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Airport noise assessment and mitigation: A simple and flexible methodology

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A B S T R A C T

Airport noise assessment and mitigation have been recognized as major challenges in the current civil aviation context. This paper aims to provide a general, simple, and flexible methodology to approximate airport noise-influenced zones and quantify the social cost of noise pollution. The proposed methodology performs this assessment without the need for specific software, monitoring stations, and sophisticated data. Airport noise-influenced zones are estimated by relying on publicly available aircraft certification data, while the social cost of such estimation is computed by taking into account the distribution of residential units located within zones affected by noise. We present an application of this method to a group of Italian and Spanish airports, as well as possible beneficial policy interventions in terms of minimization of noise impact on the population living in the airport neighborhoods. In addition, possible mitigation policies are presented in the form of noise surcharges applied to different aircraft categories.

1. Introduction

Air traffic is associated with several environmental impacts. Among these, noise pollution is one of the most significant and probably the main causes of hostile community reactions to airport activities (Thompson et al., 2013;ICAO, 2016b; da Silva et al., 2020). Airport noise assessment and mitigation have therefore been recognized as issues of great relevance in the empirical literature and for policymakers. Previous studies have highlighted the serious health risks to people living near airports (Zheng et al., 2020). From an urban economic perspective, other empirical contributions have shown that airport proximity affects real estate prices and, more specifically, exerts a non-negligible negative impact on house prices (Schipper et al., 1998). From an economic perspective, there is no market for airport noise impacts, such as the greenhouse gas (GHG) emissions trading scheme (ETS) of the European Union (EU). However, economists have applied the effect of proximity to airports on house prices to obtain a hedonic price of the noise costs generated by aircraft in their landing, take-off, and taxing activities. This takes the form of a noise price depreciation index (NDI), i.e., a percentage reduction in the house price due to a marginal variation in house characteristics. In the case of an airport, the NDI is given by the percentage reduction in the house price if the noise generated by airport operations increases by 1% (Wadud, 2013).

In the current European context, green programs are being developed as well as recovery funds related to green transition and sustainability (e.g., Green Deal, Commission Sustainable and Smart Mobility Strategy, Next Generation EU recovery fund). Therefore, airport noise assessment and mitigation measures become timely challenges for these environmental programs. However, as further discussed in the review of the literature, the approaches traditionally adopted to estimate airport social costs have some non-negligible limitations, especially in terms of complexity, a lack of flexibility, and the requirement of sophisticated data/instruments. Therefore, we believe that there is a need for a general, relatively simple, and flexible methodology that relies on easily accessible data. The procedure we propose is able to approximate airport noise contours (we call such approximations noise-influenced zones, NIZs) and to provide estimates of the social cost of noise that are comparable across airports. This methodology may result in an accessible tool for policymakers and airport managers to formulate appropriate noise compensation schemes.

The recent literature on airport noise assessment and mitigation has been built on complex models based on field experiments to estimate noise levels (Simons et al., 2022; Ganić et al., 2023). Furthermore, field experiments have been the basis for generating the information required

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for the evaluation of noise impacts and the development of abatement measures (Evangelinos et al., 2020; Friedt and Cohen, 2021). This means that airport noise measurement, and the policies to mitigate it, can be achieved only if airports truthfully and voluntarily disclose the noise levels generated by aircraft ground, landing, and takeoff operations, a condition that may be difficult to fulfill. Furthermore, a comparison of noise levels among airports would require joint disclosure by different management companies and their availability to find their airports in poor positions in the noise mitigation ranking. This may make the comparison impossible, unless airports are managed by the national government (as in Spain), or noise level disclosure is enforced by law. Our novel methodology can be applied to most airports since it is based on generally available data and policy interventions without the need for field experiments or airport noise level disclosure, given that our method can be applied to all airports and is based on generally available data. Ultimately, the goals of our paper include: (i) developing a simple procedure to compute airport's NIZs, (ii) providing multiple case studies in which NIZs are computed and the social cost of noise is estimated, and (iii) illustrating how our methodology can be easily used to set policy interventions based on obtained results.

2. Literature review

According to the existing literature (Efthymiou and Antoniou, 2013; Martini et al., 2020), the estimation of civil aviation social costs can be carried out essentially in four ways: (i) a risk assessment analysis (RAA), (ii) the stated preference approach (SPA), (iii) the hedonic price method (HPM) and (iv) the (aircraft) certification-based approach (CBA). As airport operations generate noise costs for the exposed communities living in the surrounding areas, these procedures can also be applied to assess noise levels. We briefly discuss such methodologies here.

RAA represents the standard in Europe and is the basis of the END 2002 EU Directive.[1] This methodology is applied at the single-airport level and based on the use of simulation models to quantify noise annoyance. The social cost is then estimated based on the definition of noise contours correlated with health problems (WHO, 2018). The main limitation of RAA is posed by the complexity of the simulation and its integration with other models. This implies that this methodology is not always practical for decision-making processes and strategic planning (Bernardo et al., 2016).

SPA is an indirect method based on surveys and interviews aimed at measuring residents' willingness to pay for reducing the amount of noise (Kroes and Sheldon, 1988; Baranzini and Ramirez, 2005; Fosgerau and Bjørner, 2006). As in the case of the RAA, SPA is usually applied to a single airport. The main limitations of SPA are the reliability of the answers provided in the surveys due to the bias of a small sample combined with the significant influence of local conditions (Martini et al., 2020).

Within the literature on social cost assessment, HPM has been the most used approach to estimate noise annoyance. It is comprehensively discussed in Zheng et al. (2020) and is based on the idea that prices of real estate incorporate, in the form of depreciation, the disutility associated with airport-generated noise. As mentioned before, this type of analysis relies on a noise depreciation index that represents the average decrease in home values caused by an increase in decibels in noise level. The dependency on the real values provided by the housing market is the main advantage of HPM (Navrud, 2002).

So far, HPM has usually been applied to specific airport case studies: Lu and Morrell (2006) investigate the social noise cost of five major airports according to different aircraft categories; Morrell and Lu (2000) propose a charging mechanism for the noise generated by the Schiphol Amsterdam Airport. Püschel and Evangelinos (2012) assess the impact of noise nuisance generated by Dusseldorf Airport using data from the rental apartment market and a spatial regression technique. Similarly Dekkers and van der Straaten (2009) apply this type of approach to house transaction data in the Amsterdam Schiphol area. Evangelinos et al. (2020) estimate the magnitude of noise costs generated at Zurich airport and formulate a nested logit model to test whether the probability of operating a specific aircraft depends on the level of noise surcharges.

The more novel certification-based approach (CBA) estimates the noise generated by airport operations during a specific period of time by integrating aircraft certification data with information on airport airline schedules (Adler et al., 2013; Grampella et al., 2017; Simons et al., 2022). Adler et al. (2013) estimate the efficient production frontier considering both socially positive (passenger revenues) and negative outputs (noise and emissions), assess which aircraft models are on the Pareto frontier, and ultimately compute the social benefits when the fleet operating at Arlanda, Florence, and Schiphol airports is replaced with efficient aircraft. They show that noise costs are substantial, and airport charges may increase the aircraft substitution pattern. Grampella et al. (2017) illustrate how to estimate the social costs of aircraft noise starting from the noise certification data. Taking into account Amsterdam's Schiphol Airport, Simons et al. (2022) evaluated the distance between predicted and real levels of aircraft noise obtained from field experiment data. They find that it is possible to achieve substantial noise abatement by adopting more efficient aircraft, implementing noise abatement departure procedures, and adopting optimized descent approaches at night. Despite the limitation imposed by the standardization of the measurement of certification values, the CBA has the advantage of being easily applicable to airports throughout the world. This methodology provides a good proxy for the amount of noise produced since it requires only information on aircraft movements and models. The main limitation of CBA, as demonstrated in Grampella et al. (2017), is that it is less effective in translating the amount of noise to social costs because it does not consider the actual population affected by airport operations. This implies the risk of overestimating and underestimating airport social costs, especially in areas with heterogeneous population density (Martini et al., 2020).

Including optimization of slot and schedule allocation in evaluating airport noise can contribute to developing more efficient noise mitigation policies (Feng et al., 2023; Feng et al., 2023). Feng et al. (2023) developed a model considering scheduling from a time-dimensional perspective on noise abatement. They observe that an optimal slot scheduling allocation may reduce noise at Shanghai Airport. In the spirit of precedent analysis, Feng et al. (2023) also includes the spatial component in the noise assessment of Shanghai Airport. They identify that take-off trajectories are more efficient than slot scheduling in noise reduction, and they may contribute to the slot allocation process toward airlines.

Given the limitations of the described approaches, we aim to develop a relatively simple and scalable methodology that combines parts of the CBA and HPM. First, we rely on easily retrievable CBA data (i.e., aircraft certification data and flight operations) to quantify the amount of noise produced by aircraft movements at a specific airport. Second, we exploit the mathematical relationship between aircraft-certificated noise levels and the volume of airport traffic to obtain an estimate of the noise generated by annual operations. This noise level is a benchmark to design different noise contours surrounding the airport, called noise-influenced zones (NIZz), corresponding to different decibel levels. NIZs can be obtained without the need for simulation procedures or monitoring stations. Third, using Geographical Information System (GIS) algorithms, we combine NIZs and house distribution in the airport

[1] Directive 2002/49/EC aims at avoiding, preventing, or reducing harmful effects produced by exposure to environmental noise. It is based on (i) noise monitoring through strategic noise maps, (ii) public participation in the effects of noise exposure, (iii) addressing local noise issues as a guarantee of environmental noise quality, and (iv) developing a long-term strategy to reduce the number of people affected by noise and developing the existing EU policy on noise reduction from the source.

vicinity to identify possible overlaps. Fourth, we rely on the HPM to estimate the social cost generated by aircraft movements at each airport and price the noise generated. Finally, we proposed a damage-related charge scheme based on the results of our model.

3. Methodology

This section presents our methodology for assessing the social cost of airport noise. It is made up of five steps. Further details can be found in Appendix B, in which we provide a practical step-by-step application to one of the airports analyzed in Section 4. All intermediate results associated with each step are shown in detail.[2]

3.1. Step 1

The first two steps start from CBA and later derive the NIZs. First, similar to Grampella et al. (2017), data from the aircraft certification database are matched with those related to airport movements. The latter information is provided by the OAG Schedule Analyzer. Every aircraft movement at a specific airport is labeled according to (i) aircraft model, (ii) maximum take-off weight value (MTOW), (iii) aircraft category, (iv) period of the day in which the movement occurs, and (v) type of operation. Five aircraft categories have been identified: regional jet, narrow body, wide body, propeller, and super (this last group includes only the Airbus A380). Three temporal spans are used to classify each movement from a temporal point of view: daytime, from 6.00 am to 8.00 pm; evening, from 8.00 pm to 10.00 pm; and night, from 10.00 pm to 6.00 am. Regarding the type of operations, aircraft movements are classified as arrivals or departures.

Second, once operations data have been collected and classified as explained above, they are matched to their respective noise levels. When dealing with aircraft noise levels, it is important to remember that noise metrics are classified as single events or cumulative (Peirce et al., 1998). The former is a measure of the noise generated by the operation of a single aircraft. It includes several indicators, among them the effective perceived noise level (EPNL) used by the ICAO for aircraft certification. Cumulative metrics are measures of long-term exposure to aircraft noise (e.g., during a day, a week, or a year) and are used to estimate the noise generated by airport activities. Consequently, we match OAG data with EASA aircraft certification data, which are expressed in EPNL. EPNL are computed in decibels (dB) and provide noise emission levels for each aircraft according to the noise level registered at three specific points located in the airport area (ICAO, 2016b): (1) the ”approach” certification point is located 2,000 meters before the runway in the landing procedure; (2) the ”lateral” certification point is positioned at a lateral point to the runway at a distance of 450 meters to capture the noise during take-off when the engines are at maximum thrust; and (3) the ”flyover” certification point is positioned in front of the runway at 6,500 meters to capture the noise during the ascending phase of the take-off.

