

Network DEA models in transportation. Application to airports

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Abstract

Data Envelopment Analysis (DEA) has been applied in many efficiency and benchmarking studies in the transportation sector. Conventional DEA models consider the system as a single-process black box. There are however a number of so-called network DEA approach that consider the system as composed by distinct processes or stages, each one with its own inputs and outputs and with intermediate flows among the stages. In this paper some of these approaches that have been applied to urban transit systems, railways, etc are reviewed and in particular applications of network DEA to airports are presented and discussed. The conclusions of this research is that network DEA models have a greater discriminant power than conventional, single-process DEA and since they allow a more fine-grained analysis their results are generally more valid and useful. The main drawbacks are the need for more detailed data (i.e. at the process level) and the greater complexity of the resulting models, specially if there are inputs or outputs that are shared among the processes.

Keywords: transportation; airports; efficiency; productivity change; DEA; network DEA

1. Introduction

Data Envelopment Analysis (DEA) is a non-parametric mathematical tool for assessing the relative efficiency of homogeneous Decision Making Units (DMU). DEA has been applied in many sectors (education, health care, finance, utilities, etc). In particular, there are many applications of DEA in transportation. Thus, DEA has been

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applied to ports (e.g. Barros 2006, Lin and Tseng 2007, Lozano 2009), to railways (e.g. Hilmola 2007, Martín and Reggiani 2007), to airlines (e.g. Scheraga 2004, Greer 2006), urban transit (e.g. Karlaftis 2004, Jain et al 2008) and, of course to airports (e.g. Gillen and Lall 1997, Pels et al 2001, 2003, Martín and Román 2001, 2006, Pacheco and Fernandes 2003, Yu 2004, Pacheco et al 2006, Yoshida and Fujimoto 2004, Lin and Hong 2006, Barros and Dieke 2007, 2008, Barros and Peypoch 2008, Yu et al 2008, Pathomsiri et al 2008, Lam et al 2009, Lozano and Gutiérrez in press).

Most of these DEA studies consider the units under assessment as a single process and assume that this aggregate process consumes all the different inputs and produces all the different outputs (some of them perhaps undesirable). No modeling of the inner structure of the system is performed. No subprocess or stages are considered and intermediate products produced and consumed within the system are recognized. This black box approach is the most common one in DEA.

There are some papers, however, that consider the system as the composition of several stages or process that can have a series structure or that are executed in parallel or that have a more general interrelationships pattern. The common feature of all these approaches is that they work at a more fine-grained level so that each process has its own inputs and its own outputs and there may be intermediate flows among the processes. Although DEA studies of this type have existed for some time in the last few years the topic has received more attention from researchers and the number of papers that deal with both theoretical issues and applications have increased significantly. A recent and interesting review of innovative DEA approaches of this type can be found in Castelli et al (in press). The groundwork for network DEA models are due to works like Färe and Grosskopf (1996, 2000), Löthgren and Tambour (1999), Seiford and Zhu (1999), Färe et al (2007), Lewis and Sexton (2004a, 2004b), etc. More recently, Liang et al (2008), Kao and Hwang (2008, in press), Kao (2009a, 2009b) and Chen et al (2009) have presented game-theoretic DEA, relational network DEA and weighted additive efficiency decomposition approaches for series, parallel and eventually for general networks of processes. Dynamic network DEA approaches have also been proposed (Chen 2009). There have appeared applications of network DEA to banks (Seiford and Zhu 1999, Chen et al 2006, Avkiran 2009), electric utilities (Tone and Tsutsui 2009), manufacturing (Liu and Wang 2009), hotels (Yu and Lee 2009), sports

(Lewis et al 2009), supply chains (Liang et al 2006, Cook et al 2007, Yang et al in press), etc.

In this paper, in section 2, a number of network DEA applications in transportation are reviewed. In section 3, two applications of network DEA to airports operations are presented and in section 4 the results of these approaches are discussed. Finally, in section 5, conclusions are drawn and further research outlined.

