# Airline Network: Critical Leg Assessment via Variation in Practical Capacity

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***Abstract*—This research to the best of our knowledge is the first to quantify airline network sustainability in the presence changeable capacity of legs and alternative flights. In this article we try to recognize critical legs via changing practical capacity of airline network components. We try to assess the behavior of legs and network via variation of leg capacities while proposing a new leg cost function, also we demonstrate how to capture the robustness of airline network in the case of variable legs represented by decreasing and increasing capacities. We are using Relative Total Cost indices to assess airline network sustainability in the case of behavior associated with User–Optimization. In this article from different point of view, passenger's rout preference behaviors are the main subject. Numerical case study is presented for illustration purposes.**

***Index Terms*—Airline network, arc capacity variation, calibrated link cost function, Relative Total Cost indices, Network Sustainability, User-Optimization.**

## I. Introduction

Networks are complex, typically, large-scale systems, and their formal study has attracted much interest from a plethora of scientific disciplines [4].

As *Ortúzar and Willumsen*, (2001) mentioned, The transportation system can be viewed as a conventional economic system with demand and supply subsystems. The demand side is comprised by mode specific origin destination (O-D) matrices. The supply side of a transportation system is comprised by a network represented by links, nodes and their associated costs.
In traffic assignment, an O-D trip matrix is loaded onto the network and a set of link flows is produced [15].

In this paper, we propose a novel approach for evaluating the sustainability of an airline network based on the relative total cost of the transportation network in the case of leg variation captured through a uniform link capacity ratio. The relative total cost index can be evaluated at either User-Optimal (U-O) traffic flows or System-Optimal (S-O) traffic flows. A modified leg cost function enables the quantitative assessment of the changes in the relative total cost of a transportation network, in the case of alternative travel behavior, when the link practical capacities are decreased or increased.

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The increase and decrease of air carriers in networks due to maintenance, scheduling and routing approaches, air planes and airports deterioration over time, as well as politic decisions lead to time consuming and costly connection flights, lack of flights and poor service quality would effect passenger decision manners. The important factors in flight selection process for passengers are fare, welfare and flight time possibility [11].

The research into the robustness of transportation networks in the presence of disruptions is relatively recent. To the best of our knowledge, the papers of Sakakibara et al. (2004) and of Scott et al. (2006) stand as the first attempts to address the robustness of transportation networks. Nagurney and Qiang (2010) provides an overview of some of the recent developments in the assessment of network vulnerability and robustness through appropriate tools that assist in the quantification of network efficiency (performance) and the identification of the importance of network components, such as nodes and links [13]. In an airline network there are hub and spokes that every leg and flight variance is affecting the whole network sustainability. In this try all the words link or arc are mentioning a flight and the word node is mentioning airport.

This paper is organized as follows. In Section 2, we propose the components of the relative total cost index. Forasmuch as the well-known U-O and S-O transportation network models corresponding, respectively, to Wardrop's first and second principles of travel behavior (cf. Wardrop, 1952; see also, e.g., Beckmann, McGuire and Winsten, 1956, Dafermos and Sparrow, 1969, Smith, 1979, Dafermos, 1980, Sheffi, 1985, and Nagurney, 2000) We will show that, for the same network topologies and with user link cost functions, but linear, that the relative total cost index under the U-O flow pattern can be obtained via an slightly modified formula. In section 3 we describe the relative total cost index that can be used to assess transportation network robustness and which permits either U-O or S-O travel behavior. In section 4 for the first time we are trying to evaluate the airline network sustainability by the reduction and inflation of flight capacity by network robustness measure which has been established by Nagurney and Qiang. In section 5, a case



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study with real data from a partial network of an airline has been considered.

## II. Principal and Components of Relative Total Cost Indices

### A. Decentralized Decision-Making and Centralized Decision-Making (U-O and S-O)

Wardrop (1952) explicitly recognized alternative possible behaviors of users of transportation networks and stated two principles, which are commonly named after him. These principles correspond, in effect, to decentralized versus centralized behavior on networks and, although stated in a transportation context, have relevance to many different network systems. Hence, we now recall Wardrop's two principles:

*First Principle:* The journey times of all routes actually used are equal and less than those that would be experienced by a single vehicle on any unused route.

*Second Principle:* The average journey time is minimal [2].

The first principle corresponds to the behavioral principle in which travelers seek to (unilaterally) determine their minimal costs of travel whereas the second principle corresponds to the behavioral principle in which the total cost in the network is minimized.