The matching procedure between the OAG and EASA data is not trivial due to the different nomenclature of aircraft adopted in the two databases. To overcome this issue, we take the aircraft model identified by its name as it appears in both OAG and EASA, for example Airbus A319. Of this model-name, we obtain from OAG the reference value of MTOW and then construct a range of ±3% MTOW from this value. In EASA each model-name may have many more observations than in OAG because it associates all possible engine types currently in use with the aircraft model-name. Of each model-name-engine triplet in EASA, we know the value of MTOW. We eliminate all observations in EASA that do not fall within the ±3% range of MTOW mentioned above, as in Grampella et al. (2017). From those remaining, we calculate the average in dB of the EASA lateral, flyover and approach.[3] As a result, all OAG aircraft models are associated with at least one EASA model. Table 1 presents some examples of the certified noise levels generated by aircraft during the LTO cycle. It is evident that smaller aircraft tend to generate less noise and that, within each category, older designed aircraft have higher certified noise levels. For instance, at the Lateral point, the regional jet Bombardier CRJ900 has 89.5 dB, while the widebody Boeing 787–8 has 91.0 dB. However the latter generates much less noise, since it is a new model, than the other older widebody aircraft in the example, i.e., Airbus A330-200, which has a Lateral certified value equal to 98.4 dB.

The resulting database includes all aircraft movements in each airport grouped by (i) type of aircraft (i.e., model and category), (ii) time of the day, (iii) certified noise values for each type of operation and (iv) type of operation (arrival/departure).

3.2. Step 2

The second step consists of defining a noise index at the airport level. In doing this, the starting point is to consider that for some noise sources (e.g., a railway or an airport), the noise produced is not continuous over time. It can be represented by a series of sound events that occur when the source is active and that exhibit different durations.[4] To move from a single movement-noise level (expressed in EPNL) to the noise level produced by a series of sound events (as in our case), it is necessary to convert the EPNL values in terms of the sound exposure level (SEL). This metric represents the acoustic energy contained in the event. SEL is a measure of noise exposure that incorporates the amount of noise energy associated with the period of interest by normalizing its duration to one second. Since there is no straightforward way to make this conversion, we use the conversion parameters provided by Grampella et al. (2013).[5] To minimize possible differences between real and simulated values, we performed category-specific calculations of the average difference between EPNL and SEL. These values are reported in Table 2. For instance, for a narrow body aircraft during the approach phase, it is necessary to reduce the EPNL level by 3.75 decibels in the flyover measurement and by 2.25 dB in the lateral computation.

Once data are converted into proper acoustic power measures, the SEL, it is possible to estimate the airport noise level. In this way, we compute a cumulative noise measure starting from the single-movement level. Hence, we calculate the annual average noise produced by an

Table 1
Examples of aircraft certified noise levels.

Aircraft model	Certified noise value (dB) after OAG-EASA matching		
	Lateral	Flyover	Approach
Bombardier CRJ900	89.5	82.9	92.5
Embraer 175	91.8	83.5	95.1
Airbus A319	91.3	85.3	93.5
Boeing 737–300	90.5	85.1	98.7
Boeing 737–700	92.9	84.4	95.9
Airbus A330-200	98.4	92.4	98.8
Boeing 787–8	91.0	87.4	96.7

[2] Appendix B is intended to facilitate the implementation of the methodology for any interested reader. Supplemental material online includes all the resources needed to replicate our approach for a sample subset of operations.

[3] We created a table to allow a match between the two databases. An example of the matching is available in the supplementary material provided by the authors. The full matching table is available from the authors on request.

[4] The noise produced by an airport, consists of a series of sound ”events” each of which corresponds to a landing/takeoff.

[5] Grampella et al. (2013) obtain the conversion by applying the Integrated Noise Model (INM), a simulation model validated by the Federal Aviation Administration (FAA) to evaluate the impact of aircraft noise in airport surroundings.

Table 2
Conversion from EPNL noise level to SEL by aircraft category (Grampella et al., 2013)

	Certification point (in EPNL)		
	Approach dB variation EPNL → SEL	Flyover dB variation EPNL → SEL	Lateral dB variation EPNL → SEL
Propeller	−5.00	−3.00	−4.00
Regional	−3.75	−2.00	−1.75
Narrow Body	−3.75	−2.25	−2.25
Wide Body	−4.25	−3.25	−2.75
Super	−4.25	−3.25	−2.75

airport by estimating the European Day-evening-night level (*Lden*). This is an internationally standardized metric that measures the environmental noise exposure generated from infrastructures (e.g., airports, railways, motorways, etc.), consistent with the EU Directive 2002/49/EC. The *Lden* is computed as shown in Eq. 1 (Grampella et al., 2017):

$$Lden_t^j = 10 \times log_{10}\left(\frac{1}{3600 \times 24 \times 365}\sum_{i=1}^{M} 10^{\left(\frac{SEL_i^j + E_i + N_i}{10}\right)}\right) \quad (1)$$

where t is the year, j is the certification point ($j \in \{FO, LA, AP\}, FO =$ Flyover, $LA =$ Lateral, $AP =$ Approach), M are the annual aircraft movements, SEL_i^j is the SEL dB value of the aircraft movement i at the certification point j, E_i and N_i are penalized respectively by 5 dB if movement i occurs during the evening and penalization of 10 dB if it occurs at night. The fraction $\frac{1}{3600\times24\times365}$ highlights that the cumulative airport noise level (which is meaningless since noise annoyance is related to events such as takeoffs or landings) is then translated into the noise level generated, on average, in each second during a specific year). Therefore, each airport is characterized by three yearly indices, namely $Lden_t^{AP}$, $Lden_t^{LA}$, and $Lden_t^{FO}$, representing the average noise levels produced at each certification point in a specific year. It is important to note that the time period can be changed to any interval of time. This allows a flexible analysis of also for peak and highly seasonal periods.

3.3. Step 3

The third step is the design of noise contours around the airport. This step allows to link CBA to HPM. A noise contour is an area surrounding the airport within which the noise exposure is greater than or equal to a given level (Powell, 2013). Therefore, a noise contour can be used to identify the land exposed to the same level of noise during airport annual operations and the surrounding affected population. We compute a representative of these noise contours by drawing the noise-influenced zones around the airport. A NIZ is drawn by exploiting the logarithmic relationship between the $Lden_t^j$ and the constant noise level that identifies a contour (L_h), as explained in Powell (2013). More specifically, the logarithmic relation between the fixed noise contour L_h ($h = \{55, \ldots, 65\}$) and the *Lden* produced by take-off operations at the two relevant certification points (i.e., *FO* and *LA*) is given by the following two equations:

$$Lden_t^{FO} - L_h \approx C \times log_{10}(x/x^{FO}) \quad (2)$$

$$Lden_t^{LA} - L_h \approx C \times log_{10}(y/y^{LA}) \quad (3)$$

where $Lden_t^{FO}$ is the noise level generated at the flyover certification point (Eq. (1)), C is the constant for spherical spreading [6], x^{FO} is the distance between the brake release point (BRP), at the beginning of the runway, and the *FO* certification point, and equal to 6,500 meters, while x is the distance between the take-off point (TOP) and the noise contour L_h. Fig. 1(a) shows the location of x^{FO} and x. Similarly, in Eq. (3) $Lden_t^{LA}$ is derived from Eq. (1), y^{LA} is the lateral distance between the center of the runway and the *LA* certification point (equal to 450 meters), while y is the distance between the runway and the noise contour. The location of y^{LA} and y is shown in Fig. 1(a). It is straightforward to move from the exponential form of Eqs. 2,3 and obtain x and y as in Eqs. 4,5:

$$x = x^{FO}\left(\frac{10^{Lden_t^{FO}/C}}{10^{L_h/C}}\right) \quad (4)$$

$$y = y^{LA}\left(\frac{10^{Lden_t^{LA}/C}}{10^{L_h/C}}\right) \quad (5)$$

Similar to Powell (2013), x and y are then used to draw an ellipse with GIS as shown in Fig. 1(b)-(c).[7] More specifically, the noise contour is drawn using two auxiliary buffers surrounding the airport as shown in Fig. 1(b). The first buffer (in blue) is the locus of points whose distance from the runway is x. The second buffer (in red) is the locus of points whose distance from the runway is y. Fig. 1(c) shows the ellipse related to the take-offs drawn using GIS. The starting position is the BRP, as the ellipse reaches the blue buffer and always maintains a distance of y from the runway.

Regarding landing operations, the logarithmic and exponential relations between the noise contour L_h and $Lden_t^{AP}$ are given by the following two equations:

$$Lden_t^{AP} - L_h \approx C \times log_{10}(z/z_{AP}) \quad (6)$$

$$z = z^{AP}\left(\frac{10^{Lden_t^{AP}/C}}{10^{L_h/C}}\right) \quad (7)$$

where, as shown in Fig. 2(a), z is the distance between the BRP and the noise contour L_h, and z_{AP} is the distance between the approach certification point (*AP*) and the BRP (equal to 2,000 meters). Although the lateral noise component generated during landing is not subject to certification, the landing noise is lower than that produced during take-off, which is certified instead at the y^{LA} point. Therefore, it is assumed that the lateral noise component in landing is equal to 70% of that in the take-off phase. [8] Fig. 2(a) shows the point z^{LA}, which allows the identification of the ellipse for the noise contour L_h, the one related to arrivals.

As previously stated, to draw the NIZs for arrivals using GIS, we need to identify two buffers, as shown in Fig. 2(b): the blue buffer is the locus of points whose distance from the runway is z, while the red buffer is at distance z^{LA}. Fig. 2(c) shows the ellipse drawn in GIS that identifies the NIZ for landing operations: from the TOP, the ellipse reaches the blue buffer in the landing direction, while the lateral component is shown by the red buffer.

To obtain the complete set of contours, this procedure was repeated

[6] Consistently with Powell (2013), we set it to 20.

[7] Differently from (Powell, 2013), who considered a single aircraft operation, we derive our contours applying the logarithmic relationship to $Lden_t$. This is correct from a theoretical perspective, although it requires validation to locate the point x because it gives the distance between the take-off point (TOP) and the noise contour, and not between the BRP and the contour (as in Powell (2013)).

[8] The choice of 70% as the reduction factor of the sideline noise level during the landing phase is given by the lower noise generated by engines compared with the departure process in which the engine thrust is maximum. Choosing a different reduction factor would not significantly affect the analysis, as the sideline component lies close to the airport boundaries in most scenarios.

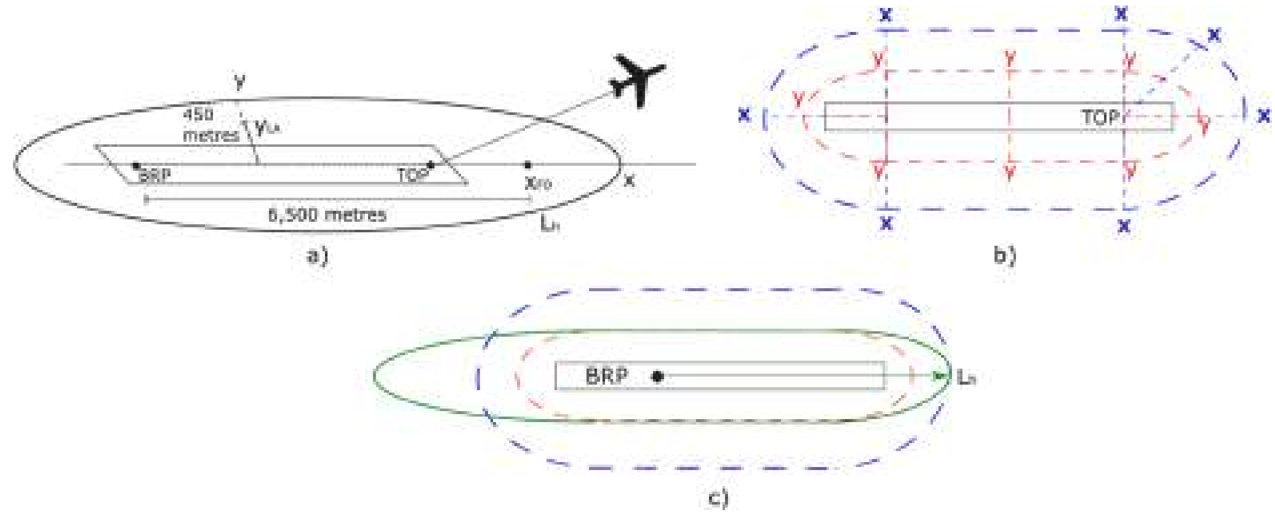

Fig. 1. The process of drawing a NIZ related to take-off operations using GIS. (a) The theoretical ellipse identifies the noise contour. (b) The two buffers to identify using GIS for the height length of the ellipse. (c) The NIZ identifies the area where the airport noise is fixed at L_h.

