.nctu.edu.tw (C.-I. Hsu).

an agreement between partners, which is created to achieve the strategic objectives of their common interests. However, the real-world alliance decision-making problems may involve multiple strategic objectives or rationales for the alliances. Evans (2001) stated that the strategic assessment of airline alliances must use multifaceted objectives. In the strategic planning process for alliances, objectives are measures of effectiveness for evaluating the "results" or performances of the alliance strategies. Many studies have discussed the strategic motives and driving forces for airline code-share alliances, including the benefits of traffic gains, cost efficiency (as well as increased profits), and improved quality of transportation services (Oum and Park, 1997; Park and Zhang, 2000). Alliances may allow partner airlines to increase market densities and simultaneously reduce operating costs by coordinating activities through code-sharing agreements or coordinated flight schedules (Park et al., 2001; Pels, 2001). Furthermore, airline alliances may better coordinate flight schedules to minimize scheduled delays between flights, and provide a greater choice of flights linking an expanded range of origins and destinations while earning air-miles for awards, which are strong drivers of market share. Realizing these benefits of airline alliances thus requires that the effectiveness of integrated networks for international airline code-share alliances be evaluated using multiple objectives.

In industrial economics, the "strategic" inherence of alliance refers to a two-stage decision making process, in which partners arrive at an alliance agreement with their common goals in the alliance forming phase and then the alliance agreement is used as a strategic device to influence the partners' objectives in the individual planning phase (see Mockler, 1999; Morasch, 2000 for a similar concept). According to strategic marketing formulations, the objective of output-maximizing (as well as maximizing market share) is considered when accessing a new market and throughout the growth phase; on the other hand, firms aim to maximize profits while defending market shares during mature market stages (Walker et al., 1996). Entering a code-share alliance, for some airlines, it is created to access new markets; whereas for others, it involves an effort to penetrate existing markets. Code sharing involves partner airlines individually maximizing their own profits, while mutually considering overall profitability, traffic gains, and quality benefits for the markets in which they cooperate with their partners. However, due to the differences and possible conflicts among these strategic objectives in forming the code-share alliance, the task of designing the integrated alliance-based airline network for assessing the alliance effectiveness should be considered a multiobjective programming problem. The multiobjective optimization is a generalization of single-objective optimization (Sakawa, 1993). The single-objective of profit-maximizing programming for alliance planning is just like a special case of multiobjective programming problem. In such a special case where all the partner airlines only decide to aim at the total profitability in their alliance formation, then the multiobjective programming problem can be reduced to a single-objective of profit-maximizing optimization. Since multiobjective programming problems rarely have points that simultaneously maximize all of the objectives, the multiobjective programming is typically in a situation of trying to maximize each objective to the "greatest extent possible" (Steuer, 1986). Under conditions that alliance airlines simultaneously maximize the total profits, the multiobjective problem in this study aims to further evaluate the performance of airline alliances in terms of striving total traffic gains. In multiobjective optimization, the notion of Pareto optimality has been introduced, which is the solution in which no objective can be reached without simultaneously worsening at least one of the remaining objectives (Cohon, 1978). Decisions with Pareto optimality are not uniquely determined; the final decision must be selected from the set of Pareto optimal solutions (Sakawa, 1993). The multiobjective programming allows different strategic market settings to be analyzed for the airline alliance. Partner airlines also might be jointly seeking an optimum that either merely maximizes the total profits of the integrated alliance network or the total number of passengers, or selecting a combination of them, all of which optimums are Pareto optimums. Consequently, the goal of solving the multiobjective programming problem for the integrated alliance network is to derive a satisfactory solution to partner airlines, which is also Pareto optimal, given as a "mixed" strategy by combining these objectives in the alliance forming stage. It is oriented more towards strategic planning. Notably, the multiobjective programming

can provide partner airlines with increased flexibility of aiming and weighting different strategic objectives in alliance decision making (Hsu and Wen, 2000).

International airline code-share alliances should be formed with network design in mind. The airline network design problem in this paper 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 maximize total airline profits (Teodorovic et al., 1994; Jaillet et al., 1996; Hsu and Wen, 2000, 2002). Airline network design refers to decisions on routing plans, flight frequencies and aircraft types on individual routes (Jaillet et al., 1996; Hsu and Wen, 2000). Network design is strongly emphasized, because the selected code-shared routes, coordinated routing plans, proposed flight frequencies and aircraft types on individual routes of partner airlines' networks and their integrated alliance network directly affect the coordinated operating effectiveness of the alliance-based network and the quality of the service provided to passengers. Airline network design therefore crucially determines the effectiveness of an international alliance network (Pels, 2001). An international airline alliance combines alliance partners' networks. Not only must each individual network function effectively, but so must the integrated alliance-based network. From a network perspective, the international airline alliance can be classified as a complementary and parallel alliance, or as a combination of the two. The complementary alliance refers to two airlines' linking up their existing partial networks and building a new complementary network to feed traffic to each other. The parallel alliance refers to collaboration between two formerly competing airlines competing on routes they flew in common.

Research into airline alliances continues to attract the attention of academicians, airline planners and policy makers. Most studies of airline alliances have been devoted to investigating empirically the effects of alliances. Notable examples include Youssef and Hansen (1994), Hannegan and Mulvey (1995), Oum et al. (1996), Oum and Park (1997), Zhang and Aldridge (1997), Brueckner and Whalen (2000), Li (2000). Park and Zhang (2000) demonstrated that fares in alliance markets decreased with costs, while market shares on alliance routes increased. In other studies, Dennis (2000) considered scheduling issues and network strategies for international airline alliances; Oum et al. (2001) addressed regulatory issues; and Brueckner (2003a,b) analyzed the benefits of code-sharing and antitrust immunity. Cumulatively, above empirical studies demonstrate that both airlines and passengers are likely to be advantaged when airlines enter alliance agreements. Theoretical studies of airline alliances have focused on analyzing their economic effects (Park, 1997; Park and Zhang, 1998; Brueckner, 2001; Park et al., 2001). Such studies compared the profitability, partner outputs, market outcomes, and welfares of different network configurations with and without alliances. In contrast to the studies of Park and Brueckner, this study addresses the airline network design and mathematical programming models to formulate the decision making process and determine flight frequencies on airline code-share alliance networks.

In light of above researches, this study attempts to develop an interactive airline network design procedure to determine alliance airlines' networks, with reference to alliance performance and the bargaining interactions between partner airlines. Models of individual partner airlines' networks and of the integrated alliance network are developed. The models are 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 between two partner airlines is considered an interactive multiobjective programming problem. The reference point method (Wierzbicki, 1980, 1982), employing achievement scalarizing programming, is used to solve the problem. When decision-makers (DMs) of individual partner airlines specify reference points for their objective functions, optimizing the corresponding achievement scalarizing function yields the Pareto optimal solutions close to or better than those reference points, if the reference points are attainable. The decision-makers compare the current Pareto optimal solutions determined using the achievement scalarizing function with those determined from their single airline network design models. The decision-makers then either choose these current Pareto optimal solutions or modify the reference points of one or more objective functions to obtain

satisfactory solutions. Decision-makers can change the reference levels interactively following learning or an improved understanding gained during the solution process.

The rest of this paper is organized as follows. Section 2 develops the single airline network design model. Section 3 elucidates a multiobjective programming problem for the integrated alliance network. Section 4 uses interactive multiobjective programming techniques and proposes an iterative algorithm to determine the alliance network programming model that supports bargaining between partner airlines' DMs. Section 5 presents a case study that demonstrates the effectiveness of the proposed model. Concluding remarks are made in Section 6.

2. Single airline network programming model

Consider an object airline network, $G^0(N^0, A^0)$, where N^0 and A^0 represent, respectively, the set of nodes and the set of links in graph G^0, and the superscript '0' indicates the object airline. Let R^0 ($R^0 \subseteq N^0$) represent the set of origin cities, and S^0 ($S^0 \subseteq N^0$) represent the set of destination cities in graph G^0, where $R^0 \cap S^0 \neq \emptyset$. Any given origin–destination (OD) pair r–s is connected by a set of routes P^0_{rs} ($r \in R^0, s \in S^0$) through the network. Similarly, $G^1(N^1, A^1)$ represents a partner airline's network, in which N^1 and A^1 are the set of nodes and the set of links in graph G^1, respectively, and the superscript '1' indicates the partner airline.

The modeling of airline flight frequency programming on an airline network herein follows the formulation of Teodorovic et al. (1994) and Hsu and Wen (2000, 2002). This section summarizes the flight frequency programming model proposed by Hsu and Wen (2002). An airline fleet that serves international routes normally includes several aircraft of various sizes. Correspondingly, the main decision variables in an airline network modeling are assumed to be the flight frequencies on individual routes served by various types of aircraft in the airline network (Hsu and Wen, 2000, 2002). Let N^0_{rspq} represent the flight frequencies served by the object airline's (airline '0') type q aircraft, flying between OD pair r–s, along route p ($p \in P^0_{rs}$). Restated, if N^0_{rsp} represents the total flight frequencies of all aircraft used by the object airline on its route p between OD pair r–s, then $N^0_{rsp} = \sum_q N^0_{rspq}$. The total flight frequencies served by the object airline between OD pair r–s, N^0_{rs}, is $N^0_{rs} = \sum_p N^0_{rsp}$.

