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Nonlinearity, Outliers and Reference Market Depth: Risk Factors in Searching for the Relationship Between Real Estate Prices and Airport Noise

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Abstract:

Purpose: *The primary objective of this study was to verify the hypothesis of nonlinearity in the relationship between noise levels and unit prices of single-family homes in the Restricted Use Area of Warsaw Chopin Airport. Furthermore, an endeavour was made to ascertain the benchmark for the depth of the reference market. The impact of sample heterogeneity and the significance of outliers for estimation results were examined.*
Design/Methodology/Approach: *A variety of methodologies were employed, including general linear models, methods for identifying outliers, and optimisation-based clustering.*
Findings: *The study's findings corroborated the deleterious effect of elevated aircraft noise levels on property transaction values, concomitantly emphasizing the non-linear nature of this effect. It has been demonstrated that as the distance of a property from the center of the airport runway increases, the discrepancy in unit prices between properties located inside and outside the Restricted Use Area decreases. It has been demonstrated that the presence of unconventional observations can have a detrimental effect on the quality of the resulting models.*
Practical Implications: *The findings have important planning and policy implications. It is submitted that they can serve as a basis for defining restricted use zones, developing compensation mechanisms, and designing spatial planning principles for residential areas located near airports. These actions are consistent with the objectives of Directive 2002/49/EC on the assessment and management of environmental noise, which underscores the necessity of incorporating noise protection measures into urban and transport policies. Furthermore, the findings emphasise the risk dimension associated with residing or investing in areas exposed to elevated levels of aircraft noise. From the perspective of investors and local governments, this risk is manifested in market volatility, reduced liquidity, and the necessity for risk mitigation strategies.*
Originality/Value: *The study was based on unique data gathered as part of projects carried out on behalf of the largest Polish airports between 2008 and 2023. Another significant innovation was the utilisation of cluster analysis to enhance the homogeneity of the research sample. However, the greatest added value was the estimation of the maximum depth of the reference market, i.e. the area with an acceptable noise level from which transactions used in comparative analyses may originate, and the confirmation of the non-linear impact of noise levels on the unit price of properties located in Restricted Use Areas.*

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1. Introduction

Research into the impact of noise on the value of neighbouring properties is multi-faceted. Firstly, it may include the combined impact of noise as a negative external effect generated by various types of infrastructure, such as roads, railways, industrial facilities and airports. A substantial body of research has demonstrated that the impact of noise on residential property values is predominantly deleterious.

However, the extent of this impact varies significantly depending on the source of the noise. The validity of this assertion is supported by the findings of studies conducted by researchers who do not exclusively focus on aircraft noise, but rather undertake a comprehensive examination of traffic noise, encompassing both road and rail noise (Wilhelmsson, 2000; Simons and El Jaouhari, 2004; Diao *et al.*, 2016).

Aircraft noise is perceived as a more significant nuisance than road noise, which typically results in a greater decline in property value within its respective range. Analyses of data concerning Dutch airports have demonstrated that aircraft noise exerts a more significant influence on residential decisions than noise emanating from road or rail traffic. This phenomenon can be attributed to the inherently unpredictable nature of aircraft noise and its extensive range (Theebe *et al.*, 2000).

The diversity of results determining the negative impact of noise on property prices is also exacerbated by the use of different research methods. These include quantitative approaches that use primarily simple and complex econometric models, as well as qualitative studies based, as a rule, on surveys. Quantitative analyses of data spanning periods before and during the recent coronavirus pandemic have demonstrated that the market for single-family homes in close proximity to airports exhibits a response to reductions in noise levels. For instance, as demonstrated by (Ngo *et al.*, 2023), a decline in air traffic in New Zealand resulted in a temporary increase in the value of residential properties in close proximity to airports.

The findings of research conducted into the impact of noise emanating from the airport in Quebec, Canada, on the housing market provide an illustration of the implementation of qualitative methodologies.

The findings of this research demonstrated that subjective perceptions of aircraft noise exhibited a strong correlation with diminished quality of life and a negative perception of the area. Nevertheless, the estimation of these phenomena in monetary terms is challenging (Levesque, 1994).

The authors of such studies also draw attention to the impact of psychological factors, such as health concerns and lack of control over the source of noise, as causes of property value depreciation (Bateman *et al.*, 2001). This assertion is substantiated by empirical evidence derived from simulations and public surveys conducted for the property market in the vicinity of planned airport expansions in the United Kingdom.

These studies demonstrated that expectations of future noise associated with the planned airport expansion induce a decline in property prices (Bristow *et al.*, 2015). Utilizing transaction and survey data, the authors concluded that the mere information about planned expansion and an increase in the number of flights leads to a decline in house prices.

It is also important to note that, in addition to assessing the negative impact of noise, the authors of the research also analyse the positive aspects of living in a noisy neighbourhood, which increase property prices, for example due to improved transport links (Cohen and Coughlin, 2009).

Furthermore, the authors draw attention to the subjective nature of determining the nuisance value of such neighbourhoods and the resulting stigmatisation of the real estate market.

However, Debrezion *et al.* (2007) demonstrated that although proximity to transport infrastructure enhances property values due to enhanced accessibility, its deleterious effects, such as noise, can result in price depreciation. In the context of airports, the net effect of noise is contingent on the relationship between benefits and social costs.

The accurate valuation of the decline in property value caused by external effects of airport operations is hindered by numerous limitations and problems. The selection of appropriate data sets for valuation has been demonstrated to have a significant impact on the estimated value, which, in turn, affects the accuracy of the valuation.

Consequently, the selection of the correct data sets is of paramount importance in the process of compensating for damage due to changes in property value as a result of restrictions introduced in areas of limited use. The following aspects are also of particular significance:

- The market participants' perception of the effects of changes in the neighbourhood of the property is that they are short-term. The aforementioned effects are characterised by relational, contextual, processual, reinforcing, reversible, morally charged and contagious stigmatisation (Zhang *et al.*, 2020),
- The utilisation of heterogeneous data sets, which are often of substandard quality (Salvi, 2008), in conjunction with a plethora of divergent research methodologies and models, which exhibit marked discrepancies in terms of variable specifications and analytical forms, is a key issue (Cohen and Coughlin, 2009; Mohammad *et al.*, 2017),
- The impact of public intervention on property prices is subject to variation both geographically and temporally (Bełej *et al.*, 2023),
- The necessity for market segmentation, which is imperative in circumstances where heterogeneity is observed within the sample population. Furthermore, the disruption of the price adjustment process, consequent to the incorporation of relocation and transaction costs (Nelson, 2008),
- The non-linearity of the relationship between noise levels and price levels (Jud and Winkler, 2006),
- The inadequacy of scales for the measurement of property characteristics (Pennington *et al.*, 1990).