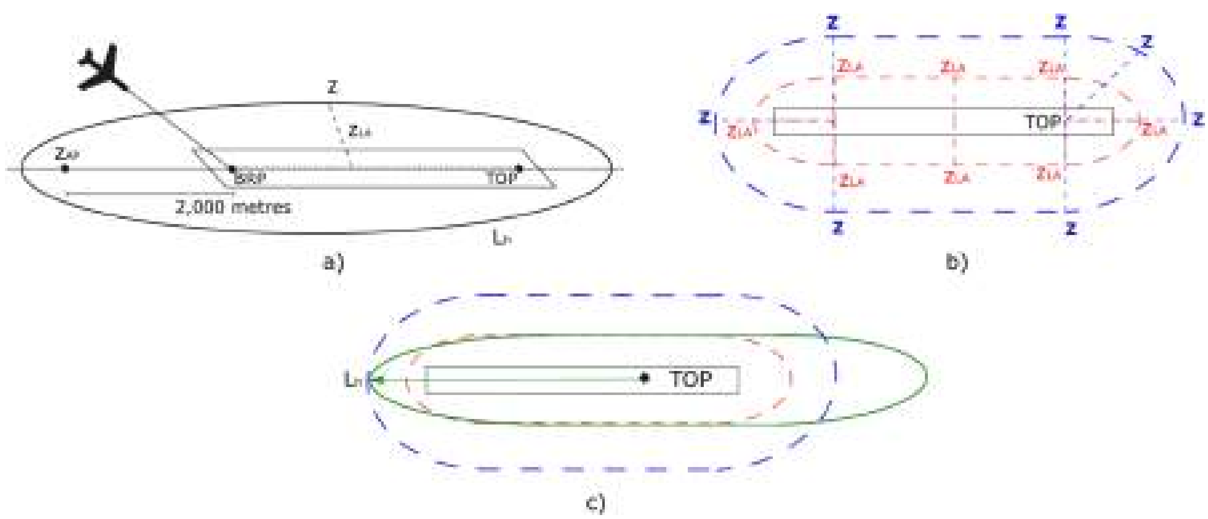

Fig. 2. The process to draw a noise contour NIZ related to landing operations using GIS. (a) The theoretical ellipse identifies the noise contour. (b) The two buffers to identify the length of the height of the ellipse with GIS (c) The NIZ that identifies the area where the airport noise is fixed at L_h.

for 11 noise exposure levels L_h, ranging from 55 to 65 dB, according to each year of the period under investigation. [9] Noise exposures can then be represented through these simplified contour areas, the NIZs, whose geometrical definition is generated by the intersection of two ellipses: one for the departure phase and one for the landing one, as shown in Fig. 3. More specifically, the two ellipses are divided into four elements (i.e. two for each ellipse) through a slice that is orthogonal to the runway and applied at the BRP. As shown in Fig. 3, the green line is the NIZ with a noise level measured in SELs and equal to 65 dB. The blue line corresponds to the lower-noise NIZ, equal to 55 dB, and is more distant from the runway.[10]

The methodology proposed for the definition of NIZ is clearly an approximation of the noise curves to which communities surrounding an airport are subjected. Clearly, noise measurements made directly on-site, using specific tools, such as sound meters, are more accurate.

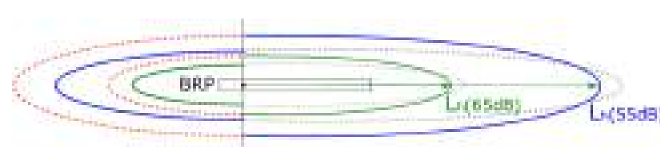

Fig. 3. An example of the NIZs for 55 dB and 65db surrounding an airport.

[9] The lower bound of 55 dB is the value with almost no impact on human health; the upper bound of 65 dB coincides with the maximum level of noise compatible with residential buildings (FAA, 2004). Dekkers and van der Straaten (2009); Püschel and Evangelinos (2012); Püschel and Evangelinos (2016) show that the depreciation of real estate due to noise begins at levels lower than 55 dB. Our model can be easily extended to NIZs starting from 50 dB.

[10] Our method can take into account flight path adjustments, implemented precisely to reduce the social costs of noise. This is done by changing the orientation of the ellipses in Fig. 3. An example for take-off is shown in the figure provided in the supplementary material.

Therefore, it is important to analyze the magnitude of the distortion between the NIZ contours and the noise contours that are identified with specific investigations. Fig. 4 shows a comparison of Milan Linate Airport. The noise contours in red are identified using direct data recorded by the company managing the airport and transferred to the European Environmental Agency (EEA) in charge of monitoring the noise level generated by the main European airports. NIZ contours are instead displayed in black.

Upon inspection, the two types of contours show similar patterns. There is a distortion related to take-offs since the EEA noise contours are slightly wider and closer to the runway. Moreover, during landings, the EEA contours have the same width as NIZ but cover more land. However, considering that the NIZ method might overestimate the noise level generated at airports during take-offs and might instead underestimate it during landings, it is possible to argue that the overall estimated noise level has very small differences.

3.4. Step 4

The NIZs are then overlapped with the geographical distribution of houses near an airport. Data about residential buildings, in shapefile format, have been retrieved from the Open Street Map open source database through the Geofabrik API (Geofabrik, 2020).[11]

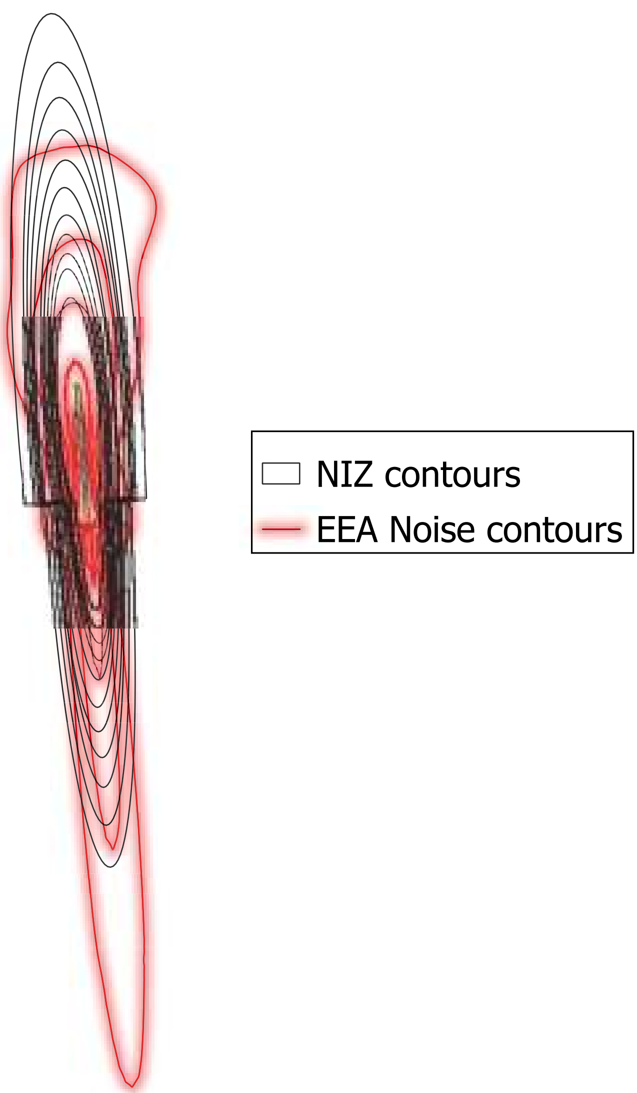

Fig. 4. NIZ contours and noise contours computed using an on-site investigation with sound meters. A comparison of Milan Linate airport.

The outcome of the intersection between the contour layer and the residential one is a database listing all residential buildings below the noise level that affects them. To pass from bi-dimensional house data to a quantification of the number of residential units in each building, we relied on the average data on the distributions of flats in each building. To get more accurate estimates, we use granular data at the municipality level.[12] In this way, we weighted the number of residential buildings according to the distribution of apartments in each building for each municipality. Clearly, this is a limitation of our approach, since houses are likely to be concentrated in specific areas. However, most of the municipalities affected by airport noise are small, while in larger municipalities, we consider houses at the block level. Therefore, the distortion in the calculation of airport noise social costs is negligible. As a result, we have a representation of the number of residential units under each contour. Consequently, we define F_h as the number of residential units located under the noise contour L_h.

3.5. Step 5

The last step of our methodology consists in estimating the social costs of airport noise. The economic literature focuses largely on the noise depreciation index (NDI) defined as the percentage increase in loss of property value due to a unit increase in noise exposure (i.e., +1 dB) (Nelson, 2004). Hence, NDI represents the percentage loss in property value associated with additional noise levels. Therefore, by computing the loss in property values of houses exposed to the same level of noise (compared to property values in the absence of perceived level of noise), it is possible to obtain an estimate of the social costs of noise (Kopsch, 2016). By repeating this procedure for different noise levels (i.e. different noise contours, approximated through NIZs), we obtain an estimate of the social costs generated by airport noise.

NDIs are parameters resulting from a regression model where house prices from real estate transactions are the dependent variable, and factors related to house attributes, characteristics of the neighborhood, social-economic conditions of the local population, accessibility to the airport (which represents a benefit) and noise are the independent variables. Furthermore, spatial effects may be included in the estimation (i.e., taking into account spillover effects from nearby neighborhoods and spatial correlations in regression errors (Dekkers and van der Straaten, 2009; Püschel and Evangelinos, 2012)).

Since we aim to estimate the social costs of airport noise using the approach illustrated so far, which has to be applied to different airports, we cannot perform a direct estimation of NDI using data from the real estate market (e.g., Dekkers and van der Straaten (2009); Püschel and Evangelinos (2012); Evangelinos et al. (2020)). To overcome this limitation, we rely on meta-analyses obtained from several contributions in the literature that provide NDI estimates and focus on the suggested NDI for value transfer. Specifically, Schipper et al. (1998); Nelson (2004) and Wadud (2013) present meta-analyses of NDI estimates, whose important consequence is the possibility of integrating an NDI for an airport without implementing a specific hedonic price estimate, which is very often a limited procedure due to the lack of data on house transactions. NDI value transfers from meta-analyses allow policymakers to compare

[11] To obtain accurate estimates, we adopted a level of detail at the electoral district level for each municipality. Data for small and rural municipalities are not available every year. Since missing observations concern only a minor number of years, we decided to approximate these values through linear interpolation.

