Model for Evaluating the Hub-Spokes Network for Air Cargo Transport: Single Hub vs. Dual Hub

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Contents

INTRODUCTION

- Growth of International Air Cargo Transport Markets.
- Shape of Network
  - Single Hub System in a region (most Asian carriers)
  - Multiple Hub System in a region (FedEx, UPS, ANA)
- Design of the Network
  - O'Kelly (1989, 1992): p-median hub
  - Adler and Smilowitz (2007): hub location considering competition between carriers.

INTRODUCTION (cont.)

- Hub Location Problem: Usually considered as "cost minimization problem" of single carrier.
- Adler and Smilowiz disucss the hub location problem considering competition among carriers, but <u>they neglect the network design</u> (frequency, aircraft choice,etc.)
- Mission: Discuss the hub location considering competition and network design.

Purpose of This Work

- We propose the computable model for understanding the relation between the hub location and network design from the theoretical point of view and discuss the competitiveness of hub-spokes system comparing single hub system with multiple (dual) hub system.

Model Formulation

Concept of the model

- Bi-level Transport Market Model: Based on carrier-passenger interaction model (2007).
  - Carrier: Profit maximization. Oligopoly market.
  - User: Generalized cost minimization. Stochastic user equilibrium state (SUE) under capacity constraints.

Shippers and Cargo Flow

- Purpose: Generalized cost minimization.
  - Generalized cost: travel time, shipping tariff, load/off-load charges, and congestion.
- OD cargo flow: predetermined and fixed.
- Service information: given by carriers.

Shippers' Route Choice Behavior: Cargo Allocation Problem

$$Object: \Gamma(x_k^{rs}) = \frac{1}{\theta} \sum_{rs\in\Omega} \sum_{k\in K^{rs}} x_k^{rs} (\ln x_k^{rs} - 1) + \sum_{rs\in\Omega} \sum_{k\in K^{rs}} u_k^{rs} x_k^{rs} \rightarrow \min \qquad (1)$$

Subject to

$$\sum_{k\in K^{rs}} x_k^{rs} = X^{rs},\ for\ \forall rs \in \Omega, \qquad (2)$$

$$x_{l^n} = \sum_{rs} \sum_{k} x_k^{rs} \delta_{l^n}^{rsk} \le v_{l^n} f_{l^n},\ for\ \forall l^n \in I^n, \forall n \in N, \qquad (3)$$

$$x_k^{rs} \ge 0,\ for\ \forall k \in K^{rs}, \forall rs \in \Omega, \qquad (4)$$

$$u_k^{rs} = p_k^{rs} + \sum_{l^n} \left(\alpha_1 t_{l^n} + \alpha_2 \frac{1}{f_{l^n}} + \lambda_{l^n} \right) \delta_{l^n}^{rsk}$$

Air Cargo Carriers' Behavior

- Purpose: Profit maximization by designing the network.
  - Network design: choose the aircraft size and determine the flight frequency.
  - Tariff: predetermined and fixed.
  - Shape of network (hub location): given as scenarios.

Carrier's Profit Maximization Problem

$$Object: \pi^n(f_{l^n \in I^n}, v_{l^n \in I^n}, \tilde{f}_{l^{-n} \in I^{-n}}, \tilde{v}_{l^n \in I^{-n}}) = \sum_{rs}\sum_{k} p_k^{rs} \hat{x}_k^{rs} \delta_n^{rsk} - \sum_{l \in I^n} C_{l^n}^{OP}(v_{l^n}) f_{l^n}, \ for \quad \forall n \quad , \tag{6}$$

subject to

$$f_{l^n} v_{l^n} \geq x_{l^n} = \sum_{rs}\sum_{k} \hat{x}_k^{rs} \delta_{l^n}^{rsk}, \ for \forall l \in I^n, \tag{7}$$

$$\sum_{l^n} f_{l^n} \delta_{l^n}^h \leq F_h^n \quad for \ \forall h \in H, \tag{8}$$

$$f_{l^n} \geq 0, \ for \forall l^n \in I^n, \tag{9}$$

$$\hat{x}_k^{rs} = \arg\{\min : \Gamma(x_k^{rs}) \ subject\, to (2)\, to (4)\}, \ for \forall k \in K^{rs} \quad and \quad rs \in \Omega \quad , \tag{10}$$

Obtaining the Sub-game Perfect Solution for Carriers

- We adopt two-stage game framework.
  - In first stage, carriers choose aircraft size for each leg.
  - In second stage, they design their network (determine the flight frequency).
- Nash equilibrium or prisoner's dilemma?
  - Consider both “General Nash equilibrium” and “Stackelberg (leader-follower) Equilibrium.”

