Benchmarking the noise-oriented efficiency of major European airports

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BENCHMARKING THE NOISE-ORIENTED EFFICIENCY OF MAJOR EUROPEAN AIRPORTS: A DIRECTIONAL DISTANCE FUNCTION APPROACH

ABSTRACT

The EU Environmental Noise Directive (END) requires member states to produce noise action plans for all major airports every five years. Using that data, this paper employs a directional distance function approach to estimate noise-oriented efficiency of 60 European airports between 2006 and 2011. Technical change is calculated using the Malmquist productivity index. The results indicate that European airports have improved their noise efficiency between 2006 and 2011, and some degree of convergence in noise performance across countries is seen. Larger aircraft size is linked to better noise performance. Inefficient airports would also benefit from more stringent night movement limits.

Keywords: Airport noise, directional distance function, environmental efficiency, Malmquist-Luenberger index.

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1. INTRODUCTION

Aircraft noise is one of the most relevant undesirable outputs of air transport as it affects human health and property values in the vicinity of airports. As the demand for air transport is expected to grow significantly in the coming decades (ICAO, 2013a), the management of aircraft noise has become a main concern for local communities, airport managers, and regulators. In a context of long-term policy development, the European Commission approved a directive in 2002 relating to the management of environmental noise, typically referred to as the Environmental Noise Directive (END, 2002). The END requires member states to produce strategic noise maps for their main sources of environmental noise, including major airports (defined as those serving above 50,000 annual aircraft operations). The Directive also provides a set of guidelines that cover, among other aspects, the process of mapping noise exposure in neighboring areas. The first round of airport noise mapping was completed in 2007 and the second round in 2012, based on the traffic from the preceding years. This paper uses the publicly available data from both mapping exercises in order to benchmark the noise-oriented efficiency and productivity growth of major European airports in the presence of aircraft noise. Results have both policy and management implications.

A directional distance function (DDF) approach is used to estimate noise-oriented efficiency of 60 major European airports between 2006 and 2011. This is the first time an undesirable-output oriented frontier is employed in the airport literature. Technical change and efficiency catch-up are calculated using a decomposition of the Malmquist-Luenberger productivity index (MLPI). The area of the END 55dB(A) Lden noise contour is defined as a proxy for the total production of noise around each airport. Previous studies on noise-adjusted airport efficiency employed data on noise fees or average sound levels. However, these approaches fail to account for the spatial distribution of noise around the airport, which ultimately determines the number of affected residents. A third methodological contribution is the introduction of average length of haul as a non-discretionary output in the DDF model in order to account for heterogeneity in destination mixes across airports. This is also one of the first papers to estimate airport environmental efficiency using a cross-country dataset. A second-stage truncated regression investigates the impact on noise-oriented efficiency of factors such as airport size, aircraft size, share of night flights, population density, and noise abatement procedures.

The rest of this paper is organized as follows: Section 2 reviews the existing literature on the estimation of airport environmental efficiency. Section 3 describes the airport sample and DDF methodology, with special focus on the measurement of aircraft noise. This is followed by Section 4 which analyzes the efficiency results. Several policy implications are discussed. Finally, Section 5 summarizes the main findings and provides suggestions for future research.

2. LITERATURE REVIEW

Färe et al. (1989) adapted the standard Farrell approach to efficiency measurement in order to allow for an asymmetric treatment of desirable and undesirable outputs within a non-parametric framework. Adapting their theoretical models to the Directional Distance Function (DDF) structure developed by Chambers et al. (1998) is straightforward. An advantage of these methods is the flexibility to choose between different orientations, depending on the behavioral assumptions of the sample firms (i.e. maximizing output (Y), minimizing inputs (X) or undesirable outputs (U), or any combination of these objectives). These orientations are formalized as vectors in whose direction the distance to the technological frontier is measured. While, in theory, there are an infinite number of directional vectors, they can be grouped attending to the variables included (See Table 1). For example, if undesirable outputs are ignored, one can choose between the output, input, or simultaneous orientations – Y(X), X(Y), and YX, respectively –. When undesirable outputs are included, the YU(X) and YUX orientations aim to produce a global efficiency measure that combines several objectives, one of which relates to environmental management.

In the context of this paper, it is also worth reviewing the alternatives that are primarily oriented to reductions in undesirable outputs – also mentioned by Färe et al. (1989) –, but discussed in depth by Tyteca (1997). These include the U(YX) and U(Y) orientations, which set the model to search for the maximum feasible contraction in undesirable outputs given the observed levels of desirable outputs and inputs, or desirable outputs only, respectively. Stressing the partial nature of these measures, Tyteca (1997) concludes that they provide complementary information and should be all taken into account by decision-makers.

Table 1. Different orientations to measure the efficiency of firms in the presence of undesirable outputs.

Orientation	*Interpretation of efficiency estimates*
Y(X)	Maximum output expansion given desirable inputs (ignores undesirable outputs)
X(Y)	Maximum input contraction given desirable outputs (ignores undesirable outputs)
YX	Maximum simultaneous expansion of desirable outputs and contraction of inputs
YU(X)	Maximum simultaneous expansion of desirables and contraction of undesirables given inputs
YUX	Maximum simultaneous expansion of desirables and contraction of undesirables and inputs
U(YX)	Maximum contraction of undesirables given desirable outputs and inputs
U(Y)	Maximum contraction of undesirables given desirable outputs (ignores inputs)

Sources: Fare et al. (1989), Tyteca (1997).

This flexibility in the analysis of environmental performance is not seen in the airport-related literature (See Table 2). DDF has been the most popular methodology, with the exception of Lozano and Gutiérrez (2011) and Lozano et al. (2013), who chose a Slacks-based method (SBM) and a Network-DDF, respectively; and the paper by Martini et al. (2013b) that used a parametric hyperbolic output distance function. In spite of that, all these alternative methods still require an orientation for efficiency measurement. Table 2 shows that all contributions, except Fan et al. (2014), have chosen the typical YU(X) orientation along with the basic Y(X) in order to measure the change in efficiency and airport rankings when the externalities are considered. In relation to that, Martini et al. (2013a) found YU(X) to be a superior choice than U(YX) because the latter assumes that i) airports are already operating at optimal levels of desirable outputs and inputs and ii) desirable outputs are fixed. For the purposes of this paper, the first argument can be challenged by stating that, as opposed to Martini et al. (2013a) we do not exclusively aim for a global measure of efficiency, rather than a partial, environmentally-focused indicator. The second argument can also be challenged by referring to the large number of airport efficiency studies that have chosen input-orientations in a Data Envelopment Analysis (DEA) context, or cost function specifications in a Stochastic Frontier Analysis (SFA) context (See Liebert and Niemeier, 2013). All of these studies assume outputs (e.g. passenger traffic) to be exogenous to the airport, thus shifting the behavioral objective to cost or input minimization given an output target. We aim to translate this concept to the treatment of undesirable outputs and fill a gap in the literature.

To that end, this paper uses Tyteca's U(YX) orientation in a DDF model, with an application to airport operations and the generation of aircraft noise. This is the first undesirable output-oriented efficiency study in the airport literature. From the airports' perspective, this orientation is of interest since it indicates the maximum proportional reduction of noise contour (U) that can be achieved at the levels of traffic currently served (Y), while taking into account the impact of existing runway infrastructure (X) in the generation of said externality. Efficient airports under this orientation will have typically engaged in policies related to aircraft mix, evening/night curfews, or noise preferential routes in order to mitigate the level and spread of noise around the airport. There are indeed other relevant aspects at the time of assessing how airports approach the management of noise, such as geographical location and population density in the area. However, the chosen orientation is consistent with one of the pillars of ICAO's Balanced Approach to Aircraft Noise Management (ICAO, 2008): the reduction of noise at source. With a second-stage regression on the resulting efficiencies, we can further investigate how airports' noise policies relate to that goal.