[12] In the application presented in Section 4, data are retrieved from ISTAT (2020) and IDESCAT (2020) for Italian and Spanish airports, respectively.

estimates of airport noise social costs across markets, regions, and countries.[13]

In selecting the NDI value transfer, across different locations, the most important aspect is taking into account their different economic characteristics. This heterogeneity may be expressed by house prices, the purchasing power of the population, and income per capita. All previously cited contributions agree that house prices have to be combined with available income since individuals' purchasing power is a crucial characteristic. Furthermore, both Nelson (2004) and Wadud (2013) point out that when comparing different regions and/or countries, the income per capita in purchasing power parity is the reference variable for NDI value transfer.

The estimated NDI value transfer retrieved from Wadud (2013) demonstrated to be the most suitable for our methodology since it takes into account income per capita and accessibility to the airport. Furthermore, it can be easily applied to different geographic areas. Taking into account the spatial autocorrelation, small sample size, and using the GDP per capita in different countries and adjusting for different purchasing power parity (PPP) among the explanatory variables, he provided statistically significant evidence regarding an NDI value transfer. The latter is shown in the equation below:[14]

$$NDI = 0.07 + 1.76 \times GDP \times 10^{-5} \tag{8}$$

where the constant 0.07 is the estimated value of a variable for good airport accessibility.[15] The NDI meta-analysis performed by Kopsch (2016) presents higher estimates for airport accessibility (i.e., 0.22). Under this value of NDI, airport noise social costs will be higher.[16]

Eq. (8) implies that if the GDP per capita in PPP for Italy is \$28,000, and if the airport has good accessibility, we have a NDI equal to $0.07 + 1.76 \times 0.28 = 0.56$—i.e., the NDI is equal to 0.56%, implying that house prices decrease by this percentage for each additional dB generated by an airport. We apply this depreciation index to the property values measured in terms of yearly square-meter price.[17] Let p be the price/sqm of a flat/house in a location that is not affected by airport noise, while p_h is the price/sqm in an area under the NIZ contour L_h. Hence, since the contour with dB $= 55$ corresponds to a situation without noise, we have $p_{55} = p$, while the price under the contour dB $=$ 56 is $p_{56} = p_{55} \times (1 - NDI) = p \times (1 - NDI)$. Similarly, $p_{57} = p_{56} \times (1 - NDI) = p \times (1 - NDI)^2$. Last, $p_{65} = p_{64} \times (1 - NDI) = p \times (1 - NDI)^{10}$. In notation, $p_h = p \times (1 - NDI)^{h-55}$. Having defined the prevailing price under contour L_h, the social cost of airport noise NSC is the reduction in the price of real estate due to exposure to a given level of noise defined as $p - p_h = p \times [1 - (1 - NDI)^{h-55}]$. We define H_h as the total of square meters of the houses under the contour L_h. Hence, the social noise cost under the contour L_h is:

$$NSC_h = p \times [1 - (1 - NDI)^{h-55}] \times H_h \tag{9}$$

while the total social noise cost generated in a given year by an airport is:

$$\widehat{NSC} = \sum_{h=55}^{65} NSC_h \tag{10}$$

In Appendix B a detailed application of the methodology related to steps 4 and 5 is provided.

A potential criticism of the use of average house prices of municipalities or districts under the noise curves could be that these averages may already incorporate a portion of the noise effect, which would cause an underestimation of the noise-related depreciation. However, this issue does not appear to arise for a number of reasons: (i) the prices are averages of the entire municipality (district), which is barely below the airport curves;[18] (ii) these average values are commonly computed applying homogeneity conditions so that "excessively high or low" prices are discarded; and (iii) confirming the two previous points, a direct inspection suggests that there are no significant differences between the average municipality prices affected by the curves and those of neighboring "similar" municipalities not affected by the curves.[19] In computing the NSC over time, it is necessary to limit the possible influences due to volatility in the real estate market prices. Hence, the social noise costs in Eqs. 9,10 should be expressed in constant prices. This implies choosing a given period as the reference year.

3.6. Methodology-related policies

The methodology illustrated so far produces two important results for policymakers. The first is represented by the airport NIZs. NIZs are useful instruments for monitoring the evolution of noise exposure over time and for preliminary address land use planning, management, and externality assessment in cost-benefit analysis. An estimate of the noise exposure suffered by the population living near the airport can be obtained without needing to rely on complex software and data such as wind and temperature or variability in the operational procedures adopted during take-off.[20] In this sense, NIZs may help to achieve the essential *compatible land use planning and management target* (ICAO, 2002): To prevent further residential development around airports that may counteract improvements in reduced noise through developments in the latest generation of aircraft.

The second output–namely an estimate of the airport social noise cost NSC–is extremely important as a basis for policy interventions that foster innovation and minimize the impact of aircraft noise on populations living in an airport vicinity. Such improvements are in turn expected to reduce related land use restrictions and constraints to urban development in airport neighborhoods. In the empirical application presented in Section 4, in addition to showing how our approach is easily applicable to any airport in which flight schedules are known, we also briefly discuss how the final output can be used as a base for a noise charge mechanism. Among the various methods used to define noise

[13] Schipper et al. (1998) used 30 estimates retrieved from 19 studies, Nelson (1979) 29 estimates mostly from the US and Canada regions, while Wadud (2013) implemented a meta-analysis on 65 NDI estimates. Kopsch (2016) performs a meta-analysis of airport and road noise costs and finds that the noise costs of road infrastructure are higher than those generated by airport operations.

[14] In Wadud (2013) GDP per capita PPP is measured in US dollars and cents and adjusted using the US consumer price index from the year 2000.

[15] Airport accessibility accounts for train stations, distance from the central business district, highways, shopping centers, and other important infrastructures.

[16] We have performed a separate analysis using as NDI value transfer the expression $NDI = 0.22 + 1.76 \times GDP \times 10^{-5}$ and the effect is indeed to estimate higher social costs.

[17] These data are easily available from the statistical agencies of most countries (in the application presented in Section 4 we retrieve this information from Agenzia Entrate (2020) and IDESCAT (2020).

[18] Using average prices may give rise to some endogeneity problems, since these prices may already include a real estate devaluation due to noise. However, we include in the analysis the average price in the center of the municipality, which is usually located outside the range of the NIZs and is therefore not affected by the devaluation.

[19] For example, Italian house prices are defined according to homogeneous zones in which the characteristics of the surrounding area are similar. In our empirical application, two adjacent municipalities located near Bergamo, Azzano San Paolo, and Stezzano have the same property value range (i.e., minimum €1,300/sqm, maximum €1,500/sqm, although the first municipality has a portion of land falling under the NIZ of Bergamo Airport, while the territory of the second has no overlaps.

[20] See for example ICAO (2016a) for some examples of noise contour predictions.

charges (Yeahiya, 1995), the total amount of a noise charge T is typically defined by a Pigouvian approach or by the definition of a noise reduction investment (Morrell and Lu, 2000). The use of a noise charge as a regulatory instrument has been proven to be a socially efficient way to address noise externality (Brueckner and Girvin, 2008).

The idea behind the Pigouvian approach is to employ a tax for firms in order to internalize the cost of the negative externalities they produce (Kallbekken et al., 2011), i.e., NSC (that is a function of the level of production Q). In other words, the socially optimal level of production Q^* is determined by the intersection between the marginal social cost (MSC) that includes NSC and the marginal benefits (MB) (in Fig. 5(a)). The tax t^* is essentially the instrument used to align the marginal private cost (MPC) that does not consider noise costs to the MSC, in order to reach the desired (healthy) equilibrium Q^*. The area under the MPC curve up to Q^* represents the total private production cost of airport operations, and the area under the MSC curve represents the total social costs. As the total social noise cost is the difference between the MSC and the MPC, it is evident that the area between the MSC curve and the MPC curve up to Q^* is $NSC^* = NSC(Q^*)$ (in light red in Fig. 5(a)). The optimal tax t^* produces a total tax revenue of $T^* = Q^* \times t^*$ that could be used as noise abatement investments – i.e., to reduce the negative impact of noise on the population (since without t^*, traffic would be higher, that is, at the level where $MPC = MB$). Unfortunately, a major issue limits the cases in which it is feasible to correctly define a Pigouvian tax. It is indeed often difficult, if not impossible, to identify Q^* (Baumol, 1972), particularly in the case of noise (Button, 2020) because we do not know the private marginal cost curves or the marginal benefits ones.[21]

The generation of a set of economic resources by the imposition of a Pigouvian tax proxy raises the question of how to allocate these resources. The uses are manifold. As shown by Bosquet (2000), the tax revenues can create the potential to generate a combination of environmental improvement and economic benefit. For example, they can be used to provide incentives for local employment or to attract local investment. However, the internalisation of an external cost does not mean that noise disappears (it simply means that the airlines/airports should bear the cost) and creates problems for the population living around the airport. Therefore, optimal taxation, defined as the efficient allocation of environmental goods through taxation, may be lower than "effective protection", where "effective" refers to a level that ensures environmental sustainability (Bithas, 2006). This argument paves the way for the possible compensation of those most affected by airport noise, for example through investments in their property financed by the airports (which receive tax revenue), such as the installation of double or triple-glazed windows or soundproofing of perimeter walls. In fact, as Evangelinos et al. (2020) shows, these compensatory investments are already being made by several airports in different European countries.[22]

To obtain a Pigouvian tax proxy, as previously shown, using the observed airport traffic Q_0, it is possible to identify an estimate of social noise costs (Fig. 5(b)). Under the assumption that the observed output should be the result of profit maximization, Q_0 is chosen where $MPC = MB$, which cannot be computed since MPC is not observed. However, our method provides an estimate of social noise costs, $\widehat{NSC}$, given by Eq. (10), and represented by the light blue area in Fig. 5(b).

The introduction of a noise surcharge can affect the level of Q in the short term, particularly in the absence of technological improvement. However, this effect depends on several factors such as the magnitude compared to the marginal/unit costs of the airline and whether the charge is passed through from airports to airlines/passengers. These issues are briefly discussed in Section 4.

To incorporate the technological effect into our analysis, given that airlines operate a fleet composed of different aircraft configurations (Grampella et al., 2017), and since generally noise surcharges are aircraft category specific, a charge based on the specific aircraft category is required. To convert the NSC of an airport, which is an aggregate measure that does not distinguish among different types of aircraft operations, into a per movement charge, we proceed in two steps. First, we identify a reference value for a generic tax that is based on the single MTOW, i.e., the amount of noise generated on average by a single tonne weight. Second, we determine the value of the tax per movement based on different categories of aircraft noise that take into account the technological advancement (and thus lower noise) of new generation aircraft compared to those introduced several years ago, i.e., we adjust the reference value of the average noise social cost per tonne according to different categories of aircraft models taking into account certified noise levels.[23]. Specific details will be provided in Section 4.

4. Results

In this section, we show the results obtained by applying the method proposed here. We consider five airports, three Italian airports (Bergamo (BGY), Milan Linate (LIN), and Milan Malpensa (MXP)), and two Spanish airports (Barcelona (BCN) and Girona (GRO)). The choice of two different countries is done to demonstrate that, independently of the specific geographic context, the required data are obtainable in a relatively easy way. The choice of BCN and GRO provides the possibility of testing our methodology with different geographical contexts (i.e., seaside vicinity in the case of BCN and rural neighborhoods in the case of GRO). The analysis covers the period 2009–2018. More details on the practical implementations of the methodology across the different steps are provided in Appendix B, where a step-by-step procedure is applied to one of the selected airports (BGY).[24] Step 4 is implemented manually using GIS and overlapping the relevant shapefiles.