Analyses of housing markets operating in the vicinity of airports constituted an integral part of projects carried out by researchers from several Polish academic centres on behalf of the largest Polish airports in the years 2008-2023.

The objective of these studies was to provide a scientific basis for resolving the methodological challenges that arose during the process of determining compensation for the reduction in property value and evaluating the effectiveness of interventions implemented within the Restricted Use Areas (RUAs).

As part of the analytical process, a range of approaches and methodologies were employed. The functioning of housing markets in the vicinity of airports was assessed, and the spatial distribution of compensation claims was evaluated. It is imperative to undertake an in-depth legal analysis in order to resolve conflicts that arise between property owners located in the RUAs and airport authorities.

This analysis encompassed the issue of intervention with a systemic error (including claims by property owners in the absence of any restrictions on existing buildings as a result of the introduction of the RUA), the search for economic justification for this intervention in the context of social costs, and the assessment of the legitimacy of compensation payments for acoustic revitalization of buildings in the absence of such revitalization.

A particularly important issue requiring further research is the spatial scope of the analyzed market, its subjective selection and, consequently, the selection of specific properties from this area for analysis. In this regard, the relevant real estate market is determined by the subject, scope, purpose, method of valuation and availability of data, as well as its type and area, and the period of the study, according to the guidelines set out in Rozporządzenie… (2023).

Concurrently, it is imperative that this market reflects the socio-economic affinities that influence property prices within it. It is crucial to take into account the fact that its area does not correspond to the extant administrative division (Forys, 2024; Foryś *et al.*, 2021).

The subject of the present study are properties in the form of single-family houses located in the vicinity of the Fryderyk Chopin Airport in Warsaw, for which market transaction prices were available in 2013-2022. Notwithstanding the expanding role of regional airports, this particular airport continues to hold the greatest significance in the implementation of air connections for Poland (Fijorek and Leśniewska, 2012).

The conclusions of preceding studies fail to offer a conclusive response to the query regarding the nature of the relationship between aircraft noise levels and property prices in areas subject to such noise. Specifically, the research does not elucidate whether the relationship is non-linear.

Furthermore, the methodology for determining the depth of reference market, which functions as a benchmark for RUA, remains ambiguous. The absence of research in this area provides substantial justification for conducting this particular study, to fill the existing research gap.

The primary objective of the present study is to ascertain whether the differences in unit prices of single-family houses located in the RUA of the Fryderyk Chopin Airport in Warsaw exposed to excessive noise levels and those outside this area change with the increase in the distance from the center of the airport runway.

The identification of such regularity would facilitate the determination of the scope of the reference market, thereby enabling the estimation of the value of land properties developed with single-family houses, and finally compensation for the reduction in property value that results from the introduction of the RUA.

The hypothesis under scrutiny, utilising models for qualitative data, cluster analysis and an exponential model, posits that the discrepancy in prices of 1 square metre of houses located within and without the RUA significantly diminishes as the distance of such properties from the centre of the airport runway increases.

The remainder of the study is organized as follows. The second section of this study methodically explores the extant literature to provide a more profound insight into the nonlinear character of the relationship between noise and property prices. The third section of this study presents the methods that were utilized in the research.

The fourth section of the text comprises data characteristics, received results and their interpretation. As the concluding section of the text puts forward a concise discourse on the findings, conclusions, policy recommendations, and suggestions for further research.

2. Literature Review

Research into the impact of noise on property prices has been undertaken in a number of areas. One such area of research involves the assessment of whether changes in noise levels, most often measured by distance from the source, affect the unit prices of land, residential properties, single-family homes and commercial properties.

Gautrin (1975) was the first to emphasise in his work that noise should be considered a significant negative factor affecting the local real estate market. Furthermore, he presented a method for estimating the impact of aircraft noise on land and property prices in an urban model.

The impact of aircraft noise on the value of land in the vicinity of an airport has been demonstrated to be a subject of considerable interest. Moreover, it was determined that an increase in noise levels was associated with a decline in property values.

McMillen's (2004) research yielded analogous outcomes. Utilising hedonic regression models, he substantiated the substantial and deleterious effect of noise on the valuation of single-family residences. Furthermore, he established that the severity of this effect escalates in conjunction with the degree of noise exposure.

Property price variations resulting from excessive noise may also be contingent on the surrounding environment, such as the character of a given neighbourhood. A number of comparative analyses have been conducted on the impact of transport infrastructure, including airports, on the real estate market.

These analyses have demonstrated that the extent to which noise has a detrimental effect is contingent on the degree of urbanisation and the quality of spatial planning. In a study of residential properties in the vicinity of Los Angeles Airport (Collins and Evans, 1994), the model incorporated a range of variables beyond noise levels, including the age of the buildings, the income of residents, and the distance from the city centre. The author's findings demonstrated that wealthier neighbourhoods exhibited a lower degree of price-sensitivity to noise compared to poorer areas.

A study of the long-term impact of aircraft noise on the housing market in Germany utilized a difference-in-differences model, which indicated that exposure to noise levels exceeding 55 dB results in a substantial decline in housing values, particularly in densely populated urban regions (Mense and Kholodilin, 2014).

Duarte and Tamez's (2009) study of residential property prices in Mexico similarly demonstrated that the negative impact of aircraft noise on house prices is not stationary, but rather contingent on the local urban context and residents' perceptions. The researchers concluded that analyses should take into account the spatial factor in the context of the non-linearity of noise effects observed in the valuation models used.

A study of the perception of aircraft noise in Japan and its impact on property values in areas surrounding airports, based on survey research, demonstrated a strong correlation between subjective noise perception and a decline in housing prices (Fujiwara *et al.*, 2017). The most significant losses in property value were observed in areas where noise levels exceeded 70 dB.

