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COMPARATIVE PERFORMANCE ANALYSIS OF EUROPEAN AIRPORTS BY MEANS OF EXTENDED DATA ENVELOPMENT ANALYSIS

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Abstract

Data Envelopment Analysis (DEA) has become an established approach for analyzing and comparing efficiency results of corporate organizations or economic agents. It has also found wide application in comparative studies on airport efficiency. The standard DEA approach to comparative airport efficiency analysis has two feeble elements, viz. a methodological and a substantive weakness. The methodological weakness originates from the choice of uniform efficiency improvement assessment, while the substantive weakness in airport efficiency analysis concerns the insufficient attention for short-term and long-term adjustment possibilities in the production inputs determining airport efficiency.

The present paper aims to address both flaws by: (i) designing a data-instigated Distance Friction Minimization (DFM) model as a generalization of the standard Banker-Charnes-Cooper (BCC) model with a view to the development of a more appropriate efficiency improvement projection model in the BCC version of DEA; (ii) including as factor inputs also lumpy or rigid factors that are characterized by short-term indivisibility or inertia (and hence not suitable for short-run flexible adjustment in new efficiency stages), as is the case for runways of airports. This so-called fixed factor (FF) case will be included in the DFM submodel of DEA. This extended DEA – with a DFM and an FF component – will be applied to a comparative performance analysis of several major airports in Europe. Finally, our comparative study on airport efficiency analysis will be extended by incorporating also the added value of the presence of shopping facilities at airports for their relative economic performance.

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1. Airports in a Competitive Environment

The deregulation of the aviation market over the past decades has induced the need for developing reliable performance measurements in the airline industry. Airlines nowadays operate in competitive markets and have to evaluate critically the performance of airports served by them. Clearly, they find it hard to pass the relatively higher operating costs at inefficient airports onto the passengers in these markets. Furthermore, many airports nowadays are operated as semi-private enterprises (Freathy, 2004). Airport operators and shareholders need, therefore, quantitative information on the relative performance of 'their' airport in terms of passengers, cargo, revenues or market share. Comparative analysis of airports' performance indicators using benchmarking principles has become a useful method for efficiency improvement (see Barros and Sampaio, 2004; Graham, 2005; Kamp et al., 2007; Kamp and Niemeier, 2007; Yoshida and Fujimoto, 2004).

Airport efficiency can be determined by relating airport capacity to demand levels[1]. A complicating factor is the fact that airport capacity is 'lumpy' in the sense that one cannot make short-term marginal adjustments. Construction of a new runway or terminal may therefore create over-capacity in the short run. In an efficiency analysis, one should control for the 'lumpiness' of airport or runway capacity, for instance, by including runways as fixed factors (see e.g. Pels et al., 2003). Given the high costs involved in runway construction, it may be economically justifiable for a (semi-)privatized airport to postpone investments in runway capacity, and accept delays, especially when there are other investment opportunities with higher rates of return. For instance, non-aviation activities in the commercial sector (e.g., shopping) are very important for many (privatized) airports[2]. Airport operators (public or private) may have the ambition to attract hubbing airlines, so that the airport can serve as an international or intercontinental gateway. Major international hub airports have often developed into complex multi-product business where aviation is the key product, but certainly not the only source of revenues. Such airports may be active in retailing, real estate development,

[1] Revenues and expenditures are also used in analyses of airport efficiency; see the discussion below.

[2] For instance, in 2005 the share of commercial revenues at London Heathrow was estimated to be 49.9%, London Gatwick 52.1%, and London Stansted 56% (source: ATRS, 2007).

consulting etc. Hub airports provide hubbing airlines the capacity to facilitate the complex hub-spoke operations, while offering passengers extensive shopping, meeting and catering opportunities. However, the newly formed low-cost airlines often ignore the major hubs, because the turnaround time of aircraft at the hubs is too high to fit their strategy. In other words, low-cost airlines may be looking for more efficient airports of a smaller scale (see Cento, 2008).

The Air Transport Research Society and Transport Research Laboratory both publish annual reports on airport efficiency indicators. These reports are primarily based on partial factor productivity indicators or total factor productivity indicators. Although such reports provide useful information to airport managers and investors, the results may be quite different (see e.g. Graham, 2005). This indicates the importance of understanding the purpose and limitations of separate studies.

A popular and frequently used technique to assess the relative efficiency of airports is Data Envelopment Analysis (DEA). Examples can be found amongst others in Adler and Berechman (2001), Barros (2008), Barros and Dieke (2007), Gillen and Lall (1997, 2001), or Pels et al. (2001). The general purpose of DEA in comparative airport efficiency analysis is to provide a decision making unit with indications how to improve the performance of airports and how to reach the efficiency frontier by reducing the inputs (or increasing the outputs). We will concisely describe three interesting DEA studies on airport efficiency. Bazargan and Vasigh (2003) apply DEA to U.S. airports, including the number of passengers; aircraft movements; general aviation movements; commercial revenues; aeronautical revenues and percentage of on-time operations as outputs and the operating and non-operating expenses; number of runways and number of gates as inputs. The main conclusion is that large hubs are relatively inefficient compared to smaller hubs, showing that the traffic flows at the very large airports create delays, which in turn may create inefficiencies. Martín and Román (2001, 2006) use the number of passengers, the number of air transport movements and the amount of cargo shipped as outputs, and expenditures on labor, capital and materials as inputs in an analysis of Spanish airports. Commercial activities are not included in their analysis. Sarkis (2000) uses operating costs, labor (measured in full-time equivalents) and the number of gates and runways as inputs and the operating revenues; number of aircraft movements and general aviation movements; passenger movements and the amount of cargo shipped as outputs. The author finds that hub airports are more efficient than non-hub airports.

The three studies mentioned above show that there is a lot of heterogeneity among DEA airport studies. Most studies using DEA to analyze airport efficiency (including the studies not reviewed in this paper) use the number of passengers and the number of air transport movements (aircraft movements) as outputs; these are usually seen as the 'core activities' of the airport. As mentioned above, commercial revenues are very important for a lot of airports. Some studies include commercial activities (e.g. Bazargan and Vasigh (2003)), while others do not (e.g. Martín and Román (2001, 2006)). Commercial activities are difficult to include in an airport efficiency analysis for different reasons. Firstly, commercial activities are very heterogeneous. Some airports have some shops and parking lots at the airport, while other airports operate hotels and are active in consulting work and the real estate sector. Secondly, the question is how to define the necessary variables that act as indicators for commercial activities. Bazargan and Vasigh (2003) use commercial revenues. A potential problem is that such revenues may also depend on activities or inputs not included in the input set. An airport that is active in the real estate sector may include the revenues of real estate transactions in the total commercial revenues. When there are no variables on the input-side that explain these high revenues, this may lead to biased conclusions. Alternatively, one can include terminal space dedicated to commercial activities as an indicator of commercial outputs, but as pointed out above, this may only capture part of the true commercial effort of the airport.

In the current paper we use output variables that are commonly used in the literature: passenger and air transport movements. We use the number of gates, number of employees, number of runways and the terminal space as inputs. The number of runways is included as a fixed factor in the short run. This is important, because an airport manager cannot easily change its number of runways to become more efficient (i.e., to copy the performance of its peers). Information on the number of slots coordinated by airports are hardly available. The same holds for financial data of airports. Therefore, we will take a look at the technical relationship between aeronautical inputs and outputs. We acknowledge the influence of commercial activities on airport operations. Since we model the efficiency of aeronautical outputs (passengers and aircraft movements), we account for the effect of commercial activities taking place inside the terminal. The shopping facilities area may not be strictly necessary for passenger handling, but it may be important in the sense that it improves the perceived quality of airports, because passengers can spend transfer times (or delay times) in a relatively attractive area. In our comparative efficiency analysis of European airports we include total terminal floor space, and terminal floor space dedicated to aviation activities, to investigate how the efficiency parameters differ among airports.

Our DEA study on the relative efficiency of airports in Europe distinguishes itself from other studies in that it regards runway capacity as a fixed input factor that cannot be flexibly adjusted by airport managers in the short run. In addition to this fixed factor (FF) approach, also commercial non-aviation activities (in particular, retailing and shopping) are explicitly taken into consideration, as these activities form a significant share of the airports' revenues.

In addition to this substantive novelty, we will also introduce a new methodological contribution to DEA in efficiency management. In the literature, DEA is used to assess the relative inefficiency of companies or organizations, in this case, airports, from a comparative perspective. An inefficient airport can improve its performance and reach the efficient frontier by reducing its inputs (or increasing its outputs) (see also Cooper et al., 2006). In the standard DEA approach, this is achieved by a uniform and undifferentiated reduction in all inputs. But in principle, there is an infinite number of improvements to reach the efficient frontier, so that there are also many solutions for a firm to become fully efficient. The existence of an infinite number of solutions to reach the efficient frontier has led to a stream of literature on the integration of DEA and Multiple Objective Linear Programming (MOLP), which was initiated by Golany (1988). In short, this line of literature offers several paths to efficiency, taking into account the preferences of the decision maker. A drawback, however, is that when the a-priori information used by decision makers is wrong or incomplete, a wrong path to efficiency may be chosen. In the present paper we propose an alternative method, called the Distance Friction Minimization (DFM) approach. A generalized distance friction function is presented to assist a decision maker in improving his or her efficiency by a smart move towards the efficient frontier.