2. Network DEA approaches in transportation

To the best of our knowledge only a few papers have been published that use network DEA approaches in the transportation realm. Thus, Sheth et al (2007) applies network DEA to bus routes. An interlinked network of nodes is used to represent the service along a bus route and the efficiency of service provided along the bus route is assessed from two different perspectives: the providers' viewpoint and the customers' viewpoint. The aim is to compute disaggregate performance measures that could "provide decision-makers with operational insights as to how to improve the performance of the network as a whole". The provider node uses headway, service duration, costs, number of intersections, and number of priority lanes as inputs and vehicle miles and two quality measures (schedule reliability and average travelling time) as outputs. These outputs act as inputs to the passenger node which produces passenger-miles as final output. The passenger node also considers a non-controllable variable that results from the combination of environmental variables (such as accessibility factor, parking space availability factor, population density factor, connectivity factor, and comfort standards factor) so that the efficiency of the service along a bus route is computed with respect to only those services along other bus routes that are provided (operate) in similar or harsher environments. A goal programming model is finally formulated to maximize the final-output increase and minimize deviations from local and global targets related to specific societal variables (e.g., emissions, noise pollution, resources degraded, etc.).

Yu (2008a) uses a multi-activity DEA model for measuring the efficiency of multi-mode bus transit. Two main processes are considered: Highway Bus (HB) service and Urban Bus (UB) service. Each process consumes specific amounts of four inputs, namely number of drivers, fleet size, fuel consumption and kilometres served. In

addition, there is a fifth input, the number of mechanics, but this input is shared between the two processes. The output of the HB process is vehicles-km and the output of the UB process is the frequency of service. In addition, two environmental variables are considered which represent transportation demand, long-haul transportation demand in the case of HB and short-haul transportation demand in the case of UB. A weighted objective function that involves the radial input-oriented efficiencies of the two processes is considered.

Yu and Fan (2006) studies this same problem but including a shared output for both the HB and the UB processes. That shared output is the cost of accidents and since it is undesirable, an appropriate technology (that assumes joint weak disposability of desirable and undesirable outputs) is used for both processes. The objective function is a weighted sum of the directional distance function of each process where the direction vector used tries to increase the desirable outputs, at the same time, reduce the inputs and the undesirable output.

Yu and Fan (2009) studies the same problem but considers an enhanced network that in addition to the HB and UB processes includes a Consumption (C) process. The final outputs are passenger-km and passenger. Intermediate products generated by the HB process and the UB process are their respective vehicle-km. Process HB and UB have specific inputs (such as drivers, fleet and fuel) and in addition they share two inputs (number of mechanics). There is an additional input (management) that is shared but not only by HB and UB but also by the C process. Each process has its own environmental variable: population density (regional for HB and local for UB) and car ownership for the C process. The objective function weights the increase in the final outputs and decrease in all types of inputs, specific and shared.

Yu (2008b) presents a network DEA approach to assess the technical efficiency, plus the service and technical effectiveness of a selected sample of 40 global railways. The proposed approach considers two stages in series: the Production process and the Consumption process. The production process has three specific inputs (length of the lines, number of passenger cars and number of freight cars) plus one additional input (number of employees) that is shared with the Consumption process. The two outputs of the Production process (passenger train-km and freight train-km) are intermediate products that are inputs to the Consumption process. The consumption process also

considers some environmental factors (such as population density and Gross National Income) and produces two final outputs (passenger-km and ton-km). Technical efficiency corresponds to the efficiency of the Production process while service effectiveness refers to that of the Consumption process and technical effectiveness corresponds to the overall system efficiency. The objective function involves weighting two directional distance functions, one that aims at reducing the inputs of the Production process and another that aims at increasing the final outputs of the Consumption process.

Finally, Yu and Lin (2008) presents a multi-activity network DEA model for measuring the efficiency and effectiveness of railway performance. Three processes are considered: a Passenger Production (PP) process, a Freight Production (FP) process and a Consumption (C) process. PP and F have each a specific input (Passenger cars and Freight cars) plus a shared input (Length of the lines) plus another input (Employees) that they share also with the C process. Passenger train-km and Freight train-km) are the outputs of the PP and FP processes respectively. These intermediate products are inputs to the C process (together with the shared input Employees). Passenger-km and Ton-km are the final outputs generated by the C process which also considers the same environmental factors as Yu (2008b), i.e. population density and Gross National Income. The objective function of the proposed DEA model corresponds to a weighted mixed graph orientation that takes into account reductions in the amounts of Passenger and Freight trains required as well as an increase in the number of passengers-km and ton-km. Although the proposed DEA model considers an aggregate C process, the authors state that separate Passenger Consumption and Freight Consumption process could be considered, leaving the topic for further research.