The NIZs at the levels of 55 and 65 dB, generated for the five airports in our sample, are shown in Fig. 6. Since land use restrictions tend to overlap airport noise curves, the usefulness of using this method is straightforward (independently from the social cost estimate at this stage). Indeed, in this way, it is easy to monitor the evolution of the different contours and observe changes in the area sizes where the noise is more severe. Moreover, we can take into account that land use controls and restrictions may vary on the type of area under a specific curve. For example, the same noise level may affect a rural area differently than an urban area because of the different levels of background noise. Therefore, land use policy interventions or updates in terms of compatibility could be defined, at least in their preliminary form, based on noise curves such as those shown in Fig. 6 and according to the type of use (e.g., residential, commercial, manufacturing, etc.). Looking more specifically at the airports in our sample, both the characteristics of the areas under the contours and the evolution of such contours are not unique. While we observe a predominantly urban neighborhood for BGY and similarly for LIN and MXP, GRO seems predominantly rural, and a significant portion of BCN contours overlap the sea. Furthermore, LIN and GRO exhibit a contraction in their contours over time (more evident in the case of GRO), while BGY, MXP, and BCN exhibit an expansion (especially BGY). Such expansions/contractions can be determined by the variation in traffic level and the fleet operated and, as will be shown shortly, are reflected together with previously discussed levels of urbanization in the estimates of airport social noise costs.

We report the noise social costs obtained for each airport and each year in Table 3. Noise social costs at current prices (NCS) in column (2)

[21] Since we do not know the MPC and MB curves our approach does not exactly lead to Pigouvian taxation, but to a proxy of it.

[22] We are grateful to an anonymous referee for suggesting this point.

[23] We are grateful to an anonymous referee for comments on this part of the work concerning the airport noise surcharge.

[24] The procedure is composed of 2 codes written in R—the first for Steps 1–3 and the second for Step 5 (available in the supplemental material).

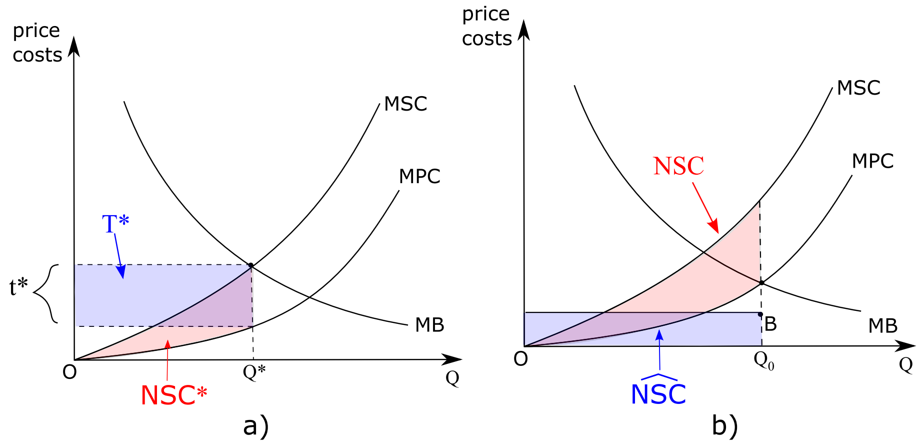

Fig. 5. Pigouvian and estimated social noise costs charge.

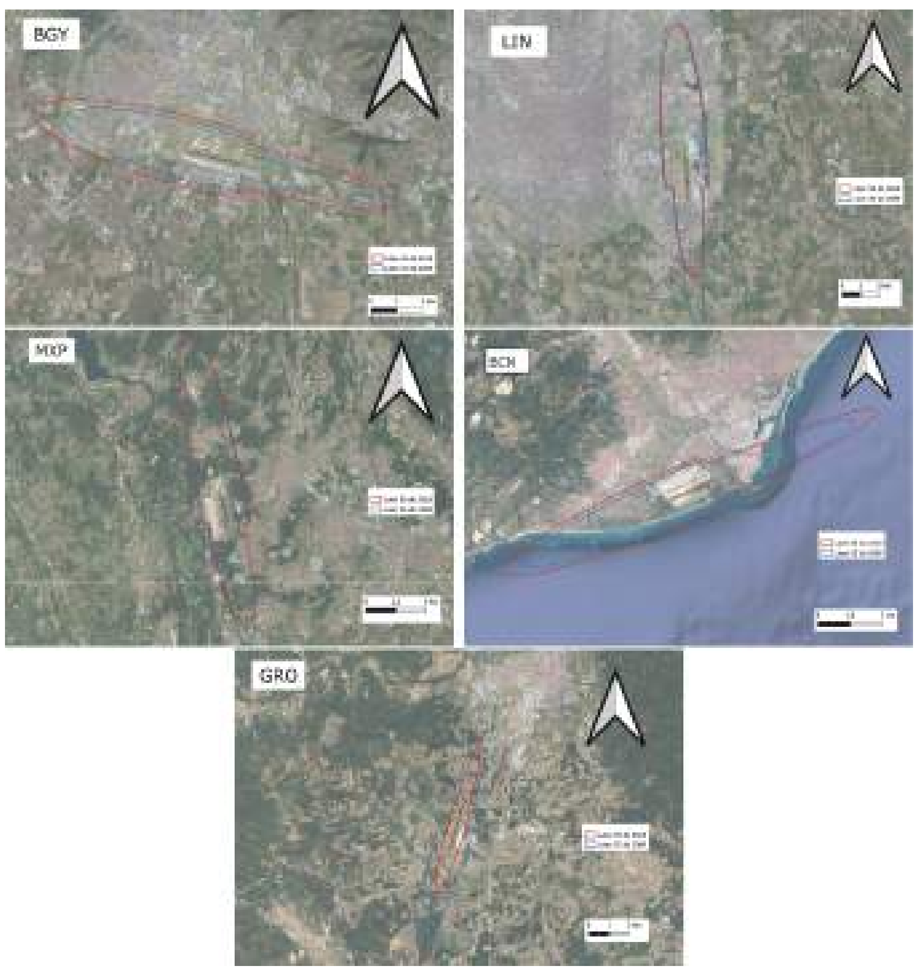

Fig. 6. 2009 and 2018 55 dB contours measured by NIZs at different airports: Bergamo (BGY), Milan-Linate (LIN), Milan-Malpensa (MXP), Barcelona (BCN) and Girona (GRO).

are calculated based on the house prices of the specific year, while for NCS_{2018} in column (3), the computation is carried out at constant prices, keeping the house prices fixed in the year 2018, which acts as the base year. Hence, as previously mentioned, NSC_{2018} is the best estimate of social noise costs in each year at a specific airport. Columns (4) and (5) describe the differences (in absolute terms and in percentage, respectively) between the social costs at current and constant prices. Such differences provide a proxy for the impact of real estate market dynamics and the possible distortion in estimating airport externalities if current prices are used. The idea is that the first application of the method gives rise to a starting level of *NSC*, while in the following years, the costs of social noise are expressed in differential terms with respect to the previous period. In this way, it is possible to provide incentives to airport managers to adopt noise mitigation strategies.

As expected, the highest noise costs are associated with airports closer to urban areas, as previously discussed (refer to the maps in Ap-

Table 3
Estimated noise social costs and noise surcharge by airports and years.

Year (1)	NSC(€) (2)	NSC_{2018}(€) (3)	Diff. (€) (4)	% Diff. (5)
		BGY		
2009	11,020,296	8,426,031	2,594,265	24
2010	12,627,277	10,272,103	2,355,174	19
2011	13,337,112	11,240,151	2,096,961	16
2012	14,292,022	12,103,392	2,188,630	15
2013	13,437,236	11,346,515	2,090,721	16
2014	10,751,264	9,731,301	1,019,963	9
2015	13,431,792	12,558,061	873,731	7
2016	16,610,418	15,019,317	1,591,101	10
2017	21,047,946	21,724,045	−676,099	−3
2018	23,634,543	23,634,543	0	0
		LIN		
2009	4,618,107	5,251,537	−633,430	−14
2010	4,765,624	5,284,768	−519,144	−11
2011	4,407,806	4,753,541	−345,735	−8
2012	4,301,070	4,631,037	−329,967	−8
2013	3,550,904	4,130,169	−1,080,133	−30
2014	4,144,876	4,188,045	−43,169	−1
2015	4,998,363	5,178,817	−180,454	−4
2016	5,070,880	5,055,268	15,612	0
2017	4,257,547	4,358,048	−100,501	−2
2018	5,003,279	5,003,279	0	0
		MXP		
2009	5,288,256	5,852,291	−564,035	−11
2010	6,945,804	7,998,905	−1,053,101	−15
2011	9,104,882	10,578,907	−1,474,025	−16
2012	7,709,554	9,051,119	−1,341,565	−17
2013	6,779,246	7,962,869	−1,183,623	−17
2014	8,801,660	9,227,981	−426,321	−5
2015	11,574,241	12,140,007	−565,766	−5
2016	11,727,877	12,302,557	−574,680	−5
2017	14,962,940	15,678,104	−715,164	−5
2018	12,908,087	12,908,087	0	0
		BCN		
2009	3,075,955	2,431,501	644,454	21
2010	3,012,785	2,710,178	302,607	10
2011	3,896,027	3,303,081	592,946	15
2012	3,530,532	3,148,750	381,782	11
2013	2,356,118	2,917,294	−561,176	−24
2014	2,450,159	3,277,258	−827,099	−34
2015	3,480,591	3,788,210	−307,619	−9
2016	4,255,363	4,769,247	−513,884	−12
2017	4,464,867	5,008,718	−543,851	−12
2018	5,061,298	5,061,298	0	0
		GRO		
2009	375,217	674,210	−298,993	−80
2010	323,974	560,054	−236,080	−73
2011	158,218	251,895	−93,677	−59
2012	187,088	297,459	−110,371	−59
2013	193,633	259,693	−66,060	−34
2014	146,358	119,188	27,170	19
2015	64,184	56,576	7,608	12
2016	59,895	47,471	12,424	21
2017	100,298	90,945	9,353	9
2018	115,480	115,480	0	0

pendix A for greater detail on urbanization). However, the trends exhibited by the airports are different. BGY exhibits a constantly increasing trend in the traffic level and in the total (the only exception is represented by the year 2014). More specifically, BGY almost tripled the amount of nuisance over the ten years and went from €8.4 million in 2009 to €23.6 million in 2018. MXP also exhibits a double NSC_{2018} (from €6 million to €13 million) between 2009 and 2018, although the path is more irregular than that of BGY. Despite a higher traffic level in MXP compared to BGY, BGY exhibits a significantly higher NSC_{2018} in all years, which is mainly due to the different number of residential areas in the noise contours.

LIN and BCN exhibit a comparable amount of NSC_{2018} (respectively €5.0 million and €5.6 million in the year 2018), but, interestingly, completely different traffic levels (in 2018, respectively, about 95,000 and 323,000 movements). This result is due to the location of the Spanish airport runways, which are close to the seaside and therefore exert a lower impact on the population living in the airport surroundings. LIN and BCN exhibit an irregular path in both traffic level and amount of noise over time.

A different situation is observed for GRO. The lowest total and per movement social costs (respectively, €115,000 and €9.63 in 2018) are due (1) to the airport being located in a rural area and (2) to the low level of traffic. Moreover, the decreasing trend in NSC_{2018} over time is caused by a drastic loss in movements due to the decision of Ryanair, the dominant carrier in GRO, to redirect routes to BCN. It is interesting to note that all five airports experienced a decrease in noise costs in 2013. This can be explained by the effects of the European economic recession that struck between 2012 and 2013 on the travel sector.

It is not easy to make comparisons with previous studies. A study on Düsseldorf Airport by Püschel and Evangelinos (2012), used HPM and estimated a rent loss of all housing units within the airport noise footprint equal to €7.5 million for the year 2009. The authors' annual social cost amount seems in line with those found with our methodology, but once again (i) the airport operations are different, and (ii) estimates based on house rents are not necessarily comparable to estimates based on house prices.

As discussed in Section 3, the obtained values could be used to implement damage-related compensation. Indeed, given that Pigouvian taxation cannot be implemented, as explained in Section 3, we adopted $T = NSC_{2018}$ as the best proxy for economic compensation. If we take 2009 as the first application period for the method, the full noise costs, NSC_{2018}, for the year should be charged to the airports for compensation. The latter amounts to €8.4 million for BGY, €5.2 million for LIN, €5.9 million for MXP, €2.4 million for BCN and €0.7 million for GRO. The idea is that in the first year of implementation, full annual costs should be charged. In the following years, each airport should be charged a variation in NSC_{2018} with the previous year. In this way, it should be possible to reward/penalize the airport that is improving/worsening its noise performance over time. When the variation is negative—i.e., less social noise costs than the previous year—the compensation is 0.