Furthermore, the sensitivity levels exhibited by residents were found to be contingent upon their individual experiences with aviation, as well as the accessibility of airport-related amenities. Hedonic models have been utilised in studies of Swedish airports (Bromma Airport). The findings of the study demonstrated that an augmentation of 1 dB in aircraft noise resulted in a diminution of housing values by 0.3 per cent, amounting to an average loss of $1,200 (Lindgren, 2018).

Jud and Winkler's (2006) research revealed that airport noise constitutes a pivotal detrimental external factor, with property values in areas encompassing the take-off and landing trajectory exhibiting a decline in comparison to those in comparable locations outside the designated noise zone.

At the time of the announcement regarding the location of the FedEx air hub at Piedmont Triad International Airport in North Carolina, a decline in property prices within a 2.5-mile radius of the site was estimated to be 9.2%. It has been demonstrated that when residents have superior access to noise data, the price effect is more pronounced.

Analogous conclusions were arrived at by researchers when analysing the impact of noise from Incheon Airport in South Korea on the local housing market (Kim *et al.*, 2007), emphasising the role of environmental education and transparency of information in reducing social conflicts occurring in the vicinity of airports. As demonstrated in their study, exposure to noise levels in excess of 65 dB has been shown to result in a substantial decline in property values, particularly in peripheral areas.

In the context of an investigation into the diverse repercussions of noise within Singapore's urban environment (Diao *et al.*, 2016), it was observed that aircraft noise exerts a deleterious influence on property prices, with the most pronounced declines in valuation being evident within the medium and low-end property sectors.

The analysis also highlighted the importance of the so-called 'screening effect', i.e., the presence of large buildings and green areas, which can reduce the negative impact of noise. Converging conclusions were arrived at by Kopsch (2016), who indicated the neutralizing effect of sound barriers and natural acoustic barriers.

The same author, in a study of the impact of aircraft noise on property prices in the vicinity of Arlanda Airport in Sweden, utilized hedonic models based on transaction data, indicating a decline in property value, averaging 1.5%, with each 1 dB increase in noise levels ranging from 50 dB to 70 dB.

Cohen and Coughlin's (2008) analysis of the impact of changing levels of aircraft noise on house prices depending on distance from Hartsfield-Jackson Atlanta Airport between 1995 and 2002, demonstrated that an increase in noise reduces property values, with this effect varying significantly depending on the research period considered. In a separate study, the same authors emphasized that technological advancements leading to a reduction in noise levels also exert a substantial influence on prices observed in real estate markets (Cohen and Coughlin, 2009).

Researchers studying the impact of noise on properties in the vicinity of Essendon Airport in Melbourne, Australia, based on data on single-family home sales prices from 1998 to 2013, noted that home prices do not directly correlate with the noise contours delineated on the noise map.

However, subsequent research has demonstrated a strong correlation between residential property prices and the number of flights, as well as the distance from the nearest runway (Kaur *et al.*, 2021). A comparison of property prices in closer proximity to the airport with those in more remote locations revealed a significant discrepancy, with the former being higher by up to 37%.

A decline in property prices as they approach the main runway was also observed in the vicinity of Athens Airport in Greece (Thanos *et al.*, 2015). This observation was made even after taking into account other features of the buildings.

A study was conducted to ascertain the impact of distance from the runway axis on single-family home prices in the vicinity of Malpensa Airport in Italy's Lombardy region. Salvi (2008) demonstrated that a 1.3% decrease in house prices was observed for every 1 dB increase in noise levels above 55 dB, which was attributed to aircraft noise. Furthermore, it was highlighted that properties situated along the runway approach axis are particularly susceptible to price declines and fluctuations in air traffic, consequent to the inauguration of a new terminal.

Rahmatian and Cockerill's (2004) research yielded analogous results, demonstrating that aircraft noise has the capacity to diminish the value of single-family residences by up to 10%, a phenomenon that is particularly salient when the residences are located within the flight path of aircraft.

A comprehensive analysis was conducted on 50,000 single-family residences situated in proximity to 23 airports in Southern California, USA. The findings revealed a notable increase in property value with increasing distance from major airports, with an approximate increase of $1.23 for every mile. Additionally, a range of $0.65 to $0.77 was observed for properties located near smaller airports.

As illustrated in Table 1, the subsequent research outcomes demonstrate the non-linear effect of noise levels resulting from airport operations on property prices.

Table 1. *A selection of references that refer to the non-linearity of the relationship between airport noise and property prices*

Author(s)	**Airport**	**External effects**
Salvi, 2008	Zurich, Switzerland	For every 1 dB increase in noise, the price of single-family homes decreased by 0.97%.
Suksmith and Nitivattananon, 2015	Suvarnabhumi, Thailand	For every 1 dB increase in noise above 65 dB, property prices dropped by 5%.
Mense and Kholodilin, 2014	Berlin Brandenburg, Germany	Property prices decreased by 9.6% within 3 km of the planned flight altitude. For altitudes below 1 km, prices fell by between 11.8% and 12.8%. For higher flight altitudes, the average price decline was 8.3%.
Winke, 2017	Frankfurt, Germany	Following the construction of the new runway, prices of single-family homes decreased by around 1.7%, if noise levels grew by 1 dB.
Tsao and Lu, 2022	Taoyuan, Taiwan	The decline in house prices was USD 2,356.02/dB and USD 3,622.78/dB in the 60–64 dB.
Trojanek *et al.*, 2017	Ławica, Poland	In areas with noise levels of 55–60 dB, 60–65 dB, and 65–70 dB, single-family homes were, respectively, 4.59%, 9.18%, and 13.77% cheaper than comparable properties in a buffer zone with noise levels below 55 dB.
Herman, 2014	Ławica, Poland	Prices of single-family houses within the RUA varied depending on location, with prices being 7.0% lower in Zone III, 9.3% lower in Zone II, and 11.9% lower in Zone I characterized by the highest level of noise.
Batóg *et al.*, 2019	Ławica, Poland	On average, the unit prices of houses located outside the RUA were 17.05% higher than those observed inside the area with a daytime noise level of 60 dB, and 8.95% higher than those in the zone with a daytime noise level of 55 dB.

Source: *Own study.*

3. Research Methodology

The development of a reliable model to describe the impact of airport noise levels on the prices of single-family homes in the vicinity of Warsaw Chopin Airport will proceed in three stages. The initial stage of the research will entail the identification of anomalous observations through the utilisation of cluster analysis methodologies.