Beckmann, McGuire, and Winsten (1956) established the equivalence between the *traffic network equilibrium* conditions, which state that all used paths connecting an origin-destination pair will have equal and minimal travel times (or costs); corresponding to Wardrop's first principle, and the Kuhn-Tucker conditions of an appropriately constructed optimization problem, under a symmetry assumption on the underlying functions. Hence, in this case, the equilibrium link and path flows could be obtained as the solution of a mathematical programming problem.

Dafermos and Sparrow (1969) coined the terms *user-optimized* (U-0) and *system- optimized* (S-0) transportation networks to distinguish between the two distinct situations in which users act unilaterally, in their own self-interest in selecting their routes, and in which users select routes according to what is optimal from a societal point of view, in that the total cost in the system is minimized. In the latter problem, marginal (total) costs rather than average costs are equilibrated equalized. The former problem coincides with Wardrop's first principle, and the latter with Wardrop's second principle. In this paper we only mentioned the U-O attitude [13].

### B. The Network Equilibrium (U-0) Model with Fixed Demands

Consider a general network $\mathcal{G} = [\mathcal{N}, \mathcal{L}]$, where $\mathcal{N}$ denotes the set of nodes, and $\mathcal{L}$ the set of directed links. Let *a* denotes a link of the network connecting a pair of nodes, and let *p* denote a path consisting of a sequence of links connecting an origin destination (O/D) pair of nodes. The paths are assumed to be acyclic, in transportation networks, nodes correspond to origins and destinations. Let $P_w$, denote the set of paths connecting the O/D pair of nodes w. Let *P* denote the set of all paths in the network and assume that there are $n_w$ origin destination pairs of nodes. We assume in all models that the networks are (strongly) connected, that is, that there is at least one path connecting each pair of O/D nodes [1].

Let $X_p$ represent the nonnegative flow on path *p* and let $f_a$ Denote the flow on link $a$. These flows, in different settings, would correspond passenger flows.

Denote the demand associated with O/D pair w, for all $w \in W$, *Assumed*, for now, as being fixed and known, where path p contains link $a$, $\delta_{ap}$ = 1, and otherwise $\delta_{ap}$ = 0 [2].

- *Optimization problem for User Optimality*

$$Min \quad \sum_{a\in A} \int_0^{f_a} t_a(y) d_y . \tag{1}$$

$$s.t. \quad \sum_{p\epsilon P_w} x_p = d_w \quad , \quad \forall w \epsilon W$$

$$f_a = \sum_{p\epsilon P} x_p \delta_{ap} \quad , \quad \forall a \epsilon A,$$

$$x_p \geq 0 \quad , \quad \forall p \epsilon P$$

The cost experienced by a user traversing flight ***a*** is denoted by $t_a(f_a)$ [12].

### C. Trip Cost function

In this section we are using a developed trip cost function that is a combination of passenger flow function and arc cost function.

- We know cost of a path in an airline network is cost of legs+ cost of transshipment or hub [15].

- Also we know flows of passenger by plane a and b are $f_a$ and $f_b$.

- If nominal capacity of plane a is $c_a$ then, practical capacity of a is $lf \times c_a$ where *lf* is load factor [4].

- We will show flight cost or ticket price by *fc*.

- The rate of flow by plane number a is $\frac{f_a}{lf \times c_a}$.

But we have two types flight, direct and indirect flights (flight with transshipment or connection flights), so;

If flight with plane a is a direct flight, then our trip cost function, is

$$\mathrm{t_a} = fc[\alpha \left(\frac{kf_a}{lf \times c_a}\right)^{\beta}] + \text{arc cost}, \tag{2}$$

If flight with plane b is indirect flight, then our trip cost function varies to

$$t_a = fc[\alpha \left(\frac{kf_a}{lf \times c}\right)^{\beta}] + arc1\ cost + arc2\ cost + tsc \tag{3}$$

*tsc*: Transshipment Cost

α, β and *k*: the congestion rates. (Are positive and special coefficiences for every field and company)

### D. Algorithms for solving Variational Inequality and Trip Assignment

1. The Projection Method
2. The Modified Projection Method
3. The Euler Method
4. Balance Algorithm

E. *Performance measure of Nagurney and Qiang for Evaluating of critical arcs*

The network performance / efficiency measure is as below;

$$\varepsilon = \varepsilon\left(G, d\right) = \frac{\sum_{w \in W} \frac{d_w}{\lambda_w}}{n_w} \qquad (4)$$

where $d_w$ is demand between O/D. $n_w$ is the number of O/D pairs in the network and $\lambda_\omega$ is minimum cost flights between O/D.