An important issue in the proposed method is related to the possible reaction of industry players. For instance, we expect that following the introduction of the method, it will be noted as a downward adjustment of the traffic and as a response to the increased marginal private cost. Therefore, a key point in evaluating the impact of estimated compensation is if the traffic reduction implemented by industry players is greater or smaller than Q^* in Fig. 5(a), i.e., the social optimum. We do not observe Q^* and therefore it is difficult to provide comparisons. However, it might be assumed that the proposed method does not reduce traffic below Q^*. Several factors go in this direction. First, in a (reasonable) scenario in which airports pass the noise surcharge onto airlines and airlines in turn pass it onto passengers, the average per-passenger tax appears to be quite tolerable, even for airports with the highest social costs. For example, BGY shows the highest total estimated social noise costs in 2009, equal to €8.4 million, which could be split between 7.2 million annual passengers in the same year; therefore, the per-passenger tax is equal to about €1.18/pax. Second, moving to a dynamic approach, the proposed compensation mechanism based on annual variations is in line with the approach defined by CORSIA for CO_2 emissions and reduces the total noise surcharge following years after the first.[25] Therefore, we could argue that the compensation will not substantially reduce the traffic that should remain greater than Q^*. If the compensation in the second and third (and so forth) years of application is too small, policymakers could increase it and require the airports to establish a reduction in the level of social costs generated over time. This could be done by setting an efficiency parameter $x \in [0,1]$ so that in the following regulatory period the generated social cost target should be equal to $(1-x)NSC_{2018,t} < NSC_{2018,t-1}$. For instance, x could be set at 5% and thus the compensation asked in year t would be 95% of that in the previous year.[26] In this sense, x has to be intended as a driver of technical progress. In fact, in the long run, the need for less impact every year would lead to a convergence of the actual Q toward the optimal (unknown) Q^* due to a reduction *ceteris paribus* of the generated noise and in turn to a contraction of the noise curves. This would also certainly have non-negligible positive effects in terms of long-term land use and urban policies considering the fact that limited (or restricted) land use areas are quite often explicitly based on noise maps.

We finally note that, as previously mentioned in Section 3, we can also present, as an additional incentive for technological progress, a scheme for the airport noise surcharge. The latter can be modulated according to the noise level of the aircraft, in order to provide some incentive for airlines to adopt more modern, and therefore less noisy, aircraft. The baseline monetary value is the per-MTOW average noise social costs. To calculate it, we divide the NSC of the individual airport by the sum of the MTOW of the total annual movements. In this way we obtain a value of social cost of noise per MTOW.

The second step in this procedure is based on the methodology proposed by some airports, e.g., Schipol Airport (Schipol, 2024), and it is built upon ICAO, Annex 16, volume 1, that identifies Chapter 2, Chapter 3 and Chapter 4 aircraft category (Appendix C) based on their noise levels (ICAO, 2016b). This method identifies seven aircraft categories, as shown in Table 4. The starting point is the calculated EPNL noise level of the individual aircraft as per ICAO certification. The certification reference value for Chapter 3 and Chapter 4 of Annex 16 is taken. For example, for two-engine aircraft Chapter 3 (aircraft certified before 2006) has a maximum limit value at the flyover point of 101 dB. It is, therefore, necessary to take the sum of the 3 maximum EPNL limits (at Flyover, Lateral, and Approach), and then compare them with the sum of the 3 certification values (again at Flyover, Lateral and Approach) of each aircraft model with its engine. This gives a noise reduction value in dB, defined as $\Delta EPNdB$, as shown in Table 4.[27] For example, older aircraft generate a noise reduction compared to ICAO maximum limits of less than 11 dB (category 1), while newer aircraft have a reduction greater than or equal to 27 dB (category 7). Aircraft in Category 1 have a noise charge per movement that is 200% of the average charge, those in Category 7 only 40%, for movements during the day, much higher during the night (with differentiation between a landing and a take-off movement). (see Table 5).

Table 4
Noise categories and percentage increase of surcharge from average movement noise social costs per tonne.

		Tax day	Tax Night	
		Landing/ take-off	Landing	Take-off
Category S1	$\Delta EPNdB > -11$	200%	500%	600%
Category S2	$-11 \geqslant \Delta EPNdB > -15$	145%	225%	250%
Category S3	$-15 \geqslant \Delta EPNdB > -18$	100%	140%	165%
Category S4	$-18 \geqslant \Delta EPNdB > -21$	80%	120%	145%
Category S5	$-21 \geqslant \Delta EPNdB > -24$	65%	100%	120%
Category S6	$-24 \geqslant \Delta EPNdB > -27$	50%	80%	95%
Category S7	$\Delta EPNdB \leqslant -27$	40%	65%	75%

The proposed taxation can reproduce the estimated NSC with an accuracy higher than 95% for the airports considered. The noise surcharge at Bergamo airport (BGY) is applied only to the narrow body category since this is the relevant aircraft type. It is equal to €/*tonne* 3.1 for Airbus 321 and Boeing 737–800 during a departure in the daytime. The two models are similar regarding the embedded technology, as it is evident also for the noise surcharge in the other airports. However, at the Bergamo airport, the noise social costs are much higher than in the other airports given the surrounding population density. Indeed the same aircraft models have much smaller noise surcharges in all other airports, varying from the lowest in Girona (GRO) to the highest in Milan Malpensa (MXP). These differences generate a noise surcharge per movement (during the day) for Airbus 321 and Boeing 737–800 equal to €289 and €246 (respectively) at Bergamo airport and to only €23 and €19 at Girona airport. Wide-body aircraft have a higher noise surcharge at Milan Malpensa (MXP) since many long-haul flights are operated with these aircraft models and the noise affects a relevant portion of the local population. For instance, a Boeing 777-300ER has a noise surcharge per movement equal to €351 at Milan Malpensa, and to €111 in Barcelona (many routes are flying over the sea). Finally, the super-body aircraft, namely the Airbus 380, has a surcharge equal to €348 at MXP and to €110 at Barcelona (BCN). Despite being bigger than the other long-haul aircraft, its modern technology generates less noise than smaller but older aircraft.

5. Conclusions

We have developed a new, general and relatively simple methodology to define airport noise-influenced zones and to estimate the related social cost. The new method combines the features of the approaches based on aircraft certification data with those typically applied in hedonic price analyses. The main advantage of this methodology is that it does not require the use of either specific and complex software or data collections that are difficult to obtain, such as meteorological data or information from noise monitoring stations.

Starting with aircraft certification data and airport traffic schedules, we built three indices depicting average yearly noise at the airport level for each certification point. Exploiting the logarithmic relationship between aircraft noise certification levels and the size of a noise contour, we then defined the contours associated with these indices. Looking at the overlaps between the contours and the distribution of the houses located in the airport neighborhood, we computed the total social cost by summing up the depreciation of all residential units affected by the noise. This was done by applying a noise depreciation index obtained from the existing literature.

We then provided an application of the method to a set of five airports–three Italian (Bergamo, Milan Linate, and Milan Malpensa) and two Spanish (Barcelona and Girona). The obtained results show that

Table 5
Selected charges by noise category for day departures in 2018.

		Airport				
Aircraft	Category	BGY	LIN	MXP	BCN	GRO
Airbus 321Neo	S6	289	95	117	37	23
Boeing 737–800	S6	246	81	100	31	19
Airbus 318	S3	-	45	55	17	-
Embraer 170/175	S2	-	62	76	24	-
Boeing 777	S2	-	-	351	111	-
Airbus 380	S6	-	-	348	110	-

[25] CORSIA is the Carbon Offsetting and Reduction Scheme for International Aviation adopted to stabilize net CO2 emissions from international aviation and has been approved by ICAO.

[26] Note that the efficiency parameter x should be carefully set with expected variations in the traffic level and their influence on the social noise cost generated by a specific airport kept in mind.

[27] This table takes as reference Schipol (2024).

social noise costs depend mainly (1) on the airport location, (2) on the routes for take-offs and landings, and (3) on the residential density. For example, we found that Barcelona airport, even if it has annual movements almost five times higher than Bergamo airport, has estimated social noise costs in 2018 equal to only €5.1 million, while in Bergamo they are about €24 million. Similarly, the Milan Malpensa airport has almost three times the annual movements of Bergamo, but its estimated social noise costs in 2018 were only €13 million. The low social noise costs in Barcelona are mainly due to take-off and landing routes over the sea, while at the Milan Malpensa, the low values are due to the surrounding rural area. Bergamo costs are significant due to the high and uniform population density around the airport (so that it is virtually impossible to follow take-off and landing routes with different impacts on the population and land).

Our method might help policymakers (i) implement compatible land-use planning in developing accurate cost-benefit analysis and management, especially in case of airport expansion, (ii) define appropriate compensation mechanisms based on a damage-related charge, and (iii) fostering technological progress through the design of economic incentives towards the adoption of new and less-noisy aircraft by applying aircraft category noise surcharges. As shown by Thompson et al. (2013) the construction of a new airport or the expansion of an existing one is a very complex process, involving a multitude of dimensions, from demand forecasts, to the role of hub economies, to environmental impacts (not just noise). The proposed method is an opportunity to estimate the effects of noise and can feed into the cost-benefit analysis process of new airport projects.

Furthermore, our approach may be combined with air navigation systems to improve airport operations. The latter can be designed in such a way as to reduce the social costs of noise by planning take-off and landing routes that reduce impacts on the population. This can be calculated by using routes with limited passages over areas of higher population density, also taking into account the damage differential between day and night. On the other hand, our method does not allow for the assessment of management impacts during cruise or landing approach phases that are not part of the LTO cycle, because it is unable to assess the effect of height variations outside of these strictly airport operations.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

Population and houses surrounding airports (see Figs. 7–12).

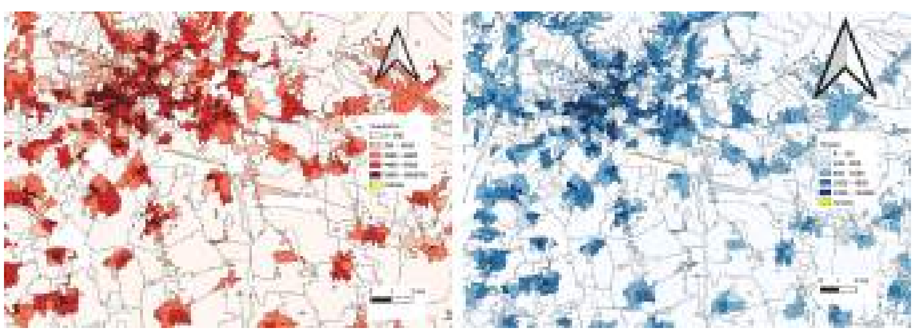

Fig. 7. Bergamo population (left) and houses (right).

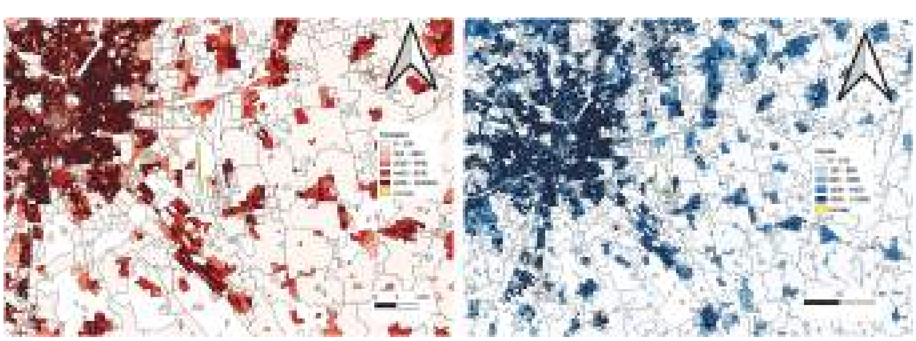

Fig. 8. Milan Linate population (left) and houses (right).