It is evident that these observations have a detrimental effect on the creation of a model of satisfactory quality. In the second step of the research process, independent variables that significantly describe the change in unit prices of the properties under study, depending on the level of perceived noise and other attributes, will be selected. The final step in ensuring the model has a high goodness of fit will be to identify outliers.

Cluster analysis is a data mining technique that can be used to identify a subset of properties for which the relationship between location and unit price has been disrupted. One such method is k-means clustering, an optimisation method that uses normalised variable values.

As Panek (2009) demonstrate, the various variants of the k-means method differ in three principal ways: firstly, in the definition of the grouping quality criterion function; secondly, in the determination of the centres of gravity of the initial group arrangement; and thirdly, in the manner in which objects are moved between groups and the process of improving the grouping quality is halted. The application of this method is comprised of the following steps (Hill and Lewicki, 2004):

1) Determining the number of clusters.
2) Initial assignment of objects to individual clusters.
3) Relocation of objects between clusters based on the criterion of maximizing intergroup variance and minimizing intragroup variance.
4) The cessation of the clustering process governed by the STOP rule, which may reflect either the loss function or the number of iterations accepted.

An outlier is often defined as an observation that differs significantly from the others (Maddala, 2006). Its precise definition depends on the structure of the analyzed data and the identification method used (Ben-Gal, 2005). Outliers may be attributed to a number of factors, including but not limited to, incorrect measurements, incorrect determination of the study population, statistical population heterogeneity, extreme observations or random events, incorrect assumptions about the generated data distributions, or deliberate actions (Walfish, 2006). One potential method of identifying outliers in econometric models is to calculate standardized residuals. The formula for this calculation is as follows (Ben-Gal, 2005):

$$e_i^s = \frac{e_i}{\hat{\sigma}_u}, \tag{1}$$

where:
e_i – model residual for the *i*-th observation,
$\hat{\sigma}_u$ – standard estimation error calculated according to the formula:

$$\hat{\sigma}_u = \sqrt{\frac{1}{n-k-1}\sum_{i=1}^{n} e_i^2}, \tag{2}$$

where:
n – number of observations;
k – number of independent variables.

If the condition $|e_i^s| > 2$ is met, the observation is considered as an outlier. For a comprehensive overview of the methods used to identify outliers, see Ampanthong (2009), among other sources.

Standard linear models are not appropriate for research purposes when the set of explanatory variables includes qualitative variables, such as the technical condition of real estate, which is measured on an ordinal scale. This is due to the fact that linear models operate under the assumption that a change in a qualitative variable by one category invariably corresponds to the same change in the dependent variable.

In such cases, a more appropriate solution is to employ general linear models (GLMs) (see e.g. Hill, Lewicki, 2006; Hardin, Hilbe, 2007). In this model, qualitative variables are introduced in the form of dummy variables.

In circumstances where sigma-constrained coding (parameterization) is employed for qualitative variables, the Generalised Linear Model (GLM) assigns a value of -1 to observations belonging to a selected category of a qualitative feature. The parameter quantifying the impact of this category is not estimated directly; rather, its value is calculated as the inverse of the sum of all other scores obtained for the dummy variables.
This type of parameterization suggests that the specific coefficient estimates the difference between this particular category (level) of the predictor and the average of the other categories (levels).

The GLM consists three elements (Nelder and Wadderburn, 1972):
Model hypothesis:

$$Y_i = \beta_0 + \beta_1 X_{1i} + \cdots + \alpha_k X_{ki} + \upsilon_i \tag{3}$$

Link function:

$$\rho(\mu_i) = Y_i \tag{4}$$

A variance function of dependent variable on its mean:

$$var(Y_i) = \theta(\mu_i) \quad (5)$$

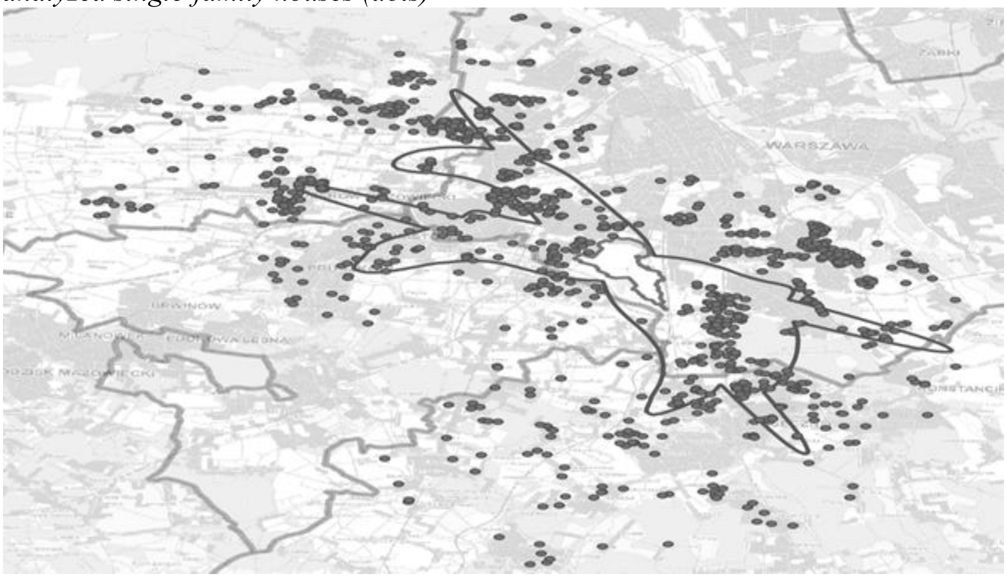
where: θ is a known or estimated dispersion parameter.

4. Research Results and Discussion

4.1 Research Sample and Research Area

The properties analysed in this study comprise 1,136 single-family houses situated within the administrative boundaries of the south-western part of Warsaw, in close proximity to Warsaw Chopin Airport. These properties are marked with dots in Figure 1. The database under consideration contains the transaction prices and other attributes of the properties in question from the period 2013–2022. The RUA boundary for the airport is delineated by a solid line in Figure 1.