NUMERICAL EXAMPLES

Market Conditions

1. We consider duopoly market: there are two carriers in the market.
2. The target area consists of <u>five zones</u> and <u>each zone has one airport</u>. Each OD shippers can use its local airport as a departure/arrival airport. Each OD volume is 500.
3. The shape of service network is predetermined and fixed.
4. Each OD tariff (airfare) is predetermined and fixed.
5. We consider the <u>single assignment hub-spokes</u> system.
6. Each carrier chooses the aircraft type: 100-space (type A) or 200-space (type B).
7. Constant marginal cost of each link (type 1>type 2). Operational cost is formulated as a function of stage length.

Shapes of Network

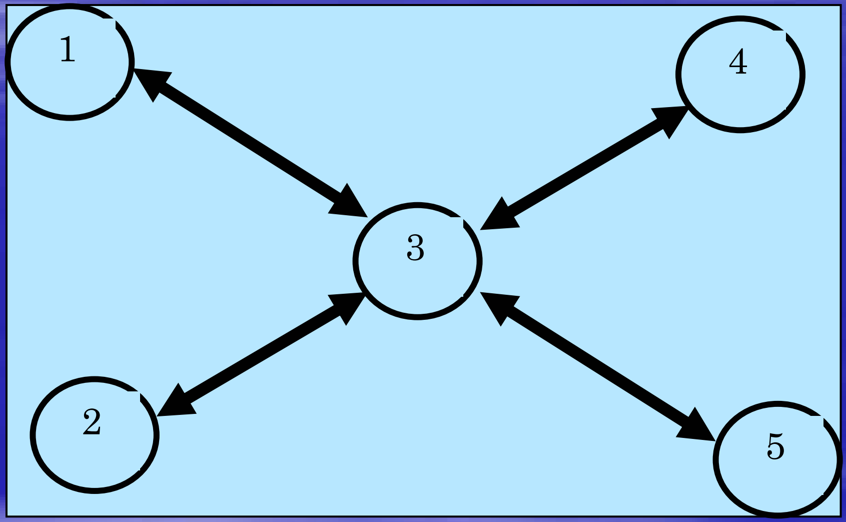


Figure 1 Single-Hub System (type 1)

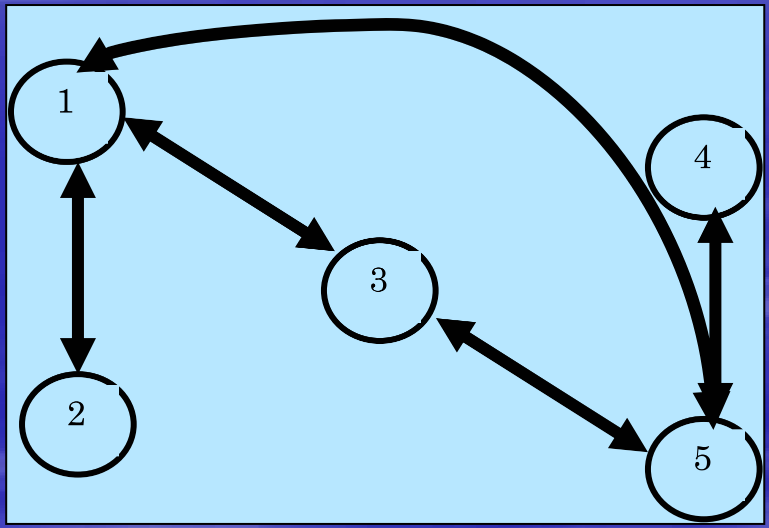


Figure 2 Dual-Hub System (type 2)

Table 1 List of Strategies (1) type 1 network

Strategy	Combination	No.	Combi.	No.	Combi.	No.	Combi.
1	A, A, A, A	5	A, B, A, A	9	B, A, A, A	13	B, B, A, A
2	A, A, A, B	6	A, B, A, B	10	B, A, A, B	14	B, B, A, B
3	A, A, B, A	7	A, B, B, A	11	B, A, B, A	15	B, B, B, A
4	A, A, B, B	8	A, B, B, B	12	B, A, B, B	16	B, B, B, B

(2) type 2 network

Strategy	combination	No.	Combi.	No.	Combi.	No.	Combi.
1	A, A, A, A, A	5	A, A, B, A, A	9	A, B, A, A, A	13	A, B, B, A, A
2	A, A, A, A, B	6	A, A, B, A, B	10	A, B, A, A, B	14	A, B, B, A, B
3	A, A, A, B, A	7	A, A, B, B, A	11	A, B, A, B, A	15	A, B, B, B, A
4	A, A, A, B, B	8	A, A, B, B, B	12	A, B, A, B, B	16	A, B, B, B, B
Strategy	combination	No.	Combi.	No.	Combi.	No.	Combi.
17	B, A, A, A, A	21	B, A, B, A, A	25	B, B, A, A, A	29	B, B, B, A, A
18	B, A, A, A, B	22	B, A, B, A, B	26	B, B, A, A, B	30	B, B, B, A, B
19	B, A, A, B, A	23	B, A, B, B, A	27	B, B, A, B, A	31	B, B, B, B, A
20	B, A, A, B, B	24	B, A, B, B, B	28	B, B, A, B, B	32	B, B, B, B, B

