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15. SOUND EXPOSURE LEVELS RECORDED BY CHOPIN AIRPORT MONITORS OVER A PERIOD OF SIX YEARS

15.1. Introduction

Continuous unattended monitoring of aircraft sound is one of the basic instruments for managing the acoustic environment around airports. The monitoring system records acoustic events. Based on the recorded data appropriate noise indicators are calculated.

Warsaw Chopin Airport provides monthly monitoring reports [14]. Since 2014 the reports cover the entire present network of monitors, and indicate if the aircraft sound event occurred under meteorological conditions consistent with the requirements as well as without an interference of the non-aircraft sources [6].

The present study presents research on sound exposure levels in the years 2014 - 2019. The sound exposure level for the mean single event is an aircraft noise index, which is independent of the number of aircraft events. For this reason, it may depict changes in sound exposure without the influence of changes in air traffic. The annual averaging of data reflects the periodicity of air traffic demand and the periodicity of meteorological conditions.

Two kinds of data aggregation within a year were used. The one aggregation was more analytical, data were separately treated for approaches/departures and daytime/nighttime. In the second one all sound events in the year were averaged together.

The analyses concerned the dependence of annual sound exposition levels on years. Regression analysis was used, in which years were treated as an independent variable [12]. In the ANOVA variance analysis [1, 13] the data from individual years were treated as repetitions. The second issue was the dependence of the sound exposure level on the distance from the airport. The analysis was carried out for both aggregated data as well as for individual combinations of aircraft operation type and period of day.

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15.2. Noise monitoring system of Chopin Airport

15.2.1. Characteristics of the monitoring system

Warsaw Chopin Airport is an international airport located in Warsaw, Poland. It is Poland's busiest airport with 18.9 million passengers in 2019.

Since 2009, P-RNAV procedures for precise area navigation have been used in the airport area. Flight tracks of RNAV procedures are determined by waypoints, which are defined by geographical coordinates [11].

The airport has two intersecting runways: 11/29 Ursynów - Ursus and 15/33 Bemowo - Piaseczno. To protect densely populated districts of Warsaw from aircraft noise the order of preferences of runway use have been introduced (Table 1).

Table 1

Preferential runway system of the Chopin Airport

Order of preference	Approaches		Departures	
	runway	monitors along the track	runway	monitors along the track
1.	RWY33	P03	RWY29	P01, P08, P10
2.	RWY11	P10, P08, P01	RWY15	P03
3.	RWY15	P05, P07	RWY33	P05, P07
4.	RWY29	P04	RWY11	P04

The noise monitors located on the inbound and outbound tracks associated with individual runways are indicated (cf. Fig. 1). Only monitoring points located on inbound and outbound tracks were included. Therefore, the P02 monitor was omitted, as well as the P06 monitor registering noise from the airport area. P09 monitor is located outside the tracks. The P07 monitor was omitted because it records very few operations, three times less than the P05 monitor located on the same low-preference approach track.

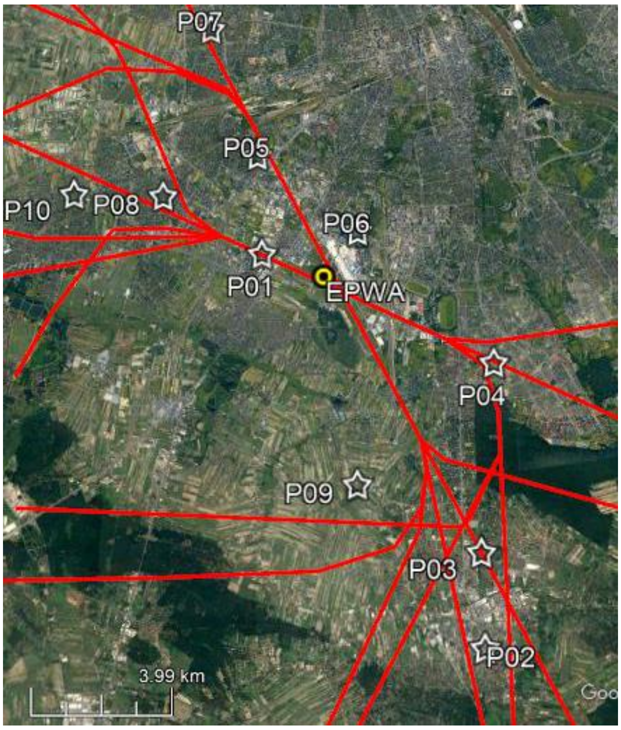

Fig. 1. Location of noise monitors (stars) relative to flight tracks (red lines), EPWA - Chopin Airport
Rys. 1. Położenie monitorów hałasu (gwiazdki) względem tras lotów (czerwone linie), EPWA - lotnisko Chopina

The analysis included the remaining six monitoring stations, which form two groups. The first one includes P01, P03, P08 and P10 located in the busiest directions. The second group consists of P04 and P05 stations located on tracks with low average traffic. On one track there are three monitors (P01 - P08 - P10), and on the remaining tracks - one monitor each.