Figure 1. *RUA of Warsaw Chopin Airport (solid line) and spatial distribution of the analyzed single-family houses (dots)*



Source: *Own study.*

The research sample encompasses the characteristics of 428 properties situated within the RUA. The remaining properties are located on the reference market outside the RUA. This finding indicates an imbalance in the composition of the research sample. In the field of economic research, three distinct approaches are utilised when dealing with unbalanced samples (Batóg, 2024).

The initial approach entails the execution of analyses employing the original sample, a course of action that is substantiated by the prevalent observation of an absence of impact of alterations in sample proportions on modelling outcomes. The second approach involves the balancing of the sample through the utilisation of various techniques, including but not limited to bootstrap algorithms.

Nonetheless, this may result in a decline in the properties of parameter estimators. The third approach utilises estimation or classification methods that employ the weights of individual observation segments or alter the threshold values that determine objects' membership of specific classes.

The minimum and maximum distances from the center of the airport runway for these properties were 2.15 km and 20.80 km, respectively, as determined by the intersection of the traffic lanes.

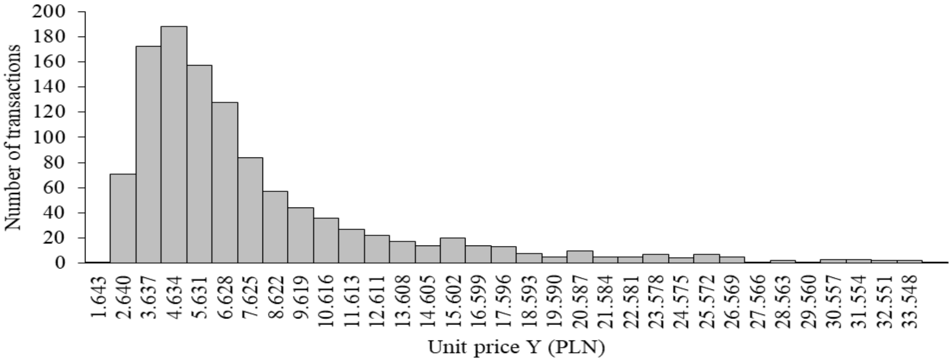
The following variables were utilised in the construction of an econometric model with the objective of describing the relationship between the unit price of single-family homes and the airport noise level:

Y – Price per square meter (unit price), calculated as the ratio of the house's transaction price to its usable floor space, as determined by a notarial deed, or as a comparative floor space [PLN/m2],
X1 – Technical and functional condition: (1) Unfavorable: buildings classified for demolition or in a clearly poor technical condition. (2) Intermediate minus: buildings not classified for demolition, but requiring significant renovation work. (3) Intermediate: buildings at least several years old, requiring renovation work, or with visible renovation work carried out. (4) Intermediate plus: buildings at least several years old, in fairly good technical condition, with at least one visible element requiring renovation or replacement. (5) Favorable: new buildings, or older buildings with all visible elements renovated,
X2 – Surroundings: (1) Deteriorated: industry, warehouses, roads, railway lines, sewage treatment plants and farms in the vicinity. (2) Average: the neighborhood includes residential buildings typical of the area, as well as good access to services and transport. (3) Favorable: the neighborhood includes green areas and water,
X3 – Additional buildings: (1) None. (2) Occur,
X4 – Type of development: (1) Terraced. (2) Semi-detached or end-of-terrace. (3) Detached,
X5 – Location: (1) Within RUA. (2) Outside RUA,
X6 – Usable floor space of the building [m2],
X7 – Plot area [m2],
X8 – Distance from the center of the airport runway [m],
X9 – Distance from the city center marked by the location of the Palace of Culture and Science, 1 Defilad Square [m],
X10 – Subjective location: (1) –(5), where:

(1) Peripheral areas with average access to transport and green spaces, a small proportion of detrimental facilities and the lowest social prestige and sense of security. (2) Peripheral or highly urbanized peripheral areas outside the city limits or intermediate zones with a significant proportion of detrimental facilities, average access to transport and green spaces, and average social prestige and sense of security. (3) Peripheral areas with a large proportion of green spaces or areas in an intermediate zone with a significant proportion of land built up with structures detrimental to residential development. These areas have average social prestige and a sense of security, as well as at least average accessibility to public transport and green spaces. (4) Areas that are attractive to potential buyers, with at least average access to public transport, pleasant surroundings and a negligible proportion of land developed with structures that are detrimental to residential development, offering a high sense of security. (5) Areas that are the most attractive to potential buyers, with good access to public transport and average aesthetics, no land developed with structures that are detrimental to residential development and mostly a high standard of living and a high sense of security.

The valuation of qualitative variables for individual properties was determined by appraisers, who drew on their experience and site visits in making these assessments. Figures 2–5 illustrate the distribution of selected characteristics of single-family houses in the full sample.

Figure 2. *Distribution unit price Y (N = 1136)*

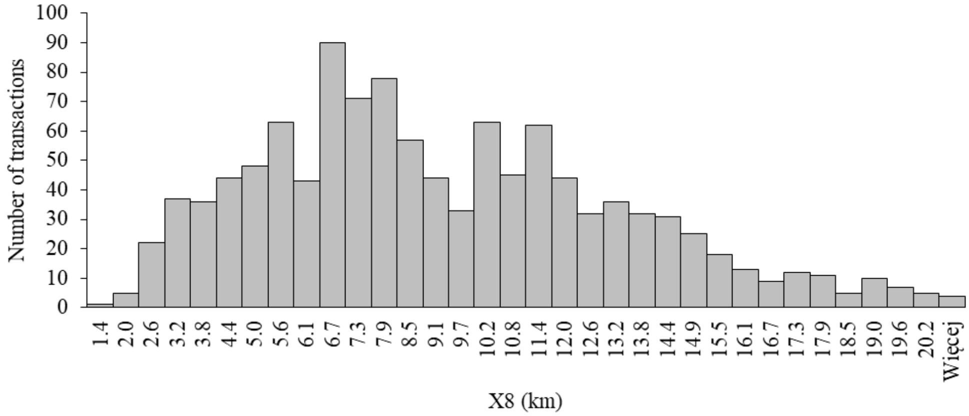


Source: *Own study.*

As demonstrated in Figure 3, the distribution of the unit price is characterised by a pronounced right-sided asymmetry, indicating that the predominant unit prices are below the average value of this variable.