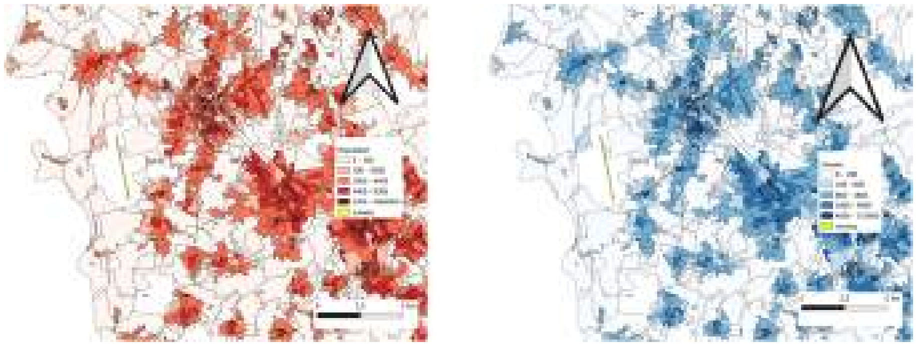

Fig. 9. Milan Malpensa population (left) and houses (right).

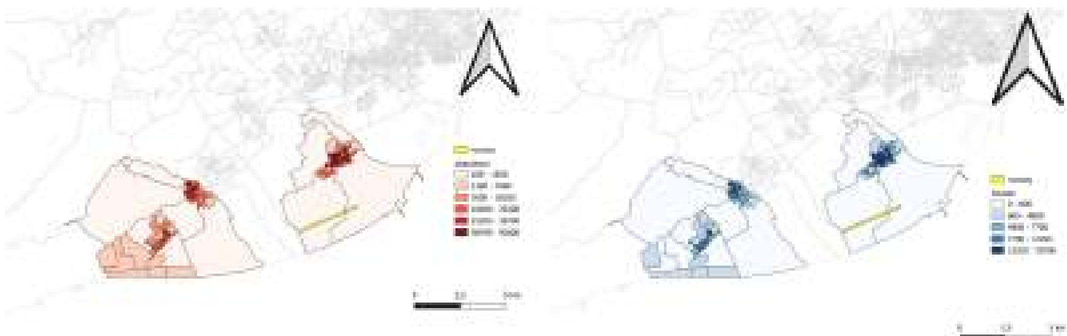

Fig. 10. Barcelona population (left) and houses (right). Note: the empty area between the two colored zones is due to the presence of two rivers (*Delta do Llobregat*).

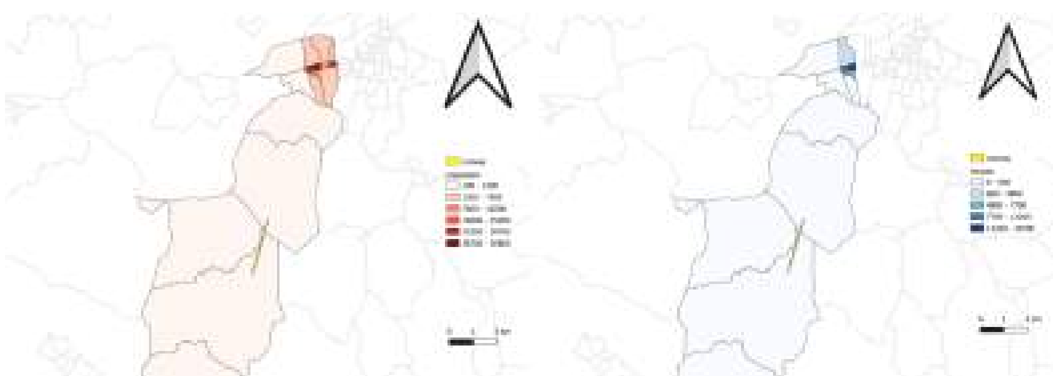

Fig. 11. Girona population (left) and houses (right).

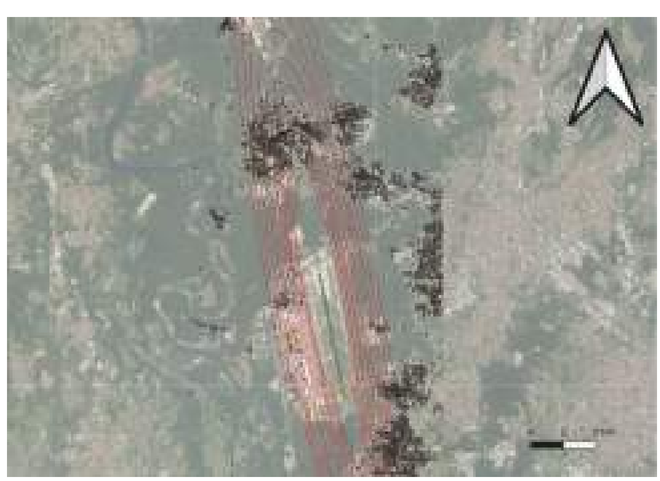

Fig. 12. Intersection of buildings data with noise contour NIZs for Milan Malpensa airport.

Appendix B

Step-by-step computation of the social noise costs of Bergamo Airport (BGY)

B.1. Step 1

The starting point for calculating the amount of noise generated by Bergamo airport is to retrieve data on OAG scheduled flights for the analysis horizon. The information needed is related to O-D pairs, departure and arrival time, the airframe used in each specific movement, and the frequency of operations for each route and year. This process should be done for both arrival and departure operations. A sample of OAG data is reported in Table 6 (as shown later, maximum take-off weight (MTOW) data are essential for the implementation of the method).

Once the data set has been created, it is necessary to add a column indicating if the movement should be treated as a day, evening, or night operation. This task can be done using the departure and arrival time of each flight taking into account that the *day* movements are those occurring from 6.00 am to 8.00 pm; in the evening from 8.00 pm to 10.00 pm; and at night operations, from 10.00 pm to 6.00 am.

At this stage it is necessary to merge the data set regarding flights with the aircraft certification data on noise, which is freely accessible on the EASA website. The association is done using the aircraft model[28] and taking only the aircraft with a difference in MTOW within 3%. This filtering process is applied to avoid possible mismatches among the many possibilities of aircraft configurations.

From the newly generated data set, it is possible to calculate the average noise for each aircraft model for the three certification phases: approach, lateral, and flyover, as shown in Table 7. The last three columns on the right provide the lateral, flyover, and approach noise levels using the EPNL metric of the certification data.

Table 6
A sample of OAG data for arrival operations at BGY.

Carrier Code	Carrier Name	Dep Airport	Arr Airport	Dep Time	Arr Time	Specific Aircraft Name	Aircraft MTOW (t)	Frequency	Year
FR	Ryanair	LBC	BGY	1910	2045	Boeing 737–800 Passenger	80	4	2009
FR	Ryanair	CRL	BGY	1155	1330	Boeing 737–800 Passenger	80	22	2009
FR	Ryanair	TRF	BGY	1755	2020	Boeing 737–800 Passenger	80	5	2009
FR	Ryanair	EIN	BGY	1420	1550	Boeing 737–800 Passenger	80	89	2009
AZ	New Alitalia	FCO	BGY	1720	1835	Embraer 170	42	26	2009

Table 7
A sample of the merged data set with information regarding operations and single event EPNL noise certification levels for BGY airport.

Type	Carrier	Dep Airport	Arr Airport	Dep Time	Arr Time	Specific Aircraft Name	MTOW	Freq	Year	Operation	D/E/N	Lateral (dB)	Flyover (dB)	Approach (dB)
Regional	8I	REG	BGY	1310	1450	Canadair	42,000	8	2009	arrival	Day	82.33	77.99	92.13
Regional	8I	NAP	BGY	0900	1015	Canadair	42,000	3	2009	departure	Day	82.33	77.99	92.13
Propeller	V5	KSC	BGY	1410	1640	ATR 72	23,000	5	2010	arrival	Day	84.02	81.46	92.78
Regional	BM	MUC	BGY	1745	1845	Embraer RJ135	25,000	3	2016	arrival	Day	84.6	78.8	92.3
NarrowBody	FR	BRI	BGY	1335	1505	Boeing 737–800	80,000	9	2011	departure	Day	93.66	83.96	96.09

B.2. Steps 2–3

From the EPNL noise levels, we obtain the SEL levels using the conversion values shown in Table 2 and applying the relative penalization according to the daytime period. We compute the values as those shown, as an example, in Table 8.

Using SEL values, it is possible to compute the *Lden* components by applying Eq. (1). The calculated *Lden* for the period 2009–2018 at Bergamo Airport are reported in Table 9, for lateral, flyover, and approach operations throughout the year. In take-offs, the instant average noise level generated in the year 2018 is 64.46 dB (lateral) and 54.99 dB (flyover). During landing operations, it is (same year) 64.57 dB. From $Lden_t^{FO}$,$Lden_t^{LA}$, and $Lden_t^{AP}$, and applying Eqs. (4), (5) and (7), we get the distances x,y, and z used to draw the NIZ ellipse in GIS. Table 9 shows the distance values x, y and z in meters for the 55 dB NIZ and for the 65 dB NIZ, always at Bergamo Airport. For example, in 2018, for the 55 dB NIZ, the distance x is set at 6,491 meters from the take-off point, while for the 65 dB NIZ x, it is set at 2,052 meters. y, the lateral component to draw the take-off ellipse is 1,336 meters for the 55 dB NIZ and 422 meters for the 65 dB NIZ. Concerning landing operations, z is at 6,015 meters for the 55 dB NIZ and at 1,902 meters for the 65 dB NIZ. Z^{LA} is 70% of y^{LA}.

Having identified distances x, y and z,z^{LA}, we can draw the NIZ using GIS. The starting point of this procedure is the airport runway definition. This task is accomplished by creating a vector object using satellite images, as shown in Fig. 13.

[28] since some aircraft models are reported differently between EASA and OAG database nomenclature, a connection table with the type of aircraft from both databases has been created to allow the association process.

Table 8
A sample of the merged data set with information regarding conversion from EPNL noise certification levels to SEL, BGY airport

Type	Dep Airport	Arr Airport	Specific Aircraft Name	Freq	Year	Operation	D/E/N	Lateral (EPNL)	Flyover (EPNL)	Approach (EPNL)	Lateral (SEL)	Flyover (SEL)	Approach (SEL)
Regional	REG	BGY	Canadair	8	2009	arrival	Day	82.33	77.99	92.13	80.58	75.99	88.38
Regional	NAP	BGY	Canadair	3	2009	departure	Day	82.33	77.99	92.13	80.58	75.99	88.38
Propeller	KSC	BGY	ATR 72	5	2010	arrival	Day	84.02	81.46	92.78	80.02	78.46	87.78
Regional	MUC	BGY	Embraer RJ135	3	2016	arrival	Day	84.6	78.8	92.3	82.85	76.8	88.55
NarrowBody	BRI	BGY	Boeing 737–800	9	2011	departure	Day	93.66	83.96	96.09	91.41	81.71	92.34

Table 9
Instant annual average noise levels in SEL (*Lden*), and distances x, y, and z for Bergamo airport, by year and noise contour NIZ between 55 dB and 65 dB.