Our new methodological approach will be explained in three steps. First, in Section 2 the standard Banker-Charnes-Cooper (BCC) model in Data Envelopment Analysis (DEA) will concisely be outlined. Then, Section

3 will be devoted to a concise description of our new efficiency-improving projection model, i.e., the DFM model. Next, in Section 4, we will present the implications of the presence of fixed factors (FF) for our generalized DEA model. The final part of the study of the study offers results from our empirical application of comparative efficiency analysis to 19 airports in Europe, including their shopping facilities. Our empirical results will also present a sensitivity analysis on the FF-assumptions and shopping facilities assumptions in our model. In conclusion, our study serves to highlight the importance of a more appropriate projection model in DEA, while it illustrates its usefulness for European airports, in particular when fixed factors and non-aviation activities are considered.

2. The Banker-Charnes-Cooper Model in Data Envelopment Analysis

In its evolution over time, DEA has led to various mathematical specifications. We will offer here a concise formal representation, based on the Banker-Charnes-Cooper (1984) model (abbreviated hereafter as the BCC-Input model), which is a well-known and established approach in DEA. It takes for granted that inputs can be reduced to increase efficiency. For a given decision-making unit *j*, DMU$_j$ $(j = 1, \cdots, J)$, to be evaluated on any trial generally designated as DMU$_o$ (where *o* ranges over 1, 2 …, *J*), the BCC-Input model may be represented as the following fractional programming (FP_o) problem:

$$(FP_o) \qquad \max_{v,u} \quad \theta = \frac{\sum_s u_s y_{so} - u_o}{\sum_m v_m x_{mo}}$$

$$\text{s.t.} \qquad \frac{\sum_s u_s y_{sj} - u_o}{\sum_m v_m x_{mj}} \le 1, \ \ (j = 1, \cdots, J) \tag{2.1}$$

$$v_m \ge 0, \ u_s \ge 0, \ u_o \ \text{ free in sign,}$$

where θ is an objective variable (efficiency score), x_{mj} is the volume of input *m* (*m*=1,…, *M*) for DMU$_j$ (*j*=1,…,*J*), and y_{sj} the output *s* (*s*=1,…,*S*) of DMU$_j$, while v_m and u_s are respectively the weights given to input *m* and output *s*. The BCC model allows for returns to scale, and this is represented by the index u_o ($u_o < 0$, then increasing; $u_o = 0$, then constant; $u_o > 0$, then decreasing).

Model (2.1) is often called an input-oriented BCC (BCC-I) model. It is obviously a fractional programming model, which may be solved stepwise by assigning an arbitrary value to the denominator in (2.1), and maximizing next the numerator. BCC-I model (2.1) can be shown to have the following equivalent linear programming (LP_o) specification for any DMU $_j$:

$$
\begin{aligned}
(LP_o) \qquad & \max_{v,u,u_o} \quad \theta = \sum_s u_s y_{so} - u_o \\
\text{s.t.} \qquad & \sum_m v_m x_{mo} = 1 \\
& -\sum_m v_m x_{mj} + \sum_s u_s y_{sj} - u_o e \le 0 \\
& v_m \ge 0, \; u_s \ge 0, \; u_o \ \text{free in sign,}
\end{aligned}
\tag{2.2}
$$

where e is a unit row vector.

The dual problem of (2.2), DLP_o, can now be expressed by means of a real variable θ using the following vector notation:

$$
\begin{aligned}
(DLP_o) \qquad & \min_{\theta,\lambda} \quad \theta \\
\text{s.t.} \qquad & \theta x_o - X\lambda \ge 0 \\
& Y\lambda \ge y_o \\
& e\lambda = 1 \\
& \lambda \ge 0
\end{aligned}
\tag{2.3}
$$

where e is again a row vector with unit elements, $\lambda = (\lambda_1, \; \cdots \; \lambda_J)^T$ is a non-negative vector (corresponding to the presence of slacks for each DMU$_j$), X is an ($M\times J$) input matrix and Y is an ($S\times J$) output matrix. The dual variable associated with the constraint $e\lambda = 1$ is equal to u_o from (2.1).

We can now define the input excesses $s^- \in R^m$ and the output shortfalls $s^+ \in R^s$, and identify them as 'slack' vectors as follows:

$$
s^- = \theta x_o - X\lambda \tag{2.4}
$$

and:

$$s^{+} = Y\lambda - y_o \tag{2.5}$$

Then we can solve the following two-stage LP problem in a straightforward way. We first find a solution for the dual problem DLP. Let the optimal result for the objective value be θ^*. Next, given the value of θ^*, we solve the following LP model using $(\lambda, \quad s^-, \quad s^+)$ as slack variables:

$$\max_{\lambda, s-, s+} \quad es^- + es^+ \tag{2.6}$$

s.t.

$$s^- = \theta^* x_o - X\lambda \tag{2.7}$$

$$s^+ = Y\lambda - y_o \tag{2.8}$$

$$\lambda \geq 0, \quad s^- \geq 0, \quad s^+ \geq 0 \tag{2.9}$$

For any inefficient DMU$_o$, we can now define the reference set E_o, based on the max-slack solution obtained above as follows:

$$E_o = \{ j \mid \lambda^* > 0 \} \; (j \in \{1, \cdots, J\}) \tag{2.10}$$

where E_o is a reference set for any inefficient DMU$_o$. The optimal solution can then be expressed as follows:

$$\theta^* x_o = \sum_{j \in E_o} x_j \lambda_j^* + s^{-*} \tag{2.11}$$

and:

$$y_o = \sum_{j \in E_o} y_j \lambda_j^* - s^{+*} \tag{2.12}$$

The improvement projection $(\hat{x}_o, \hat{y}_o)$ is now specified in (2.13) and (2.14) as:

$$\hat{x}_o = \theta^* x_o - s^{-*} \tag{2.13}$$

and:

$$\hat{y}_o = y_o + s^{+*} \tag{2.14}$$

These relationships suggest that the efficiency of (x_o, y_o) for DMU$_o$ can be improved, if the input values are reduced radially by the ratio θ^* and if the input excesses s^{-*} are eliminated. Similarly, the efficiency can be improved, if the output values are augmented by the output shortfall s^{+*}. We will now turn to a new approach to efficiency improvement, by introducing in Section 3 a more flexible and general projection model.

3. The Distance Friction Minimization Approach to the BCC Model

As mentioned, the improvement solution in the original BCC-I model imposes that the input values are reduced radially by a uniform ratio θ^* (θ^*=OC'/OC in Figure 1). In other words, the improvement solution for any arbitrary inefficient DMU_j is C' in Figure 1 (in cases the input space is a non-weighted (i.e., normal) *x*-space). Clearly, a similar exercise may be used for the output space. If input reductions would not get equal weights by a decision-maker, a weighted x-space (i.e., a non-uniform projection model) would emerge (see Figure 2). We will now deal with both weighted inputs and outputs in our extended DEA model, so that we obtain a generalized projection model. The (v^*, u^*) values obtained as an optimal solution for (2.2) result in a set of optimal weights *v* and *u* for DMU_o. Then the efficiency score can be evaluated by:

$$\theta^* = \frac{\sum_s u_s^* y_{so} - u_o^*}{\sum_m v_m^* x_{mo}} \tag{3.1}$$

As mentioned earlier, (v^*, u^*) is the set of most favourable weights for DMU_o in the sense of maximizing the ratio scale given by θ^*. Now v_m^* is the optimal weight for the input factor *m* and its magnitude expresses how much this factor is contributing in relative terms to efficiency. Similarly, u_s^* does the same for the output item *s*. Furthermore, we can then derive the relative importance of each item with reference to the value of each $v_m^* x_{mo}$. The same holds for u_s^* y_{so}, where u_s^* provides a measure of the relative contribution of y_{so} to the overall value of θ^*. These values do not only show which factors contribute to the performance of DMU_o, but also to what extent they do so. In other words, it is possible to express the distance frictions (or alternatively, the potential increases) in improvement projections.

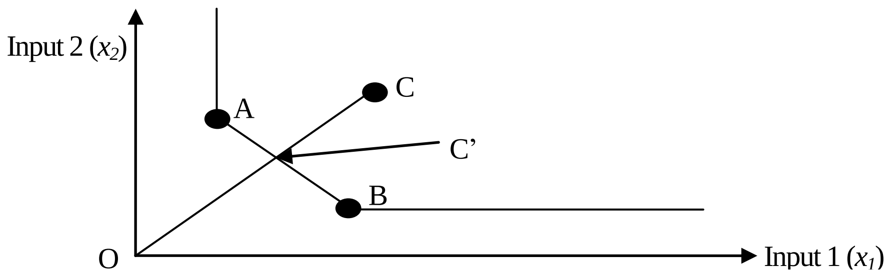

Figure 1. Illustration of original DEA projection in Input space

In our study we will use the optimal weights u_s^* and v_m^* from (3.1). We will now explain our efficient improvement projection model, BCC-DFM, based on a generalized distance friction minimization (DFM). A visual presentation of this new approach for both input spaces and output spaces is given in Figures 2 and 3, respectively. In this approach, a generalized distance friction is deployed to assist a DMU in improving its efficiency by a movement towards the efficient frontier. The direction of efficiency improvement depends on the input/output data characteristics of the DMU. It is now appropriate to define the projection functions for the minimization of the distance friction by using a Euclidean distance in weighted spaces. A suitable form of multidimensional projection functions serving to improve efficiency is given by a Multiple Objective Quadratic Programming (MOQP) model which aims to minimize the aggregated input reduction frictions as well as the aggregated output augmentation frictions. Thus, the DFM approach can generate a new contribution to efficiency enhancement problems in decision analysis, by deploying a weighted Euclidean projection function, while it may address both input reduction (see Figure 2) and output augmentation (see Figure 3).