Table 2. Previous literature on airport environmental efficiency

Author/s	*Database*	*Method*	*Orientation*	*Externality*
Yu (2004)	14 Taiwan 94-00	DDF	YU(X), Y(X)	Noise (noise fees)
Yu et al. (2008)	4 Taiwan 95-99	DDF/MLPI	YU(X)	Noise (noise fees)
Pathomsiri et al. (2008)	56 US 00-03	DDF/LPI	YU(X), Y(X)	Delays (delayed flights, time delays)
Lozano and Gutiérrez (2011)	39 Spain 06-07	SBM	YU(X)	Delays (delayed flights, time delays)
Martini et al. (2013a)	33 Italy 05-08	DDF	YU(X), Y(X)	Noise (average noise level) and local air pollution (monetized emissions)
Martini et al. (2013b)	34 Italy 05-08	HDF	YU(X), Y(X)	Air pollution (monetized emissions)
Lozano et al. (2013)	39 Spain 08	NDDF	YU(X)	Delays (delayed flights, time delays)
Fan et al. (2014)	20 China 06-09	DDF	YU(X), X(Y)	Delays (delayed flights)
Scotti et al. (2014)	44 US 05-09	DDF	YU(X), Y(X)	Noise (average noise level), local air pollution (monetized emissions), and delays (time delays)
Present study	60 Europe 06-11	DDF/MLPI	U(YX)	Noise (55dB contour area)

Notes: DDF: Directional Distance Function, SBM: Slacks-based method, HDF: Hyperbolic output distance function (parametric approach), NDDF: Network DDF, MLPI: Malmquist-Luenberger Productivity Index, LPI: Luenberger Productivity Index. Y: desirable outputs; U: Undesirable outputs; X: Inputs.

As seen in Table 2, previous studies have analyzed the impact of noise, delays, and air pollution on airport efficiency, with Scotti et al. (2014) accounting for the three factors simultaneously. Aircraft noise has been proxied by the noise fees paid by airlines (Yu, 2004; Yu et al. 2008) or average noise levels (Martini et al., 2013a). The latter is based on a method developed by Grampella et al. (2012) that combines data on aircraft movements with certified noise levels for each aircraft model. While we do not challenge the merit and simplicity of this approach, especially for dealing with large airport samples, we propose to use a measure that reflects one of the most common indicators used in the evaluation of airport noise performance: the area of the noise contour (See e.g. EC, 2007). This complements Grampella's method by adding information on the spatial distribution of noise, which can account for impacts on residents, schools, hospitals, parks, public places, and even wildlife (Lim et al., 2008; Eagan et al., 2011). Besides providing that information, noise contour maps reflect many discretionary variables relating to airport operations and noise abatement (e.g. day/night movements, runway split, preferential routes, etc…). This makes them ideal for benchmarking airport noise management.

Regarding desirable outputs, the most common variables have been passengers, cargo, and Air Transport Movements (ATMs), with Martini et al. (2013a, 2013b) combining the first two into workload units (WLUs)[1]. A variation from this trend is seen in Yu et al. (2008),

[1] A WLU is defined as a passenger or 100 kg of cargo.

which specified revenues as output, and ATMs and passengers as non-discretionary variables, with the objective to facilitate like-to-like comparisons. However, when translating that idea to our case study, we found the ATM variable problematic. Indeed, serving the same traffic units with less ATMs should lead to reduced contours and thus higher noise-oriented efficiency. Any decisions on e.g. average aircraft size that airports would try to implement would be excluded from the efficiency measurements if ATMs (or average aircraft size) are included in the DDF model. Instead, we facilitate like-to-like comparisons by using average length-of-haul (alh) as a non-discretionary variable. This aims to effectively set a constraint to aircraft mix flexibility, and also schedule flexibility, linked to the airport's destination mix.

Previous papers have also analyzed the drivers of airport environmental efficiency using second-stage analysis. For example, Martini et al., (2013a) found a significant relationship between fleet mix and environmental efficiency. In particular, airports with higher proportions of narrow-body aircraft we found to be less environmentally efficient. The reason is that larger aircraft allows for higher passenger traffic with fewer noise events. Larger airports were also found to be more environmentally efficient, a result that the authors interpreted as a sign of the existence of scale economies in the airport industry. They also concluded that the share of low-cost traffic does not have any impact on environmental performance. Similarly, Scotti et al., (2014) regressed their efficiency scores against aircraft size (average seats per aircraft movement), airport size (total passenger traffic), percentage of night flights, and percentage of international traffic. They also found both aircraft size and airport size to have a positive impact on environmental efficiency when noise impacts are considered. The percentage of night flights, on the other hand, was not a significant efficiency driver of US airports. We build on these previous contributions and also regress our noise-oriented efficiency estimates against aircraft and airport size indicators, share of night flights, and, for the first time, local population density.

Previous papers have only employed country-specific datasets featuring a limited number of observations. For example, Yu et al. (2008) was able to estimate environmental efficiency of just 4 domestic airports in Taiwan, using a three-year "window" approach to expand sample size. A consequence of these limited samples is overestimation of efficiency due to the reduced number of comparable airports to construct a reference set. Furthermore, introducing the undesirable output actually increases the level of efficiency in comparison with the traditional models that do not include them (Yu, 2004; Yu et al, 2008; Martini et al. 2013a, 2013b). For example, Lozano and Gutiérrez (2011) found 22 out of their 39 Spanish airports to be on the frontier and they explicitly mention that introducing airports from other countries will likely decrease the number of efficient airports. Martini et al. (2013a) also mention using a multiple-country database as a potential direction for future research. By doing so, we do not only aim to improve the discriminatory power of the DDF model but also estimate environmental efficiency in airports and countries that have not been covered before in the literature, such as Austria, France, Germany, or the UK.

3. DATA AND METHODOLOGY

3.1 DDF model and MLPI decomposition

The noise-oriented efficiency of our sample airports will be measured against an EU-wide technological frontier. This frontier is fomalized as the upper boundary of a production possibility set *P(x)* that comprises all feasible desirable (y) and undesirable output (u) combinations that can be obtained from a given input set (x). According to Färe et al. (1989), for *P(x)* to represent an actual production process, it should satisfy the axioms of i) inactivity: it is always feasible to produce zero quantity of y for any given x; ii) compactness: for each finite x it is feasible to obtain finite levels of y and u; iii) free disposability of y: every reduction in y is feasible while keeping x constant; iv) free disposability of x: every increase in x is feasible while keeping y constant; and v) null jointness: it is not possible to produce y without also producing u. Previous papers on airport environmental efficiency that consider noise production (e.g. Yu et al., 2008; Martini et al., 2013a; Scotti et al., 2014) have also implemented the condition of weak disposability of u: it is not possible to reduce u without also reducing y. In this case, however, we define our undesirable output as strongly disposable to recognize the possibility of reducing noise impact by means of costly, yet affordable, abatement policies, such as those related to fleet mix or operational restrictions (Yang and Pollitt, 2010).