Let Y^0_{aq} represent the flight frequencies served by the object airline's type q aircraft on link a ($a \in A^0$). This value is the sum of the flight frequencies of all of the object airline's routes that include link a served by aircraft q. That is,

$$Y^0_{aq} = \sum_{r,s} \sum_p \delta^{r,s}_{a,p,q} N^0_{rspq}, \tag{1}$$

where $\delta^{r,s}_{a,p,q}$ is the indicator variable,

$$\delta^{r,s}_{a,p,q} = \begin{cases} 1 & \text{if link } a \text{ is part of route } p \text{ served by type } q \text{ aircraft from city } r \text{ to city } s, \\ 0 & \text{otherwise.} \end{cases}$$

The total flight frequencies on link a of the object airline, Y^0_a, can now be expressed as $Y^0_a = \sum_q Y^0_{aq} = \sum_q \sum_{r,s} \sum_p \delta^{r,s}_{a,p,q} N^0_{rspq}$. Let f^0_a represent the link flow on link a, such that f^0_a is the sum of the flows on all routes of the object airline's network that passes through that link f^0_a can be expressed as

$$f^0_a = \sum_{r,s} \sum_p \delta'^{r,s}_{a,p} f^0_{rsp}, \tag{2}$$

where f^0_{rsp} is the passenger traffic carried by the object airline on its route p between OD pair r–s, and $\delta'^{r,s}_{a,p}$ is the indicator variable,

$$\delta_{a,p}^{\prime r,s} = \begin{cases} 1 & \text{if link } a \text{ is part of route } p \text{ from city } r \text{ to city } s, \\ 0 & \text{otherwise.} \end{cases}$$

In airline network modeling, two-way OD passenger flows are assumed to be symmetric. Most airlines make this assumption when designing their networks. This assumption is also made in relevant studies, such as Jaillet et al. (1996) and Hsu and Wen (2000, 2002). Let F_{rs} represent the total expected OD demand between OD pair r–s during a specific study period, and f_{rs}^0 be the total number of passengers carried by the object airline between OD pair r–s. f_{rs}^0 can then be estimated as $f_{rs}^0 = F_{rs}\mathrm{MS}_{rs}^0$, where MS_{rs}^0 is the object airline's market share of passengers who traveled between OD pair r–s. Moreover, the following condition must then be satisfied such that the sum of all passengers carried by the object airline on individual routes between OD pair r–s equals the total number of passengers traveling between OD pair r–s, carried by the object airline: $\sum_p f_{rsp}^0 = f_{rs}^0 = F_{rs}\mathrm{MS}_{rs}^0$.

Many studies have formulated the market share of an airline as a function of its flight frequency share (e.g., Powell, 1982; Teodorovic and Krcmar-Nozic, 1989; Cohas et al., 1995). These studies have established that the relationship between airline market share and flight frequency share is non-linear, and typically can be described by an S-shaped curve. For simplicity, market share formulation is considered to be an aggregate model, apart from disaggregate discrete choice modeling based on passenger airline-flight choice behavior. This study does not consider the relationship between airfares and airline market share. Teodorovic and Krcmar-Nozic (1989) made a similar assumption. Then, the object airline's market share, MS_{rs}^0, for passenger demand in an OD market can be expressed as

$$\mathrm{MS}_{rs}^0 = \gamma(\mathrm{FS}_{rs}^0)^\alpha, \tag{3}$$

where FS_{rs}^0 is the object airline's flight frequency share between OD pair r–s; and γ and α are parameters estimated by regression analysis. The object airline's flight frequency share between OD pair r–s, FS_{rs}^0, can be expressed as

$$\mathrm{FS}_{rs}^0 = \frac{\sum_p N_{rsp}^0}{\sum_p N_{rsp}^0 + \sum_{x, \forall x \neq 0} \sum_p N_{rsp}^x}, \tag{4}$$

where N_{rsp}^0 and N_{rsp}^x represent, respectively, the flight frequency offered by airline '0' (the object airline) and that offered by competing airline x ($x \neq 0$) on route p between OD pair r–s; superscript x is the index of the airline.

Furthermore, total OD demand, F_{rs}, is a function of the socioeconomic attributes and airline supply attributes of the OD pair. This study applies a grey systematic model, GM(1,N), to construct a polyfactor model for estimating OD pair demand. F_{rs} can be expressed by

$$F_{rs} = \mathrm{GM}_{(1,N)}(X_{rs}, N_{rs}), \tag{5}$$

where X_{rs} are socioeconomic variables (such as per capita GNP and per capita income); N_{rs} denotes the total flight frequency between OD pair r–s, such that $N_{rs} = \sum_x \sum_p N_{rsp}^x$, and $\mathrm{GM}_{(1,N)}(X_{rs}, N_{rs})$ represents a GM(1,N) model with variables X_{rs} and N_{rs}. The grey systematic model used here examines the effects of socioeconomic variables and total flight frequencies on passenger demand for individual OD pairs in an airline network. For detailed descriptions of methods for constructing GM(1,N), see Deng (1988a,b) and Hsu and Wen (2002).

Airline operating cost is assumed to be a piece-wise linear function for each link (O'Kelly and Bryan, 1998). Following the assumption in O'Kelly and Bryan (1998), the piece-wise linear cost function approximates a nonlinear cost function that allows costs to increase at a decreasing rate as traffic increases. Fig. 1 shows a set of cost line pieces, approximating a nonlinear function. Let C_a^T represent the airline operating costs on link a:
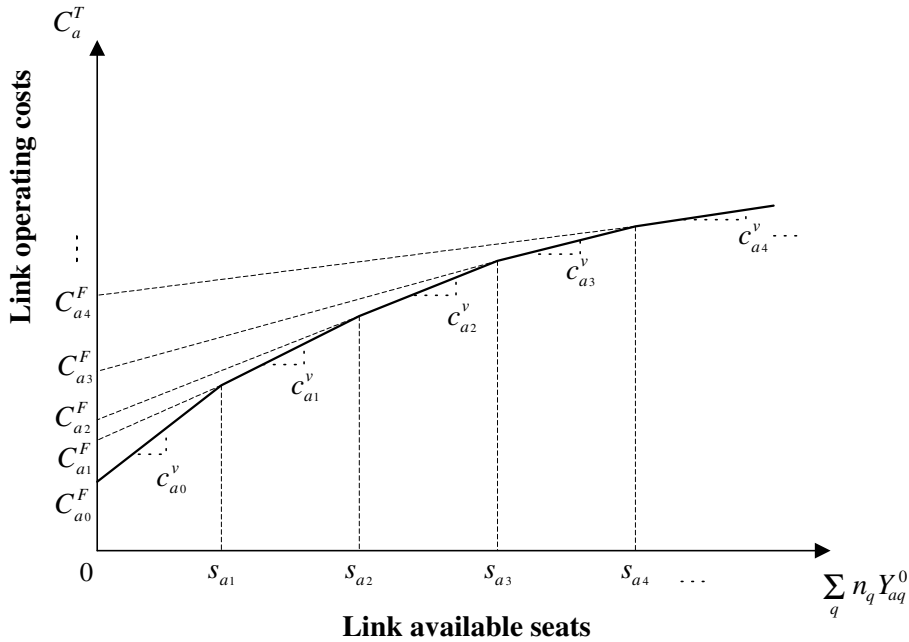
Fig. 1. Piece-wise linear cost function curve.

$$
C_a^T(Y_{aq}^0) = \begin{cases}
C_{a0}^F + c_{a0}^v \left(\sum_q n_q Y_{aq}^0 \right), & 0 \leqslant \sum_q n_q Y_{aq}^0 \leqslant s_{a1}, \\[2ex]
C_{a1}^F + c_{a1}^v \left(\sum_q n_q Y_{aq}^0 \right), & s_{a1} \leqslant \sum_q n_q Y_{aq}^0 \leqslant s_{a2}, \\[2ex]
\vdots & \vdots \\[1ex]
C_{ai}^F + c_{ai}^v \left(\sum_q n_q Y_{aq}^0 \right), & s_{ai} \leqslant \sum_q n_q Y_{aq}^0 \leqslant s_{ai+1}, \\[2ex]
\vdots & \vdots \\[1ex]
C_{an}^F + c_{an}^v \left(\sum_q n_q Y_{aq}^0 \right), & s_{an} \leqslant \sum_q n_q Y_{aq}^0 \leqslant \infty,
\end{cases}
\tag{6}
$$

where $C_{a0}^F \leqslant C_{a1}^F \leqslant \cdots \leqslant C_{an}^F$ and $c_{a0}^v \geqslant c_{a1}^v \geqslant \cdots \geqslant c_{an}^v$, and C_{ai}^F (the intercepts of the line pieces) and c_{ai}^v (the slopes of the line pieces) are parameters specific to segment i, and s_{ai} is the threshold of available seats for segment i. This class of function is sufficiently general to capture the economies of scale in operating various networks with various routes and network patterns.

The flight frequency programming problem is typically considered apart from short-run yield management issues during the global airline network planning phase. For simplicity, yield management issues are not considered here, and airfare-setting is assumed to simply involve basic airfare determination. The basic airfare is the backbone of the airfare structure in that it applies to all passengers at all times and moreover provides the basis for all other airfare levels (Wells, 1993). This study assumes that the object airline selects basic route airfares at or above the average operating costs on every route. Lederer (1993) makes a similar

assumption, and mentions that this represents expected behavior on the routes served by an airline. All competing airlines are also assumed to have fixed their basic fares on all routes during the long-term network planning phase. The basic airfare, tp_{rsp}^0, per passenger on route p between OD pair r–s can then be determined as $tp_{rsp}^0 = (1 + \bar{r}_{rsp}^0)C_{rsp}^T / \sum_q n_q l_p N_{rspq}^0$, where $\bar{r}_{rsp}^0$ is the profit margin specified by the airline, C_{rsp}^T is the total operating cost of the airline on route p, n_q is the number of available seats on aircraft type q, and l_p is the specified load factor associated with route p. If $N_{rsp}^0 = 0$, then $C_{rsp}^T = 0$ and $tp_{rsp}^0 = 0$. The total revenue generated by the object airline then can be expressed as $\sum_{r,s} \sum_p tp_{rsp}^0 f_{rsp}^0$.