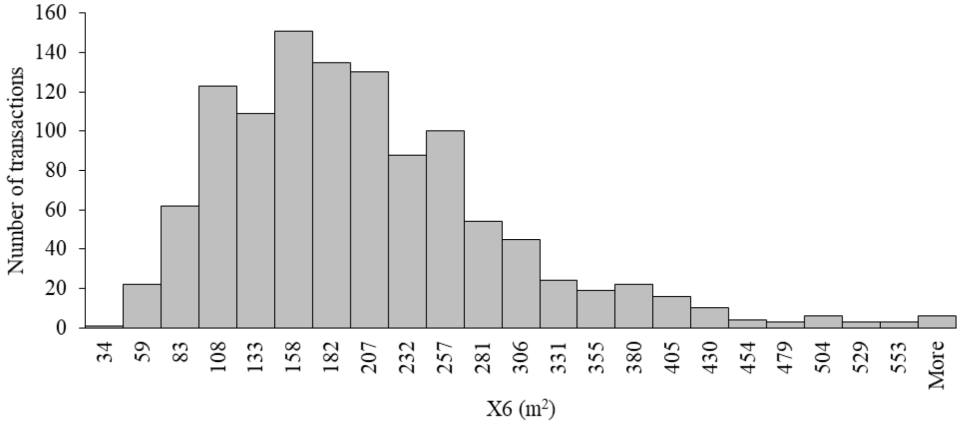
The distribution of distances from the centre of the airport runway is bimodal, with the majority of properties located between 6 and 7 km away.

Figure 3. *Distribution of distance from the center of the airport runway X8 (N = 1136)*



Source: *Own study.*

Figure 4. *Distribution of the floor space X6 (N = 1136)*

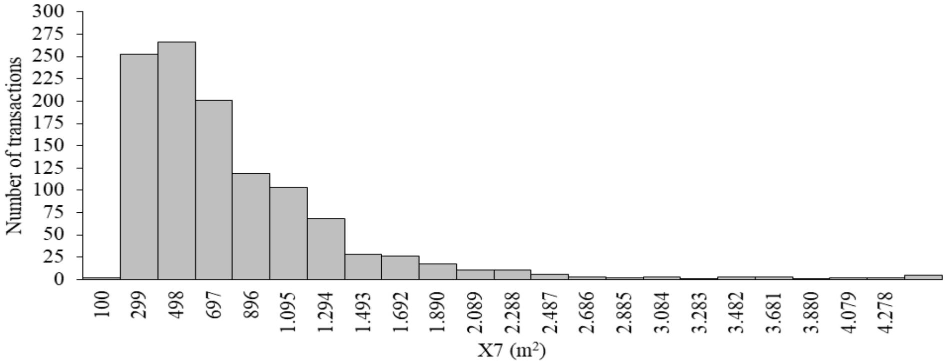


Source: *Own study.*

The distribution of the usable floor space (see Figure 5) is characterised by a relatively pronounced right-sided asymmetry. The mean usable floor area of a dwelling is 201.0m², with a coefficient of variation of 36.0%.

The distribution of the plot area is found to be extremely skewed to the right, indicating that transactions involving relatively small plots are predominant. The mean plot size was 433.0 m², with a coefficient of variation of 71.0% for this variable. As illustrated in Table 2, the mean and standard deviation of the unit prices of the properties under analysis are presented.

Figure 5. *Distribution of the plot area X7 (N = 1136)*



Source: *Own study.*

Table 2. *Selected unit price parameters for houses for the full sample (N = 1136)*

Localization	**Mean**	**Standard deviation**
Within RUA	7,054.7	5,099.6
Outside RUA	7,462.2	5,677.4
All	7,308.7	5,470.5

Source: *Own calculations.*

The average transaction prices observed for properties surveyed inside and outside the RUA in 2014 were PLN 5,137.3 and PLN 8,800.7, respectively. However, in 2022, these values increased considerably. In the RUA, they were PLN 14,050.2, while outside this area they were PLN 17,120.3. It is noteworthy, however, that the price differential between these two regions diminished from 71.31% to 21.85% over a period of eight years.

4.2 Estimation Results for GLM (full sample)

The substantial increase in single-family house prices that has been observed in the aftermath of the Corona-virus pandemic has the potential to result in elevated ratings for the models currently under construction. As illustrated in Table 3, the results of the parameter estimation for the general linear model of the unit price of the analysed properties across the entire research sample are presented. The calculations were performed using STATISTICA 13's econometric package.

Table 3. *Selected unit price parameters for houses for the full sample (N = 1136)*

Variable	**Coefficient**	**Standard error**	**t**	**p**
Intercept	11,498.29	335.34	34.29	0.000
X6	-22.18	1.56	-14.24	0.000
X5(1)	-299.64	154.49	1.94	0.053
				$R^2 = 0.15$

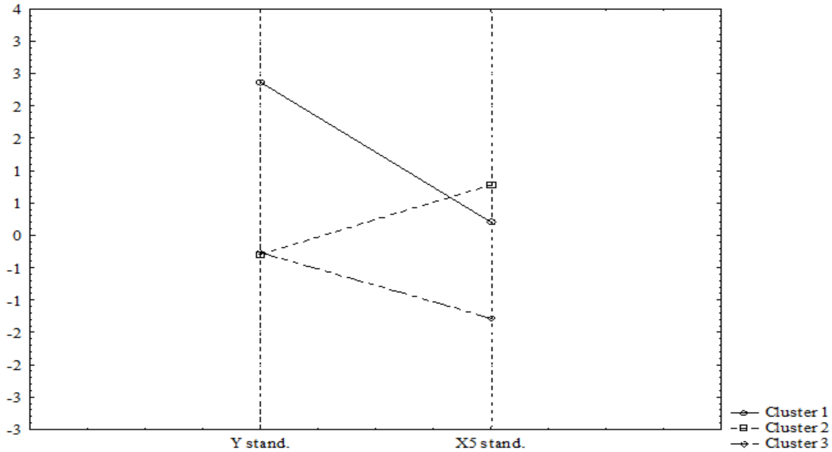
Source: *Own calculations.*

Following the specification of the variables in the set of independent variables, two variables were identified: X6 is an indicator of the usable floor space of the house, and X5 is a measure of the location.