These conditions, in combination with the observed data (y_{it}, u_{it}, x_{it}), can be implemented in a set of linear optimization programs to obtain a non-parametric approximation to the technological frontier. This method, proposed by Chambers et al. (1998), is known as Directional Distance Function (DDF), which adapts the basic framework of Data Envelopment Analysis (DEA) to allow for asymmetrical treatment of y and u. Traditionally, airports have been credited for simultaneously expanding y and contracting u, given x and technology. However, this paper only measures contractions in u, given y and x. Once the orientation is set, the DDF optimization program finds the best-performing "peer", or linear combination of them, in the sample. Ensuring that this "reference set" remains similar to the airport under evaluation can be achieved by imposing variable returns to scale (VRS) in the model, so that optimal productivity is allowed to vary with airport size. Nonetheless, additional heterogeneity in operating conditions can be accounted for with the inclusion of environmental (non-discretionary) variables (e_{it}). In the context of this paper, this means that the model will be calculating noise-oriented efficiency as the maximum proportional reduction in noise contour area (u) given traffic levels (y), average-length-of-haul (e), and infrastructure (x). Note that, under the asumption of free disposability of x, reference sets may have levels of infrastructure lower than the airport under evaluation.

Using a panel dataset of n airports, s inputs, m desirable outputs, h undesirable outputs, k environmental variables, and two time periods $(t,t+1)$, our DDF linear program can be written as follows:

$$(1)\quad \begin{aligned} & \max \theta_{it,t}=\theta_u \\ & s.t.\ y_{it} \leq Y_t\lambda, \\ & (1-\theta_u)u_{it} \geq U_t\lambda, \\ & x_{it} \geq X_t\lambda, \\ & e_{it} = E_t\lambda, \\ & \lambda \geq 0,\ \Sigma\lambda=1,\ \theta_u \geq 0 \end{aligned}$$

$$(2)\quad \begin{aligned} & \max \theta_{it+1,t+1}=\theta_u \\ & s.t.\ y_{it+1} \leq Y_{t+1}\lambda, \\ & (1-\theta_u)u_{it+1} \geq U_{t+1}\lambda, \\ & x_{it+1} \geq X_{t+1}\lambda, \\ & e_{it+1} = E_{t+1}\lambda, \\ & \lambda \geq 0,\ \Sigma\lambda=1,\ \theta_u \geq 0 \end{aligned}$$

where X is the $s \times n$ input matrix, Y is the $m \times n$ desirable output matrix, U is the $h \times n$ undesirable output matrix, and E is the $k \times n$ matrix of non-discretionary variables. These matrices determine the state of technology at a given time, indicated by the subscript t or $t+1$. λ is a $n \times 1$ vector of firm-specific weights that add up to 1 in order to impose VRS (Martini et al., 2013a; and Scotti et al., 2014 conclude that scale economies exist in the presence of undesirable outputs). $\theta_{it,t}$ denotes the undesirable-output oriented level of efficiency of airport i, observed in t, measured against the state of technology from t, indicating the maximum feasible reduction of u that the airport could achieve by adhering to the best practices of its peers. Thus, $\theta_{it,t} = 0$ denotes full efficiency. The meaning of $\theta_{it+1,t+1}$ can be deduced by analogy.

Mixed-period DDFs evaluate observations against the technology from a different time period. These are similar to (1) and (2) but without the non-negativity[2] restrictions on θ, i.e.

$$\begin{aligned}
(3) \quad & \max \theta_{it+1,t}=\theta_u \\
& s.t.\ y_{it+1} \leq Y_t\lambda, \\
& (1-\theta_u)u_{it+1} \geq U_t\lambda, \\
& x_{it+1} \geq X_t\lambda, \\
& e_{it+1} = E_t\lambda, \\
& \lambda \geq 0,\ \Sigma\lambda=1
\end{aligned}$$

$$\begin{aligned}
(4) \quad & \max \theta_{it,t+1}=\theta_u \\
& s.t.\ y_{it} \leq Y_{t+1}\lambda, \\
& (1-\theta_u)u_{it} \geq U_{t+1}\lambda, \\
& x_{it} \geq X_{t+1}\lambda, \\
& e_{it} = E_{t+1}\lambda, \\
& \lambda \geq 0,\ \Sigma\lambda=1
\end{aligned}$$

Where $\theta_{it+1,t}$ denotes efficiency of airport i in time period $t+1$, with respect to the technology of period t. The opposite applies to $\theta_{it,t+1}$.

The availability of panel data allows us to study technical change and "catch-up" effects in the airport industry. The idea of comparing firm performance across diferent time periods was first proposed by Malmquist (1953) and then formalized by Caves et al. (1982) in the Malmquist Index. Chung et al. (1997) adapted the latter to accommodate DDFs, leading to the Malmquist-Luenberger Productivity Index (MLPI) that measures total productivity change between t and $t+1$ by combining the results of (1), (2), (3), and (4):

$$(5) \qquad MLPI_{it,t+1}=[((1+\theta_{it,t})\times(1+\theta_{it,t+1}))/((1+\theta_{it+1,t})\times(1+\theta_{it+1,t+1}))]^{0.5}$$

The MLPI can be disaggregated in its two major components: efficiency change (EFFCH) and technical change (TECH), i.e.

$$(6) MLPI_{it,t+1}= EFFCH_{it,t+1}\times TECH_{it,t+1}$$

$$(7) EFFCH_{it,t+1}=(1+\theta_{it,t})/(1+\theta_{it+1,t+1})$$

$$(8) TECH_{it,t+1}=[((1+\theta_{it+1,t+1})\times(1+\theta_{it,t+1}))/((1+\theta_{it+1,t})\times(1+\theta_{it,t}))]^{0.5}$$

A value of MLPI>1 indicates overall productivity growth between the two time periods. In the context of this paper, this indicator provides information on whether the "absolute" noise performance of the airport has improved between both rounds of noise mapping. EFFCH>1 indicates that the airport has increased its level of relative noise efficiency by "catching up" with the technological frontier of period $t+1$. TECH>1 indicates that the segment of the frontier relevant to the airport is experiencing technical progress, i.e. the efficient airports are, on average, more productive than in the previous period and, hence, the benchmark for efficiency becomes more demanding. In theory, this can occur because of improvements at the time of reducing the noise impact of aircraft operations. In practical terms, technical progress can also be affected by traffic trends, as the efficient airports become busier the frontier moves as well.

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[2] An observation from $t+1$ can be "superefficient" if it lies beyond the frontier of period t, and vice versa.

Finally, the impact of several variables on noise efficiency of period $t+1$ will be tested using a second-stage truncated regression.

3.1 Variables and data sources

Similarly to previous papers, passengers (*pax*) and cargo (*cgo*, measured in metric tons), are defined as the two outputs in the model. These variables were collected from ACI's World Airport Traffic Reports. This focus on the aeronautical side of airport operations is common in previous studies on airport environmental efficiency, which did not define other variables, such as commercial revenues, as outputs. Accounting for the mix of passenger/cargo traffic is essential to measure noise efficiency due to the peculiarities of cargo operations in regards to aircraft types and flight schedules (many cargo flights need to operate during the night). Neither ATMs nor average aircraft size are included in the DDF model since one of the objectives of our approach is to analyze how airport policies in regards to aircraft mix affect their noise efficiency. Taking either variable as a given would defeat that purpose. Instead, the model includes average length of haul (*alh*, measured in km) as non-discretionary factor. This serves to characterize each airport's destination mix as it affects the policies of airport managers in terms of aircraft size, nighttime restrictions, and/or level of infrastructure, all of which will be considered in a second-stage analysis[3]. Data on flight length was obtained from the Official Airline Guide (OAG) that covers all scheduled flights at each airport. The same source was used to calculate two second-stage variables: the proportions of night flights (*snight*) − from 11pm to 6am −, and the average maximum take-off weight (*mtow*) − as a proxy for aircraft size −.

The number of boarding gates (*gat*) and total runway layout area (*run*, measured in km^2) are specified as inputs. Runway layout area is defined as the total area delimited by the runway system, including all associated taxiways and movement areas. This variable was considered appropriate to convey the information on the variables "number of runways" as well as "surface area of runways" that past authors have used (e.g. Yu, 2004; Yu et al., 2008), while also capturing additional information on the runway layout as it affects the noise contour[4]. Previous papers have also included terminal area, boarding gates, check-in desks, or baggage belts (e.g. Yu et al., 2008; Lozano and Gutiérrez, 2011; Lozano et al., 2013; Martini et al., 2013a). From this set of "landside" inputs, we select boarding gates because 1) information was easier to collect for all sample airports, and 2) it was highly correlated with the other indicators[5].