## III. Relative Total Cost Indices

Network total cost is;

$$TC = \sum_{g \in A} \hat{t}_g = \sum_{g \in A} t_g(f_g) f_g \qquad (5)$$

Let's suppose $g \in A$ is an arc on network and $\Psi$ *({g})* is relative total cost increase of *G*, and if we eliminate *{g}* from network, relative total cost increase is equal to:

$$\Psi\left(\{g\}\right) = \frac{TC(G - \{g\}) - TC(G)}{TC(G)} \qquad (6)$$

Where TC (G) is total cost of the network *G, TC (G - {g})* is total cost of the network *G - {g}*.

Because of deriving total cost from U-O, we can write the following functions.

$$\Psi_{U-O}(\{g\}) = \frac{TC_{U-O}(G - \{g\}) - TC_{U-O}(G)}{TC(G)} \qquad (7)$$

**Note:** *Above-mentioned function will distinguish critical nodes; when one eliminates a node all of the arcs, which terminated to this node will be eliminated.*

If g has been affected by capacity changes then, the relative total cost index appears as*:*

$$\Psi^{\gamma}_{(g)} = \frac{TC^{\gamma}_{(g)} - TC}{TC} \qquad (8)$$

$$\Psi^{\alpha}_{(g)} = \frac{TC^{\alpha}_{(g)} - TC}{TC} \qquad (9)$$

$TC$ : Total cost of network, if there is not any capacity changes.

$TC^{\gamma}_{(g)}$: Network total cost if capacity decrease rate is $\gamma$.

$TC^{\alpha}_{(g)}$: Network total cost, if increase rate of capacity is α.

## IV. Airline Network Robustness Assessment

### A. *Airline Network Robustness with Reduction Flight Capacity*

To evaluate network robustness let's decrease legs (flight) carrying capacity with a fix rate. Network efficiency measures are capturing under this reduction. If original capacity of a leg is $c_g$ and $\gamma(\gamma \in (0,1])$ is the reduction rate of capacity, $\gamma c_g$ , is the leg's decreased capacity and, $c_g - \gamma c_g$ is reduction or fall measurement of leg. The network of G robustness measurement is $R^{\gamma}$ [14].

$$R^{\gamma} = R^{\gamma}(G, d, t, c, \gamma) = \frac{\varepsilon^{\gamma}}{\varepsilon} \times 100\% \qquad (10)$$

*d: G demand vector*
*t: Flight cost function*
*c: Flight capacity vector*
$\gamma$*: Flight capacity reduction rate*
*ε: Network performance index when capacity is c*
$\varepsilon^{\gamma}$ *: Network performance index when capacity decreased to* $\gamma c$

If the performance index of a network with $\gamma c$ capacity is approximate c, then that network is sustainable [12].
If there is only one flight between O/D; then robustness upper bound is $\gamma^b \times 100\%$ and,

$$R^{\gamma} = \frac{\gamma^b [c_g^b + kd_w^b]}{\gamma^b c_g^b + kd_g^b} \times 100\% \qquad (11)$$

If there are more than one flight between O/D Then; $c \equiv c_a + c_b + ... + c_n$ And lower bound is $\gamma \times 100\%$ ,

$$R^{\gamma} = \frac{\gamma c + k\gamma d_w}{\gamma c + kd_w} \times 100\% \qquad (12)$$

### B. *Airline Network Robustness With Inflation Of Flight Capacity*

To evaluate network robustness let's increase legs (plane) carrying capacity with a fix rate. Network efficiency measures are capturing under this reduction. If original capacity of a leg is $c_g$ and $\alpha$; $(\alpha \geq 1)$, is the inflation rate of capacity, $\alpha c_g$ , is the leg's increased capacity and, $\alpha c_g - c_g$ is inflation measurement of leg (flight) [6]. The network of G sustainability or robustness measure is

$$R^{\alpha} = R^{\alpha}(G, d, t, c, \alpha) = \frac{\varepsilon^{\alpha}}{\varepsilon} \times 100\% \qquad (13)$$