Base Case

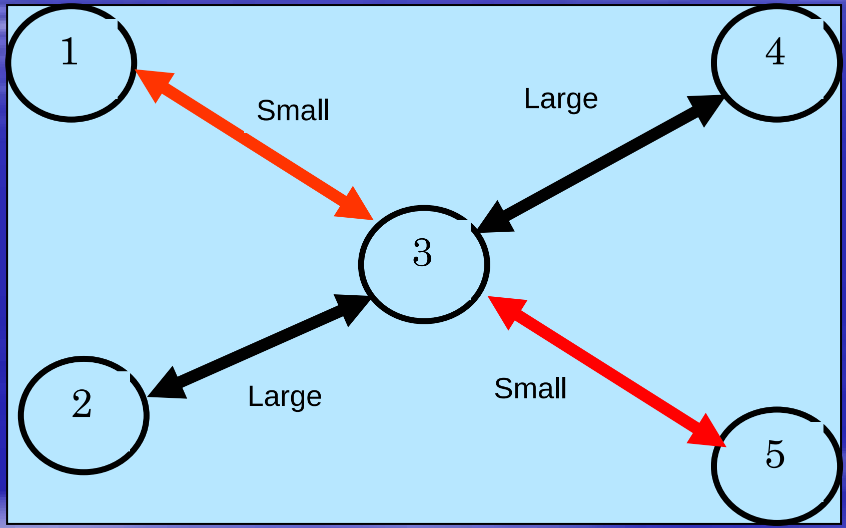
- We cannot have the stable and unique Nash equilibrium.
- We have (16, 1) or (1, 16) equilibria in terms of Stackelberg equilibrium.
- If we assume that each carrier adopt mini-max strategy, we have (1, 1) combination as mini-max solution
  - The profit of each carrier is 26,089.

Base Case: Discussion

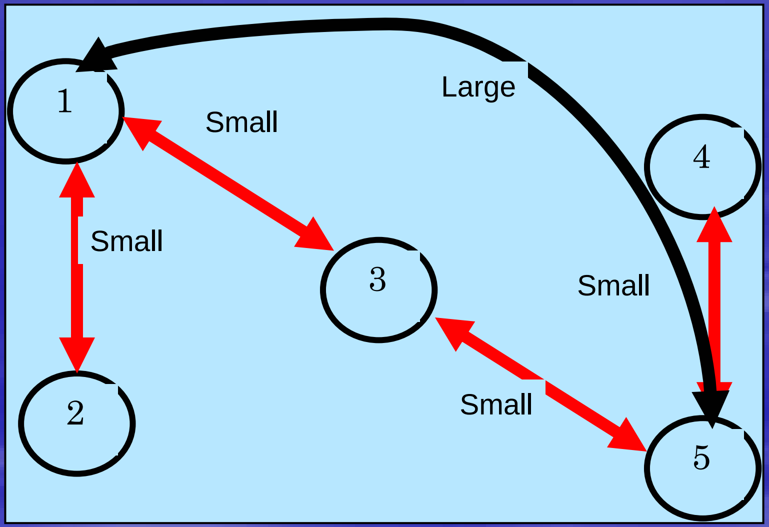
- Mini-max result suggests that if each carrier has a pessimistic prediction about rival's response, we have a unique solution.
  - If they have an optimistic forecast—taking Strategy 16, their profit gets worse because each leg has enough space to carry cargos and is not congested.
- This result changes if the OD volume increases.
  - We have scenarios in which we set doubled and tripled OD volume for each OD market.
  - The results show if OD volume increases, carriers can have (16, 16) as their reasonable mini-max solution.

Dual Hub vs. Single Hub (Case 1)

- All OD volume is 500 (same as Base Case).
- Carrier 1 adopts type 1 network and Carrier 2 adopts type 2 network.
- Result
  - We have (7, 5) as the stable Nash equilibrium.
  - Maximum profits of Carrier 1 and 2 are 38,939 and 35,752, respectively.
  - Carriers choose small aircraft in the markets where both carriers set direct flight services.
  - Conversely, if one carrier has a direct service and the other does not have, the direct service carrier (Carrier 1 in link 2-3) chooses large aircraft and the connecting service carrier (Carrier 2 in link 2-3) chooses small aircraft.