The airline network programming model for the object airline, derived from maximizing its total profit π_0, can then be modeled as

$$\max_{Y_{aq}^0, N_{rspq}^0} \quad \pi_0 = \sum_{r,s} \sum_p tp_{rsp}^0 f_{rsp}^0 - \sum_{a \in A} C_a^T(Y_{aq}^0) \tag{7a}$$

$$\text{s.t.} \quad \sum_q n_q l_a Y_{aq}^0 - \sum_{r,s} \sum_p \delta_{a,p}^{\prime r,s} f_{rsp}^0 \geqslant 0 \quad \forall a \in \mathbf{A}^0, \tag{7b}$$

$$\sum_p f_{rsp}^0 = F_{rs} MS_{rs}^0, \quad p \in P_{rs}^0, \ \forall r,s, \tag{7c}$$

$$Y_{aq}^0 = \sum_{r,s} \sum_p \delta_{a,p,q}^{r,s} N_{rspq}^0, \tag{7d}$$

$$\sum_a t_{aq}^0 Y_{aq}^0 \leqslant u_q^0 U_q^0 \quad \forall q, \tag{7e}$$

$$Y_{aq}^0, N_{rspq}^0 \geqslant 0 \text{ and are integers;} \quad f_{rsp}^0 \geqslant 0. \tag{7f}$$

Eq. (7a) yields the objective function that maximizes the total profit π_0 of the object airline network. Eq. (7b) indicates that the transportation capacities offered in terms of numbers of seats on each link must be equal to or greater than the numbers of passengers on all routes that include that link. Eq. (7c) indicates that the total number of passengers carried by the object airline on any route p between OD pair r–s must equal the total number of passengers carried by the object airline between the OD pair. Eq. (7d) defines the relationship between link frequency and route frequency. Eq. (7e) states that total aircraft utilization must be equal to or less than the maximum possible utilization, where t_{aq}^0 is the block time for the object airline's type q aircraft on link a; u_q^0 is the maximum possible utilization, and U_q^0 is the total number of type q aircraft in the object airline's fleet. Eq. (7f) constrains variables Y_{aq}^0 and N_{rspq}^0 to be nonnegative integers, and also constrains f_{rsp}^0 to be nonnegative. Using similar approaches, the partner airline (airline '1') can estimate its OD market shares, MS_{rs}^1, and simultaneously determine its route flight frequencies, N_{rspq}^1, on its network to maximize profit, π_1. Finally, π_0^* and π_1^* represent the optimal objective function values (optimal profits) of the object airline and the partner airline, respectively.

3. Integrated alliance network programming model

When establishing an international code-share alliance, the object airline (airline '0') and the partner airline (airline '1') may select some nodes at which to provide jointly flight services for passengers who pass through these nodes. Let $\mathbf{N}^{0'}$ represent the subset of the object airline's nodes selected to participate in the code-share alliance, where $\mathbf{N}^{0'} \subseteq \mathbf{N}^0$; and let $\mathbf{N}^{1'}$, $\mathbf{N}^{1'} \subseteq \mathbf{N}^1$, denote the corresponding subset of nodes of the partner airline. Then, let $\mathbf{N}^{\wedge} \equiv \mathbf{N}^{0'} \cap \mathbf{N}^{1'}$ denote the intersection of sets $\mathbf{N}^{0'}$ and $\mathbf{N}^{1'}$.

Consider the object airline and the partner airline in a code-share alliance: the integrated alliance-based network can then be seen as the set union of two alliance partner airlines' networks. Let $\mathbf{J}^0$ represent the set of all OD pairs in the object airline network such that $\mathbf{J}^0 \equiv \{r$–$s \mid \forall r \in \mathbf{R}^0, \forall s \in \mathbf{S}^0\}$. Let $\mathbf{J}^1 \equiv \{r$–$s \mid \forall r \in \mathbf{R}^1,$

$\forall s \in \mathbf{S}^1\}$ be the set of all OD pairs in the partner's network. In the integrated alliance network, all OD pairs can be classified as non-alliance, parallel-alliance or complementary-alliance OD pairs. Consider a situation in which airlines '0' and '1' make a parallel alliance on an alliance OD pair that belongs to the intersection of sets $\mathbf{J}^0$ and $\mathbf{J}^1$, in the sense that they were formerly competitors in this alliance OD market, but now are partners in that OD market. Both airlines '0' and '1' simultaneously serve the parallel-alliance OD pair, of which both the origin and the destination are in set $\mathbf{N}^\wedge$. Thus, the set of potential parallel-alliance OD pairs can be defined as $\mathbf{J}^p \equiv \{r\text{–}s \,|\, r\text{–}s \in \mathbf{J}^0 \cap \mathbf{J}^1 \text{ and } r, s \in \mathbf{N}^\wedge\}$, where the superscript 'p' indicates parallel alliance.

Consider another situation in which airlines '0' and '1' establish a complementary alliance. A complementary-alliance OD pair is one of which the origin and the destination separately belong to the two partner airlines. Both the alliance partners jointly provide connecting services for passengers who travel between the complementary-alliance OD pair, and continue to provide local nonstop flights as before. The set of potential complementary-alliance OD pairs can thus be defined as $\mathbf{J}^c \equiv \{r\text{–}s \,|\, \forall r \in \mathbf{N}^{0'} - \mathbf{N}^\wedge, \forall s \in \mathbf{N}^{1'} - \mathbf{N}^\wedge\}$, where the superscript 'c' indicate complementary alliance. When airlines '0' and '1' establish a complementary alliance and provide connecting flights, the complementary-alliance OD pair can be considered to be a newly entered market for them. Furthermore, the non-alliance OD pairs on individual alliance partners' networks indicate their local OD pairs that are not also parallel-alliance OD pairs. Then, sets $\mathbf{J}^0 - \mathbf{J}^p$ and $\mathbf{J}^1 - \mathbf{J}^p$ are the sets of non-alliance OD pairs for the object airline's and its partner's network, respectively.

For example, consider the object airline's network, $\mathbf{G}^0(\mathbf{N}^0, \mathbf{A}^0)$, where $\mathbf{N}^0 = \{1, 2, 3, 4, 5\}$ and $\mathbf{A}^0 = \{(1, 2), (2, 3), (1, 4), (1, 5)\}$, as depicted in Fig. 2. Consider also the partner airline's network, $\mathbf{G}^1(\mathbf{N}^1, \mathbf{A}^1)$, where $\mathbf{N}^1 = \{2, 3, 4, 6, 7\}$ and $\mathbf{A}^1 = \{(3, 2), (6, 4), (7, 3), (7, 4), (7, 6)\}$. In this example, the set of all OD pairs in the object airline network is assumed to be $\mathbf{J}^0 = \{1\text{–}2, 1\text{–}3, 1\text{–}4, 1\text{–}5, 2\text{–}3, 2\text{–}4, 2\text{–}5, 5\text{–}4\}$, while the partner airline is assumed to serve OD pairs, $\mathbf{J}^1 = \{3\text{–}2, 6\text{–}3, 6\text{–}4, 7\text{–}2, 7\text{–}3, 7\text{–}4, 7\text{–}6\}$. The object airline selects $\mathbf{N}^{0'} = \{1, 2, 3, 4\}$ to participate in the code-share alliance with airline '1', while the partner airline selects $\mathbf{N}^{1'} = \{2, 3, 4, 6\}$ to participate in the code-share alliance with airline '0'; thus $\mathbf{N}^\wedge = \{2, 3, 4\}$. In this example, the parallel-alliance OD pair is the $\mathbf{J}^p = \{2\text{–}3\}$ and the complementary-alliance OD pair is $\mathbf{J}^c = \{1\text{–}6\}$. Route 1–4–6 (or route 6–4–1) is a complementary-alliance route, in which both alliance partners jointly provide connecting flights between the complementary-alliance OD pair $\{1\text{–}6\}$, while continuing to provide nonstop flights on their local OD pairs, $\{1\text{–}4\}$ and $\{6\text{–}4\}$, as before. On the object airline's link $(1, 4)$, the link flow $f^0_{(1,4)}$ is the sum of its route flows, $f^0_{1\text{–}4}$, $f^0_{2\text{–}1\text{–}4}$, $f^0_{5\text{–}1\text{–}4}$, and the complementary-alliance route flow, $f^{(0+1)c}_{1\text{–}4\text{–}6}$. Similarly, the partner airline's link flow $f^1_{(6,4)}$ is the sum of its route flows, $f^1_{6\text{–}4}$ and $f^1_{7\text{–}6\text{–}4}$, and the complementary-alliance route flow, $f^{(0+1)c}_{6\text{–}4\text{–}1}$. Link $(2, 3)$ (or route 2–3) is a

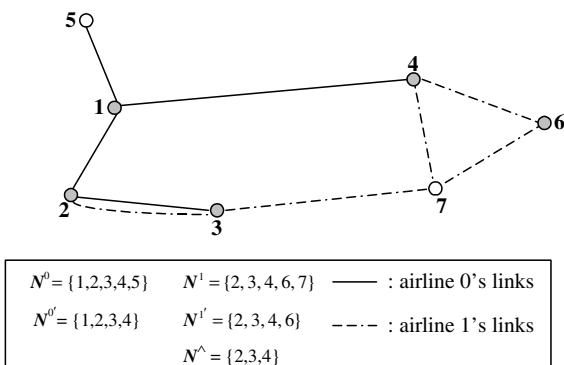| $\mathbf{N}^0 = \{1,2,3,4,5\}$ | $\mathbf{N}^1 = \{2, 3, 4, 6, 7\}$ | —— : airline 0's links |
| $\mathbf{N}^{0'} = \{1,2,3,4\}$ | $\mathbf{N}^{1'} = \{2, 3, 4, 6\}$ | –– · – · : airline 1's links |
| | $\mathbf{N}^\wedge = \{2,3,4\}$ | |

Fig. 2. Simple example for an alliance-based network of two partners.

parallel-alliance link (or route), so the total link flow on this parallel-alliance link is the sum of the object airline's route flows f_{2-4}^0 and f_{1-2-3}^0, and the partner airline's route flows, f_{3-2}^1 and f_{7-3-2}^1.