$\alpha$ *: leg capacity inflation rate*

$\alpha^b \times 100\%$ is upper bound of network robustness and $\alpha \geq 1$, and upper bound is $\alpha \times 100\%$

$$R^{\alpha} = \frac{\alpha c + k\alpha d_w}{\alpha c + kd_w} \times 100\% \qquad (14)$$

## V. Case Study

The data for a partial network of an airline in Turkey illustrated in Fig 1, there are 5 airports in 5 cities and Ankara is a Hub station. We are interested to assess this network sustainability with critical legs upon supply and demand between the nodes Istanbul-Antalya and

Istanbul-Trabzon. Load factor policy of firm averagely is 90%. Transshipment cost for every hour 7$ per passenger. All ticket prices averagely 15$ per path (without taxes). The other data are illustrated in Fig 1. We are interested in daily calculations. One can observe further information in appendix.


| O/D | Flight count | Plane Type | Demand |
|---|---|---|---|
| IST-TRZ | 5 | 1,3,5 | 1700 |
| IST-ANK | 38 | 1,2,3,4,8,9 | 12000 |
| IST-KNY | 3 | 2,3 | 1400 |
| IST-ANT | 10 | 1,2,5,4 | 4200 |
| ANK-ANT | 2 | 8 | 1150 |
| ANK-TRZ | 2 | 4 | 780 |
| TRZ-ANT | 2 | 6 | 750 |
| KNY-ANT | 1 | 5 | 330 |

Figure 1. The airline network with one hub and several spokes and flight data

Solving the problem:

Step 1. Using trip cost function.

Step 2. Deriving $f_g$ via Coding of Balance Algorithm for variational inequality and trip assignment, which are using C++ (Appendix A), and MATLAB for coding of Balance algorithm and calculations.

Step 3. To identify critical paths through the results.

Definitions of Tables:

As illustrated in Fig.2, the effects of every increasing or decreasing rates in legs capacities, from total cost index is demonstrated.

For an instance, if the firm decrease the capacity of flights from IST-TRZ, users reflexes will increase the total cost amounts and this will effects ticket prices. Fig.3 illustrates the relative total cost indices with U-O and the rates of inflation and reduction of leg capacities. For example, with increasing the rate of flight capacities in IST-TRZ leg, the Relative Total Cost will decrease (from -0.026 to -0.11).

Fig.3 illustrates Network Sustainability with whole network capacity changes via U-O. If you increase the whole capacity of network by the rate of 1.6 the network robustness will improve.

| $TC^{\gamma}$ | $\gamma = 0$ | $\gamma = 0.2$ | $\gamma = 0.4$ | $\gamma = 0.6$ | $\gamma = 0.8$ |
|---|---|---|---|---|---|
| IST-TRZ | 3567 | 3590 | 3605 | 3700 | 3945 |
| IST-ANK | 4044 | 4030 | 4060 | 3840 | 3765 |
| IST-KNY | 4900 | 4900 | 4900 | 4900 | 4900 |
| IST-ANT | 5442 | 5545 | 5625 | 5664 | 5619 |
| ANK-ANT | 5209 | 5209 | 5199 | 5199 | 5091 |
| ANK-TRZ | 3416 | 3416 | 3416 | 3416 | 3416 |
| TRZ-ANT | 6309 | 6309 | 6309 | 6309 | 6309 |
| KNY-ANT | 2670 | 2670 | 2670 | 2670 | 2670 |

| $TC^{\alpha}$ | $\alpha = 1$ | $\alpha = 1.2$ | $\alpha = 1.4$ | $\alpha = 1.6$ | $\alpha = 1.8$ |
|---|---|---|---|---|---|
| IST-TRZ | 3567 | 3472 | 3357 | 3158 | 3158 |
| IST-ANK | 4044 | 4190 | 4230 | 4304 | 4370 |
| IST-KNY | 4900 | 4900 | 4900 | 4900 | 4900 |
| IST-ANT | 5442 | 5012 | 5230 | 5307 | 5411 |
| ANK-ANT | 5209 | 5400 | 5469 | 5498 | 5502 |
| ANK-TRZ | 3416 | 3128 | 3139 | 3141 | 3260 |
| TRZ-ANT | 6309 | 6309 | 6302 | 6309 | 6309 |
| KNY-ANT | 2670 | 2670 | 2670 | 2670 | 2670 |