Airport	Year	$Lden_t^{LA}$ dB	$Lden_t^{FO}$ dB	$Lden_t^{AP}$ dB	x, L_{55} meters	y, L_{55} meters	z, L_{55} meters	…	x, L_{65} meters	y, L_{65} meters	z, L_{65} meters
Bergamo	2009	63	53	65	5,175	1,096	6,370	…	1,636	347	2,014
Bergamo	2010	63	53	66	5,375	1,141	6,727	…	1,670	361	2,127
Bergamo	2011	63	53	66	5,384	1,132	6,985	…	1,703	358	2,209
Bergamo	2012	63	54	66	5,598	1,170	7,267	…	1,770	370	2,298
Bergamo	2013	63	53	66	5,451	1,146	7,267	…	1,724	363	2,298
Bergamo	2014	63	53	66	5,222	1,102	7,101	…	1,651	349	2,246
Bergamo	2015	63	54	66	5,558	1,174	7,364	…	1,758	371	2,329
Bergamo	2016	64	54	67	5,801	1,229	7,611	…	1,834	389	2,407
Bergamo	2017	64	55	67	6,153	1,277	7,903	…	1,946	404	2,499
Bergamo	2018	64	55	65	6,491	1,337	6,016	…	2,053	423	1,902

Fig. 13. BGY airport runway (yellow) with take-off/touch-down line (blue).

Using x, y, z, z^{LA} it is possible to generate buffers of points equally distanced from the runway, as shown in Figs. 1(b)-2(b). Using the buffers as a reference, it is possible to draw two ellipses, one for the departure operations and one that is reduced in size for the arrival movements. The two ellipses bring with them two ”tails” elements, as shown in Fig. 14, that should be removed through a cut at the beginning of the runway.

The final NIZ is similar to the one drawn in Fig. 3. This process is repeated for all the noise levels between 55 dB and 65 dB, and for each year analyzed. The final result is reported in Fig. 12.

Fig. 14. An example of departure and arrival ellipses with their "tails" for a specific NIZ at BGY airport.

B.3. Step 4

Once the NIZ contours have been defined, the next step is to identify the houses located within these NIZ contours. We obtain it in two steps: (1) we use GIS to overlap the shapefile containing the geo-referenced buildings with the previously obtained NIZs, and (2) we count the buildings under each NIZ noise level. An example of the output obtained is shown in Table 10 for the year 2009 and for a subsample of municipalities surrounding Bergamo Airport. For instance, in the city of Bergamo, there are 131 residential buildings in the 55 dB contour, while there are only 22 in the 61 dB contour. In the Orio al Serio municipality, there are 18 buildings under the very noisy 65 dB NIZ contour.

Since there may be more than one residential unit in each building, we calculate the total number of residential units in each NIZ using the information regarding the distribution of units in each residential building available from ISTAT (2020). Table 11 shows the distribution of units in each building according to the number of residential units in the Bergamo municipality (ISTAT, 2020). There are about 12,500 residential buildings in Bergamo Municipality: 2,449 single unit buildings (about 20% of the total), 2,968 buildings with 2 residential units (about 24% of the total), etc.

We apply the distribution of residential units shown in Table 11 to all buildings in a specific NIZ for each municipality and for each year. For example, in Bergamo, we identified 131 buildings in the 55 dB NIZ (see Table 10) in 2009. Hence, 19.67% of them are single units, 23.84% are double units, 20.15% has 3 units, 16.37% have 6 units, and so on.[29] This computation shows that in 2009 in Bergamo, there were 648 residential units in the 55 dB NIZ contour, 1,261 units in the 56 dB contour, etc. Table 12 presents the distribution of residential units.

The next step consists of transforming the number of residential units in their size using the square meters metrics. We need this number since house prices are in square meters. The size distribution of residential units for the Bergamo municipality is available from ISTAT (2020) and reported in Table 13. ISTAT (2020) provided several sizes, from very small residential units (i.e., 29 square meters) to the largest ones (i.e., 150 square meters). There are 372 residential units with sizes equal to 29 sqm (0.09% of total units), 5,692 units of 35 sqm (1.3%), etc.

Hence, of the 648 residential units in the 55 dB NIZ contour in Bergamo (Table 12), about 6 are 29 sqm (0.09% of 648), 8 units have a size of 35 sqm, etc. This procedure is repeated for all the NIZ contours in each municipality.

Table 10
A sample of the number of buildings beneath each NIZ contour for each municipality.

Year	Municipality	NIZ (dB)										
		55	56	57	58	59	60	61	62	63	64	65
2009	Azzano San Paolo	67	23	16	4	1	0	0	0	0	0	0
2009	Bergamo	131	255	185	128	56	49	22	0	0	0	0
2009	Grassobbio	2	15	16	4	1	0	0	0	0	0	0
2009	Orio Al Serio	0	0	0	11	19	14	7	14	19	17	18
2009	Seriate	23	0	1	3	5	5	2	2	1	2	0

[29] We assume 3 units for the 3–4 interval, 6 units for the 5–8 interval, 12 for the 9–15 interval, and 15 for the last unit interval.

Table 11
Distributions of residential units per building in Bergamo municipality, ISTAT (2020).

Number of flats in a building	1	2	3–4	5–8	9–15	>15
Number of buildings	2,449	2,968	2,508	2,038	1,277	1,206
% of buildings	19.67	23.84	20.15	16.37	10.26	9.68

Table 12
Distributions of residential units under each NIZ contour by municipality.

		NIZ (dB)										
Year	Municipality	55	56	57	58	59	60	61	62	63	64	65
2009	Azzano San Paolo	331	114	79	20	5	0	0	0	0	0	0
2009	Bergamo	648	1,261	915	633	277	242	109	0	0	0	0
2009	Grassobbio	10	74	79	20	5	0	0	0	0	0	0
2009	Orio Al Serio	0	0	0	54	94	69	35	69	94	84	89
2009	Seriate	114	0	5	15	25	25	10	10	5	10	0

Table 13
Distributions of houses according to the square meters in the Bergamo area, ISTAT (2020).

Residential unit size (sqm)	Number of residential units	Percentage of residential units
29	372	0.09
35	5,692	1.30
45	17,266	3.95
55	24.997	5.71
70	87,909	20.09
90	127,789	29.21
110	77,474	17.71
130	51,375	11.74
150	44,600	10.19

Table 14
House prices (€/m^2) according to the Italian Finance Ministry in municipalities surrounding Bergamo airport during the period 2009–2018.

Year	Curno	Treviolo	Azzano San Paolo	Seriate	Orio al Serio	Grassobbio	Brusaporto	Bagnatica	Bergamo
2009	1,900	1,650	1,550	1,700	1,500	1,500	1,400	1,400	1,900
2010	1,750	1,500	1,450	1,550	1,350	1,350	1,300	1,300	1,800
2011	1,700	1,450	1,400	1,500	1,300	1,300	1,300	1,250	1,750
2012	1,650	1,400	1,350	1,550	1,250	1,250	1,250	1,250	1,750
2013	1,650	1,400	1,350	1,500	1,250	1,250	1,200	1,200	1,750
2014	1,700	1,400	1,600	1,400	1,250	1,250	1,300	1,200	1,600
2015	1,700	1,500	1,600	1,450	1,250	1,250	1,300	1,200	1,550
2016	1,700	1,500	1,600	1,750	1,250	1,250	1,300	1,100	1,600
2017	1,700	1,500	1,600	1,600	1,250	1,250	1,300	1,100	1,350
2018	1,700	1,600	1,600	1,750	1,250	1,250	1,300	1,200	1,400

B.4. Step 5

The last step consists of estimating the social noise costs using the hedonic price method. Therefore, for Italian airports, we retrieve the prices of houses for each municipality from the database Agenzia Entrate (2020) and select the maximum square meter price for a representative building, ie, a residential unit in normal status with the lowest market value in the interval provided by Agenzia Entrate (2020). These values are reported in the following table for all municipalities surrounding Bergamo Airport for each year during the 2009–2018 period.[30] .

House prices must be depreciated according to their exposure to noise, and we use the noise depreciation index as shown in Eq. (8). This means using the Italian per capita GDP in PPP in the different years, expressed in US dollars as in Wadud (2013). Similarly, we need to calculate the NDI of another country—Spain in our application—and use its per capita GDP in PPP.[31] Table 15 shows the GDP in Italy and Spain and the corresponding NDIs ranging from 0.68% in 2009 for Italy to 0. 83% in 2018, while in Spain we have 0.64% in 2009 and 0.79% in 2018 (per additional dB), respectively.

Having calculated the annual NDI for each additional dB generated by airport operations, we estimate the social noise costs. An example is shown in Table 16. We discussed two municipalities (Grassobbio and Bergamo) for three years (2009–2011). All square meters related to residential units located in a specific NIZ contour are multiplied by their price, taken from Table 14. There are no social noise costs for residential units under the 55 dB

[30] The prices for Bergamo are related to the neighborhoods closer to the airport, not those units located in the central business district.
[31] The Italian and Spanish GDP per capita is taken from World Bank (2020) and it is expressed in US dollars.

Table 15
Per capita GDP in PPP in US dollars and NDI for Italy and Spain.

Year	Italy		Spain	
	GDP ($)	NDI (%)	GDP ($)	NDI (%)
2009	34,628	0.68	32,116	0.64
2010	35,185	0.70	31,707	0.63
2011	36,598	0.71	31,868	0.63
2012	36,486	0.71	31,720	0.63
2013	36,315	0.71	32,434	0.64
2014	36,195	0.71	33,526	0.66
2015	36,899	0.72	34,903	0.68
2016	39,927	0.77	37,286	0.73
2017	41,581	0.80	39,529	0.77
2018	43,124	0.83	40,720	0.79

Table 16
An example of market value depreciation of all residential units in euro due to noise annoyance by NIZ contour, municipality and year.

Municipality	Year	NIZ (dB)										
		55	56	57	58	59	60	61	62	63	64	65
Grassobbio	2009	0	−9,112	−67,431	−71,987	−18,225	−4,556	0	0	0	0	0
Grassobbio	2010	0	−225,075	−117,549	−90,212	−99,324	−13,669	0	0	0	0	0
Grassobbio	2011	0	−184,980	−99,324	−198,649	−49,207	−53,763	−49,207	−9,112	0	0	0
Bergamo	2010	0	−590,479	−1,149,065	−833,779	−576,811	−252,412	−220,519	−99,324	0	0	0
Bergamo	2011	0	−472,930	−1,063,409	−869,317	−815,554	−256,968	−206,850	−180,424	−9,112	0	0
Bergamo	2012	0	−567,698	−1,230,165	−905,766	−689,804	−315,287	−215,962	−162,200	−13,669	0	0

NIZ contour since they are not affected by noisy airport operations, while the market value of all residential units in a specific contour between 56 dB and 65 dB is depreciated using the annual NDI for Italy. In Table 16 we show the total depreciation for each year by municipality and contour. The market value of all residential units in Grassobbio, in 2009, located at 56 dB is reduced by €9,112, while it is €184,990 in 2011. This drastic increase in depreciation is due to (1) the higher number of movements in 2011, and (2) enlargement of the 56 dB NIZ contour. The latter is due to an increased SEL value and the consequent widening of the ellipses surrounding BGY.

Summing all depreciation levels in all municipalities, we obtain and estimate the annual social noise costs generated by an airport and provide the results in Table 3.

Appendix C

(see Table 17).

Table 17
Examples of aircraft models in different airport noise surcharge categories.

Category						
S1	S2	S3	S4	S5	S6	S7
B737-400	B737–300/500/900	B737-600/700/800	A319	A318	A380-800	A350-900
B757-200	B767-300	A321	A320	ATR 42/72	E135	B787-9/9
MD-82/83	F100	A340-200	A340-300/500/600	MD-90	F70	CRJ 200/1000
B747-100/200/300/400	MD-80/81/87	B757-300	B717-200	E135/140/145	S340	
	A330	B767-200/400	B777-200/200ER	A340		
	ARJ85/100	B777-200/300	DHC-8			
	E170/175	CRJ700/900	FD 328–100			
	A310	E190/195				

Appendix D. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.cstp.2024.101240.

Appendix E. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.cstp.2024.101240.

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