However, the structural parameter for the latter variable was found to be statistically insignificant at a significance level of 0.05. Nevertheless, the model's suboptimal alignment with the empirical data precludes its utilisation in subsequent analyses.

The issue of the model's substandard quality for the entire sample may be attributable to the heterogeneity of the analysed observations with regard to their unit prices. In order to ascertain whether this is indeed the case, cluster analysis was applied to the standardised values of the dependent variable (Y) and the variable determining the location of single-family houses (X5). As illustrated in Figure 6, the results of the clustering process, which was executed utilising the k-means method, demonstrate the formation of three distinct clusters.

Figure 6. *Group averages obtained in cluster analysis for k = 3*



Source: *Own study.*

The findings suggest that properties located outside the RUA possess distinctly different characteristics, with low unit prices being recorded. As illustrated in Figure 6, a subset of the properties under consideration is presented as Cluster No. 2, which contains 620 single-family houses.

4.3 Estimation Results for GLM (reduced sample)

In the subsequent stage of the process, the coefficients of the GLM were estimated for the set that had been filtered to remove any outliers. As illustrated in Table 4, the mean and standard deviation of the unit prices of the properties under scrutiny in the reduced sample are presented.

Table 4. *Selected unit price parameters for houses for the reduced sample (N = 516)*

Localization	**Mean**	**Standard deviation**
Within RUA	7,054.7	5,099.6
Outside RUA	20,049.5	5,490.4
All	9,270.9	7,113.3

Source: *Own calculations.*

Following the elimination of outliers, a substantial increase in the average property price outside the RUA becomes evident. The observations that were removed were predominantly comprised of single-family houses, for which transactions were concluded prior to the onset of the pandemic and were characterised by low unit prices.

The increase in homogeneity of the research sample has the potential to enhance the constructed models and impact the increase in their parameters' value, resulting in greater differences between the observed unit prices of analysed properties within and outside the RUA.

Table 5 shows the results of the parameter estimation for the GLM of unit prices for the analyzed properties, based on a reduced research sample.

Table 5. *Estimation results for GLM (truncated sample, N = 516)*

Variable	**Coefficient**	**Standard error**	**t**	**p**
Intercept	15,985.40	443.75	36.02	0.000
X6	-21.14	2.21	-9.57	0.000
X7	1.25	0.35	3.57	0.000
X5(1)	-5,739.50	290.46	-19.76	0.000
				$R^2 = 0.55$

Source: *Own calculations.*

All parameters of this model were statistically significant. Nevertheless, the model's goodness of fit remained comparatively unsatisfactory. In order to enhance the quality of the model, 35 outliers were identified and subsequently removed from the analysis. The identification process was based on the utilisation of standardized residuals. The results of estimating the parameters of the GLM of the unit price of the analysed properties after the removal of outliers are presented in Table 6.

Table 6. *Estimation results for GLM (truncated sample without outliers, N = 481)*

Variable	**Coefficient**	**Standard error**	**t**	**p**
Intercept	14,265.81	303.72	46.97	0.000
X6	-16.29	1.51	-10.81	0.000
X7	1.19	0.26	4.52	0.000
X5(1)	-5,757.74	200.95	-28.65	0.000
				$R^2 = 0.72$

Source: *Own calculations.*

Further enhancement of the homogeneity of the research sample permitted the development of a high-quality model, characterised by statistically significant parameters and a satisfactory fit with the empirical data. It is evident from the findings that an augmentation in the usable floor space of residential properties by 1 m² has been demonstrated to result in a mean diminution in the unit price of PLN 16.29.

Conversely, an increase in plot area by 1 m² resulted in an average increase in house prices of PLN 1.19. The model presented in Table 5, which encompasses 481 objects and incorporates a parameter demonstrating the impact of the location of single-family houses in the RUA on their unit price, was developed utilising a truncated sample with extreme observations removed. This parameter is significant, indicating that the location of a property within the RUA results in a substantial difference in unit prices compared to houses located outside the RUA.

A sample of 516 observations was utilised to estimate the model parameters for properties located within a specified radius of the centre of the airport runway, employing the same set of independent variables. Due to the limited number of residential properties located in proximity to the airport, the initial value was set at 4.0 km and then increased by 500 m. The values obtained for all parameters are presented in Table 7.

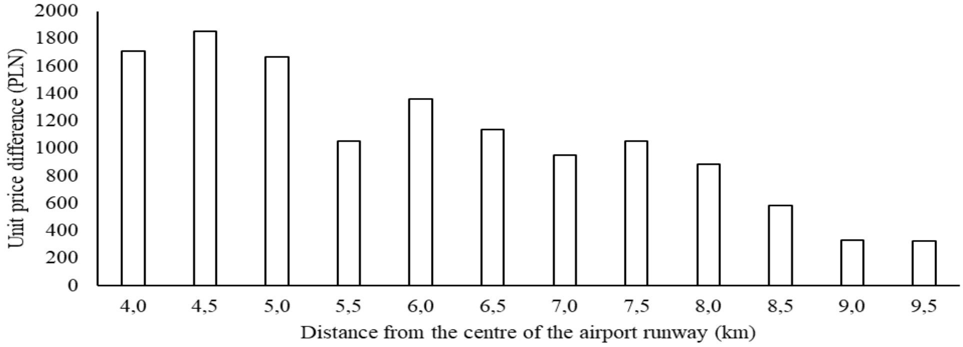
Table 7. *The parameter values for location variable X5, which correspond to different distances from the center of the airport runway*

Distance from the airport runway	Coefficient value
4.0	7,452.7
4.5	7,595.6
5.0	7,405.4
5.5	6,796.7
6.0	7,103.0
6.5	6,876.2
7.0	6,692.6
7.5	6,793.5
8.0	6,626.5
8.5	6,325.2
9.0	6,074.0
9.5	6,068.0

Source: *Own calculations.*

This enabled the calculation of the difference between the parameter estimate for the location variable X5, which was equal to -5739.50 for the model built for the reduced sample (N = 516), and the parameter estimates obtained for subsequent, increasing samples according to increasing distance from the centre of the airport runway. The values presented herein are illustrated in Figure 7.

Figure 7. *The differences between parameter estimates for variable X5, obtained from successive samples taken at increasing distances from the center of the airport runway and for all observations included in the reduced sample*



Source: *Own study.*

The disparities between successive parameter estimates decrease relatively gently as the distance from the noise source increases. The most significant disparities are observed in residential properties situated within a 5-kilometre radius of the runway centre, with a cost differential exceeding PLN 1,650.