On a parallel-alliance OD pair, the total flight frequencies provided by the object airline and its partner are, $\sum_p N_{rsp}^0 + \sum_p N_{rsp}^1$, where $r-s \in J^p$. Then, the parallel-alliance market share can be calculated as

$$\mathrm{MS}_{rs}^{(0+1)\mathrm{p}} = \gamma \left[\frac{\sum_p N_{rsp}^0 + \sum_p N_{rsp}^1}{\sum_p N_{rsp}^0 + \sum_p N_{rsp}^1 + \sum_{x,\forall x \neq 0,1} \sum_p N_{rsp}^x} \right]^\alpha \quad \forall r-s \in J^p. \tag{8}$$

Any given complementary-alliance OD pair $r-s$ ($r-s \in J^c$) is assumed to be connected by a set of complementary-alliance routes, $P_{rs}^{(0+1)\mathrm{c}}$ ($r-s \in J^c$), through the alliance-based network. Variable $N_{rsp}^{(0+1)\mathrm{c}}$ is introduced to represent the frequencies of cooperative flights between complementary-alliance OD pair $r-s$ ($r-s \in J^c$) along complementary-alliance route p ($p \in P_{rs}^{(0+1)\mathrm{c}}$). Let $f_{rsp}^{(0+1)\mathrm{c}}$ represent the route passenger traffic served by coordinated flights through the complementary-alliance route p ($p \in P_{rs}^{(0+1)\mathrm{c}}$) between complementary-alliance OD pair $r-s$ ($r-s \in J^c$). Then, the complementary-alliance market share can be calculated as

$$\mathrm{MS}_{rs}^{(0+1)\mathrm{c}} = \gamma \left[\frac{\sum_{p,\forall p \in P_{rs}^{(0+1)\mathrm{c}}} N_{rsp}^{(0+1)\mathrm{c}}}{\sum_{p,\forall p \in P_{rs}^{(0+1)\mathrm{c}}} N_{rsp}^{(0+1)\mathrm{c}} + \sum_{x,\forall x \neq 0,1} \sum_p N_{rsp}^x} \right]^\alpha \quad \forall r-s \in J^c. \tag{9}$$

Let $f_{rs}^{(0+1)\mathrm{p}}$ and $f_{rs}^{(0+1)\mathrm{c}}$ represent the passenger traffic served by alliance airlines between parallel and complementary OD pairs, respectively. $f_{rs}^{(0+1)\mathrm{p}}$ and $f_{rs}^{(0+1)\mathrm{c}}$ can then be estimated as $f_{rs}^{(0+1)\mathrm{p}} = F_{rs}\mathrm{MS}_{rs}^{(0+1)\mathrm{p}}$ and $f_{rs}^{(0+1)\mathrm{c}} = F_{rs}\mathrm{MS}_{rs}^{(0+1)\mathrm{c}}$, respectively.

Determining airline flight frequencies on the integrated alliance network can be formulated as a multi-objective programming problem. This study follows the consideration by Teodorovic and Krcmar-Nozic (1989) of three objective functions. When alliance airlines determine flight frequencies on their alliance-based network, they aim to maximize total profits, maximize the total number of passengers and minimize the total passenger schedule delays on the integrated alliance network. The airline service level is typically quantified by schedule delays (Swan, 1979; Kanafani and Ghobrial, 1982; Teodorovic and Krcmar-Nozic, 1989; Park et al., 2001). Following the definition of Swan (1979), Kanafani and Ghobrial (1982) and Teodorovic and Krcmar-Nozic (1989), the schedule delay per passenger between OD pair $r-s$ is one quarter of the average headway,

$$\mathrm{sd}_{rs}^0 = \frac{\overline{T}}{4 \sum_p N_{rsp}^0} \quad \forall r-s \in J^0, \tag{10}$$

where $\overline{T}$ is the average operating time at the (origin) airport over a specific period of analysis; similarly, sd_{rs}^1 is the schedule delay per passenger between the partner airline's OD pair $r-s$ ($r-s \in J^1$). Moreover, total schedule delays for all passengers on all non-alliance OD pairs of the object airline and the partner airline are $\sum_{r,s \in J^0 - J^p} \mathrm{sd}_{rs}^0 f_{rs}^0$ and $\sum_{r,s \in J^1 - J^p} \mathrm{sd}_{rs}^1 f_{rs}^1$, respectively. The total flight frequencies provided by the object airline and its partner on the parallel-alliance OD pair are $\sum_p N_{rsp}^0 + \sum_p N_{rsp}^1 \ \forall r-s \in J^p$. Therefore, the schedule delays per passenger between the parallel-alliance OD pair can be expressed as $\mathrm{sd}_{rs}^{(0+1)\mathrm{p}} = \overline{T}/4(\sum_p N_{rsp}^0 + \sum_p N_{rsp}^1)$. Similarly, the schedule delays per passenger between complementary-alliance OD pairs can be expressed as $\mathrm{sd}_{rs}^{(0+1)\mathrm{c}} = \overline{T}/4 \sum_p N_{rsp}^{(0+1)\mathrm{c}} \ \forall r-s \in J^c$. Then, the total schedule delays for all passengers for all parallel-alliance and complementary-alliance OD pairs are $\sum_{r,s \in J^p} \mathrm{sd}_{rs}^{(0+1)\mathrm{p}} f_{rs}^{(0+1)\mathrm{p}}$ and $\sum_{r,s \in J^p} \mathrm{sd}_{rs}^{(0+1)\mathrm{c}} f_{rs}^{(0+1)\mathrm{c}}$, respectively.

Herein, a triple-objective programming problem is formulated and solved to design the integrated alliance network:

$$\max \quad Z_1 = \pi_0 + \pi_1 \tag{11a}$$

$$\max \quad Z_2 = \sum_{r,s \in J^0 - J^p} f_{rs}^0 + \sum_{r,s \in J^1 - J^p} f_{rs}^1 + \sum_{r,s \in J^p} f_{rs}^{(0+1)p} + \sum_{r,s \in J^c} f_{rs}^{(0+1)c} \tag{11b}$$

$$\min \quad Z_3 = \sum_{r,s \in J^0 - J^p} \mathrm{sd}_{rs}^0 f_{rs}^0 + \sum_{r,s \in J^1 - J^p} \mathrm{sd}_{rs}^1 f_{rs}^1 + \sum_{r,s \in J^p} \mathrm{sd}_{rs}^{(0+1)p} f_{rs}^{(0+1)p} + \sum_{r,s \in J^c} \mathrm{sd}_{rs}^{(0+1)c} f_{rs}^{(0+1)c} \tag{11c}$$

$$\text{s.t.} \quad \sum_q n_q l_a Y_{a_0 q}^0 - \sum_{r,s \in J^0} \sum_p \delta_{a_0,p}^{\prime r,s} f_{rsp}^0 \geqslant 0 \quad \forall a_0 \in \{(i,j) \mid i,j \in \boldsymbol{N}^0 - \boldsymbol{N}^{\wedge}\}, \tag{11d}$$

$$\sum_q n_q l_a Y_{a_1 q}^1 - \sum_{r,s \in J^1} \sum_p \delta_{a_1,p}^{\prime r,s} f_{rsp}^1 \geqslant 0 \quad \forall a_1 \in \{(i,j) \mid i,j \in \boldsymbol{N}^1 - \boldsymbol{N}^{\wedge}\}, \tag{11e}$$

$$\sum_q n_q l_a Y_{a_0' q}^0 - \left(\sum_{r,s \in J^0} \sum_p \delta_{a_0',p}^{\prime r,s} f_{rsp}^0 + \sum_{r,s \in J^c} \sum_p \delta_{a_0',p}^{\prime\prime r,s} f_{rsp}^{(0+1)c} \right) \geqslant 0 \quad \forall a_0' \in \{(i,j) \mid i \in N^0 - N^{\wedge}, j \in N^{\wedge}\}, \tag{11f}$$

$$\sum_q n_q l_a Y_{a_1' q}^1 - \left(\sum_{r,s \in J^1} \sum_p \delta_{a_1',p}^{\prime r,s} f_{rsp}^1 + \sum_{r,s \in J^c} \sum_p \delta_{a_1',p}^{\prime\prime r,s} f_{rsp}^{(0+1)c} \right) \geqslant 0 \quad \forall a_1' \in \{(i,j) \mid i \in \boldsymbol{N}^1 - \boldsymbol{N}^{\wedge}, j \in \boldsymbol{N}^{\wedge}\}, \tag{11g}$$

$$\sum_q n_q l_a Y_{a'' q}^0 + \sum_q n_q l_a Y_{a'' q}^1 - \left(\sum_{r,s \in J^0} \sum_p \delta_{a'',p}^{\prime r,s} f_{rsp}^0 + \sum_{r,s \in J^1} \sum_p \delta_{a'',p}^{\prime r,s} f_{rsp}^1 \right) \geqslant 0 \quad \forall a'' \in \{(i,j) \mid i,j \in \boldsymbol{N}^{\wedge}\}, \tag{11h}$$

$$\sum_{p \in P_{rs}^0} f_{rsp}^0 = F_{rs} \mathrm{MS}_{rs}^0 \quad \forall r,s \in J^0 - J^p, \tag{11i}$$