The noise monitors of Chopin Airport included in the study are shown and listed in Table 2 along with distances from the runway threshold.

Table 2

Noise monitors of Chopin Airport included in the study

No.	Monitor name	Runway		Distance *d* in km
		approach	departure	
P01	Załuski	RWY11	RWY29	1.08
P03	Mysiadło	RWY33	RWY15	6.55
P04	Onkologia	RWY29	RWY11	3.75
P05	Meral	RWY15	RWY33	3.19
P08	Ursus	RWY11	RWY29	4.53
P10	Piastów	RWY11	RWY29	6.99

15.2.2. Monitoring data

The monitoring system records data from individual monitors. A separate monthly report is issued for each monitor. The report contains a summary of aircraft sound events and the results of calculations of the equivalent sound pressure level for individual days during daytime and nighttime. The description of each event includes results of measurement of acoustic parameters and metadata characterizing the conditions of the event. The reports are submitted to the local authorities but also published [14], which makes it possible to use them as source data in studies concerning e.g. protection of people in buildings against aircraft noise [7].

The recorded acoustic data of a single aircraft sound event are its sound exposure level L_{E}, equivalent sound pressure level L_{Aeq} and maximum level L_{Amax}. L_{Aeq} and L_{Amax} are not analyzed in this work.

The metadata situate the event in time and space and determine its source and mode of operation. The monitor and date and time of the event are specified. The time of the event was recorded with a resolution of 1 s. One event was recorded simultaneously. The type of aircraft and the flight operation is given.

All events when meteorological conditions were inconsistent with the requirements [6] and/or non-aircraft sound events occurred were omitted.

All events from the reports were classified based on the above metadata, using the following symbols:

m_j – monitor location: m_1 = P01, m_2 = P03, m_3 = P04, m_4 = P05, m_5 = P08, m_6 = P10, and the corresponding monitor distance from the runway threshold d_j,

y_p – year: y_1 = 2014, …, y_6 = 2019,

t_q – time of day: t_1 = D (Daytime), t_2 = N (Nighttime),

o_r – operation: o_1 = App (Approach), o_2 = Dep (Departure)

Among the above-mentioned variables d_j and y_p are measured on the quantitative scale. Other variables are determined on the nominal scale.

Accordingly, the exposure level of the i-th sound event in the group (m_j, y_p, t_q, o_r) is recorded as

$$L_{E(m_j,y_p,t_q,o_r)i} \tag{1}$$

The above classification criteria form 6·6·2·2 = 144 data groups. The group sizes are not the same.

15.2.3. Method of analysis

Mean sound exposure levels of single event $L_{\bar{E}}$ were subjected to analysis. Averaging covered individual years in the period 2014 - 2019.

The main aim of the analysis was to determine whether in the years 2014 -2019 the levels of $L_{\bar{E}}$ have changed, what is the nature of these changes and what factors have affected the changes. If $L_{\bar{E}}$ were unchanged, changes in the equivalent sound pressure level would only result from changes in air traffic.

The sound exposure level of the aircraft operation depends on factors which, from the point of view of this analysis, can be divided into controlled and uncontrolled by the monitoring system. Typical monitoring systems, including the Chopin Airport monitoring system, are only aimed at providing data for environmental assessment. The important variables affecting noise levels at the noise monitor are not recorded, e.g. the aircraft gross weight at take-off and the aircraft altitude when the aircraft pass by the monitor [2] and many others that may also affect L_E of an event [8].

From the point of view of the analysis objectives, the static and dynamic state of the aircraft as a source of noise, its actual flight trajectory and the conditions of propagation of the acoustic wave between the aircraft and the noise monitor should be indicated as important factors not controlled by the monitoring.

The uncontrolled factors can be divided into deterministic and random. Deterministic factors are changes introduced as a result of decisions aimed at achieving certain effects (economic, technical, environmental protection, etc.). Such changes are e.g. changes in the procedures of performing air operations [3, 10]. Deterministic factors also include changes in the composition of the fleet and changes in the trajectory of flights, which are economically influenced. In the case of factors such as the introduction of less noisy aircraft, it is to be expected that this will cause a steep drop in sound exposure. Possible changes of deterministic factors should be captured when comparing means from subsequent years.