Figure 2. Total costs with U-O and the rates of reduction and inflation of leg capacities

| $\psi^{\gamma}$ | $\gamma = 0$ | $\gamma = 0.2$ | $\gamma = 0.4$ | $\gamma = 0.6$ | $\gamma = 0.8$ |
|---|---|---|---|---|---|
| IST-TRZ | 0 | 0.0065 | 0.011 | 0.037 | 0.1 |
| IST-ANK | 0 | -0.004 | 0.0039 | -0.05 | -0.069 |
| IST-KNY | 0 | 0 | 0 | 0 | 0 |
| IST-ANT | 0 | 0.0005 | 0.033 | 0.04 | 0.032 |
| ANK-ANT | 0 | 0 | -0.002 | -.002 | -.02 |
| ANK-TRZ | 0 | 0 | 0 | 0 | 0 |
| TRZ-ANT | 0 | 0 | 0 | 0 | 0 |
| KNY-ANT | 0 | 0 | 0 | 0 | 0 |

| $\psi^{\alpha}$ | $\alpha = 1$ | $\alpha = 1.2$ | $\alpha = 1.4$ | $\alpha = 1.6$ | $\alpha = 1.8$ |
|---|---|---|---|---|---|
| IST-TRZ | 0 | -0.026 | -0.058 | -0.11 | -0.11 |
| IST-ANK | 0 | 0.036 | 0.046 | 0.064 | 0.08 |
| IST-KNY | 0 | 0 | 0 | 0 | 0 |
| IST-ANT | 0 | -0.08 | -0.039 | -0.024 | -0.005 |
| ANK-ANT | 0 | 0.036 | 0.05 | 0.055 | 0.056 |
| ANK-TRZ | 0 | -0.08 | -0.081 | -0.08 | -0.045 |
| TRZ-ANT | 0 | 0 | 0 | 0 | 0 |
| KNY-ANT | 0 | 0 | 0 | 0 | 0 |

Figure 3. Relative total cost with U-O and the rates of reduction and inflation of leg capacities

| $\beta = 4, \alpha = 1, k = 0.15$ | $R^{\gamma}$ | $\beta = 4, \alpha = 1, k = 0.15$ | $R^{\alpha}$ |
|---|---|---|---|
| $\gamma = 0$ | 0 | $\alpha = 1$ | 0 |
| $\gamma = 0.2$ | 0.988 | $\alpha = 1.2$ | 1.1432 |
| $\gamma = 0.4$ | 1.054 | $\alpha = 1.4$ | 1.1328 |
| $\gamma = 0.6$ | 0.941 | $\alpha = 1.6$ | **1.1556** |
| $\gamma = 0.8$ | 1.014 | $\alpha = 1.8$ | 1.1437 |

Figure 4. Network sustainability measures with whole network capacity changes via U-O using (10)

*Results*: IST-TRZ, IST-ANK, IST-ANT, ANK-ANT and ANK-TRZ are critical legs. (Fig. 2). Reduction capacity of (IST-TRZ) is not suggested but inflation in rate 1.6 is the priority. (Fig. 2 and Fig. 3). Decreasing capacity of (IST-ANK) with rate of 0.8 is suggested. Increasing capacity of (IST-ANT) with the rate of 1.2 is firmly suggested. Changes in the capacity of (ANK-TRZ) are not logical. (Fig. 2 and Fig. 3). Decreasing capacity of (ANK-ANT) with the rate of 0.8 will be logical. (Fig. 2 and Fig. 3). Decreasing or increasing the capacity of (TRZ-ANT) is not suggested.

Whole network sustainability while reducing the flight capacities is positive and means smaller network is more sustainable but the most important vision of all Airlines is to progress, so in this certain example, increasing total capacity of network by 1.6 is suggested. (Fig. 4).

## VI. Conclusion

In this paper we looked from different perspective and for the first time airline leg and flight assignment, evaluated from modified leg cost function for airlines. We tried to assess the behavior of legs and network via variation of leg capacities; besides, in this article we tried to identify critical legs via changing practical capacities of airline network components, also we demonstrated how to capture the robustness of airline network in the case of variable legs represented by decreasing and increasing capacities. We used Relative Total Cost indices to assess airline network sustainability in the case of behavior associated with User- Optimization. In this article from different point of view, passenger's rout preference behaviors were the main subject. Future work will use Relative Total Cist Indices to evaluate the robustness of an Airline network considering both U-O and S-O.

## Appendix

Appendix A is a C++ codding, Appendix B contains the flight information of the certain airline. One can reach this information via email from the first author.

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