$$\sum_{p \in P_{rs}^1} f_{rsp}^1 = F_{rs} \mathrm{MS}_{rs}^1 \quad \forall r,s \in J^1 - J^p, \tag{11j}$$

$$\sum_{p \in P_{rs}^0} f_{rsp}^0 + \sum_{p \in P_{rs}^1} f_{rsp}^1 = F_{rs} \mathrm{MS}_{rs}^{(0+1)p} \quad \forall r,s \in J^p, \tag{11k}$$

$$\sum_{p \in P_{rs}^{(0+1)c}} f_{rsp}^{(0+1)c} = F_{rs} \mathrm{MS}_{rs}^{(0+1)c} \quad \forall r,s \in J^c, \tag{11l}$$

$$Y_{aq}^0 = \sum_{r,s} \sum_p \delta_{a,p,q}^{r,s} N_{rspq}^0; \quad Y_{aq}^1 = \sum_{r,s} \sum_p \delta_{a,p,q}^{r,s} N_{rspq}^1, \tag{11m}$$

$$\sum_a t_{aq}^0 Y_{aq}^0 \leqslant u_q^0 U_q^0; \quad \sum_a t_{aq}^1 Y_{aq}^1 \leqslant u_q^1 U_q^1, \tag{11n}$$

$$Y_{aq}^0, N_{rspq}^0, Y_{aq}^1, N_{rspq}^1 \geqslant 0 \text{ and are integers;} \quad f_{rsp}^0, f_{rsp}^1, f_{rsp}^{(0+1)c} \geqslant 0. \tag{11o}$$

Eqs. (11a)–(11c) are the three objective functions, and Eqs. (11d)–(11o) are constraints. Eq. (11a) maximizes the sum of the profits of the object airline and the partner airline networks. Eq. (11b) maximizes the sum of number of passengers who travel between all non-alliance, parallel-alliance, and complementary-alliance OD pairs. Eq. (11c) minimizes the sum of schedule delays for all passengers between all non-alliance, parallel-alliance, and complementary-alliance OD pairs. Eqs. (11d) and (11e) state that the transportation capacities offered in terms of number of seats on each non-alliance link must be equal to or greater than the total number of passengers on all routes that include that link. Eqs. (11f) and (11g) state similar constraints for each complementary-alliance link, and Eq. (11h) does so for each parallel-alliance link.

Eqs. (11i) and (11j) state that the sum of the passengers carried by the object airline and the partner airline, respectively, on any route p between non-alliance OD pairs must equal the total number of passengers who travel between those OD pairs. Eqs. (11k) and (11l) state similar constraints for parallel-alliance OD pairs and complementary-alliance OD pairs, respectively. Eq. (11m) defines the relationship between link frequency and route frequency. Eq. (11n) states that total aircraft utilization must be equal to or less than the maximum possible utilization. Finally, Eq. (11o) constrains variables Y_{aq}^0, N_{rspq}^0, Y_{aq}^1, N_{rspq}^1 to be nonnegative integers, and also constrains f_{rsp}^0 and f_{rsp}^1 to be nonnegative. However, during the phase of determining flight frequencies for an alliance network, some joint costs and revenues yielded from detailed alliance activities are unknown. In the proposed programming model, partner airlines individually determine their own costs, and revenues only depend on the number of their own passengers on alliance routes. That is, partner airlines allocate the costs and revenues on code-share alliance routes only according to market shares.

Models of the integrated alliance network model and the two individual alliance airline network design models can then be combined in a two-level hierarchical programming process, of which the upper level is the integrated alliance network model and the lower level includes two single alliance airline network models. An interactive reference point method is used to determine the two-level hierarchical programming model, accounting for bargaining between the partner airlines' decision-makers (DMs). In the two-level hierarchical programming, partner airlines individually maximize their own profits, while considering total profits, total number of passengers, and total schedule delays for their integrated alliance network. Through the interactive process, the DMs of partner airlines can iteratively examine the effects of code-share alliances on flight frequencies and profits, and can examine whether another reference point exists that leads to an increase in at least one of the profit levels, while none of the profit levels decreases.

4. Interactive multiobjective programming for designing alliance-based networks

Determining flight frequencies in the alliance-based network, according to Eqs. (11a)–(11o), is a triple-objective programming problem of the general form,

$$\max\{Z_1(\mathbf{x}), Z_2(\mathbf{x}), -Z_3(\mathbf{x})\}, \quad \mathbf{x} \in \mathbf{X}, \tag{12}$$

where $\mathbf{x}$ is the set of decision variables, i.e. $\mathbf{x} = \{Y_{aq}^0, N_{rspq}^0, Y_{aq}^1, N_{rspq}^1, f_{rsp}^0, f_{rsp}^1\}$; $\mathbf{X} \in \mathbf{R}^n$ is the set of feasible points defined by the given constraints, i.e. Eqs. (11d)–(11o); $Z_1(\mathbf{x})$, $Z_2(\mathbf{x})$ and $Z_3(\mathbf{x})$ in Eqs. (11a)–(11c) are the three objective functions to be maximized. The transformation, $\min Z_3(\mathbf{x}) = \max\{-Z_3(\mathbf{x})\}$ is made since the objective function $Z_3(\mathbf{x})$ is to be minimized.

The multiobjective programming problem is solved interactively using the reference point method (RPM) (Wierzbicki, 1980, 1982), modified specifically to be applied to the problem considered here. The aim is to find satisfactory solutions so that inequalities, $Z_i(\mathbf{x}) \geqslant \widehat{Z}_i$, $i = 1, 2, 3$, hold where $\widehat{Z} = \{\widehat{Z}_1, \widehat{Z}_2, \widehat{Z}_3\}$ is the reference point suggested by the alliance airlines' DMs, reflecting the desired values of objective functions. The satisfactory solutions include a final solution. Wierzbicki (1982) introduced the achievement scalarizing function, which can generate all Pareto optimal solutions, regardless of the convexity assumptions. A typical achievement scalarizing function for nonlinear problem is

$$S_c(\widehat{Z} - Z) = \sum_{i=1}^{3}(\widehat{Z}_i - Z_i)^2 - \varepsilon \sum_{i=1}^{3}(\max[0, \widehat{Z}_i - Z_i])^2, \tag{13}$$

where $\varepsilon > 0$ (a very small positive number) is the scalar penalty coefficient. ε can be assumed to equal 0.01, according to Steuer (1986). The purpose of the achievement scalarizing function is to generate a Pareto optimal solution which is in some sense close to or better than the DMs' reference point if the reference

point is attainable. In the RPM, the Pareto optimal solutions to the multiobjective programming problem, defined by Eqs. (11a)–(11o), are then obtained by solving the achievement scalarizing problem specified by

$$\min S_c(\widehat{Z} - Z), \quad \mathbf{x} \in \mathbf{X}. \tag{14}$$

An algorithm for the proposed method, consisting of an iterative scheme to solve the multiobjective programming problems for alliance airlines in competitive environments, is presented below.

Step 0. Input the competing airlines' initial flight frequencies, $N_{rsp}^x \ \forall x \neq 0, 1, \ \forall r, s, p$, and their initial market shares, MS_{rs}^0 and $\mathrm{MS}_{rs}^1 \ \forall r, s$, respectively, for the object airline and the partner airline networks. Input other exogenous parameters.

Step 1. Determine the pre-alliance route flight frequencies, $N_{rspq}^0, N_{rspq}^1 \ \forall r, s, p, q$, and the pre-alliance profits, π_0^* and π_1^*, are determined separately for the object airline and the partner airline, using the single airline network programming model (Eqs. (7a)–(7f)). The market shares for all OD pairs on the object airline network and the partner airline network are estimated from Eq. (3).

Step 2. Specify an ideal point, $Z^{\mathrm{ideal}} = (Z_1^{\max}, Z_2^{\max}, -Z_3^{\max})$, where $Z_1^{\max}, Z_2^{\max}$ and $-Z_3^{\max}$ are the values of the objective function that maximize Z_1, Z_2 and $-Z_3$, respectively. These values remain constant throughout the process. Ask the alliance partner airlines' DMs to select the initial reference point. If the DMs find identifying such a point difficult, the ideal point Z^{ideal} can be used as an initial reference point.

Step 3. In the kth iteration, based on π_0^{k-1}, π_1^{k-1}, f_{rs}^{0k-1}, f_{rs}^{1k-1}, sd_{rs}^{0k-1}, and $\mathrm{sd}_{rs}^{1k-1} \ \forall r, s$, obtained in the $(k-1)$th iteration, the DMs are asked to give a new reference point, $\widehat{Z}^k = \{\widehat{Z}_1^k, \widehat{Z}_2^k, \widehat{Z}_3^k\}$, by considering the current levels of the objective functions; the superscripts k and $k-1$, respectively, refer to the kth and $(k-1)$th iterations.

Step 4. Solve the corresponding achievement scalarizing problem (Eqs. (14) and (11d)–(11o)) to determine a Pareto optimal solution. Let $\{Y_{aq}^{0k}, N_{rspq}^{0k}, Y_{aq}^{1k}, N_{rspq}^{1k}\}$ be the solution to the integrated alliance network programming problem in the kth iteration. Let Z_i^k, $i = 1, 2, 3$, be the values of the corresponding objective functions.