The area of the 55 dB(A) Lden[6] noise contour is defined as the undesirable output (*noise*, measured in km^2). This choice, in combination with the U(YX) orientation, is expected to deliver an efficiency metric that is consistent with the goal of reducing noise at source defined by ICAO (2008). Another advantage of using this undesirable output is that the END guidelines require that average annual traffic data be used in the noise contour simulations, as opposed to summer contours produced by many transport authorities (e.g. DFT, 2013). This

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[3] In summary, this choice of outputs implies that airports are defined as firms whose goal is to facilitate air transportation of passengers and cargo over a certain average distance. The DDF method will simply benchmark the ability of these airports to serve that level of transportation generating the smallest possible noise contours.

[4] Maximum runway capacity was also considered as an input. However, the capacities reported by airports are dependent on airport-specific aircraft mixes, which would have added undesirable heterogeneity into the model.

[5] Linear correlations between boarding gates and terminal area, baggage belts, and check-in-desks range between 80-84%.

[6] This is the threshold of significant noise impact set by the END. Lden indicates equivalent continuous day-evening-night sound level. Evening and night noise events are given a penalty of 5dB and 10dB, respectively (END, 2002). dB(A) means A-weighted decibels. The A-weighted scale incorporates a frequency weighting that approximates human hearing (ANIS, 1985).

benefits the DDF model since the END contours match the annual traffic data specified in the output vector. The time periods in our model coincide with the two rounds of END noise mapping. The first one was completed in 2007, using operational data from 2006[7]. The second round was completed in 2012, generally using data from 2011. The data is available in the website of the Noise Observation and Information Service for Europe (NOISE)[8].

One may argue why contour area was preferred to the most obvious measure of noise impact: the number of affected residents, which is also provided by the NOISE reports. While defining that variable as undesirable output does not violate null-jointness for our airport sample[9], the interpretation of the resulting frontier would be compromised. This alternative model will require the addition of an extra non-discretionary variable of population density (now the model will be one in which "traffic + infrastructure + population density" creates "affected population"). The problem with that approach is that our sample does not allow for enough variability in terms of all factors involved to allow for good reference sets to be obtained by the DDF[10]. Removing population density as extra non-discretionary variable will confound the analysis and lead to the systematic identification of airports with lower population densities (and hence lower affected populations) as the most efficient regardless of their actual strategies to reduce their noise contours, which are the aspects of airport noise management that this study focuses on.

This brings about a potential limitation of the proposed method. External variables (such as population densities) indeed affect the incentives that airports have to implement noise management policies. Airports in remote areas or very close to the sea do not face the same pressures to reduce their noise footprint than airports located close (or even within) population centers. In other cases, it is possible that the noise management policies actually increase the noise contours (e.g. preferential runway policies spreading out noise while limiting the impact on population). The impact on noise-oriented efficiency of population density (calculated using GIS), preferential runway protocols, and continuous descent approach guidelines[11] (complied from the airport's Aeronautical Information Publications-AIPs) will be tested in our second-stage regression.

Table 3. Definition of Day-Evening-Night periods at sample countries

Country	*Day*	*Evening*	*Night*
Germany	6am-6pm (12h)	6pm-10pm (4h)	10pm-6am (8h)
Italy	6am-8pm (14h)	8pm-10pm (2h)	10pm-6am (8h)
Spain	7am-7pm (12h)	7pm-11pm (4h)	11pm-7am (8h)
UK	7am-7pm (12h)	7pm-11pm (4h)	11pm-7am (8h)

Note: All times are local

A second limitation of the proposed metric is the fact that methodologies for the determination of Lden noise contours are not completely homogeneous across countries (See e.g. Murphy and King, 2010). In particular, countries are free to deviate from the default definitions of Day (7am to 7pm), Evening (7pm-11pm), and Night (11pm-7am) as long as the

[7] In 2008, Spanish Authorities submitted revised noise contours for Madrid Airport after two new runways were opened in 2006. Our dataset was corrected to include the correct traffic data that matches the noise contours.

[8] The NOISE dataset only reports the areas that cover dry land. In those cases where the contours falls over water, we manually measured the areas using ArcGIS. We aim to prevent situations in which high levels of traffic and small contours are observed due to variables not accounted for in the model. This can compromise the efficiency estimates. The option of including only the noise contours outside the airport area was discarded because it violates null-jointness for those airports whose contours fall entirely within the airport grounds.

[9] There are no sample airports with positive levels of traffic but no affected residents.

[10] We estimated that model and most airports simply became reference sets for themselves. Mixed-period linear programs were largely unfeasible.

[11] Continuous Descent Approach (CDA) is a method by which aircraft approach airports in a constant angle prior to landing. It reduces fuel consumption and noise compared to conventional descents.

coverage adds up to 24 hours. Table 3 shows the definitions adopted by the four best represented countries in our sample. Both Spain and UK use the default periods. Germany moves them back an hour while keeping the same duration for each period, and Italy does the same but also extending the duration of Day in two hours at the expense of Evening.

While EC (2007) noted that such deviations are not expected to affect the Lden noise contours significantly, their actual impact on the distribution of flight across the DEN periods can be easily measured. The hourly distribution of flights for the four countries is shown in Appendix A. Table 4 summarizes that information. Under the current definitions, and always in comparison with Spain and UK, Italian airports seem to benefit from a lower proportion of Evening and Night flights (which carry a noise penalty), while the opposite applies to German airports. Moving the four countries to default periods will make the distribution of flights more uniform. Still, a country like the UK would be at a disadvantage even in that situation, since its share of night flights is noticeably higher than the other countries.

Table 4. Distribution of Day-Evening-Night flight movements at sample countries (2011)

Current Periods				Default periods			
Country	Day	Evening	Night	Country	Day (7am-7pm)	Evening (7pm-11pm)	Night (11pm-7am)
Germany	69.7%	24.2%	6.2%	Germany	72.2%	21.2%	6.6%
Italy	81.8%	12.4%	5.9%	Italy	72.7%	22.4%	4.9%
Spain	72.3%	21.2%	6.6%	Spain	72.3%	21.2%	6.6%
UK	72.7%	18.4%	8.9%	UK	72.7%	18.4%	8.9%

Source: OAG, Own elaboration

In view of the above, we will be carrying out a set of Mann-Whitney tests to check if there are significant country effects on our efficiency estimates that support the hypothesis that differences in noise mapping methodologies actually affect the noise-oriented efficiencies.

3.2 Dataset

The dataset includes the 60 major airports (defined by the END as serving more than 50,000 ATMs) in the European Economic Area for which noise contour data is available in both time periods. Germany, Spain, Italy, and the UK are particularly well represented with 7, 7, 9, and 17 airports of different sizes, respectively, including each country's main international hubs. Large airports from other countries are included as well, such as Vienna, Brussels, Paris, and Amsterdam. The noise contour areas for all sample airports in both time periods are provided in Appendix B. Despite neither being the busiest airport nor having the longest runway system, Frankfurt presents the largest spread of aircraft noise in Europe. However, it also experienced the largest noise reduction (more than 50 km^2), despite a 6.8% increase in passengers and the opening of a new runway in 2011. Madrid also experienced a similar reduction in its noise footprint, but coupled with a 4.7% reduction in passenger traffic. The smallest noise contour in both mapping rounds is observed at Southampton, which does not open during the night period.