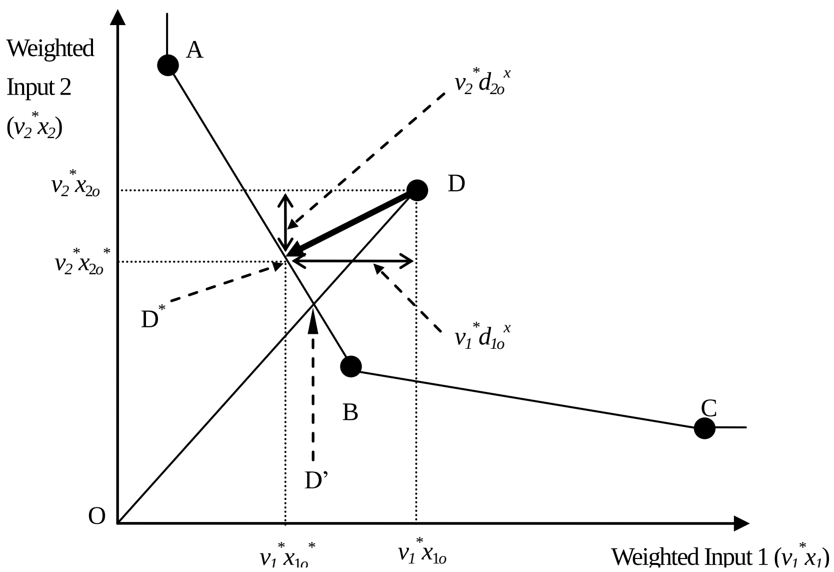

Figure 2. Illustration of the DFM approach (Input- $v_i^* x_i$ space)

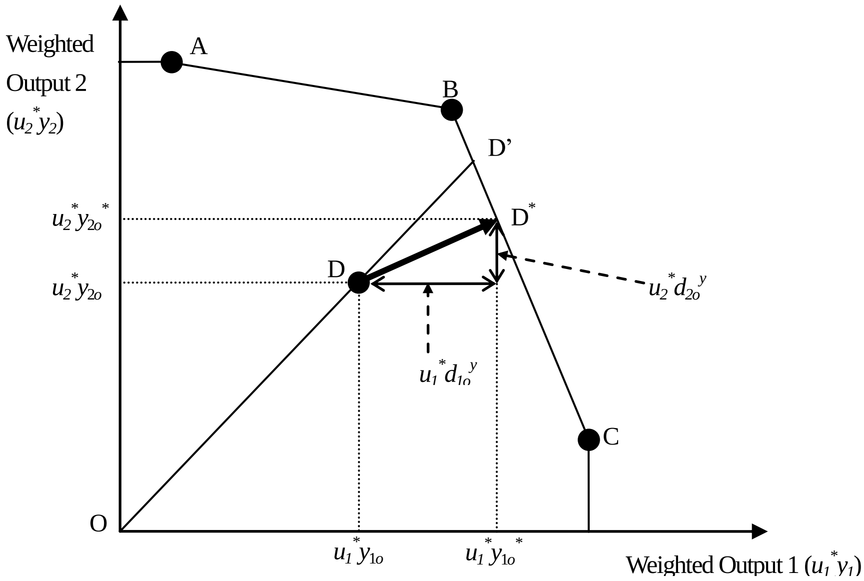

Figure 3. Illustration of DFM approach (Output- $u_r^* y_r$ space)

In Figure 2, the improvement of a DFM-projection in a weighted-input space is given by DD*, while the BCC-projection is given by DD'. Figure 3 presents similar projections in a weighted-output space. It is clear that the DFM-projections require an overall smaller decrease (increase) in inputs (outputs) to reach the efficient frontier. The BCC-DFM approach contains 5 steps which will now briefly be presented and described.

Step1. We solve DLP$_o$ in (2.3). Let the optimal value of the objective function be θ^*, and the obtained optimal weights u_s^*, v_m^* and u_o^*.

Step2. Using θ^*, we solve (2.6)-(2.9), so that we obtain s^{-*}, s^{+*}. Each DMU can then be categorized in terms of performance by θ^*, s^{-*} and s^{+*} as follows:

(i) If θ^*=1, and $s^{-*} = s^{+*} = 0$, the DMU in question is efficient.

(ii) If θ^*=1, and $s^{-*} \neq 0$ or $s^{+*} \neq 0$, improvement solutions may be generated on the basis of formulas (2.13) and (2.14).

(iii) If $\theta^* \neq 1$, and $s^{-*} \neq 0$ or $s^{+*} \neq 0$, improvement solutions may be generated by the next steps 3-5.

Step3. We introduce the distance friction function Fr^x and Fr^y by means of (3.2) and (3.3) which are defined by the Euclidean distance shown in Figures 2 and 3. Then we solve the following MOQP using d_{mo}^x (a distance reduction for x_{io}) and d^y_{so} (a distance increase for y_{so}) as variables:

$$\min \ Fr^x = \sqrt{\sum_m \left(v^*_m x_{mo} - v^*_m d^x_{mo}\right)^2} \tag{3.2}$$

and:

$$\min \ Fr^y = \sqrt{\sum_s \left(u^*_s y_{so} - u^*_s d^y_{so}\right)^2} \tag{3.3}$$

s.t.

$$\sum_m v^*_m \left(x_{mo} - d^x_{mo}\right) = \frac{2\theta^* + u_o}{1+\theta^* + u_o} \tag{3.4}$$

$$\sum_s u^*_s \left(y_{so} + d^y_{so}\right) + u_o = \frac{2\theta^* + u_o}{1+\theta^* + u_o} \tag{3.5}$$

$$x_{mo} - d^x_{mo} \geq 0 \tag{3.6}$$

$$d^x_{mo} \geq 0 \tag{3.7}$$

$$d^y_{so} \geq 0 \tag{3.8}$$

where x_{mo} is the amount of input factor m for any inefficient DMU$_o$, and y_{so} the amount of output factor s for any inefficient DMU$_o$. The aim of function Fr^x in (3.2) is to find a solution that minimizes the sum of input reduction distances which is incorporated in the improvement function. Analogously, the aim of function Fr^y in (3.3) is to find a solution that minimizes the sum of output augmentation distances which is incorporated in the improvement function.

Constraint functions (3.4) and (3.5) refer to the target values of input reduction and output augmentation. An illustration of a target value and a balanced allocation between input efforts and output efforts is shown in Figure 4. The balance in the distribution of contributions from both the input and output side to improve efficiency may be interpreted as follows. The total efficiency gap to be covered by inputs and outputs is (1-θ^*). The input side and the output side contribute according to their initial levels 1 and θ^*+ u_o, implying shares 1/{1+(θ^*+ u_o)}and (θ^*+ u_o)/{1+(θ^*+ u_o)} in the improvement contribution. Consequently, the contributions from both sides equal (1-θ^*)[1/{1+(θ^*+u_o)}], and (1-θ^*)[(θ^*+u_o)/{1+(θ^*+u_o)}], respectively. Hence we find for the input reduction target and the output increase targets:

Input reduction target: $$\sum_m v^*_m \left(x_{mo} - d^x_{mo}\right) = 1 - \left(1-\theta^*\right)\left(\frac{1}{1+\left(\theta^* + u_o\right)}\right) = \frac{2\theta^* + u_o}{1+\theta^* + u_o} \tag{3.9}$$

Output augmentation target: $\sum_s u_s^* (y_{so} + d_{so}^y) - u_o = \theta^* + (1-\theta^*) \times \frac{\theta^* + u_o}{1 + (\theta^* + u_o)} = \frac{2\theta^* + u_o}{1 + \theta^* + u_o}$ (3.10)

Constraint function (3.6) refers to a limitation of input reduction, while constraint functions (3.7) and (3.8) express simultaneously the pressure of input reduction and output rise. It is now possible to obtain the optimal distances d_{mo}^{x*} and d_{so}^{y*} by using MOQP (3.2)-(3.8).