Random factors may be of a trend or fluctuation around the mean value.

As a method of searching for the factors that influenced the recorded data, the visualization of the annual data was assumed. The annual cycle corresponds to both the yearly periodicity of demands as well as the periodicity of changes in meteorological conditions.

The observations from the exploratory data analysis were next examined using statistical methods: regression analysis and ANOVA variance analysis. ANOVA does not take into account the order of data from subsequent years [1]. Supplementation of ANOVA by regression analysis allows detecting time trends.

15.3. Calculation of the sound exposure level of single event

The basic measure of aircraft noise is the equivalent continuous sound pressure level, expressed in decibels $L_{p,\mathrm{eq},T}$, equal to ten logarithms of the ratio of the time average of the square of the sound pressure, p, during a stated time interval of duration, T (from t_1 up to t_2) [5], i.e.

$$L_{p,\mathrm{eq},T} = 10\lg\left[\frac{\frac{1}{T}\int_{t_1}^{t_2} p^2(t)dt}{p_0^2}\right] \tag{2}$$

with p_0 = 20 μPa. The sound pressure is measured with frequency correction A.

Sound exposure E of single event is defined as the integral of the square of the sound pressure, p, over event of duration $\Delta T = \tau_2 - \tau_1$:

$$E = 10\lg\int_{\tau_1}^{\tau_2} p^2(t)dt \tag{3}$$

The sound exposure level is a logarithmic measure of sound exposure

$$L_E = 10\lg\frac{E}{E_0} \tag{4}$$

where the reference value $E_0 = p_0^2$.

The equivalent continuous sound pressure level for observation time T, corresponding to a single event with the sound exposure level L_E and duration $\Delta T \le T$ is given by the equation

$$L_{p,\mathrm{eq},T} = 10\lg\frac{E}{TE_0} = L_{E,T} - 10\lg T \tag{5}$$

When n events with sound exposure E_i occurred during the observation interval T then the total exposure is equal to

$$E_T = \sum_i^n E_i \tag{6}$$

while the mean sound exposure of a single event is equal to

$$\overline{E} = \frac{\sum_i^n E_i}{n} \tag{7}$$

and the level of a mean sound exposure of a single event is equal to

$$L_{\overline{E}} = 10\lg\frac{\overline{E}}{E_0} \tag{8}$$

The equivalent sound pressure level in the observation interval T for n sound events with the level of a mean sound exposure level $L_{\bar{E}}$ equals to

$$L_{p,\mathrm{eq},T} = L_{\overline{E}} - 10\lg T + 10\lg n \tag{9}$$

The study of the dependence of $L_{\bar{E}}$ on parameters of aircraft operations allows to analyze their influence on the equivalent level, which is important for the assessment of human exposure to noise.

In this work $L_{\bar{E}}$ was calculated for the whole year, separately for individual monitoring points. Taking into account the structure of data from monthly reports the data aggregation was carried out in two steps. First $L_{\bar{E}}$ for approaches and departures was calculated with a division into daytime and nighttime.

The level of a yearly mean sound exposure of a single event $L_{\bar{E}(m_j,y_p,t_q,o_r)}$in the group (m_j, y_p, t_q, o_r) was calculated from formula (10):

$$L_{\bar{E}(m_j,y_p,t_q,o_r)} = 10\lg\left(\frac{1}{N_{(m_j,y_p,t_q,o_r)}}\sum_{i=1}^{N(m_j,y_p,t_q,o_r)} 10^{0.1L_{E(m_j,y_p,t_q,o_r)i}}\right) \qquad (10)$$

where $L_{E(m_j,y_p,t_q,o_r)i}$ is the sound exposure level of the *i*-th event in the group and $N_{(m_j,y_p,t_q,o_r)}$ is the number of events in the group.

At a higher data aggregation level the calculation was based on the levels of daily mean sound exposure and the corresponding daily mean number of events. For example, the sound exposure level of the daily mean exposure at the P01 monitor in 2019 equals

$$L_{\overline{E},P01,2019} = 10\lg\frac{\overline{E}_{P01,2019}}{\overline{N}_{P01,2019}} \qquad (11)$$

where $\bar{E}_{P01,2019}$ is the daily mean for all approaches and departures during daytime and nighttime