Tables 5 and 6 provide additional descriptive statistics of the airport sample. The observed traffic levels vary widely, from the 0.6 million passengers at Bournemouth to the 69.4 million passengers at London Heathrow. The sample also benefits of great variability in *alh*, which serves to characterize the different roles played by these airports within the European network. Indeed, *alh* ranges from 389 km for the regional airport in Bergen (Norway) to 3,025 km at Heathrow, with Tenerife South (Canary Islands) coming at a close second (2,800 km) due to its particular location. Average passenger traffic shows an annual growth rate of only 0.59% between 2006 and 2011, and cargo traffic is practically stagnated. This is related to the negative impact of the economic recession that took its toll on the European air transport industry in this period (ACI, 2011). This is a crucial factor to take into account when discussing the results, as the model is likely to interpret this contraction in traffic as technical regress. Finally, Table 6 also provides statistics for three second-stage variables: aircraft *mtow*, share of night flights, and population density.

Table 5. Descriptive statistics of the airport sample (2006)

	Round 1 (2006)						
	pax	*cgo* (t)	*alh* (km)	*gat*	*run* (km^2)	*noise* (km^2)	*mtow* (t)
avg.	13,967,502	227,295	1,043.7	48	1.8	59.9	64.4
s.d.	15,080,454	463,888	493.0	50	1.9	61.4	21.1
max	69,334,563	2,130,724	2,805.7	215	8.4	317.6	147.7
min	986,225	213	389.5	3	0.2	7.1	25.3

Source: NOISE (2014), OAG, airport annual reports, own elaboration.

Table 6. Descriptive statistics of the airport sample (2011)

	Round 2 (2011)								
	pax	*cgo* (t)	*alh* (km)	*gat*	*run* (km^2)	*noise* (km^2)	*mtow* (t)	*density* (pop/km2)	*snight* (%)
avg.	14,645,785	225,824	1,172.8	53	1.8	57.0	69.8	1,187.9	0.8%
s.d.	15,596,084	473,269	527.3	53	1.9	57.7	20.6	1,140.7	3.2%
max	69,433,565	2,215,200	3,025.8	222	8.4	277.0	153.4	3,704.2	12.4%
min	621,625	132	433.0	3	0.2	4.5	26.6	95.3	0.0%

Source: NOISE (2014), OAG, airport annual reports, own elaboration.

4. RESULTS AND DISCUSSION

4.1 Overview of DDF estimates

Table 7 shows the results of the DDF models, where a higher value of θ denotes lower noise-oriented efficiency. The MLPI decomposition is presented as well. The first conclusion is that European airports experienced some inefficiency in regards to noise generation. The average noise-oriented inefficiency of major European airports in 2006 is 32.3%. This inefficiency is significantly reduced to 21% in 2011. The impact of decreasing or stagnant traffic translates into an average 5% of technical regress. On the other hand, inefficient airports have been able to catch-up with the regressing frontier, leading to an average 9.2% efficiency change between 2006 and 2011. These effects are combined into an average 4.3% measurable productivity growth between the two rounds of noise mapping.

For benchmarking purposes, individual airports are classified using the categories defined by European authorities (EC, 2005): i) major hubs (above 25 million annual passengers); ii) large community airports (between 10 and 25 million); iii) national airports (between 5 and 10 million); and iv) large regional airports (under 5 million).

"Major hubs" tend to be located on the technological frontier in both periods[12]. One of these cases is Madrid, where the introduction of precision-area navigation (P-RNAV) procedures in late 2007 has been instrumental in reducing the dispersion of arriving and departing flight paths from their nominal routes (AENA, 2012). This effect is quantified by our model as an approx. 30% reduction in the noise contour area of Madrid airport in 2011 with respect to the technology of the previous period ($\theta_{2,1}$). The implementation of P-RNAV at Amsterdam airport may also explain the important catch-up effect of the airport. Munich and Rome also experienced significant improvement, noting the 22% and 19% increase in *mtow*, as well as a 15% and 11% increase in *alh,* respectively, between 2006 and 2011.

"Large community airports" draw a more diverse picture but it is the cluster that shows the highest efficiency change. Interesting examples are Dusseldorf and Geneva, which improved their noise performance after being severely inefficient in 2006. In both cases, we found exactly the same profile: strong growth in passenger traffic (22% and 31%, respectively) coupled with larger aircraft (13% and 17%, respectively) and longer routes (7% and 24% respectively). Airports like Milano-Malpensa and Manchester become fully noise-efficient by

[12] Note the lack of comparable airports at these levels of traffic to create a valid reference set.

2011. While both saw their passenger traffic reduced by 10%, a substantial increase in aircraft size is present (20% and 21% respectively). It is also worth noting that Geneva and Manchester rank among the top performing airports in Europe in regards to their environmental regulations, particularly in the areas of fleet monitoring, runway- and departure procedures (Helios, 2012).