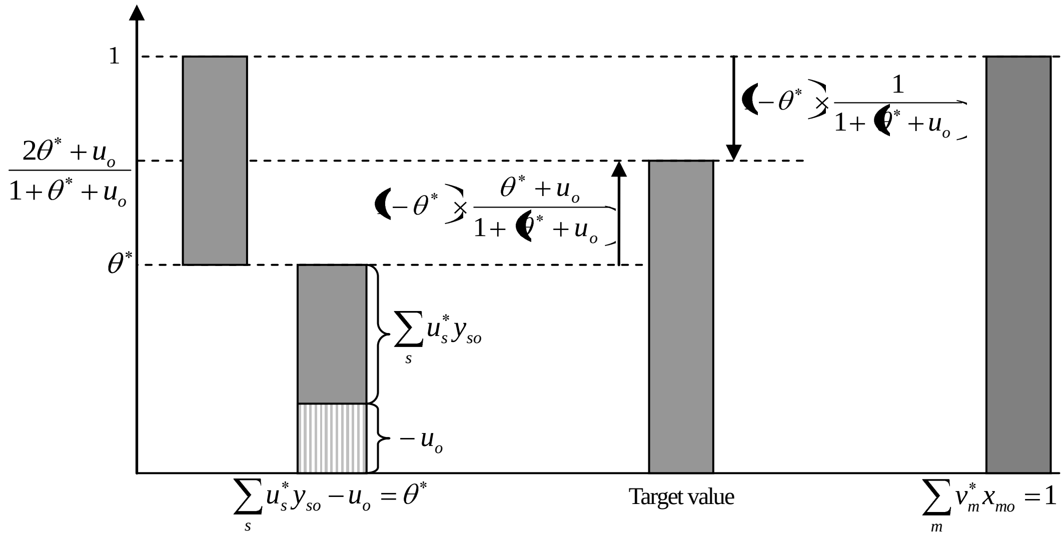

Figure 4. Presentation of balanced allocation for the efficiency gap (1-θ^*)

Step4. The friction minimization solution for an inefficient DMU$_o$ can now be expressed by means of formulas (3.11) and (3.12):

$$x_{mo}^* = x_{mo} - d_{mo}^{x*} \tag{3.11}$$

$$y_{so}^* = y_{so} + d_{so}^{y*} \tag{3.12}$$

Step5. In order to ascertain the presence of slacks for input and output variables, we have to solve formula (1.3) and (1.6)-(1.9); by using x_{mo}^*, y_{so}^*, we can obtain θ^{**}, s^{-**}, s^{+**}. In this case, we are sure that θ^{**} is calculated as 1. An optimal solution for an inefficient DMU$_o$ can be now expressed by means of formulas (3.13) and (3.14):

$$x_{mo}^{**} = x_{mo}^* - s^{-**} \tag{3.13}$$

$$y_{so}^{**} = y_{so}^* + s^{+**} \tag{3.14}$$

By using the above described BCC-DFM model, it is possible to identify a new efficiency improvement solution based on the standard BCC projection. It means an increase in options for efficiency improvement solutions in DEA. The main advantage of the BCC-DFM model is that it yields an outcome on the efficient frontier that is as close as possible to the DMU's input and output profile. In addition, the BCC-DFM model retains the property of the standard DEA approach that the measurement units of the different inputs and outputs need not be identical, while the improvement projection in a DFM model does not need to incorporate a priori information.

4. Fixed Factors in a BCC-DFM Model

4.1 Exogenous inputs and outputs in DEA

Standard DEA takes for granted that a DMU can freely adjust inputs and outputs in the relevant decision period, while this often is not the case in practice. In our case study on major European airports, airport runways cannot easily be adjusted in the short run to reach an efficient frontier. We will now analyze the case where input and/or outputs are not (entirely) to the free choice of a DMU. Banker and Morey (1986) have developed an exogenously given input model in the following way:

$$\theta - \varepsilon\left(\sum_{m\in D} s_m^- + \sum_{s=1}^{S} s_s^+\right) \tag{4.1}$$

s.t.

$$\theta x_{mo} = \sum_{m=1}^{M} x_{mj}\lambda_j + s_m^- \,,\ \ m \in D \tag{4.2}$$

$$x_{mo} = \sum_{m=1}^{M} x_{mj}\lambda_j + s_m^- \,,\ \ m \in ND \tag{4.3}$$

$$y_{so} = \sum_{s=1}^{S} y_{sj}\lambda_j - s_s^+ \ \ ,\ \ s = 1,\cdots,S. \tag{4.4}$$

where all variables (except θ) are constrained to be non-negative, and where the symbol $m \in D$ refers to the set of 'discretionary' inputs, and the symbol $m \in ND$ refers to the set of 'non-discretionary' inputs, and where ε has a non-Archimedean infinitesimal value.

It should be noted from the above constraints that the variable θ is not included in (4.3), because the pertaining inputs are exogenously fixed. It is therefore not possible to vary them at the discretion or free choice of the DMU. This is recognized by entering all $x_{mo}, m \in ND$ at their fixed value. Finally, we note that the pertaining slacks s_m^-, $m \in ND$ are omitted from the objective function. Based on the fixed factor (FF) concept of the above model, we will now develop a fixed factor component in our DFM.

4.2 Development of a BCC- DFM-FF model

In this subsection we will present a new version of the BCC-DFM model that takes into account the presence of fixed factors, which is coined the BCC-DFM-FF model. The efficiency improvement projection incorporating fixed factors as exogenous inputs or outputs (in a relevant decision horizon) in a BCC-DFM model is presented in (4.5)-(4.11):

$$\min \quad Fr^x = \sqrt{\sum_{m \in D} \left(v_m^* x_{mo} - v_m^* d_{mo}^x\right)^2} \tag{4.5}$$

and:

$$\min \quad Fr^y = \sqrt{\sum_{s \in D} \left(u_s^* y_{so} - u_s^* d_{so}^y\right)^2} \tag{4.6}$$

s.t.

$$\sum_{m \in D} v_m^* \left(x_{mo} - d_{mo}^x\right) + \sum_{m \in ND} v_m^* x_{mo} = 1 - \frac{\left(1-\theta^*\right)\left(1 - \sum_{m \in ND} v_m^* x_{mo}\right)}{\left(1 - \sum_{m \in ND} v_m^* x_{mo}\right) + \left(\theta^* - \sum_{s \in ND} u_s^* y_{so} + u_o\right)} \tag{4.7}$$

$$\sum_{s \in D} u_s^* \left(y_{so} + d_{so}^y\right) + \sum_{s \in ND} u_s^* y_{so} - u_o = \theta^* + \frac{\left(1-\theta^*\right)\left(\theta^* - \sum_{s \in ND} u_s^* y_{so} + u_o\right)}{\left(1 - \sum_{m \in ND} v_m^* x_{mo}\right) + \left(\theta^* - \sum_{s \in ND} u_s^* y_{so} + u_o\right)} \tag{4.8}$$

$$x_{mo} - d_{mo}^x \geq 0 \tag{4.9}$$

$$d_{mo}^x \geq 0 \tag{4.10}$$

$$d_{so}^y \geq 0 \tag{4.11}$$

where the symbol $s \in D$ refers to the set of 'discretionary' outputs, and the symbol $s \in ND$ refers to the set of 'non-discretionary' outputs.

Fr^x (4.5) and Fr^y in (4.6) are the distance frictions of discretionary inputs and outputs. The constraint functions (4.7) and (4.8) are incorporated in the fixed factors for the improvement room. The target values for input reduction and output augmentation with a balanced allocation depend on all input-output scores and fixed factor situations as presented in Figure 5.

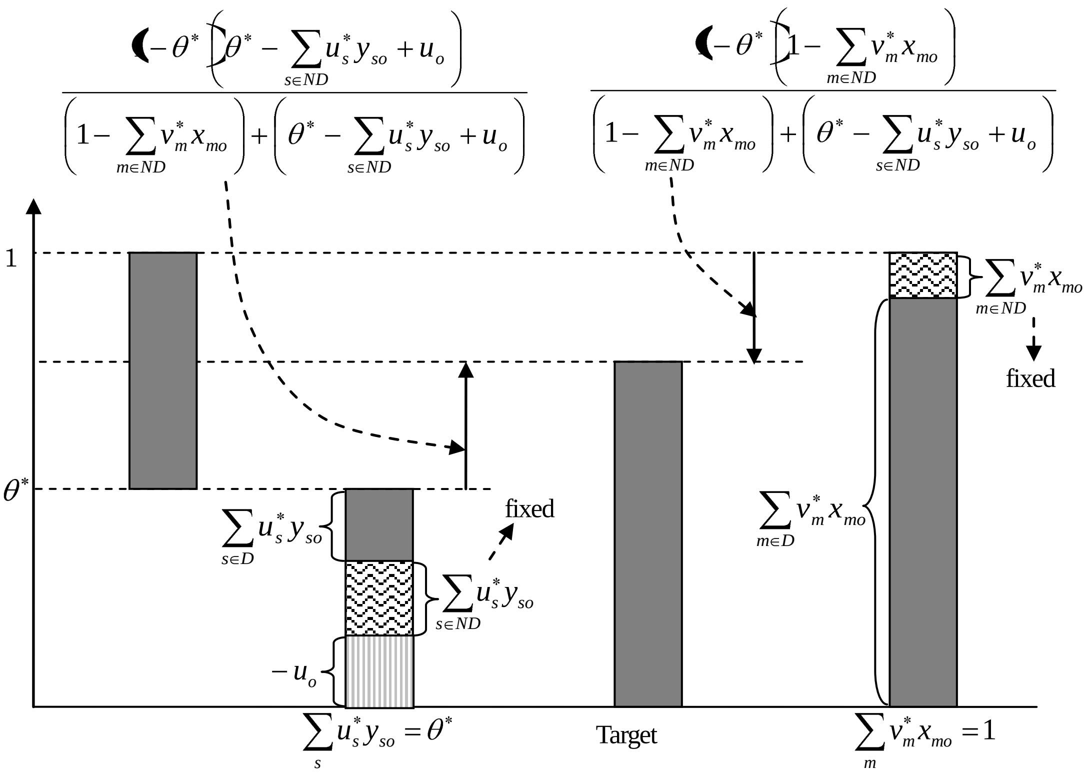

Figure 5. The distribution of the total efficiency gap (1-θ^*)