As it can be seen from the above review, network DEA models generally consider few processes which represent the main components of the system being studied. Most often the processes are executed in parallel and/or in series. Two types of interlinking relationships may exist among the processes. One is the existence of intermediate products, i.e. products that are generated in some processes and consumed in others. The other linking possibility is the sharing of inputs or outputs among the processes. This sharing mechanism corresponds to being unable to discern the amount of an input that is consumed (or the amount of an output that is produced) by a specific

process. It is mainly a matter of data unavailability, basically due to a lack of measurement of the consumption or production share of the individual processes.

3. Network DEA approaches to airports operations

Before considering possible network DEA approaches to airport operations it is convenient to note that among the many DEA studies of airports efficiency there are a few cases in which the efficiency of some airport processes have been assessed separately. Thus, Gillen and Lall (1997, 2001) analyze the airside and the terminal services separately. Similarly, Pels et al (2003) consider an airport model (related to aircraft movement) and an airlines model (related to aircraft seats). Finally, Barros et al (2009) also treat the movement and terminal productivity separately.

All these DEA approaches suggest considering two stages: a stage related to the movement of the aircrafts (AM) and a stage related to the loading of airplanes (AL). The two processes are to be linked through the Aircraft Traffic Movements (ATM) variable which is an output of stage S1 and an input to stage S2. Stage S1 uses different inputs such as total runway area, in square meters (RUNAREA), number of apron stands (APRON) and number of boarding gates (BOARDG). Stage AL, apart from variable ATM, uses as inputs the number of check-in counters (CHECKIN) and the number of baggage belts (BAGB). As for the final outputs of this process the two obvious candidates are Annual Passenger Movement (APM) and Total Cargo handled (CARGO). Figure 1 shows this two-stage network.

===== Figure 1 =====

Lozano et al (submitted) has used this network to compute radial output-oriented system efficiency scores for years 2006-2008 and, from them, network Malmquist indexes that are decomposed as per Färe et al (1994) into efficiency change, scale change and technical efficiency change components. Let

RUNAREA_j Runway area of airport j

APRON_j Number of stands of airport j

| | |
|----------------------|--|
| BOARDG _j | Number of boarding gates of airport j |
| ATM _j | ATM of airport j |
| CHECKIN _j | Number of check-in counters of airport j |
| BAGB _j | Number of baggage belts of airport j |
| APM _j | ATM of airport j |
| CARGO _j | ATM of airport j |
| γ | Radial expansion of the final outputs of airport 0 |
| λ_j^{AM} | Intensity variable of the stage AM of airport j |
| λ_j^{AL} | Intensity variable of the stage AL of airport j |

The proposed output-oriented relational network DEA model is the following

$$\text{Max } \gamma \tag{1}$$

subject to

$$\sum_j \lambda_j^{AM} \cdot \text{RUNAREA}_j \leq \text{RUNAREA}_0 \tag{2}$$

$$\sum_j \lambda_j^{AM} \cdot \text{APRON}_j \leq \text{APRON}_0 \tag{3}$$

$$\sum_j \lambda_j^{AM} \cdot \text{BOARDG}_j \leq \text{BOARDG}_0 \tag{4}$$

$$\sum_j (\lambda_j^{AM} - \lambda_j^{AL}) \cdot \text{ATM}_j \geq 0 \tag{5}$$

$$\sum_j \lambda_j^{AL} \cdot \text{CHECKIN}_j \leq \text{CHECKIN}_0 \quad (6)$$

$$\sum_j \lambda_j^{AL} \cdot \text{BAGB}_j \leq \text{BAGB}_0 \quad (7)$$

$$\sum_j \lambda_j^{AL} \cdot \text{APM}_j \geq \gamma \cdot \text{APM}_0 \quad (8)$$

$$\sum_j \lambda_j^{AL} \cdot \text{CARGO}_j \geq \gamma \cdot \text{CARGO}_0 \quad (9)$$

$$\sum_j \lambda_j^{AM} = 1 \quad (10)$$

$$\sum_j \lambda_j^{AL} = 1 \quad (11)$$

$$\lambda_j^{AM} \geq 0 \quad \lambda_j^{AL} \geq 0 \quad \gamma \text{ free} \quad (12)$$

Note that this model considers Variable Returns to Scale (VRS) and that there is an intermediate product balance equation (5) that imposes that the ATM generated in stage AM cannot be lower than the amount that is consumed in stage AL.