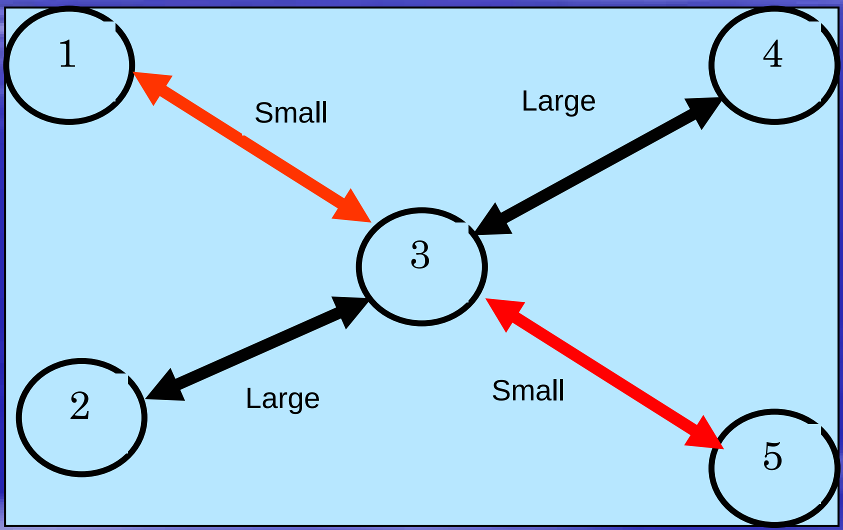
Equilibrium Network in Case 1 (type 1)



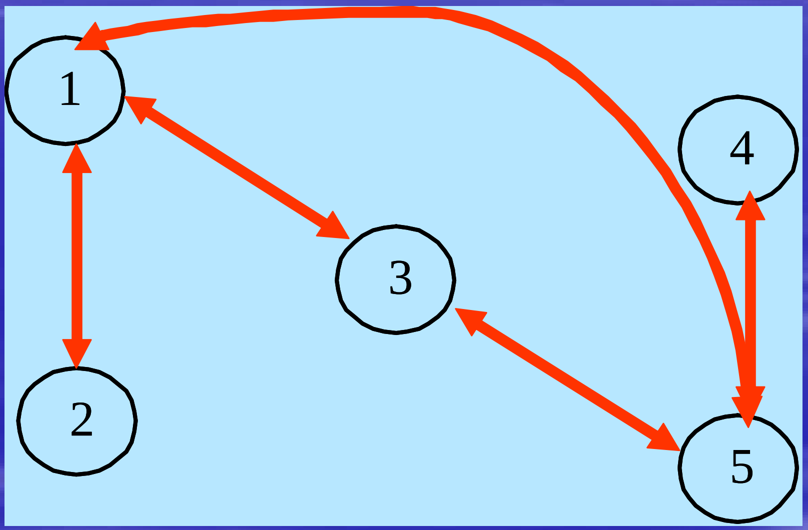
Equilibrium Network in Case 1 (type 2)

Sensitivity Analysis on Network Configuration (Case 2)

- We set up OD 1-2 and 4-5 as local markets and their distance is shorter than global markets such as OD 1-3 and 2-3.
- Results (summary)
  - Carrier 2 changes their strategy to “small aircraft for all markets,” while Carrier 1’s strategy remains the same.
  - Carrier 1’s profit changes from 38,939 to 37,975 and Carrier 2’s profit changes from 35,752 to 49,739.



Equilibrium Network in Case 1 (type 1)



Equilibrium Network in Case 1 (type 2)

Sensitivity Analysis on Network Configuration (Case 2) (Cont.)

- Result (summary: cont.)
  – Carrier 1 increases frequency in 1-3 and 3-5 due to the tougher competition, but the load factors in both links drop from 0.92 to 0.88and this causes the decline of profitability.
  – On the contrary, Carrier 2’s average load factor rises to 0.84 from 0.82.

Service Frequency and Link Flow (Case 1 and 2)

	Carrier 1					Carrier 2			
	Case 1		Case 2			Case 1		Case 2	
Link	Freq	Flow	Freq	Flow	Link	Freq	Flow	Freq	Flow
1-3	4.08	376.14	4.32	384.47	1-2	5.33	495.91	5.14	496.59
2-3	3.45	690.87	3.15	630.39	1-3	3.69	240.46	3.85	239.97
3-4	3.45	690.83	3.15	630.41	1-5	3.13	541.37	3.91	391.41
3-5	4.08	375.78	4.32	384.46	3-5	3.69	241.76	3.85	240.04
					4-5	5.33	533.98	5.14	501.22

Summary of Conclusion

1. If we have a symmetric condition regarding the distance of leg, the single (global) hub system is more profitable than dual hub system.
2. If we have an asymmetric condition such as the distance of local market is much shorter than that of global market occurs, dual hub (gateway type) system can be more profitable than single hub.

FUTURE STUDIES

- Simulation under more complex situation is required.
  - – Asymmetric OD volume.
  - – Multi assignment network.
  - – Etc.
- Application to the actual market.