An optimal solution for an inefficient DMU_o can now be expressed by means of (4.12) - (4.15):

$$x_{mo}^{**} = x_{mo} - d_{mo}^{x*} - s^{-**}, \; m \in D \tag{4.12}$$

$$y_{so}^{**} = y_{so} + d_{so}^{y*} + s^{+**}, \; s \in D \tag{4.13}$$

$$x_{mo}^{**} = x_{mo}, \; m \in ND \tag{4.14}$$

$$y_{so}^{**} = y_{so}, \; s \in ND \tag{4.15}$$

The slacks $s^{-**}, m \in ND$ and s^{+**}, $s \in ND$ are now omitted from (4.14) and (4.15), because these factors are 'fixed 'or 'non-discretionary' inputs and outputs, in a way similar to the Banker and Morey (1986) model (4.1)-(4.4). This approach will hereafter be described as the BCC-DFM-FF approach, and will be used as the core methodology for comparing the performance of 19 airports in Europe.

5. Empirical Analysis of Airport Efficiency by means of the BCC-DFM-FF Model

5.1 Analysis framework and datasets on European airports

In our empirical work, we use input and output data for a set of 19 European airports in order to determine the relative efficiency levels in producing aeronautical outputs. Furthermore, for inefficient airports we determine the shortest paths to the efficient frontier as explained in the previous sections. Data on four input variables and two output variables were obtained from the Airport Benchmarking Report 2005 (Air Transport Research Society, 2005). Specifically, following the presentation in Section 1, we use the following inputs and outputs:

Inputs:

I1: Number of runways in 2003 (RN); fixed factor

I2: Terminal space (m^2) in 2003 (TS; excluding shopping area)

I3: Number of gates in 2003 (GN)

I4: Number of employees in 2003 (EN)

Outputs:

O1: Number of passengers in 2003 (PN)

O2: Aircraft Movements in 2003 (AM)

Furthermore, we have gathered data on shopping areas (Input 5) in order to carry out a sensitivity analysis which compares between efficiency results with and without commercial activities taking place inside the terminal. The shopping area may not be strictly necessary for passenger handling, but it may be important in the sense that it improves the perceived quality of airports because passengers can usefully spend transfer times (or delay times) in relatively attractive areas. For instance, the business area '*consumers*' of Amsterdam Airport Schiphol (AMS) aims to make this airport attractive as international hub for KLM and partners, by, amongst others, offering shopping, meeting and restaurant services at the airport.[3] The airports used in our analysis are listed in Table 1. These are the main international airports in Europe.

Table 1. DMUs (airports in Europe)

No.	Airport(IATA)	City	No.	Airport (IATA)	City
1	AMS	Amsterdam	11	HAM	Hamburg
2	ARN	Stockholm	12	HEL	Helsinki
3	BHX	Birmingham	13	LGW	London-Gatwick
4	BRU	Brussels	14	LHR	London-Heathrow
5	CDG	Paris-Charles de Gaulle	15	MAN	Manchester
6	CGN	Köln	16	OSL	Oslo
7	CPH	Copenhagen	17	PRG	Prague
8	EDI	Edinburgh	18	VIE	Vienna
9	FRA	Frankfurt	19	ZRH	Zürich
10	GVA	Geneva			

We first run the standard BCC-model using 4 or 5 inputs (i.e. with and without commercial inputs). The results of this analysis are then used to determine and compare the BCC-DFM and BCC-DFM-FF projections. The steps followed in the analysis are shown in Figure 6. In terms of nomenclature: 4I-2O refers to the model with four inputs and two outputs, while 5I-2O refers to the model with five inputs and two outputs.

In Subsection 5.2, we will present the efficiency evaluation results based on the standard BCC model, while we will for comparative purposes present the different outcomes resulting from incorporating and not incorporating the shopping area factor. Next, in Subsection 5.3, we will present the efficiency improvement projection results based on the BCC-DFM-FF model (i.e., by including the fixed runways factor), while we will compare these findings with the above-mentioned BCC and BCC-DFM projections and outcomes.

[3] It is evident that a similar argumentation holds for a weighted output perception by a decision-maker (see Figure 3).

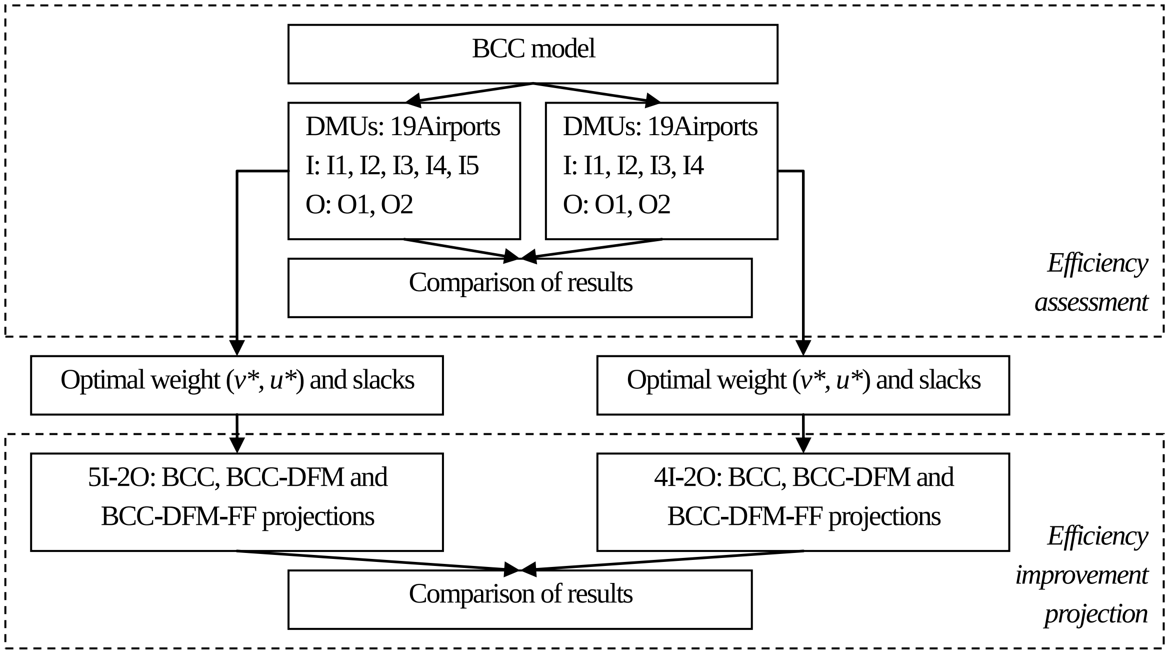

Figure 6. Stepwise presentation of analysis framework

5.2 Efficiency evaluation based on the BCC model

The efficiency evaluation results for the selected European airports based on the BCC model with 4 (i.e., 4I-2O) and 5 (i.e., 5I-2O) inputs, respectively, are given in Figure 7. From Figure 7, it can be seen that in the model with 4 inputs, AMS, ARN, BRU, CDG, CPH, EDI, GVA, LGW, LHR, OSL, VIE and ZRH are operating efficiently, at least given the input and output factors. When the commercial input (i.e., 5I-2O) is added, FRA also appears to become efficient. The efficiency score of FRA and CGN increase, if the shopping area is added to the analysis. The findings for FRA can be explained from the fact that the shopping area at FRA is relatively small compared to other airports: 2.75% of total terminal space, compared to 11% on average in our sample. When we add this input, FRA therefore can produce a given output with a relatively small input (shopping area), so that it becomes efficient. Next, we will present the comparison results based on returns to scale in Table 2.