The network shown in Figure 1 is but one possible model of airports operations. The model can be enhanced if additional data are available. In particular, note that the undesirable outputs of the AM process (such as noise or flight delays) can be logically ascribed to that stage. Hence, Lozano and Gutiérrez (submitted) has proposed the network DEA shown in Figure 2, which includes two undesirable outputs

PDF_j Percentage of Delayed Flights of airport j

ADDF_j Average Delay of Delayed Flights of airport j

===== Figure 1 =====

The corresponding network DEA model is

$$\text{Max } \beta \quad (13)$$

subject to

$$\sum_j \hat{\lambda}_j^{\text{AM}} \cdot \text{RUNAREA}_j \leq \theta_{\text{AM}} \cdot \text{RUNAREA}_0 \quad (14)$$

$$\sum_j \hat{\lambda}_j^{\text{AM}} \cdot \text{APRON}_j \leq \theta_{\text{AM}} \cdot \text{APRON}_0 \quad (15)$$

$$\sum_j \hat{\lambda}_j^{\text{AM}} \cdot \text{BOARDG}_j \leq \theta_{\text{AM}} \cdot \text{BOARDG}_0 \quad (16)$$

$$\sum_j \hat{\lambda}_j^{\text{AM}} \cdot \text{ATM}_j - \sum_j \lambda_j^{\text{AL}} \cdot \text{ATM}_j \geq 0 \quad (17)$$

$$\sum_j \hat{\lambda}_j^{\text{AM}} \cdot \text{PDF}_j = \text{PDF}_0 \cdot (1 - \beta) \quad (18)$$

$$\sum_j \hat{\lambda}_j^{\text{AM}} \cdot \text{ADDF}_j = \text{ADDF}_0 \cdot (1 - \beta) \quad (19)$$

$$\sum_j \lambda_j^{\text{AL}} \cdot \text{CHECKIN}_j \leq \text{CHECKIN}_0 \quad (20)$$

$$\sum_j \lambda_j^{\text{AL}} \cdot \text{BAGB}_j \leq \text{BAGB}_0 \quad (21)$$

$$\sum_j \lambda_j^{\text{AL}} \cdot \text{APM}_j \geq \text{APM}_0 \cdot (1 + \beta) \quad (22)$$

$$\sum_j \lambda_j^{\text{AL}} \cdot \text{CARGO}_j \geq \text{CARGO}_0 \cdot (1 + \beta) \quad (23)$$

$$\sum_j \hat{\lambda}_j^{\text{AM}} = \theta_{\text{AM}} \quad (24)$$

$$\sum_j \lambda_j^{AL} = 1 \quad (25)$$

$$0 \leq \theta_{AM} \leq 1 \quad (26)$$

$$\hat{\lambda}_j^{AM} \geq 0 \quad \lambda_j^{AL} \geq 0 \quad \beta \text{ free} \quad (27)$$

This model uses a proportional directional distance approach (Chung et al 1997) and simultaneously tries to increase the final outputs (APM and CARGO) and reduce the undesirable outputs (PDF and ADDF). The model is more complex (involving the additional variable θ_{AM}) because of the VRS technology of the AM process, which assumes the usual joint weak disposability of desirable and undesirable outputs (Färe et al 1989, Färe and Grosskopf 2003).

4. Results of network DEA approaches to airports

In this section a summary of the results of the two network DEA approaches to airports presented in the previous section is presented. More detailed results are shown in Lozano et al (submitted) and Lozano and Gutiérrez (submitted). Both approaches have been applied to study 39 Spanish airports using data from the Spanish National Air Navigation Authority (AENA, <http://www.aena.es>) and, in the case of the flights delays, from the CODA (Central Office for Delay Analysis) service of Eurocontrol (http://www.eurocontrol.int/eatm/public/standard_page/coda.html).