$$\bar{E}_{P01,2019} = 10^{0.1L_{\bar{E},P01,2019,\mathrm{D,App}}} \cdot \bar{N}_{P01,2019,\mathrm{D,App}} + 10^{0.1L_{\bar{E},P01,2019,\mathrm{D,Dep}}} \cdot \bar{N}_{P01,2019,\mathrm{D,Dep}} + 10^{0.1L_{\bar{E},P01,2019,\mathrm{N,App}}} \cdot \bar{N}_{P01,2019,\mathrm{N,App}} + 10^{0.1L_{\bar{E},P01,2019,\mathrm{N,Dep}}} \cdot \bar{N}_{P01,2019,\mathrm{N,Dep}} \qquad (12)$$

while

$$\bar{N}_{P01,2019} = \bar{N}_{P01,2019,\mathrm{D,App}} + \bar{N}_{P01,2019,\mathrm{D,Dep}} + \bar{N}_{P01,2019,\mathrm{N,App}} + \bar{N}_{P01,2019,\mathrm{N,Dep}} \qquad (13)$$

is the daily mean number of all approaches and departures during daytime and nighttime.

15.4. Sound exposure levels 2014 - 2019

The single event sound exposure levels $L_{\bar{E}}$ from 2014 up to 2019 are presented in Table 3. This table also shows the mean number of aircraft events per day.

Table 3

Mean number of flights per day $\bar{N}$ and mean sound exposure levels $L_{\bar{E}}$ at monitors

	$\bar{N}$						$L_{\bar{E}}$ in dB					
	P01	P08	P10	P03	P04	P05	P01	P08	P10	P03	P04	P05
2014	80.8	76.4	29.6	99.5	1.4	50.7	93.4	83.8	79.5	82.6	90.3	86.5
2015	129.3	117.2	84.6	107.1	0.9	11.4	92.9	84.2	79.7	82.8	86.2	85.7
2016	148.3	129.7	99.8	113.4	3.4	16.2	93.2	83.7	79.0	82.9	86.9	86.3
2017	169.1	147.0	123.3	114.6	9.5	14.4	93.2	83.9	79.0	83.1	87.4	85.2
2018	184.3	161.3	131.2	138.3	0.5	15.3	93.6	83.6	78.6	83.2	84.6	86.4
2019	120.7	101.9	88.2	155.3	0.2	68.2	93.7	83.9	78.8	83.6	84.6	87.1
Mean in dB	138.7	122.3	92.8	121.4	2.7	29.4	93.3	83.8	79.0	83.1	87.5	86.6
Range in dB							0.8	0.5	1.1	1.0	5.8	1.8
Distance in km							1.08	4.53	6.99	6.55	3.75	3.19

The “Mean” $L_{\bar{E}}$ means the average energetic mean for the entire period 2014 - 2019. The "Range" row shows the spread of $L_{\bar{E}}$. Distances from the airport are also recalled.

The data from Table 3 is graphically shown in Fig. 2: in the left part the average number of operations per day, and in the right part $L_{\bar{E}}$ for monitors and years. The order P01 - P08 - P10 corresponds to the arrangement of monitors on the runway extension (compare Fig. 1). Connecting lines have been added to the data points to make it easier to observe the time course.

15.4.1. Aircraft events 2014 - 2019

Throughout the entire period 2014-2019, there was a growing trend of a daily number of aircraft events. In accordance with the preference of runways, traffic dominated over monitors P01 - P08 - P10 and monitor P03. The number of events recorded by the P04 and P05 monitors is many times smaller.

In the years 2014 and 2019 there was a periodical transfer of traffic from P01 - P08 - P10 monitors over P05 because of runway repair. Similarly, in April 2017 traffic from P03 was moved over P04, creating a maximum number of air operations in this direction.

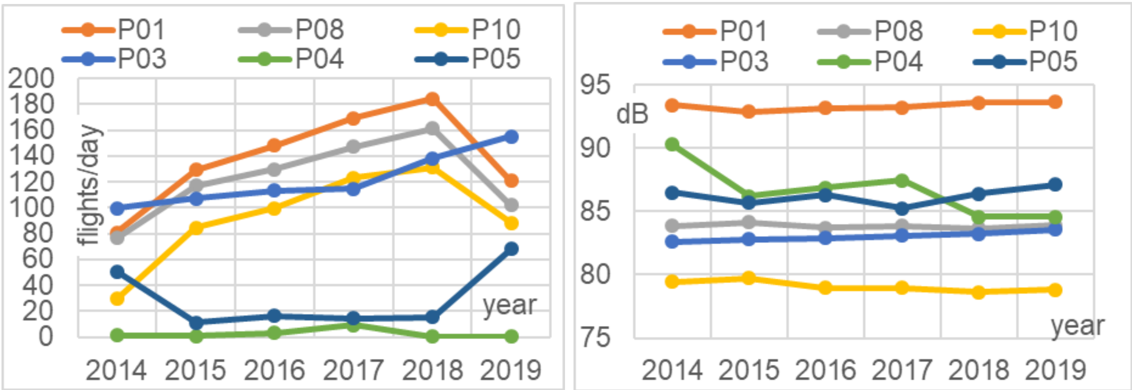

Fig. 2. Mean number of flight operations per day $\bar{N}$ (left) and mean single event sound exposure level $L_{\bar{E}}$ (right)