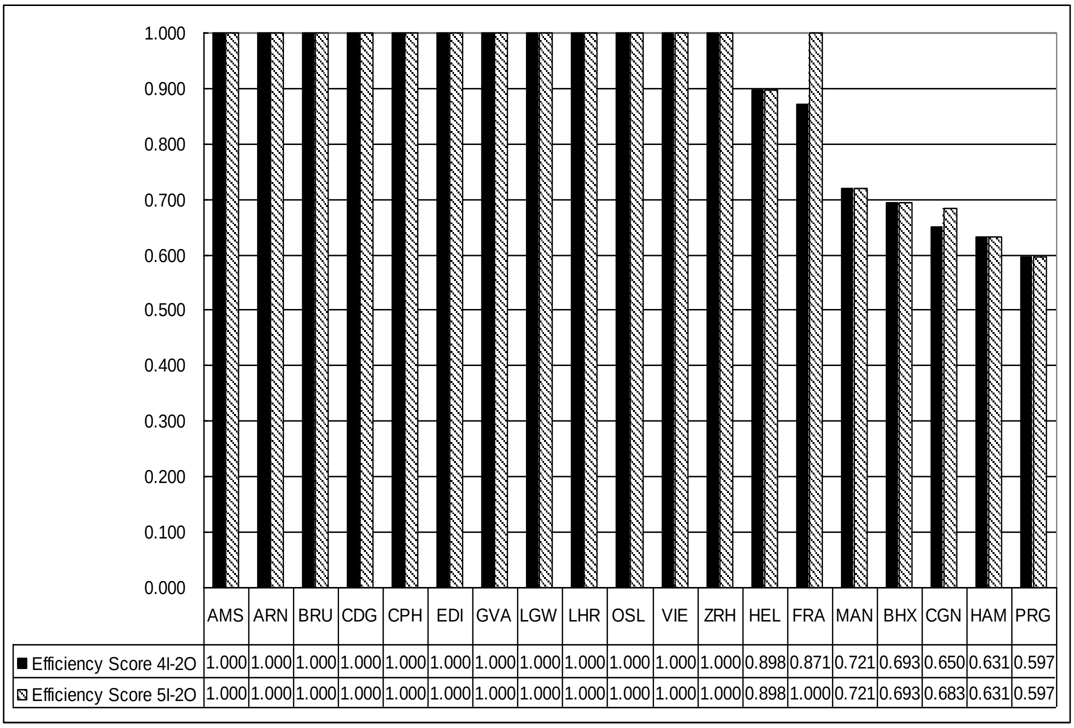

Figure 7. Efficiency scores of European airports based on BCC model (19 DMUs)

Table 2 reports whether the airports are operating under constant or decreasing returns to scale. The results are largely similar to those reported by Pels et al. (2003). Increasing returns to scale are not reported, probably due to the fact that smaller airports make up only a relatively small part of the sample. A number of airports is operating under decreasing returns to scale. Perhaps surprisingly, the largest airports are not necessarily operating under decreasing returns to scale. Although, generally speaking, the inclusion of commercial activities has little impact on the efficiency level, it appears that for some airports commercial activities influence the direction of the returns to scale. For instance, AMS, CDG and FRA operate under decreasing returns to scale, when 4 inputs are included, and constant returns to scale when 5 inputs (i.e., including shopping facilities) are included. These three airports have relatively large terminal buildings, with relatively small shopping areas (4.05%, 4.61% and 2.75%, respectively). Even though the airports may be technically efficient (in the case of AMS and CDG), the output may be relatively small compared to the terminal size. An increase in terminal size will lead to a less than proportional increase in output here. In technical terms, the constant returns to scale frontier and non-increasing returns to scale frontier lie far apart. But when the shopping area is added as an input, these airports have a relatively small input given the output level, so that the constant returns to scale frontier and the non-increasing returns to scale frontier are near to each other or overlapping, and may produce relatively large passenger numbers with relatively small shopping areas.

Table 2. Comparison results of returns to scale (Efficient DMUs)

	Efficiency Score		Returns to Scale 4I-2O		Returns to Scale 5I-2O	
DMU	4I-2O	5I-2O	Efficient DMU	Projected DMU	Efficient DMU	Projected DMU
AMS	1.000	1.000	Decreasing		Constant	
ARN	1.000	1.000	Constant		Constant	
BHX	0.693	0.693		Decreasing		Decreasing
BRU	1.000	1.000	Decreasing		Decreasing	
CDG	1.000	1.000	Decreasing		Constant	
CGN	0.650	0.683		Decreasing		Constant
CPH	1.000	1.000	Decreasing		Decreasing	
EDI	1.000	1.000	Constant		Constant	
FRA	0.871	1.000		Decreasing	Constant	
GVA	1.000	1.000	Constant		Constant	
HAM	0.631	0.631		Decreasing		Decreasing
HEL	0.898	0.898		Decreasing		Decreasing
LGW	1.000	1.000	Constant		Constant	
LHR	1.000	1.000	Constant		Constant	
MAN	0.721	0.721		Decreasing		Decreasing
OSL	1.000	1.000	Constant		Constant	
PRG	0.597	0.597		Decreasing		Constant
VIE	1.000	1.000	Decreasing		Decreasing	
ZRH	1.000	1.000	Decreasing		Decreasing	

5.3 Efficiency improvement projection of the BCC, BCC-DFM and BCC-DFM-FF models

Next, we turn to the full model use for efficiency comparison of airports in Europe. Efficiency improvement projection results based on the BCC, BCC-DFM and BCC-DFM-FF model for inefficient airports (with 4 inputs) are presented below (see Table 3).

Table 3. Efficiency improvement projection results of BCC-I, BCC-DFM and BCC-DFM-FF (4-Inputs 2-Outputs) for European airports