With respect to the network DEA approach to estimate productivity changes in the period 2006-2008 using network Malmquist indexes Table 1 shows, for each year, the airports that have been identified as technically efficient (in bold if they are also scale efficient) together with median and minimum efficiency of the 39 airports. The table also shows for each pair of consecutive years the average Malmquist index and the average of its three components, namely Efficiency Change (EFFCH), Scale Change (SCACH) and Technical Change (TECCH). Note that there is certain stability in the technically efficient airports, especially among those that are also scale efficient. The median technical efficiency score is not too high, slightly above 0.5, with very low efficiency scores in some cases. The average Malmquist index indicates a general productivity increase in the first period and a decrease in the second. The main driver of

the productivity increase is the positive technical change (i.e. technical progress) which has occurred in both periods. There occurred also an overall efficiency improvement in the first period but that was followed by an efficiency decrease in the second period. The scale change component did not contribute to improve productivity in any of the two periods.

===== Table 1 =====

Table 2 shows the same information but computed using a conventional, single-process DEA approach. Note that the number of technical and global efficient airports is greater than with network DEA. This means that the latter has more discriminate power. This can also be observed in the median and minimum technical efficiency scores, which are higher for the single-process DEA approach. The overall productivity change assessment is similar to that computed by network DEA, thus indicating productivity improvement in the first period and productivity decrease in the second. Similarly, technical progress is identified in both periods and efficiency change evolution is mixed (increased in the first period and decreased in the second). The major difference is in the scale change component, which according to single-process DEA was higher in the first period and lower in the second period. Although these average results are almost coincident they hide differences at the level of individual airports. Actually, for most airports the Malmquist index and its efficiency change component are rather similar computed with network DEA or with single-process DEA. The estimations of the other two components are similar also in some cases but in others the estimation of network DEA and single-process DEA can differ significantly, with the single-process DEA approach frequently overestimating efficiency change and underestimating technical change.

===== Table 2 =====

With respect to the network DEA model that considers flights delays as undesirable outputs of the AM process Table 3 shows the airports that have a VRS proportional directional distance $\beta^* = 0$ both according to network DEA and to single-process DEA. The median, the conditional average and the maximum β^* are also

shown. Note that the number of technical efficient (in the weak sense) airports is much larger in the case of single-process DEA and the output distance functions (along the proportional improvement direction chosen) are smaller than those computed by network DEA. This can only mean that network DEA has more discriminant power than single-process DEA. This is further confirmed by Figure 3 which shows the histogram of the output distance functions computed by both methods.

===== Table 3 =====

===== Figure 3 =====

We have carried out a number of non-parametric tests to compare the results of network DEA with undesirable outputs and those of its single-process counterpart. Thus, the left-sided Mann-Whitney test cannot reject the null hypothesis of higher β^* for network DEA than for single-process DEA using a significance level of 0.05. Similarly, a non-parametric test of the difference of the mean β^* of both approaches estimates a difference of 0.223 in favour of network DEA β^* with a 95% confidence interval for the difference in mean β^* values of (0.083, 0.308). Finally, the Spearman rank order test computes a correlation coefficient of 0.602 (significant at 0.01 level) between the rankings of airports computed by network DEA and single-process DEA, which means that the two rankings are rather dissimilar, with our opinion being that the network DEA ranking is more valid than that of single-process DEA.

5. Conclusions

In this paper, network DEA approaches in Transportation have been reviewed and two specific network DEA approach to airport operations have been presented. These approaches have been used with data on 39 Spanish airports and the results have been compared with those of the corresponding conventional, single-process DEA model. In both cases it has been observed that the network DEA approach has more discriminant power than the single-process DEA approach and that its computed targets, efficiency scores and Malmquist index components are more valid. This is because network DEA allows for a more fine-grained analysis that leads to a more realistic

estimation of the overall system production possibility set than the one assumed by conventional DEA. In other words, compared with network DEA the conventional, single-process DEA represents an aggregated analysis that merges all the system processes with their inputs and outputs and ignores their internal flows.