The parameter estimates presented in Table 7 were utilised to estimate the parameters of the trend model, which describes the reaction of the unit price of single-family houses under study to an increase in distance from the centre of the airport runway. The model under consideration is of exponential nature, and the results of the estimation of its parameters are presented in Table 8.

Table 8. *Results of parameter estimation for the exponential trend model for the dependent variable determined by the parameter values contained in Table 6*

Variable	Coefficient	Standard error	t	p
Intercept	8.960	0.015	606.27	0.000
t	-0.021	0.002	-11.36	0.000
R^2 = 0.92; F = 129.03; W(White) = 0.23; $\chi2$ = 0.89; F(Chow) = 1.26; p = 0.331; F(RESET) = 0.91; p = 0.437				

Source: *Own calculations.*

The mean decrease in parameter values was 2.1%. This finding lends further credence to the hypothesis that as the distance between single-family houses and the centre of the airport runway increases, the discrepancy in unit prices between properties located inside and outside the RUA diminishes.

The measurement of this phenomenon is derived from the values of the parameters associated with variable X5, which are instrumental in determining location.

5. Conclusions, Proposals, Recommendations

Aircraft noise is a significant external factor that affects housing prices, and it should therefore be considered in urban policies and spatial planning (Theebe *et al.*, 2000). In order to mitigate the deleterious effects of excessive noise, it is imperative to implement effective sound insulation measures and establish compensation policies that are both socially justifiable and equitable. (Rahmatian and Cockerill, 2004).

Such measures have been demonstrated to have the capacity to stabilise the property market in areas in close proximity to airports. Nevertheless, it is imperative to recognise the necessity of integrating acoustic analyses with transport policies (Mohammad *et al.*, 2017) and anticipating the anticipated level of air traffic.

The results obtained from an analysis of Warsaw Chopin Airport as a case study confirmed the hypothesis that excessive noise generated by airport activity has a negative impact on the prices of single-family homes located in the vicinity. However, it is important to acknowledge that this relationship becomes evident only when the research sample is more homogeneous, that is, when identified outliers are removed.

As demonstrated in the research conducted by Pennington *et al.* (1990) in the vicinity of Manchester Airport, and subsequently corroborated by Theebe *et al.* (2000) in the context of Amsterdam Schiphol, a correlation was observed between the augmentation of noise levels and the subsequent decline in property values. Nevertheless, the findings of other studies (Cohen and Coughlin, 2009; Diao *et al.*, 2016) suggest that the deleterious effect of noise may be provisional or partially counterbalanced by the advantageous accessibility effects associated with proximity to major transport hubs.

This highlights the intricacy of the phenomenon in question. It is also important to consider noise perception, as the impact on property values may be moderated by the subjective attitudes of residents and their perceived benefits of living close to an airport (Fujiwara *et al.*, 2017). This finding suggests that the impact of aircraft noise is not solely acoustic in nature, but is also capable of exerting a psychological and social influence.

The findings also have important planning and policy implications. It is submitted that they can serve as a basis for defining restricted use zones, developing compensation mechanisms, and designing spatial planning principles for residential areas located near airports.

These actions are consistent with the objectives of Directive 2002/49/EC on the assessment and management of environmental noise, which underscores the necessity of incorporating noise protection measures into urban and transport policies.

Furthermore, the findings emphasise the risk dimension associated with residing or investing in areas exposed to elevated levels of aircraft noise. The present situation is such that the uncertainty surrounding future airport operations, the potential for changes in flight paths, and the evolving nature of noise regulations may result in an increase in perceived investment risk, which in turn may act as a deterrent to long-term residential settlement.

From the perspective of investors and local governments, this risk is manifested in market volatility, reduced liquidity, and the necessity for risk mitigation strategies, such as targeted compensation schemes or stricter spatial planning policies (Bristow *et al.*, 2015; Batóg *et al.*, 2019; Foryś, 2024).

Furthermore, a considerable regulatory risk has been identified. This is due to the fact that alterations to environmental noise standards or the legal delineation of restricted-use zones have the capacity to exert a direct influence on property valuations and compensation eligibility.

The inherent unpredictability of such policy adjustments engenders a layer of institutional uncertainty that has the potential to deter potential buyers and investors, or accelerate speculative behaviour in border areas of noise exposure zones. In order to address this issue, it is essential to establish a transparent and stable legal framework. Such a framework would ensure the protection of residents and the maintenance of long-term market confidence.

The second hypothesis of non-linearity in this relationship was also confirmed. It has been demonstrated that there is a marked decrease in the discrepancy between the unit prices of houses located within and without the RUA as the distance of a property from the centre of the airport runway increases.

The findings underscore the significance of meticulous data cleansing and the treatment of outliers. The application of outlier detection methods has been demonstrated to facilitate a more reliable estimation of the true impact of aircraft noise on property prices. This, in turn, has been shown to enhance the precision of analyses conducted in airport-adjacent housing markets. The observed non-linearity has significant ramifications for the management and proprietors of airports, as well as for potential beneficiaries of compensation for elevated noise levels.

It is important to note that, in order to estimate the parameters of the models underlying these inferences, a database containing ordinal and nominal variables was utilised. The values of the individual categories in this database were determined by property appraisers in an expert manner, albeit to a certain extent subjectively. A further factor exerting an influence on the confidence placed in the results is the imbalance of the research sample. It is also important to note that the present study exclusively focused on single-family houses; therefore, the observed patterns may vary in other real estate types, such as undeveloped land or residential premises.

Further research could concentrate on the collection of additional observations with a view to balancing the research sample and assessing the degree of nonlinearity in the location-unit price relationship. It is acknowledged that alternative methods of determining this correlation could also be considered; for instance, elliptical areas could be constructed to differentiate between properties with the same perceived noise level but at different distances from the centre of the runway.

A further intriguing domain for investigation would be the analysis of variations within homogeneous areas (submarkets) that exhibit differing degrees of activity in the local real estate market. It is also important to note that in order to generalise the results obtained, similar analyses would need to be carried out for other airports, considering such long-term factors as changes in air traffic intensity and infrastructure investments.

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