Table 7. Summary of DDF results

Country	*Airport*	*IATA Code*	***DDF – U(YX)***						
			$\theta_{1,1}$	$\theta_{2,2}$	$\theta_{1,2}$	$\theta_{2,1}$	***MLPI***	***EFFCH***	***TECH***
UK	London Heathrow	LHR	0.000	0.000	0.214	-0.102	1.163	1.000	1.163
FR	Paris CDG	CDG	0.000	0.000	-0.116	0.081	0.904	1.000	0.904
DE	Frankfurt	FRA	0.000	0.000	0.202	0.182	1.009	1.000	1.009
NL	Amsterdam	AMS	0.101	0.000	0.033	0.031	1.050	1.101	0.954
ES	Madrid	MAD	0.000	0.000	0.112	-0.298	1.259	1.000	1.259
DE	Munich	MUC	0.541	0.000	0.179	0.418	1.132	1.541	0.735
IT	Rome Fiumicino	FCO	0.521	0.000	0.453	-0.486	2.074	1.521	1.363
UK	London Gatwick	LGW	0.000	0.000	0.051	0.136	0.962	1.000	0.962
FR	Paris Orly	ORY	0.000	0.000	0.089	0.285	0.920	1.000	0.920
Average major hubs			**0.129**	**0.000**	**0.135**	**0.028**	**1.126**	**1.111**	**1.014**
CH	Zurich	ZRH	0.421	0.245	0.370	0.328	1.085	1.141	0.951
AT	Vienna	VIE	0.526	0.347	0.446	0.469	1.056	1.133	0.932
DE	Düsseldorf	DUS	0.546	0.215	0.393	0.508	1.084	1.272	0.852
IT	Milano Malpensa	MXP	0.337	0.000	0.279	0.041	1.281	1.337	0.959
UK	Manchester	MAN	0.453	0.000	0.076	0.364	1.070	1.453	0.737
BE	Brussels	BRU	0.307	0.296	0.239	0.326	0.970	1.008	0.963
IE	Dublin	DUB	0.000	0.000	-0.840	0.337	0.345	1.000	0.345
UK	London Stansted	STN	0.000	0.159	-0.018	0.315	0.803	0.863	0.930
FI	Helsinki	HEL	0.518	0.362	0.411	0.491	1.027	1.115	0.922
PT	Lisbon	LIS	0.219	0.000	0.205	0.014	1.204	1.219	0.988
DE	Hamburg	HAM	0.602	0.356	0.480	0.508	1.077	1.181	0.912
CH	Geneva	GVA	0.703	0.329	0.622	0.674	1.114	1.282	0.870
ES	Malaga	AGP	0.304	0.060	-0.263	0.110	0.904	1.231	0.735
CZ	Prague	PRG	0.613	0.514	0.538	0.594	1.014	1.065	0.952
ES	Gran Canaria	LPA	0.439	0.172	0.390	0.207	1.189	1.228	0.968
DE	Stuttgart	STR	0.651	0.588	0.611	0.652	1.007	1.039	0.969
Average large community airports			**0.415**	**0.228**	**0.246**	**0.371**	**0.982**	**1.152**	**0.853**
ES	Alicante	ALC	0.169	0.000	-0.303	0.041	0.884	1.169	0.757
UK	London Luton	LTN	0.000	0.000	0.029	0.228	0.915	1.000	0.915
UK	Edinburgh	EDI	0.000	0.000	-0.021	0.535	0.799	1.000	0.799
PL	Warsaw	WAW	0.556	0.343	0.401	0.417	1.070	1.158	0.924
IT	Milano Linate	LIN	0.597	0.000	0.152	0.348	1.168	1.597	0.732
DE	Cologne	CGN	0.350	0.305	0.259	0.386	0.969	1.034	0.937
ES	Tenerife Sur	TFS	0.000	0.000	0.515	-0.427	1.626	1.000	1.626
UK	Birmingham	BHX	0.433	0.320	0.344	0.338	1.044	1.085	0.962
IT	Venice	VCE	0.596	0.000	0.612	0.259	1.429	1.596	0.896
IT	Orio al Serio	BGY	0.490	0.000	0.204	0.478	1.102	1.490	0.739
UK	Glasgow	GLA	0.526	0.284	0.368	0.260	1.136	1.188	0.956
IT	Catania	CTA	0.514	0.440	0.567	0.454	1.065	1.052	1.012
IT	Bologna	BLQ	0.471	0.334	0.524	0.306	1.134	1.102	1.029
UK	Bristol	BRS	0.390	0.251	0.375	0.183	1.136	1.111	1.023
IT	Naples	NAP	0.059	0.123	0.159	0.074	1.009	0.943	1.070
NO	Bergen	BGO	0.000	0.000	-0.128	0.287	0.823	1.000	0.823
DE	Hannover	HAJ	0.734	0.716	0.759	0.678	1.029	1.011	1.018
UK	Liverpool	LPL	0.252	0.182	0.214	0.213	1.030	1.059	0.972
RO	Bucharest	OTP	0.697	0.879	0.772	0.858	0.928	0.903	1.027
Average national airports			**0.360**	**0.220**	**0.305**	**0.311**	**1.053**	**1.116**	**0.944**
ES	Valencia	VLC	0.530	0.385	0.554	0.300	1.149	1.105	1.040
UK	Newcastle	NCL	0.424	0.329	0.329	0.162	1.107	1.072	1.033
UK	East midlands	EMA	0.000	0.000	-0.200	0.057	0.870	1.000	0.870
NO	Stavanger	SVG	0.000	0.554	0.176	0.673	0.672	0.644	1.045
UK	Belfast	BFS	0.420	0.188	0.272	0.188	1.132	1.196	0.946
ES	Bilbao	BIO	0.281	0.199	0.410	0.026	1.212	1.068	1.135
DE	Nuremberg	NUE	0.659	0.428	0.526	0.585	1.058	1.162	0.910
NO	Trondheim	TRD	0.309	0.621	0.157	0.585	0.768	0.807	0.951
IT	Torino	TRN	0.499	0.536	0.592	0.425	1.044	0.976	1.070
UK	Aberdeen	ABZ	0.446	0.569	0.279	0.484	0.891	0.922	0.967
UK	Leeds	LBA	0.000	0.171	-1.039	0.095	-	0.854	-
DK	Billund	BLL	0.449	0.000	0.626	0.289	1.352	1.449	0.933
LU	Luxemburgo	LUX	0.000	0.000	0.324	0.131	1.082	1.000	1.082
UK	Southampton	SOU	0.000	0.000	0.095	-0.573	1.602	1.000	1.602
LT	Vilnius	VNO	0.434	0.575	0.668	0.327	1.070	0.911	1.175
Average large regional airports			**0.297**	**0.304**	**0.251**	**0.250**	**1.048**	**0.995**	**1.042**
Average Germany			0.510	0.326	0.426	0.490	1.044	1.144	0.913
Average Italy			0.454	0.159	0.393	0.211	1.225	1.264	0.969
Average Spain			0.246	0.116	0.202	-0.006	1.153	1.111	1.038
Average United Kingdom			0.209	0.153	0.086	0.180	1.028	1.042	0.974

Average total	**0.323**	**0.210**	**0.250**	**0.269**	**1.043**	**1.092**	**0.950**

Note: MLPI, EFFCH, and TECH averages are geometric averages.

Alicante, Luton, Edinburgh, Tenerife South, Milano Linate, Venice, Bergamo, and Bergen are the top-performing "national airports" in 2011, some of them after significantly catching up to the frontier. In the case of Venice, the results show the effectiveness of the comprehensive noise-monitoring installed at the end of 2006. Among the airports that partially improved their efficiency, the case of Bristol is particularly interesting. While serving virtually the same number of passengers than in 2006, and despite a 7% increase in night flights, the airport has been able to benefit from a reduction in noise events due to the 21% increase in average aircraft size. Finally, East Midlands, Billund, Luxemburg, and Southampton are the benchmarks within the "large regional airport" group. Among other noise abatement procedures, Southampton remains closed during the night period.

This review of top-performing airports suggests that a choice of larger aircraft is directly linked to better noise-oriented efficiency. At congested airports, larger aircraft allows for increased traffic while keeping constant the number of noise events. At uncongested airports, it would be possible to increase traffic and reduce noise events with the subsequent contraction of contour areas. From the airport perspective, this result can be interpreted as a signal to encourage airlines to optimize their fleet by means of pricing or other instruments. From the airlines perspective, it signals the need to balance the benefits of serving high frequencies in particular markets (e.g. business) with potential environmental surcharges associated with smaller aircraft.

4.2 Second-stage analysis

Table 7 provides average noise-oriented efficiency for the best represented countries in the dataset: Germany, Italy, Spain, and UK. While our results are not fully comparable with those from the Italian airports in Martini et al. (2013a), due to the different airport samples and DDF orientation, the very high efficiencies reported in that paper – average noise-adjusted θ levels ranged between 0.04 and 0.06 –, suggest that the use of a cross-country dataset increases the discriminatory power of the DDF model and lowers average efficiency estimates, as predicted by Lozano and Gutiérrez (2011). We also performed a series of Mann-Whitney ranksum tests in order to check for statistically significant differences in noise-oriented efficiency or catch-up effects across the aforementioned four countries. Results in Table 8 show that German and Italian airports are significantly less noise-efficient than Spanish and UK airports in 2006. According to the data in Table 4, this result was expected for German airports, but not for the Italian ones, which benefit from less Evening and Night flight penalties. In fact, one would expect Italian airports to be the most noise-efficient as a result and certainly more noise-efficient than the German ones. None of these hypothesis is supported by the data and, furthermore, the country differences are largely diluted by 2011. Since national regulations concerning the methodology to calculate noise maps have not changed during our sample period, these results support the hypothesis that methodological differences are not significantly impacting our estimates and there are other primary drivers of noise-oriented efficiency.

Table 8. Comparison of average efficiencies per country.

Null Hypotheses		***p-values***			
Mann-Whitney ranksum test	$\theta_{1,1}$		$\theta_{2,2}$		***EFFCH***
Germany = Italy	*0.1237*		*0.1234*		*0.3865*
Germany = Spain	*0.0206*	**	*0.0823*	*	*0.8163*
Germany = UK	*0.0101*	**	*0.0863*	*	*0.1070*
Italy = Spain	*0.0390*	**	*0.7913*		*0.3679*
Italy = UK	*0.0032*	**	*0.4617*		*0.0526*
Spain = UK	*0.8937*		*0.5476*		*0.1518*

*Note: ** and * indicate statistical significance at 5% and 10% levels, respectively.*

The main drivers of noise-oriented efficiency for European airports are identified by means of a truncated regression of the efficiency estimates for 2011 against a number of relevant variables: runway layout area, average *mtow*, share of night flights (11pm-6am), population density[13], and two dummy variables indicating if the airport has preferential runway policies or continuous descent approach (CDA) guidelines. The regression excludes the efficient airports (as suggested by Simar and Wilson, 2007) so 45 observations are included. Overall, the estimated equation is globally significant. Note that a positive sign means a negative impact on noise-oriented efficiency and vice versa.