With respect to further research issues there are at least two. One is applying different network DEA models such as the network SBM (e.g. Tone and Tsutsui 2009, Avkiran 2009). More interesting and more rewarding may be refining the modelling of the network processes and their inputs and, if required, their intermediate flows. Thus, additional inputs such as operating costs, labour or capital stock could also be considered if the corresponding data are available. Note that different types of labour might be considered and also that some of these inputs might be shared with the Aircraft loading process. A starting point would be to assume the two stages proposed in this paper and try to assign the available input data to one of the stages or to both. In the latter case, an effort should be made to allocate the shared inputs to the different process *ex ante* instead of letting it be computed by the DEA model as commonly occurs in shared-input DEA models.

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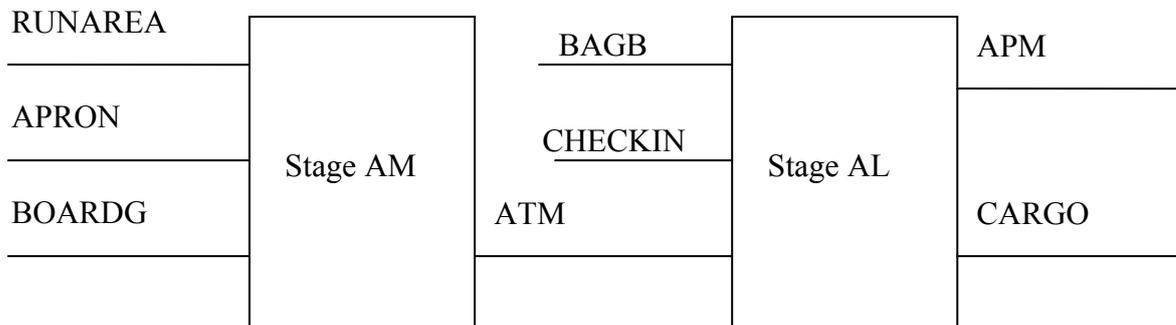


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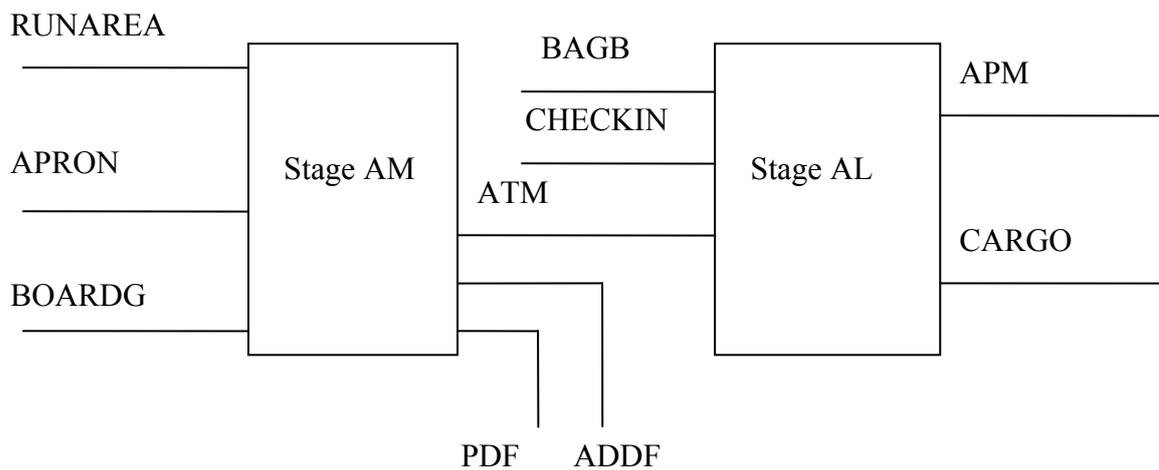