		BCC-I Projection					BCC-DFM Projection					BCC-I-DFM-FF Projection				
DMU	Score(θ*)	Score(θ**)					Score(θ**)					Score(θ**)				
I/O	Data	$\theta^* x_o$	s^{-*} s^{+*}	Projection	Difference $\theta^* x_o + s^{-*}$ s^{+*}	%	d_{mo}^{x*} d_{so}^{y*}	s^{-**} s^{+**}	Projection x_{mo}^{**} y_{so}^{**}	Difference $d_{mo}^{x*} + s^{-**}$ $d_{so}^{y*} + s^{+**}$	%	d_{mo}^{x*} d_{so}^{y*}	s^{-**} s^{+**}	Projection x_{mo}^{**} y_{so}^{**}	Difference $d_{mo}^{x*} + s^{-**}$ $d_{so}^{y*} + s^{+**}$	%
BHX	0.693	1.000					1.000					1.000				
(I-FF)RN	2	-0.6	-0.1	1.3	-0.7	-33.3%	0.0	0.0	2.0	0.0	0.0%	0.0	0.0	2.0	0.0	0.0%
(I)TS	56429	-17307.1	-5643.2	33478.8	-22950.2	-40.7%	0.0	0.0	55708.0	0.0	0.0%	0.0	0.0	55708.0	0.0	0.0%
(I)GN	31	-9.5	0.0	21.5	-9.5	-30.7%	-7.6	0.0	23.4	-7.6	-24.6%	-7.6	0.0	23.4	-7.6	-24.6%
(I)EN	685	-210.1	0.0	474.9	-210.1	-30.7%	0.0	0.0	685.0	0.0	0.0%	0.0	0.0	685.0	0.0	0.0%
(O)PN	9079172		106745.9	9185917.9	106745.9	1.2%	0.0	0.0	9079172.0	0.0	0.0%	0.0	0.0	9079172.0	0.0	0.0%
(O)AM	128740		0.0	128740.0	0.0	0.0%	18454.5	0.0	147194.5	18454.5	14.3%	18454.5	0.0	147194.5	18454.5	14.3%
CGN	0.650	1.000					1.000					1.000				
(I-FF)RN	3	-1.0	-0.3	1.6	-1.4	-45.3%	0.0	-1.0	2.0	-1.0	-32.8%	0.0	0.0	3.0	0.0	0.0%
(I)TS	196000	-68560.9	-56869.1	70570.0	-125430.0	-64.0%	0.0	-93715.6	102284.4	-93715.6	-47.8%	0.0	-93715.6	102284.4	-93715.6	-47.8%
(I)GN	40	-14.0	0.0	26.0	-14.0	-35.0%	-7.0	0.0	33.0	-7.0	-17.4%	-7.0	0.0	33.0	-7.0	-17.4%
(I)EN	1890	-661.1	-535.7	693.2	-1196.8	-63.3%	0.0	-1025.4	864.6	-1025.4	-54.3%	0.0	-1025.4	864.6	-1025.4	-54.3%
(O)PN	7758000		5005301.8	12763301.8	5005301.8	64.5%	0.0	8037822.5	15795822.5	8037822.5	103.6%	0.0	8037822.5	15795822.5	8037822.5	103.6%
(O)AM	153372		0.0	153372.0	0.0	0.0%	26718.6	0.0	180090.6	26718.6	17.4%	26718.6	0.0	180090.6	26718.6	17.4%
FRA	0.871	1.000					1.000					1.000				
(I-FF)RN	3	-0.4	0.0	2.6	-0.4	-12.9%	0.0	0.0	3.0	0.0	0.0%	0.0	0.0	3.0	0.0	0.0%
(I)TS	778000	-100161.2	-361186.0	316652.8	-461347.2	-59.3%	0.0	0.0	778000.0	0.0	0.0%	0.0	0.0	778000.0	0.0	0.0%
(I)GN	147	-18.9	0.0	128.1	-18.9	-12.9%	-13.8	0.0	133.2	-13.8	-9.4%	-11.6	0.0	135.4	-11.6	-7.9%
(I)EN	13006	-1674.4	-7512.6	3819.0	-9187.0	-70.6%	0.0	0.0	13006.0	0.0	0.0%	0.0	0.0	13006.0	0.0	0.0%
(O)PN	48359320		7265532.3	55624852.3	7265532.3	15.0%	0.0	0.0	48359320.0	0.0	0.0%	0.0	0.0	48359320.0	0.0	0.0%
(O)AM	458865		0.0	458865.0	0.0	0.0%	30696.0	0.0	489561.0	30696.0	6.7%	36089.5	0.0	494954.5	36089.5	7.9%
HAM	0.631	1.000					1.000					1.000				
(I-FF)RN	2	-0.7	0.0	1.3	-0.7	-36.9%	0.0	0.0	2.0	0.0	0.0%	0.0	0.0	2.0	0.0	0.0%
(I)TS	59410	-21909.3	0.0	37500.7	-21909.3	-36.9%	0.0	0.0	59410.0	0.0	0.0%	0.0	0.0	59410.0	0.0	0.0%
(I)GN	50	-18.4	-5.1	26.5	-23.5	-47.1%	0.0	-11.0	39.0	-11.0	-22.1%	0.0	-11.1	38.9	-11.1	-22.1%
(I)EN	777	-286.5	0.0	490.5	-286.5	-36.9%	-212.3	0.0	564.7	-212.3	-27.3%	-202.8	0.0	574.2	-202.8	-26.1%
(O)PN	9529924		0.0	9529924.0	0.0	0.0%	2074612.2	0.0	11604536.2	2074612.2	21.8%	2207901.1	0.0	11737825.1	2207901.1	23.2%
(O)AM	126878		1463.1	128341.1	1463.1	1.2%	0.0	42333.2	169211.2	42333.2	33.4%	0.0	43102.2	169980.2	43102.2	34.0%
HEL	0.898	1.000					1.000					1.000				
(I-FF)RN	3	-0.3	-0.8	1.9	-1.1	-38.0%	0.0	-1.1	1.9	-1.1	-35.1%	0.0	0.0	3.0	0.0	0.0%
(I)TS	99000	-10120.2	-37031.1	51848.7	-47151.3	-47.6%	0.0	-36762.6	62237.4	-36762.6	-37.1%	0.0	-36762.6	62237.4	-36762.6	-37.1%
(I)GN	38	-3.9	0.0	34.1	-3.9	-10.2%	-2.5	0.0	35.5	-2.5	-6.7%	-2.5	0.0	35.5	-2.5	-6.7%
(I)EN	594	-60.7	0.0	533.3	-60.7	-10.2%	0.0	0.0	594.0	0.0	0.0%	0.0	0.0	594.0	0.0	0.0%
(O)PN	9710920		1160447.7	10871367.7	1160447.7	12.0%	0.0	2161713.3	11872633.3	2161713.3	22.3%	0.0	2161713.3	11872633.3	2161713.3	22.3%
(O)AM	159520		0.0	159520.0	0.0	0.0%	7051.1	0.0	166571.1	7051.1	4.4%	7051.1	0.0	166571.1	7051.1	4.4%
MAN	0.721	1.000					1.000					1.000				
(I-FF)RN	2	-0.6	0.0	1.4	-0.6	-27.9%	0.0	0.0	2.0	0.0	0.0%	0.0	0.0	2.0	0.0	0.0%
(I)TS	102490	-28594.2	0.0	73895.8	-28594.2	-27.9%	-27081.7	0.0	75408.3	-27081.7	-26.4%	-20004.6	0.0	82485.4	-20004.6	-19.5%
(I)GN	103	-28.7	-22.2	52.1	-50.9	-49.4%	0.0	0.0	103.0	0.0	0.0%	0.0	0.0	103.0	0.0	0.0%
(I)EN	2852	-795.7	-297.5	1758.8	-1093.2	-38.3%	0.0	0.0	2852.0	0.0	0.0%	0.0	0.0	2852.0	0.0	0.0%
(O)PN	19699256		1877537.8	21576793.8	1877537.8	9.5%	0.0	0.0	19699256.0	0.0	0.0%	0.0	0.0	19699256.0	0.0	0.0%
(O)AM	207118		0.0	207118.0	0.0	0.0%	31025.9	0.0	238143.9	31025.9	15.0%	40426.6	0.0	247544.6	40426.6	19.5%
PRG	0.597	1.000					1.000					1.000				
(I-FF)RN	3	-1.2	-0.7	1.1	-1.9	-62.9%	0.0	-1.6	1.4	-1.6	-52.6%	0.0	0.0	3.0	0.0	0.0%
(I)TS	66143	-26648.4	-13563.3	25931.3	-40211.7	-60.8%	0.0	-14185.1	51957.9	-14185.1	-21.4%	0.0	-14185.1	51957.9	-14185.1	-21.4%
(I)GN	27	-10.9	0.0	16.1	-10.9	-40.3%	-5.1	0.0	21.9	-5.1	-18.9%	-5.1	0.0	21.9	-5.1	-18.9%
(I)EN	1702	-685.7	-564.5	451.8	-1250.2	-73.5%	0.0	-1109.5	592.5	-1109.5	-65.2%	0.0	-1109.5	592.5	-1109.5	-65.2%
(O)PN	7463120		1031840.6	8494960.6	1031840.6	13.8%	0.0	3520496.4	10983616.4	3520496.4	47.2%	0.0	3520496.4	10983616.4	3520496.4	47.2%
(O)AM	115765		0.0	115765	0	0.0%	21926.8	0.0	137691.8	21926.8	18.9%	21926.8	0.0	137691.8	21926.8	18.9%

In Table 3, it appears that the ratios of change in the BCC-DFM projection are smaller than those in the BCC projection, as was expected. Especially BHX, FRA and MAN, which are non-slack type airports (i.e. s^{-**} and s^{+**} is zero), became marked. The BCC-DFM projection involves both input reduction and output augmentation, and clearly, the BCC-DFM projection does not involve a uniform ratio because this model looks for the optimal input reduction (i.e. the shortest distance to the frontier, or distance friction minimization). For instance, the BCC projection shows that

BHX should reduce the terminal size by 40.7%, the number of gates by 30.7%, and the number of employees by 30.7% to become efficient. The BCC-DFM and BCC-DFM-FF results show that only a reduction in the number of gates of 24.6% is required to become efficient. Apart from the practicality of such a solution, the models show that a different and less involving solution is available than the standard BCC-projection to reach the efficient frontier. These results call for a careful investigation for each airport separately, but they demonstrate the great potential of our extended DEA model.

The efficiency improvement projection results based on the BCC, BCC-DFM and BCC-DFM-FF model for inefficient airports with 5 inputs (i.e., with shopping areas) are presented in Table 4. Again, the models show that a different, and a perhaps more efficient solution is available than the standard BCC-projection to reach the efficient frontier. The BCC-projection shows that, for instance, CGN should decrease the terminal size by 64%, the number of gates by 35%, the number of employees by 63.3%, and the shopping area by 31.7% to become efficient. The BCC-DFM and BCC-DFM-FF results show that reductions of 47.3% in terminal size, 16.9% in the number of gates, 54% in the number of employees, and 18% in shopping area are sufficient to become efficient; these reductions are smaller than those in the BCC-model. Again a more detailed analysis would be useful to understand the relative position of each airport.

6. Conclusion

In this paper we analyzed the efficiency of airports producing aeronautical outputs (number of passengers and aircraft movements) from aeronautical inputs (number of runways, number of gates and terminal size). It is clear that commercial activities are very important for airports in financial terms. In the technical relationship that we consider (a transformation from inputs to outputs) it may be less important, although we have to acknowledge that airports use commercial activities (i.e. shopping) to improve the overall perceived quality of their airport, in order to attract passengers. We therefore include the shopping area in the analysis.

Table 4. Efficiency improvement projection results of BCC-I and BCC-DFM-FF (5-Inputs 2-Outputs)