Step 5. Input N_{rspq}^{0k} and $N_{rspq}^{1k} \ \forall r, s, p, q$ to calculate π_0^k and π_1^k, respectively, from Eq. (7a), and estimate the total OD demand, $F_{rs}^k \ \forall r, s$, from Eq. (5) in the kth iteration. Once the total OD demand, F_{rs}^k, changes, other competing airlines $x \ (\forall x \neq 0, 1)$ may modify their flight frequencies. Competing airlines' flight frequencies, N_{rsp}^{xk}, in the kth iteration, are then determined using a similar approach (Eqs. (7a)–(7f)), to maximize their profits. Then, input N_{rspq}^{0k}, N_{rspq}^{1k} and $N_{rsp}^{xk} \ \forall x \neq 0, 1, \ \forall r, s, p$ to estimate MS_{rs}^{0k}, MS_{rs}^{1k}, f_{rs}^{0k} and $f_{rs}^{1k} \ \forall r, s$ and to calculate sd_{rs}^{0k} and $\mathrm{sd}_{rs}^{1k} \ \forall r, s$, respectively, in the kth iteration.

Step 6. If the alliance airlines' DMs are satisfied with the current values of the objective functions, then stop. The current Pareto optimal solution is then the satisfactory solution. Otherwise, $k := k + 1$, and return to Step 3.

Interactive multiobjective programming is a useful device with which alliance airlines can iteratively examine the effects of an airline code-share alliance on airline flight frequencies and profits. In each iteration of the described algorithm, the alliance partners' decision-makers compare the current Pareto optimal solutions obtained from the multiobjective programming model with those determined from their single airline network design models. Then, the decision-makers either choose these current solutions or modify the reference points used for one or more objective functions to yield satisfactory solutions. When modifying the reference points, the decision-makers may set some further requirements or agree to some reductions in one or more objective functions. This procedure can be seen as a bargaining interaction between two partner-airlines, and among three objective functions. The alliance partners' decision-makers can repeat the interactive procedure until a satisfactory solution is obtained.

5. Case study

This section presents a case study that demonstrates the application of the proposed models. The object airline is EVA Airways (BR) of Taiwan. EVA Air has made code-sharing arrangements with nine foreign partner airlines on Taiwan–US, –Japan, –Canada, –Australia/New Zealand, –France, and –Indonesia routes. The proposed models were applied to a simplified version of EVA Air's international network and parts of its alliance routes. For simplicity, only Continental Airlines (CO) and All Nippon Airways (ANA, EL) were selected as EVA Air's partners in this case study, since these are two major alliance partners of EVA Air.

Ten cities (nodes $\in N^0$) in six countries were selected from all cities currently served by EVA Air. The nine OD pairs selected were Taipei (TPE)–Hong Kong (HKG), –Tokyo (TYO), –Osaka (OSA), –Fukuoka (FUK), –Bangkok (BKK), –Singapore (SIN), –Los Angeles (LAX), –San Francisco (SFO) and –New York (NYC). TPE is EVA Air's home base. Traffic between these selected OD pairs represents a large proportion of all the traffic carried by EVA Air in Asia and the US. EVA's fleet currently includes ten wide-body aircraft—six Boeing 747-400s (386 seats) and four Boeing 767-300s (226 seats)—that serve these nine OD pairs. Moreover, four US cities served by Continental Airlines and three Japanese cities served by All Nippon Airways. In the case study, Continental serves US domestic OD pairs, including Houston (IAH)–LAX, –SFO, –NYC, and LAX– and SFO–NYC (where IAH is Continental's hub), using five Boeing 737-800s (155 seats) and three Boeing 757-200s (183 seats); and ANA serves Japan–Taiwan OD pairs, including TYO–, OSA–, FUK–TPE, using five Boeing 767-300s (272 seats).

For simplicity, EVA Air is assumed to have made alliances separately with Continental Airlines and All Nippon Airways. Continental chooses nodes LAX, SFO and IAH, while ANA chooses nodes TYO, OSA and FUK to enter a code-share alliance with EVA Air. Fig. 3(a) and (b) present, respectively, the EVA–Continental and the EVA–ANA alliance networks used in this case study. Fig. 3(a) indicates shows that, in the EVA–Continental alliance network, the potential complementary-alliance OD pair is TPE–IAH. Both EVA and Continental jointly provide connecting flights between TPE–IAH through complementary-alliance routes TPE–LAX–IAH and TPE–SFO–IAH, and provide nonstop flights between their local OD pairs TPE–LAX, –SFO and IAH–LAX, –SFO, respectively. Fig. 3(b) shows that the potential parallel-alliance OD pairs are TPE–TYO, –OSA, and –FUK in the EVA–ANA alliance network, on which routes EVA and ANA, simultaneously provide nonstop flights. Interactive procedures are first used to design separately EVA–Continental and EVA–ANA alliance networks, then the determined flight frequencies on relevant alliance routes are input into the single airline network programming models to design EVA, Continental and ANA's networks under alliance conditions.

Historic data (years 1995–2001) on annual country-pair/city-pair traffic among the nine OD pairs in EVA's network (for example, TPE–HKG, –BKK, –SIN, –TYO, –OSA, –FUK, –LAX, –SFO, and –NYC) were used. Annual gross national product per capita for the countries were used as socioeconomic variables. Annual total flight frequencies between OD pairs were used to build grey systematic models (Eq. (5)). Then, the grey systematic models were used to forecast the OD pair passenger traffic for the year 2001. Hsu and Wen (2002) described in detail the building of grey systematic models. Moreover, actual total passenger traffic between each US domestic OD pair (USDOT, 2001), for example, IAH–LAX, –SFO, –NYC, and LAX– and SFO–NYC, in 2001, was used. However, the historic data concerning OD traffic between OD pair TPE–IAH was unavailable, so this OD traffic was approximately estimated from Continental's time table in 2001.

Base values of the cost-function-related parameters are used to solve the network programming problems. Empirical data on operating costs per available-seat-mile for US major airlines, reported in US Bureau of Transportation Statistics (USBTS, 2001), were used to determine the piece-wise linear cost functions, since some of EVA, Continental and ANA's operating cost data were unavailable. Aircraft characteristic data presented in EVA, Continental and ANA's fleet facts, and those reported in Horonjeff and McKelvey (1994) were also used to estimate block times. The load factor for each route was specified according to the average value of the load factors on test routes during 2001.

Complementary-alliance routes: TPE-LAX-IAH, TPE-SFO-IAH

(a)

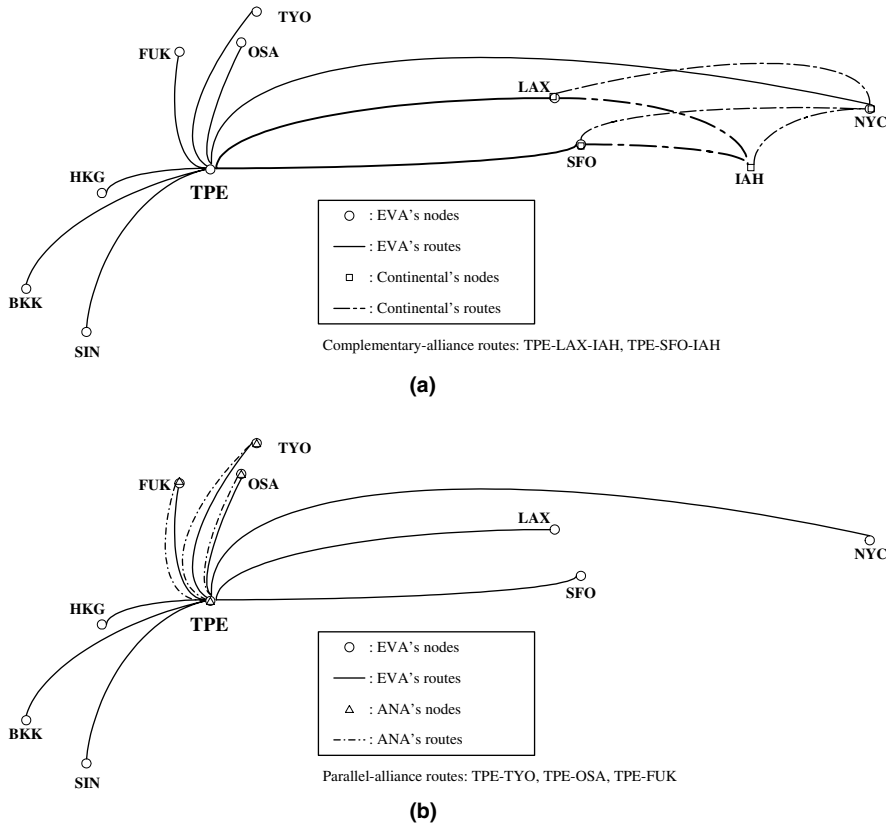Parallel-alliance routes: TPE-TYO, TPE-OSA, TPE-FUK

(b)

Fig. 3. Network patterns for (a) EVA–Continental alliance, and (b) EVA–ANA alliance.

Before the rest of the application of the model is described, the statistical estimates pertaining to the market share model are first discussed. Monthly data from 1999 to 2000, involving OD passenger demands, passenger traffic on airlines, and airline flight frequencies for all OD pairs, were used. Table 1 lists the estimation results obtained from the market share models for the nine OD pairs of EVA's network. A highly significant fit between the estimated models and the historical data was found. From Table 1, the adjusted R^2 values range from 0.72 to 0.97. F-statistics range from 60.96 to 925.34, indicating the significance of the estimated regression results. Furthermore, the t-statistics for each of the estimated γ and α are also significant. Table 1 indicates that the estimated frequency share elasticity, α, varies between 0.91 and 1.28. Cohas et al. (1995) presented similar findings.

This case study considers other major airlines that currently serve an OD pair in EVA, Continental and ANA's networks, as the alliance partners' competitors. Actual market shares of EVA, Continental and ANA for all OD pairs in year 2001 were used as the initial market shares, and actual flight frequencies were used as the initial flight frequencies for other competitors in all OD markets. Table 2 lists the initial values of market shares of EVA, Continental and ANA, the initial flight frequencies for all competitors, and initially estimated OD passenger demands in year 2001 for all OD pair markets. Then, LINGO was used to solve the airline network programming problem and the multiobjective programming problem for the alliance-based network. The interactive procedures for designing an alliance network allowing, allowing for bargaining between DMs. were then conducted by implementing the proposed algorithm.