Figure 2. Two-stage network with undesirable outputs

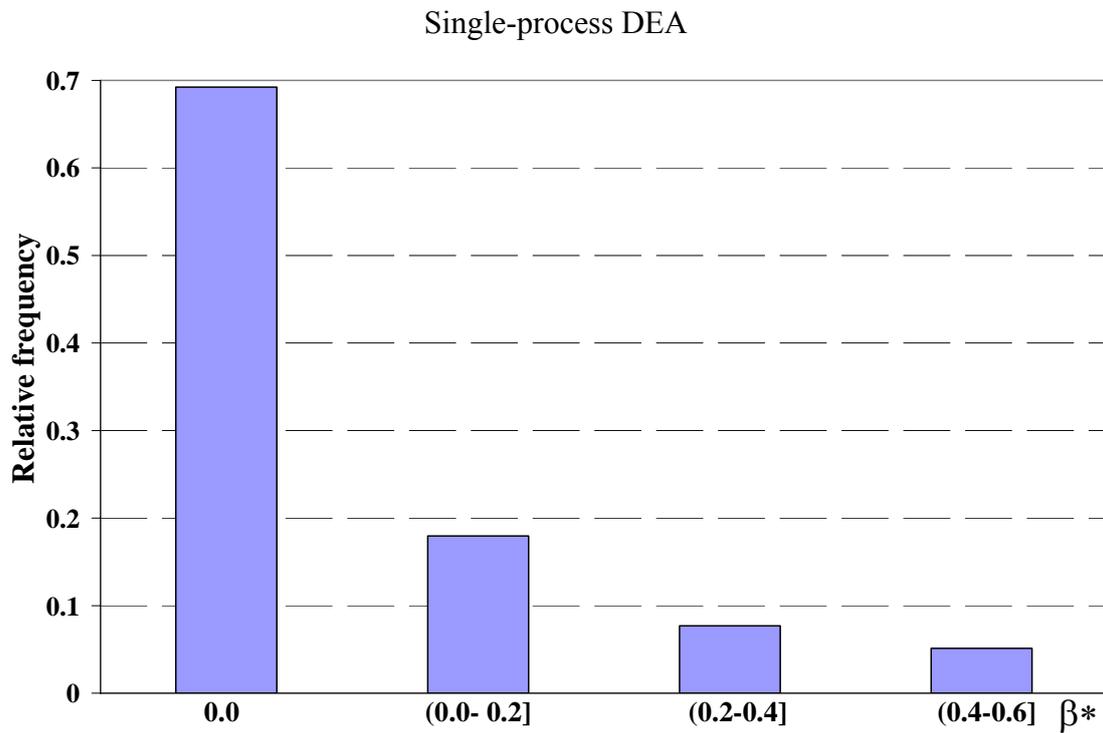
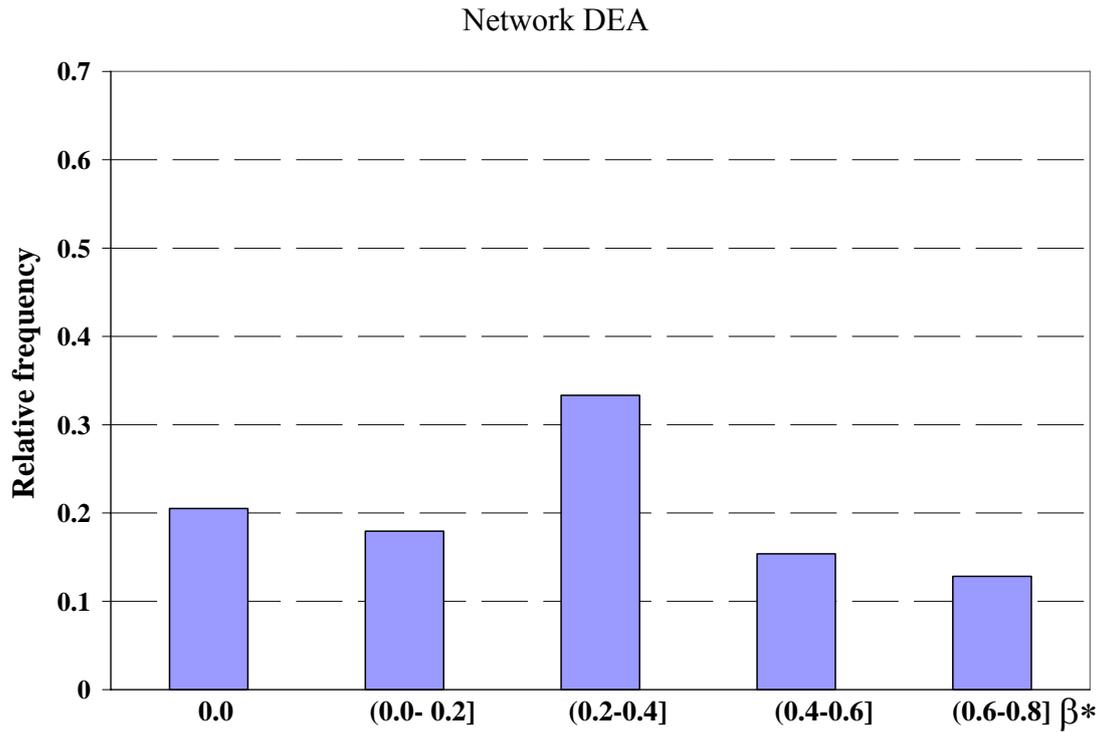