		BCC-I Projection					BCC-DFM Projection					BCC-DFM-FF Projection				
DMU	Score(θ*)	Score(θ**)					Score(θ**)					Score(θ**)				
I/O	Data	$\theta^* x_o$	s^{-*} / s^{+*}	Projection	Difference $\theta^* x_o + s^{-*}$ / s^{+*}	%	d_{mo}^{x*} / d_{so}^{y*}	s^{-**} / s^{+**}	Projection x_{mo}^{**} / y_{so}^{**}	Difference $-d_{mo}^{x*} - s^{-**}$ / $d_{so}^{y*} + s^{+**}$	%	d_{mo}^{x*} / d_{so}^{y*}	s^{-**} / s^{+**}	Projection x_{mo}^{**} / y_{so}^{**}	Difference $-d_{mo}^{x*} - s^{-**}$ / $d_{so}^{y*} + s^{+**}$	%
BHX	0.693	1.000					1.000					1.000				
(I-FF)RN	2	-0.6	-0.1	1.3	-0.7	-33.3%	0.0	0.0	2.0	0.0	0.0%	0.0	0.0	2.0	0.0	0.0%
(I)TS	56429	-17307.1	-5643.2	33478.8	-22950.2	-40.7%	0.0	0.0	55708.0	0.0	0.0%	0.0	0.0	55708.0	0.0	0.0%
(I)GN	31	-9.5	0.0	21.5	-9.5	-30.7%	-7.6	0.0	23.4	-7.6	-24.6%	-7.6	0.0	23.4	-7.6	-24.6%
(I)EN	685	-210.1	0.0	474.9	-210.1	-30.7%	0.0	0.0	685.0	0.0	0.0%	0.0	0.0	685.0	0.0	0.0%
(I)SA	10059	-3085.1	-2138.0	4835.9	-5223.1	-51.9%	0.0	0.0	10780.0	0.0	0.0%	0.0	0.0	10780.0	0.0	0.0%
(O)PN	9079172		106745.9	9185917.9	106745.9	1.2%	0.0	0.0	9079172.0	0.0	0.0%	0.0	0.0	9079172.0	0.0	0.0%
(O)AM	128740		0.0	128740.0	0.0	0.0%	18454.5	0.0	147194.5	18454.5	14.3%	18454.5	0.0	147194.5	18454.5	14.3%
CGN	0.683	1.000					1.000					1.000				
(I-FF)RN	3	-0.9	-0.4	1.6	-1.4	-45.3%	0.0	-1.0	2.0	-1.0	-32.4%	0.0	0.0	3.0	0.0	0.0%
(I)TS	196000	-62053.4	-63376.6	70570.0	-125430.0	-64.0%	0.0	-92731.7	103268.3	-92731.7	-47.3%	0.0	-92731.7	103268.3	-92731.7	-47.3%
(I)GN	40	-12.7	-1.3	26.0	-14.0	-35.0%	0.0	-6.8	33.2	-6.8	-16.9%	0.0	-6.8	33.2	-6.8	-16.9%
(I)EN	1890	-598.4	-598.5	693.2	-1196.8	-63.3%	0.0	-1020.1	869.9	-1020.1	-54.0%	0.0	-1020.1	869.9	-1020.1	-54.0%
(I)SA	8000	-2532.8	0.0	5467.2	-2532.8	-31.7%	-1436.9	0.0	6563.1	-1436.9	-18.0%	-1436.9	0.0	6563.1	-1436.9	-18.0%
(O)PN	7758000		5005301.8	12763301.8	5005301.8	64.5%	0.0	8131898.6	15889898.6	8131898.6	104.8%	0.0	8131898.6	15889898.6	8131898.6	104.8%
(O)AM	153372		0.0	153372.0	0.0	0.0%	27547.5	0.0	180919.5	27547.5	18.0%	27547.5	0.0	180919.5	27547.5	18.0%
HAM	0.631	1.000					1.000					1.000				
(I-FF)RN	2	-0.7	0.0	1.3	-0.7	-36.9%	0.0	0.0	2.0	0.0	0.0%	0.0	0.0	2.0	0.0	0.0%
(I)TS	59410	-21909.3	0.0	37500.7	-21909.3	-36.9%	0.0	0.0	59410.0	0.0	0.0%	0.0	0.0	59410.0	0.0	0.0%
(I)GN	50	-18.4	-5.1	26.5	-23.5	-47.1%	0.0	-11.0	39.0	-11.0	-22.1%	0.0	-11.1	38.9	-11.1	-22.1%
(I)EN	777	-286.5	0.0	490.5	-286.5	-36.9%	-212.3	0.0	564.7	-212.3	-27.3%	-202.8	0.0	574.2	-202.8	-26.1%
(I)SA	8890	-3278.5	-352.7	5258.8	-3631.2	-40.9%	0.0	-1301.5	7588.5	-1301.5	-14.6%	0.0	-1191.4	7698.6	-1191.4	-13.4%
(O)PN	9529924		0.0	9529924.0	0.0	0.0%	2074612.2	0.0	11604536.2	2074612.2	21.8%	2207901.1	0.0	11737825.1	2207901.1	23.2%
(O)AM	126878		1463.1	128341.1	1463.1	1.2%	0.0	42333.2	169211.2	42333.2	33.4%	0.0	43102.2	169980.2	43102.2	34.0%
HEL	0.898	1.000					1.000					1.000				
(I-FF)RN	3	-0.3	-0.8	1.9	-1.1	-38.0%	0.0	-1.1	1.9	-1.1	-35.1%	0.0	0.0	3.0	0.0	0.0%
(I)TS	99000	-10120.2	-37031.1	51848.7	-47151.3	-47.6%	0.0	-36762.6	62237.4	-36762.6	-37.1%	0.0	-36762.6	62237.4	-36762.6	-37.1%
(I)GN	38	-3.9	0.0	34.1	-3.9	-10.2%	-2.5	0.0	35.5	-2.5	-6.7%	-2.5	0.0	35.5	-2.5	-6.7%
(I)EN	594	-60.7	0.0	533.3	-60.7	-10.2%	0.0	0.0	594.0	0.0	0.0%	0.0	0.0	594.0	0.0	0.0%
(I)SA	11000	-1124.5	-3009.0	6866.6	-4133.4	-37.6%	0.0	-3942.6	7057.4	-3942.6	-35.8%	0.0	-3942.6	7057.4	-3942.6	-35.8%
(O)PN	9710920		1160447.7	10871367.7	1160447.7	12.0%	0.0	2161713.3	11872633.3	2161713.3	22.3%	0.0	2161713.3	11872633.3	2161713.3	22.3%
(O)AM	159520		0.0	159520.0	0.0	0.0%	7051.1	0.0	166571.1	7051.1	4.4%	7051.1	0.0	166571.1	7051.1	4.4%
MAN	0.721	1.000					1.000					1.000				
(I-FF)RN	2	-0.6	0.0	1.4	-0.6	-27.9%	0.0	0.0	2.0	0.0	0.0%	0.0	0.0	2.0	0.0	0.0%
(I)TS	102490	-28594.2	0.0	73895.8	-28594.2	-27.9%	-27081.7	0.0	75408.3	-27081.7	-26.4%	-20004.6	0.0	82485.4	-20004.6	-19.5%
(I)GN	103	-28.7	-22.2	52.1	-50.9	-49.4%	0.0	0.0	103.0	0.0	0.0%	0.0	0.0	103.0	0.0	0.0%
(I)EN	2852	-795.7	-297.5	1758.8	-1093.2	-38.3%	0.0	0.0	2852.0	0.0	0.0%	0.0	0.0	2852.0	0.0	0.0%
(I)SA	33910	-9460.7	-9088.9	15360.4	-18549.6	-54.7%	0.0	0.0	33910.0	0.0	0.0%	0.0	0.0	33910.0	0.0	0.0%
(O)PN	19699256		1877537.8	21576793.8	1877537.8	9.5%	0.0	0.0	19699256.0	0.0	0.0%	0.0	0.0	19699256.0	0.0	0.0%
(O)AM	207118		0.0	207118.0	0.0	0.0%	31025.9	0.0	238143.9	31025.9	15.0%	40426.6	0.0	247544.6	40426.6	19.5%
PRG	0.597	1.000					1.000					1.000				
(I-FF)RN	3	-1.2	-0.7	1.1	-1.9	-62.9%	0.0	-1.6	1.4	-1.6	-52.6%	0.0	0.0	3.0	0.0	0.0%
(I)TS	66143	-26648.4	-13563.3	25931.3	-40211.7	-60.8%	0.0	-14185.1	51957.9	-14185.1	-21.4%	0.0	-14185.1	51957.9	-14185.1	-21.4%
(I)GN	27	-10.9	0.0	16.1	-10.9	-40.3%	-5.1	0.0	21.9	-5.1	-18.9%	-5.1	0.0	21.9	-5.1	-18.9%
(I)EN	1702	-685.7	-564.5	451.8	-1250.2	-73.5%	0.0	-1109.5	592.5	-1109.5	-65.2%	0.0	-1109.5	592.5	-1109.5	-65.2%
(I)SA	11905	-4796.4	-3137.5	3971.1	-7933.9	-66.6%	0.0	-7061.6	4843.4	-7061.6	-59.3%	0.0	-7061.6	4843.4	-7061.6	-59.3%
(O)PN	7463120		1031840.6	8494960.6	1031840.6	13.8%	0.0	3520496.4	10983616.4	3520496.4	47.2%	0.0	3520496.4	10983616.4	3520496.4	47.2%
(O)AM	115765		0.0	115765.0	0.0	0.0%	21926.8	0.0	137691.8	21926.8	18.9%	21926.8	0.0	137691.8	21926.8	18.9%

Furthermore, we find that the inclusion of the shopping area (including catering) in the terminal as an input in the model has a relatively small influence on the relative efficiency levels. This might be explained by the fact that the shopping area is, in most airports, relatively small (the unweighted average is 11%), with some of the larger airports have shopping areas well below that percentage).

Finally, we offer here a new methodology for inefficient airports to reach the efficient frontier. This methodology does not require a uniform reduction in all inputs, as in the standard model. Instead, the new method minimizes the distance friction for each input. As a result, the reductions in inputs necessary to reach the efficient frontier are smaller than in the standard model. For instance, when shopping size is not used as an input, the results show that with the new methodology BHX should reduce the number of gates by 24.6% according to the new methodology. Using the standard methodology, BHX should reduce the terminal size by 40.7%, the number of gates by 30.7%, and the number of employees by 30.7% to become efficient. Overall, the new methodology yields a less involving way of reaching the efficient frontier.

It is of course questionable whether an airport can reduce its number of gates by 24.6% in practice; this depends on a set of different factors. What our analysis shows, is that when we consider the inputs and outputs mentioned above, for instance BHX could be as efficient as other airports in Europe when it reduces the number of gates by 24.6%. Further analysis should indicate whether this solution is feasible. A private operator should aim for maximum efficiency, but safety, environmental and labor regulations as well as climatological conditions can prevent the airport from reaching this solution.

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