Table 9. Truncated regression results

Dependent Variable= $\theta_{2,2}$	*Coefficient.*	*s.d.*	*z-value*	*Prob.*
Runway layout area	-0.041	0.052	-0.780	0.437
Average mtow	**-0.010**	0.005	-2.220	0.027
Share night flights	**3.016**	1.432	2.110	0.035
Density_1	0.103	0.174	0.590	0.555
Preferential runway	**0.525**	0.187	2.810	0.005
Preferential runway*Density_1	**-0.488**	0.232	-2.110	0.035
CDA	-0.202	0.146	-1.380	0.169
CDA*density	0.316	0.203	1.560	0.120
constant	**0.621**	0.243	2.560	0.010
Sigma	0.222		***Wald chi2(8)***	16.57
Observations	45		***Prob***	0.035

Note: Bold indicates significant coefficients at 95% level.

Results support the observations from the previous section in regards to aircraft size, which has a positive and significant impact on noise efficiency. This also agrees with the conclusions from previous papers like Martini et al. (2013a) or Scotti et al. (2014). In fact, many noise-inefficient airports (e.g. Helsinki, Geneva, or Warsaw) serve, on average, smaller aircraft than their reference sets, thus requiring a larger number of aircraft operations and noise events, to achieve similar levels of passengers, cargo, and *alh*. Thus, the obvious recommendation for these airports is to continue with their aircraft mix reorientation policies by giving further incentives to airlines to optimize their fleet by means of pricing and similar instruments.

The share of night flights is also found to have a negative and significant impact on noise efficiency. We can mention airports like Cologne, Hannover, or Vilnius that present a proportion of night flights higher than 10% and substantially above than that of their respective reference sets. In comparison, the night movement limit at Manchester Airport indicates a maximum proportion of 7% of total annual flights to operate during the night. Therefore, this suggests that, in order to improve noise efficiency, the existing noise-level-based regulations on night flight restrictions at the affected airports need to be complemented with more stringent movement limits and/or, as observed, in some of the top-performing airports, partial or total night closures.

Thirdly, we did not find a positive and significant impact of runway layout on noise efficiency. This is consistent with the exploratory analysis from the previous section that did not suggest any link between airport size and noise efficiency. However, our results differ from Martini et al. (2013a) or Scotti et al. (2014). Note that the first paper analyzed mostly small to medium-size airports and the second assumed constant returns to scale in their DDFs, and hence, our conclusions in regards to airport size and efficiency are not comparable. Finally, population density did not have a significant impact on noise efficiency

[13] Population density was transformed into a dummy variable, which equals 1 if the airport faces a population density higher than the median value of 986 pop/km^2.

either. This suggests that our empirical design is not capturing any additional "incentive" effects that airports in densely populated areas would experience to reduce their noise contours. This may be linked to the fact that some noise abatement procedures may actually spread flight paths and generate larger noise contours in exchange of mitigating the impact on certain communities. In that regard, we found that the use of preferential runways does not significantly affect noise-oriented efficiency for airports with high population densities (note that the interaction with density cancels the preferential runway effect). The interpretation of this result is that, in the presence of many potentially impacted communities, there may be need to combine these preferential runway policies with other measures (such as noise-preferential routings and precision area navigation) to ensure that the flight paths remain relatively concentrated.

5. SUMMARY AND FUTURE RESEARCH

This paper undertakes a comparative analysis of efficiency and productivity growth of major European airports in the context of the European Noise Directive. A directional distance function is used to estimate efficiency and productivity change of 60 European airports between 2006 and 2011, with explicit inclusion of aircraft noise as undesirable output. Technical change and efficiency catch-up are calculated using a decomposition of the Malmquist-Luenberger productivity index (MLPI). The area of the regulatory 55dB(A) Lden noise contour is defined as a proxy for the total production of noise around each airport.

The incremental contributions of this paper to the literature are 1) the use of an EU-wide dataset that allows for a comparative analysis of noise-oriented efficiency across countries, provides noise efficiency estimates for airports in countries that have not been covered before (such as Austria, France, Germany, or the UK) and improves the discriminatory power of the DDF model in comparison with single-country studies. 2) Implementing an undesirable-output orientation that provides a benchmark for environmental performance in isolation of other managerial goals such as technical efficiency that have been extensively covered by previous studies. 3) The definition of noise contours as the undesirable output allows for an efficiency analysis that accounts for aspects of noise management related to the spatial distribution of flights.

The results indicate that, on average, major European airports have improved their noise-oriented efficiency between both rounds of noise mapping, despite technological regress linked to decreasing or stagnating traffic levels. Country effects were observed in 2006, with German and Italian airports being less noise efficient that their Spanish and UK counterparts, but these differences are largely diluted by 2011, suggesting that the existence of different national regulations in regards to the calculation of noise contours does not affect the estimated efficiencies. In addition, we can conclude that there has been a process of convergence in terms of noise-oriented efficiency across the four European countries. The review of top-performing airports suggests that efficiency and catch-up effects are independent of traffic trends or airport size. A second-stage truncated regression reveals that a choice of larger aircraft is directly linked to better noise-oriented efficiency, which has implications for both airports and airlines in terms of pricing and route development. Noise-inefficient airports were also found to have higher proportion of night flights than their reference sets. Taking into account the varying levels of control that airport managers may have over said variables, our results suggest that, in general, the noise-oriented efficiency of airports would benefit from a number of policies such as: more stringent regulations regarding night movement limits, partial or total night closures, and from aircraft mix reorientation policies supported by pricing or similar instruments that incentivize airlines to optimize their fleet. Finally, there is no evidence of airports facing higher population pressures being more or less noise-efficient. While indeed airports in the vicinity of populated areas will need to pay more attention to their noise management, some noise abatement procedures may actually lead to larger noise contours in exchange of mitigating the impact on certain communities. In spite of that, we also found that the use of preferential runways does not significantly affect noise-oriented efficiency for airports with high population densities.

From a policy perspective, these results should be interpreted in terms of noise reduction at source, which is just one of the four elements of a balanced approach to aircraft noise management. The others are: 2) land use planning and management, 3) noise abatement operational procedures, and 4) operating restrictions on aircraft (ICAO, 2008). Understanding the interrelationships between these elements is also key and, via the second-stage regression, this paper provides evidence on how factors 3) and 4) affect noise reduction at source. In this overall context, ICAO (2013b) highlighted the need to undertake a global analysis on aircraft noise curfews. Our conclusions clearly show how this type of operating restrictions can have a positive impact on noise reduction at source but other operational and economic aspects beyond the scope of this paper (e.g. geographic location, passenger and cargo demand, airline economics, time zones) should be considered as well.

This research is also limited by the absence of any measures of affected population within the DDF model. Indeed, we provide a partial efficiency indicator that does not directly credit airports for achieving the primary goal of airport noise management: limit the number of affected residents. Future rounds of noise mapping will provide new opportunities to gather additional information on noise contours and affected populations to support a more holistic noise-oriented DDF model. The EU has published a proposal for a Common Noise Assessment Method in Europe (CNOSSOS) that may solve the issues of heterogeneity of the Lden methodology discussed in this paper. Furthermore, the implementation of mandatory P-RNAV operations in major European airports during the last five years will also allow for a more comprehensive test on the impact of precision navigation on noise-oriented efficiency.