Figure 3. Histogram of β^* computed by network DEA with undesirable outputs and single-process DEA

| | Year 2006 | Year 2007 | Year 2008 |
|------------------------------|--|--|--|
| Technical efficient airports | Alicante Barcelona Córdoba Madrid Barajas Vitoria | Barcelona Córdoba Girona Costa Brava Madrid Barajas Saragossa Vitoria | Barcelona Córdoba Girona Costa Brava Madrid Barajas Saragossa Vitoria |
| Median tech. eff. | 0.567 | 0.605 | 0.536 |
| Min. tech. eff. | 0.055 (Salamanca) | 0.079 (Albacete) | 0.072 (Albacete) |
| | | | |
| | Period 2006-2007 | Period 2007-2008 | |
| Aver. Malmquist | 1.173 | 0.962 | |
| Aver. EFFCH | 1.047 | 0.913 | |
| Aver. SCACH | 0.968 | 0.991 | |
| Aver. TECCH | 1.167 | 1.071 | |

Table 1. Summary of results of output-oriented network Malmquist approach for Spanish airports for years 2006-2008

| | Year 2006 | Year 2007 | Year 2008 |
|------------------------------|--|--|--|
| Technical efficient airports | Alicante Badajoz Barcelona Córdoba El Hierro Girona Costa Brava Gran Canaria Granada Jaén La Palma León Madrid Barajas Málaga Melilla Murcia Palma de Mallorca Pamplona Reus Tenerife South Vitoria | A Coruña Alicante Badajoz Barcelona Córdoba El Hierro Girona Costa Brava Gran Canaria Granada Jaén La Palma León Madrid Barajas Málaga Melilla Murcia Palma de Mallorca Pamplona Reus Saragossa Tenerife South Vitoria | Alicante Badajoz Barcelona Córdoba El Hierro Girona Costa Brava Gran Canaria León Madrid Barajas Málaga Melilla Murcia Palma de Mallorca Pamplona Reus Saragossa Tenerife South Vitoria |
| Median tech. eff. | 0.906 | 1.000 | 0.938 |
| Min. tech. eff. | 0.086 (Salamanca) | 0.125 (Albacete) | 0.138 (Albacete) |
| | | | |
| | Period 2006-2007 | Period 2007-2008 | |
| Aver. Malmquist | 1.171 | 0.961 | |
| Aver. EFFCH | 1.026 | 0.958 | |
| Aver. SCACH | 1.014 | 0.960 | |
| Aver. TECHCH | 1.122 | 1.051 | |

Table 2. Summary of results of conventional, output-oriented Malmquist approach for Spanish airports for years 2006-2008

| | Network DEA | Single-process DEA |
|---------------------------------------|---|---|
| Technical efficient airports | <p>Barcelona Córdoba Girona Costa Brava León Madrid Barajas Palma de Mallorca Saragossa Vitoria</p> | <p>A Coruña Albacete Alicante Badajoz Barcelona Córdoba El Hierro Girona Costa Brava Gran Canaria Jerez La Palma León Madrid Barajas Málaga Melilla Murcia Palma de Mallorca Pamplona Reus Salamanca San Sebastián Saragossa Sevilla Tenerife North Valencia Vigo Vitoria</p> |
| Median β^* | 0.283 | 0.000 |
| Average($\beta^* \mid \beta^* > 0$) | 0.358 | 0.254 |
| Maximum β^* | 0.796 (Valladolid) | 0.541 (Valladolid) |

Table 3. Summary of results of network DEA with undesirable outputs and single-process DEA for Spanish airports for year 2008