First, pre-alliance solutions were determined as a benchmark, describing a situation in which EVA, Continental and ANA were not involved in an alliance. Then the flight frequencies on the network of each of

Table 1
Estimation results of the market share models of individual OD pairs in EVA's network

OD pairs	Estimated model coefficient		Adjusted R^2	F
	γ	α		
TPE–HKG	1.1738 (1.76)	1.280 (7.95)	0.7302	63.25
TPE–TYO	1.0137 (1.91)	0.989 (16.35)	0.9205	267.18
TPE–OSA	0.6374 (−3.11)	0.931 (9.24)	0.7859	85.43
TPE–FUK	0.7679 (−1.91)	1.026 (10.93)	0.8375	119.51
TPE–BKK	0.8777 (−1.86)	0.962 (14.41)	0.8998	207.56
TPE–SIN	0.7718 (−5.09)	0.965 (30.42)	0.9757	925.34
TPE–LAX	1.0393 (1.76)	1.008 (23.08)	0.9585	532.76
TPE–SFO	1.0178 (1.79)	0.913 (7.81)	0.7228	60.96
TPE–NYC	1.0987 (1.80)	0.965 (22.72)	0.9573	516.38

Note: *t*-statistics are listed in parentheses.
Data source: Department of Statistics, M.O.T.C., R.O.C. (1999–2000), and Civil Aeronautics Administration, M.O.T.C., R.O.C. (1999–2000).

these three airlines was determined, using initial OD market shares, according to the single airline network design model, as in Eqs. (7a)–(7f). The determined route flight frequencies and the objective function values for EVA, Continental and ANA under pre-alliance conditions are, respectively, listed in Table 3(a)–(c).

Consider the situation in which EVA and ANA make parallel alliances on routes TPE–TYO, –OSA and –FUK. An ideal point is first specified to solve the multiobjective programming problem (Eqs. (11a)–(11o)) for the integrated alliance network, using the algorithm described in the previous section. Thus, three single-objective programming problems are solved to determine flight frequencies in the integrated alliance network by maximizing total profits, maximizing the total number of passengers carried and minimizing the total passenger schedule delays subject to the given set of constraints. In this case study, the authors took the role of decision-makers. The initial reference point was given as the ideal point Z^{ideal}, such that

Desired total profit $Z_1^{\max}$	3722279 (US $)
Desired total number of passengers $Z_2^{\max}$	33248 (passengers)
Desired total passenger schedule delay $-Z_3^{\max}$	−83029.01 (passenger-hrs)

Then, the corresponding achievement scalarizing programming problem (Eq. (14) with Eqs. (11d)–(11o)) was solved using the initial reference point. The following results were obtained.

Iteration 1-1

Desired total profit $\widehat{Z}_1^1$	3722279 (US $)
Total profit obtained Z_1^1	3653356 (US $)
Desired total number of passengers $\widehat{Z}_2^1$	33248 (passengers)
Total number of passengers Z_2^1	35262 (passengers)
Desired total passenger schedule delay $-\widehat{Z}_3^1$	−83029.01 (passenger-hrs)
Total passenger schedule delay $-Z_3^1$	−84068.11 (passenger-hrs)
EVA's total profit π_0^1	3019140 (US $)
ANA's total profit π_1^1	600980 (US $)

These results show that the total number of passengers exceeds the desired total number of passengers. However, the initial desired levels for both total profits and total passenger schedule delays were set too high to be achieved. Moreover, from the current solution (which is one of the Pareto optimal solutions) under the parallel-alliance conditions, EVA enjoys higher profits than before the alliance was established.

Table 2
Initial market shares of the object airline and its partners, flight frequencies of all competitors, and market demand on individual OD pairs

OD pairs	Object/partner airlines	Market share* (%)	OD demand in 2001* (annual traffic)	Competitor	Flight frequency* (flights/week)
TPE–HKG	BR	9	2785306	CI	64
				CX	54
				EG	7
				SQ	3
				TG	14
TPE–TYO	BR	21.9	943128	CI	21
	EL	32.7		CX	7
				SQ	3
TPE–OSA	BR	18.3	409512	CX	7
	EL	21.1		SQ	3
TPE–FUK	BR	11	212729	CI	7
	EL	11		CX	7
TPE–BKK	BR	28.4	656335	CI	21
				TG	21
				KL	7
TPE–SIN	BR	23	299633	CI	7
				SQ	8
TPE–LAX	BR	32	625700	CI	13
				SQ	7
				MH	4
				UA	7
TPE–SFO	BR	48	344840	CI	7
				UA	7
TPE–NYC	BR	31.9	132394	CI	6
				UA	7
IAH–LAX	CO	67	243520	UA	4
IAH–SFO	CO	70	219790	UA	3
IAH–NYC	CO	85	333470	–	–
NYC–LAX	CO	36	378560	AA	14
				UA	14
NYC–SFO	CO	39	345670	UA	20

Note: – not available or too small for comparison; * one direction.

However, ANA has reduced profits compared to before the alliance. See the objective function values in Table 3(c). Since the current Pareto optimal solution is unsatisfactory, decision makers are asked to offer a new reference point. The DMs of ANA are assumed to set the requirement that post-alliance profit exceeds pre-alliance profit, while the DMs of EVA are assumed to have satisfactory current profit, the maintenance of which is their desired profit. That is, the desired total profits are set to be the sum of ANA's initial profit and EVA's current profit. Furthermore, on OD pairs TPE–TYO, –OSA, –FUK, –HKG, and -SIN, OD passenger demands will increase once EVA and ANA increase their flight frequencies. Competitors in these OD markets also increased their flight frequencies with the number of OD passengers. The total OD passenger traffic was estimated using Eq. (5) and the market shares of EVA and ANA were

Table 3
Determined route flight frequencies and the values of the objective functions in single airline network programming problems under pre-alliance conditions: (a) EVA Airways; (b) Continental Airlines; (c) All Nippon Airways

(a) *EVA Airways*			(b) *Continental Airlines*			(c) *All Nippon Airways*		
Route	Flight freq. (flights/week)		Route	Flight freq. (flights/week)		Route	Flight freq. (flights/week)	
TPE–TYO	B747-400	14	IAH–LAX	B737-800	7	TPE–TYO	B767-300	21
	B767-300	0		B757-200	17			
TPE–OSA	B747-400	6	IAH–SFO	B737-800	3	TPE–OSA	B767-300	7
	B767-300	0		B757-200	19			
TPE–FUK	B747-400	2	IAH–NYC	B737-800	33	TPE–FUK	B767-300	3
	B767-300	1		B757-200	12			
TPE–HKG	B747-400	20	LAX-NYC	B737-800	5			
	B767-300	0		B757-200	15			
TPE–BKK	B747-400	0	SFO–NYC	B737-800	7			
	B767-300	22		B757-200	13			
TPE–SIN	B747-400	5						
	B767-300	1						
TPE–LAX	B747-400	14						
TPE–SFO	B747-400	11						
TPE–NYC	B747-400	5						

Objective function values ($/week):
EVA's profit: $ 2910072   CO's profit: $ 1041435   ANA's profit: $ 662087

estimated using Eq. (3) for all OD pairs in this iteration. Solving the achievement scalarizing problem then yields:

Iteration 1-2

Desired total profit $\widehat{Z}_1^2$	3681227 (US $)
Total profit obtained Z_1^2	3736523 (US $)
Desired total number of passengers $\widehat{Z}_2^2$	33248 (passengers)
Total number of passengers Z_2^2	36151 (passengers)
Desired total passenger schedule delay $-\widehat{Z}_3^2$	−83029.01 (passenger-hrs)
Total passenger schedule delay $-Z_3^2$	−84591.74 (passenger-hrs)
EVA's total profit π_0^2	3036434 (US $)
ANA's total profit π_1^2	665938 (US $)

Based on the above Pareto optimal solution, both EVA and ANA earn more profits, and also have more passengers and fewer schedule delays than before they entered the alliance. The decision makers are satisfied with this Pareto optimal solution, and thus a satisfactory solution has been obtained; Table 4 lists the determined route flight frequencies.

Consider another situation in which EVA and Continental make complementary alliances on routes TPE–LAX–IAH and TPE–SFO–IAH. For simplicity, only EVA's network and Continental's network are combined into the integrated alliance network. The partner airline (airline '1') is now Continental Airlines. The ideal point was also determined by single-objective programming to maximize total profits, maximize the total number of passengers carried and minimize the total passenger schedule delays. The initial reference point for this situation was also given as the ideal point, such that

Table 4
Satisfactory solution for the EVA–ANA parallel-alliance-based network

EVA Airways			All Nippon Airways		
Route	Flight freq. (flights/week)		Route	Flight freq. (flights/week)	
TPE–TYO	B747-400	11	TPE–TYO	B767-300	21
	B767-300	10			
TPE–OSA	B747-400	4	TPE–OSA	B767-300	9
	B767-300	4			
TPE–FUK	B747-400	1	TPE–FUK	B767-300	4
	B767-300	1			
TPE–HKG	B747-400	14			
	B767-300	13			
TPE–BKK	B747-400	9			
	B767-300	8			
TPE–SIN	B747-400	4			
	B767-300	4			
TPE–LAX	B747-400	14			
TPE–SFO	B747-400	11			
TPE–NYC	B747-400	5			
EVA's profit: $ 3036434			ANA's profit: $ 665938		

Total alliance profits ($/week) Z_1	3736523
Total number of passengers (pax/week) Z_2	36151
Total passenger schedule delays (pax-hr/week) Z_3	84591.74

Desired total profits Z_1^{max}	4972633 (US $)
Desired total numbers of passengers Z_2^{max}	52061 (passengers)
Desired total passenger schedule delay $-Z_3^{max}$	−102650 (passenger-hrs)

The corresponding achievement scalarizing programming problem was then solved using the initial reference point. The following solution was obtained.