Finally, it is also worth mentioning the potential trade-offs across different environmental and operational impacts (e.g. noise, air quality, and delays) that add another layer of complexity to airport management decisions (See e.g. Lu and Morrell, 2006; Upham et al., 2003). Accounting for these tradeoffs is necessary to put our conclusions in terms of aircraft size in an appropriate context. While larger aircraft does indeed result in less noise events, it is also necessary to account for the marginal impact on air quality emissions per passenger associated to different aircraft types (Martini et al., 2013a). Relatively sophisticated benchmarking methodologies, such as the DDF, are likely to be needed because the relationship between these variables is not linear (Lu and Morrell, 2006). Future research should aim to combine the noise contour/affected population approach with other externalities when more data becomes available.

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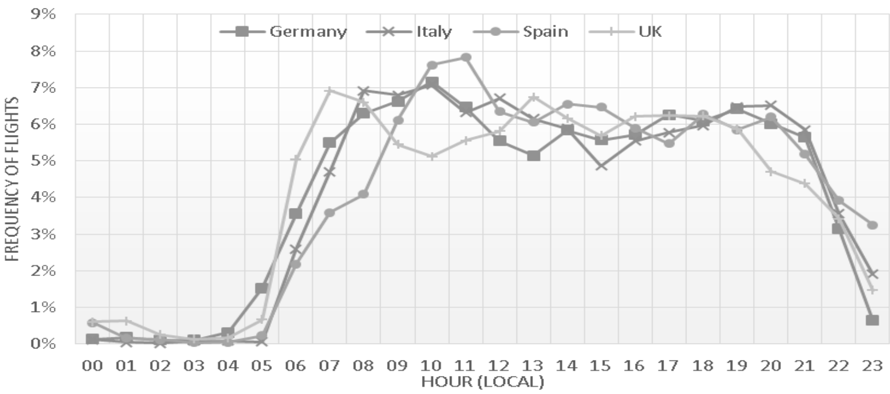
APPENDIX A. Hourly distribution of aircraft operations at sample countries (2011)



Source: OAG, Own elaboration

APPENDIX B. Noise, average length-of-haul (alh), and average MTOW for sample airports.

		Round 1 (2006)			Round 2 (2011)		
Country	*Airport*	*noise (km^2)*	*alh (km)*	*mtow (t)*	*noise (km^2)*	*alh (km)*	*mtow (t)*
AT	Vienna	84.3	1,104.4	57.7	84.2	1,093.3	66.3
BE	Brussels	109.9	1,254.9	68.1	91.7	1,571.8	80.8
CH	Geneva	61.2	842.5	62.6	70.0	1,046.0	72.9
CH	Zurich	89.5	1,357.0	73.8	91.0	1,424.9	82.5
CZ	Prague	52.7	941.1	56.2	52.0	1,006.6	62.3
DE	Düsseldorf	58.6	1,038.8	61.4	63.0	1,116.9	69.5
DE	Frankfurt	317.6	2,123.4	119.0	277.0	2,246.7	125.1
DE	Hamburg	50.9	817.6	60.7	45.0	864.7	67.6
DE	Hannover	51.5	904.9	55.1	42.0	926.8	58.5
DE	Koln/Bonn	101.6	873.2	71.9	113.0	894.5	75.1
DE	Munich	157.0	1,071.6	63.1	159.0	1,231.0	76.7
DE	Nuremberg	33.0	638.3	46.5	29.0	709.5	58.0
DE	Stuttgart	51.0	875.7	53.4	51.0	769.8	62.4
DK	Billund	14.0	566.2	27.2	14.0	730.1	37.6
ES	Alicante	23.4	1,271.9	70.3	21.7	1,326.6	76.2
ES	Bilbao	14.8	716.4	54.0	11.3	753.3	58.3
ES	Gran Canaria	35.4	1,094.0	55.6	26.4	1,231.8	51.5
ES	Madrid	153.0	1,464.3	83.0	112.8	1,696.3	90.1
ES	Malaga	35.4	1,382.6	69.5	28.1	1,504.3	72.9
ES	Tenerife Sur	27.3	2,622.6	82.1	19.1	2,840.5	87.9
ES	Valencia	25.4	736.0	47.6	17.7	812.0	56.1
FI	Helsinki	53.5	1,042.2	57.3	63.7	1,278.0	63.2
FR	Paris CDG	226.6	2,071.0	101.2	247.8	2,264.8	107.5
FR	Paris Orly	91.2	1,080.9	78.5	93.4	1,226.6	78.5
IE	Ireland	33.1	931.8	77.6	45.3	1,177.6	78.5
IT	Bologna	21.5	790.4	48.7	20.3	913.6	60.8
IT	Catania	27.1	861.2	66.9	27.1	881.9	74.3
IT	Milano Linate	42.4	731.2	67.1	25.4	759.3	72.8
IT	Milano	89.6	1,465.4	51.8	61.6	1,431.0	84.5
IT	Naples	13.2	798.6	61.4	14.3	808.2	66.5
IT	Orio al Serio	36.5	890.2	83.9	44.9	1,013.5	77.3
IT	Rome	130.2	1161.2	77.1	74.3	1,380.0	85.4
IT	Torino	19.5	669.9	51.8	18.4	732.9	60.4
IT	Venice	35.0	851.9	57.2	23.5	979.9	69.6
LT	Vilnius	17.9	997.5	38.2	13.8	831.7	43.1
LU	Luxemburg	62.9	641.3	28.6	64.2	694.2	34.9
NL	Amsterdam	189.2	1900.7	94.7	188.5	2,037.5	97.7
NO	Bergen	27.0	389.5	48.2	37.3	466.3	53.4
NO	Stavanger	22.9	420.6	49.2	40.0	472.1	57.5
NO	Trondheim	16.9	451.5	44.3	23.0	490.1	54.7
PL	Warsaw	38.5	1007.9	79.0	32.0	1,032.1	48.2
PT	Lisbon	36.1	1647.1	79.5	33.0	1,817.4	84.9
RO	Bucharest	42.1	1105.7	52.0	99.2	1,056.6	56.1
UK	Aberdeen	16.2	530.6	31.8	17.1	545.5	30.3
UK	Belfast	20.0	622.4	74.2	15.2	910.0	73.4
UK	Birmingham	30.9	927.9	49.3	28.0	1,175.8	60.6
UK	Bournemouth	10.3	1087.8	79.6	7.4	1,813.6	85.1
UK	Bristol	21.5	796.6	53.3	19.0	1,019.0	64.2
UK	East midlands	35.0	1083.5	82.1	37.0	1,335.6	76.2
UK	Edinburgh	34.1	647.5	50.6	37.0	799.4	56.2
UK	Glasgow	36.3	779.9	54.9	20.7	951.6	60.6
UK	Leeds	9.7	633.6	45.3	15.4	946.1	55.1
UK	Liverpool	17.0	841.7	66.5	17.6	1,007.8	72.0
UK	London	94.5	1860.3	92.0	95.0	1,670.8	85.6
UK	London	244.7	2805.7	147.7	222.0	3,025.8	153.4
UK	London	73.3	1074.3	84.9	58.0	1,165.2	82.8
UK	London Luton	32.1	1024.8	74.1	40.0	1,320.1	76.5
UK	Manchester	68.2	1200.1	67.6	57.0	1,614.2	77.9
UK	Newcastle	20.7	649.0	52.4	16.0	1,089.4	54.7
UK	Southampton	7.1	448.8	25.3	4.5	433.0	26.6

Source: NOISE (2014), own elaboration.