Iteration 2-1

Desired total profit $\widehat{Z}_1^1$	4972633 (US $)
Total profit obtained Z_1^1	5114008 (US $)
Desired total number of passengers $\widehat{Z}_2^1$	52061 (passengers)
Total number of passengers Z_2^1	50855 (passengers)
Desired total passenger schedule delay $-\widehat{Z}_3^1$	−102650 (passenger-hrs)
Total passenger schedule delay $-Z_3^1$	−107161.9 (passenger-hrs)
EVA's total profit π_0^1	4100197 (US $)
Continental's total profit π_1^1	1102170 (US $)

These results reveal that the initial desired total number of passengers and total passenger schedule delay were set too high to be achieved. The total profits exceeded the initial desired total profit. Under the current complementary-alliance conditions, both EVA and Continental enjoy more profit than before they established an alliance. See the objective function values in Tables 3(a) and (b). The decision-makers are most interested in earning profits and are thus willing to reduce the desired number of passengers and the

passenger schedule delay to 50855 (passengers) and −107162 (passenger-hrs), respectively. Solving the achievement scalarizing problem once again, however, yields the same results as obtained in the previous iteration. The decision makers thus accept these results as satisfactory. Table 5 lists the determined route flight frequencies.

The above satisfactory solutions determine both EVA's and ANA's flight frequencies on parallel-alliance routes TPE–TYO, –OSA and –FUK. EVA's flight frequencies on routes TPE–LAX and –SFO and Continental's flight frequencies on routes IAH–LAX and –SFO were also determined under complementary-alliance conditions. These determined flight frequencies on the parallel-alliance and complementary-alliance routes were input to the single airline network programming models for EVA's, Continental's and ANA's networks, respectively, to determine the flight frequencies on their non-alliance routes under alliance conditions. Table 6(a)–(c) list the determined route flight frequencies and the objective function values for EVA's, Continental's and ANA's networks when allied.

The alliance solutions (Table 6) for EVA, Continental and ANA are compared to the pre-alliance solutions (Table 3) to elucidate the effects of the two alliances on alliance-partners' outputs and profits. Under alliance conditions, EVA, Continental and ANA all earned more profits than before they entered alliances. The complementary alliance first created new demand for the OD pair TPE–IAH on complementary-alliance routes, TPE–LAX–IAH and TPE–SFO–IAH. Therefore, EVA increased flight frequencies on links

Table 5
Satisfactory solution for the EVA–Continental complementary-alliance-based network

EVA Airways			Continental Airlines		
Route	Flight freq. (flights/week)		Route	Flight freq. (flights/week)	
TPE–TYO	B747-400	0	IAH–NYC	B737-800	48
	B767-300	24		B757-200	0
TPE–OSA	B747-400	0	LAX–NYC	B737-800	23
	B767-300	10		B757-200	0
TPE–FUK	B747-400	0	SFO–NYC	B737-800	23
	B767-300	5		B757-200	0
TPE–HKG	B747-400	0	IAH–LAX	B737-800	36
	B767-300	34	IAH–LAX (–TPE)*	B757-200	4
TPE–BKK	B747-400	12	IAH–SFO	B737-800	0
	B767-300	0		B757-200	24
TPE–SIN	B747-400	6	IAH–SFO (–TPE)*	B757-200	2
	B767-300	0			
TPE–LAX	B747-400	16			
TPE–LAX (–IAH)*	B747-400	4			
TPE–SFO	B747-400	12			
TPE–SFO (–IAH)*	B747-400	2			
TPE–NYC	B747-400	5			
EVA's profit: $ 4100197			Continental's profit: $ 1102170		
Total alliance profits ($/week) Z_1				5114008	
Total number of passengers (pax/week) Z_2				50855	
Total passenger schedule delays (pax-hr/week) Z_3				107161.9	

Note: * complementary-alliance routes.

Table 6
Determined route flight frequencies and airline profits under the alliance, for individual partners: (a) EVA Airways; (b) Continental Airlines; (c) All Nippon Airways

(a) *EVA Airways*			(b) *Continental Airlines*			(c) *All Nippon Airways*		
Route	Flight freq. (flights/week)		Route	Flight freq. (flights/week)		Route	Flight freq. (flights/week)	
TPE–TYO	B747-400	11	IAH–LAX	B737-800	36	TPE–TYO	B767-300	21
	B767-300	10		B757-200	4			
TPE–OSA	B747-400	4	IAH–SFO	B737-800	0	TPE–OSA	B767-300	9
	B767-300	4		B757-200	26			
TPE–FUK	B747-400	1	IAH–NYC	B737-800	7	TPE–FUK	B767-300	4
	B767-300	1		B757-200	34			
TPE–HKG	B747-400	15	LAX–NYC	B737-800	18			
	B767-300	8		B757-200	4			
TPE–BKK	B747-400	12	SFO–NYC	B737-800	7			
	B767-300	1		B757-200	13			
TPE–SIN	B747-400	5						
	B767-300	1						
TPE–LAX	B747-400	20						
TPE–SFO	B747-400	14						
TPE–NYC	B747-400	5						

Individual alliance-partners' profits ($/week):

EVA's profit: $ 3309531	CO's profit: $ 1145834	ANA's profit: $ 665938

TPE–LAX and –SFO and Continental increased flight frequencies on links IAH–LAX and –SFO. On OD pairs TPE–LAX, –SFO and IAH–LAX, –SFO, the increases in EVA's and Continental's flight frequencies increased their market share in these OD markets. Consequently, in a complementary alliance, both EVA and Continental increased their flight frequencies.

On parallel-alliance routes TPE–TYO and TPE–OSA, EVA shifted some flight frequencies from larger aircraft (Boeing 747-400s) to smaller aircraft (Boeing 767-300s) with higher load factors, while ANA also increased its flight frequencies on routes TPE–OSA and TPE–FUK. This result implied that it is possible for partner airlines to eliminate indivisibilities under their parallel alliance. From the results, the partner airlines made more seats available than were available under pre-alliance conditions. Although their competitors also increased flight frequencies as OD passenger demand grew, the parallel-alliance market shares for EVA and ANA increased. On the other parallel-alliance route, TPE–FUK, ANA added one flight per week whereas EVA removed one flight. However, the total number of available seats proposed by their joint flight services on TPE–FUK decreased after the parallel alliance. On the OD pair TPE–FUK, EVA and ANA had a relatively low parallel-alliance market share (about 23%) in a market of four competing airlines. This share was also lower than the parallel-alliance market shares on TPE–TYO and –OSA, indicating that airlines are more likely to establish a parallel alliance in markets in which they have greater market shares. Park (1997) and Park and Zhang (1998) provided similar findings.

Moreover, the route flight frequencies on three alliance partners' networks obtained from our models were reasonable, as determined by comparing them with the actual 2001 time tables of EVA, ANA and Continental. Restated, this case study demonstrates how airline network programming models and interactive multiobjective programming models may be applied to planning airline code-share alliances.

6. Conclusions

This study developed an interactive airline network design procedure to determine international code-share alliance-based networks, by taking into account alliance performance and bargaining interactions. The models proposed here include a single airline network programming model in profit-maximizing programming form and an integrated alliance network design model in multiobjective programming form. When designing an integrated alliance network, the objectives are to maximize total profits, maximize the total number of passengers carried and minimize the total passenger schedule delays. Then, the integrated alliance network model and two alliance airlines' network models are combined in a two-level hierarchical programming process, of which the upper level includes the integrated alliance network model and the lower level includes two single alliance airlines' network models. Moreover, the bargaining interactions between two partner-airlines and various objective functions of partner airlines in alliance negotiations are considered. This study uses a reference point method to solve the two-level hierarchical programming model, allowing for bargaining interactions between alliance partners in competitive environments.

The developed models are applied to a simplified version of EVA Airways' network and to selected nodes in the networks of its two major alliance-partners (Continental Airlines and All Nippon Airways). An analysis of the satisfactory solutions yielded by the interactive multiobjective programming procedures reveals that all alliance partners enjoyed more profit under alliance conditions than before they established the alliance. Under complementary-alliance conditions, both EVA and Continental increased their flight frequencies. The increases in EVA's and Continental's flight frequencies increased their market shares for complementary-alliance OD pairs, and for relevant complementary-alliance links. Under parallel-alliance conditions, the alliance partners may produce less if their market shares are lower. Airlines are more likely to establish a parallel alliance in markets in which they have large market shares. The results of this case study were shown to be reasonable, by comparing them with the actual 2001 time tables of EVA, ANA and Continental.

This study demonstrates how interactive multiobjective programming models may be applied to designing alliance airlines' networks proactively and determining flight frequencies on airline code-share alliance networks. The proposed models help alliance airlines can to evaluate iteratively their outputs and profits, and are planning tools for designing alliance-based networks, to be used in code-share alliance negotiations. This study mainly examines the effects of the two alliances on alliance-partners' outputs and profits. The effects of alliances on airfare reductions and alliance immunity are beyond the scope of this study. Future studies could further incorporate pricing models into airline network programming models. Further studies also are required to consider the joint cost and revenue allocation problems. The proposed interactive programming procedure could further be developed with some modifications to analyze the bargaining involved in setting alliance pricing. However, the complexity of airfare structures and code-sharing pacts requires careful study before doing this.

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