Rys. 2. Średnia dobowa liczba operacji lotniczych $\bar{N}$ (po lewej) i średni poziom ekspozycyjny dźwięku pojedynczego zdarzenia $L_{\bar{E}}$ (po prawej)

The graphs of the average number of events at P01, P08 and P10 have a similar pattern, but the number of operations is lower when the monitor is further away from the airport (Fig. 2). This is because for longer distances the flight tacks branch off from the runway extension.

The number of operations per day in P01, P08 and P10 is of the order of 100 oper./day. A similar number of operations is in P03. In P04 and P05, the number of operations is significantly lower. In P05, it does not exceed 20 operations per day outside the periods when flights over P01 are restricted.

The data on air operations reflect the factors characterizing traffic at Chopin Airport: increase in the number of air operations in subsequent years, preference for the use of runways conditioned by the objectives of noise protection, keeping of air traffic during repairs of runways.

In this paper, only air operations in standard environmental conditions are included. According to the monitoring data, such operations constitute 78% of all operations.

15.4.2. Single event sound exposure levels 2014 - 2019

The highest $L_{\bar{E}}$ are in monitoring point P01, which is closest to the airport, and the lowest - in the farthest point P10. $L_{\bar{E}}$ in P03 and P08 are similar, although in terms of distance from the airport P03 is close to P10 rather than P08. $L_{\bar{E}}$ for P04 and P05 are similar, which corresponds to their similar distance from the airport.

$L_{\bar{E}}(y)$ for P01, P03, P08, P10 show no significant fluctuations, or at most a small upward or downward trend. The spread of the $L_{\bar{E}}$ at these monitors is 0.5 - 1.1 dB. For P05 the range is 1.8 dB, and for P04 even 4.8 dB.

$L_{\bar{E}}$ for P04 seems to consist of three parts. In 2015, $L_{\bar{E}}$ was stepped down by 4.1 dB compared to 2014. The second part is a linear increase of $L_{\bar{E}}$ between 2015 and 2017 by 1.2 dB. The third part is a 2.8 dB step decrease of $L_{\bar{E}}$ in 2019 compared to 2018.

Comparing the left and right parts of Table 3, we can conclude that the largest spread is in monitors farthest from the airport (P03, P10) and monitors with the smallest number of operations (P04 and P05).

To assess the trends, the linear model $L_{\bar{E}}(y)$ was used, where y stands for years:

$$L_{\bar{E}}(y) = b_0 + b_1 y \tag{14}$$

The value of the linear regression coefficient b_1 indicates the amount of change $L_{\bar{E}}$ from year to year, and its sign - the direction of this change. The linear regression coefficients were calculated by the method of least squares [12] (Table 4).

Table 4

Calculated linear regression coefficients $\widehat{b_1}$ in dB/year for $L_{\bar{E}}(y)$ together with empirical F. The values of b_1 verified by F-test on the right

	$\widehat{b_1}$	F	b_1
P01	0.10	2.81	0.0
P08	-0.03	0.63	0.0
P10	-0.19	9.13*	-0.19
P03	0.18	82.18**	0.18
P04	-0.94	8.55*	-0.94
P05	0.12	0.56	0.0

* Rejection of H_0 on the level $\alpha = 0.05$

** Rejection of H_0 on the level $\alpha = 0.01$

The calculated coefficients $\widehat{b_1}$ were verified using *F* distribution [12]. The zero hypothesis H_0: $b_1 = 0$ compared to the alternative H_1: $b_1 \neq 0$ was tested. The rejection of the zero hypothesis means that there is a linear relationship between y and $L_{\bar{E}}$. If the statistical test shows that there are no grounds for rejecting H_0, it will mean that $L_{\bar{E}}(y)$ has no upward or downward trend and the values of $L_{\bar{E}}$ in subsequent years oscillate around the average.

For data from Table 4, empirical *F* was calculated as the quotient of the variance resulting from linear regression and the residual variance, resulting from random side effects and disturbing factors, related to the number of degrees of freedom. If *F* is greater than the critical value of F_{crit} for a given level of significance, H_0 is rejected, because it means that the variability of $L_{\bar{E}}$ resulting from the model is much greater than the variability caused by random causes.

The critical value for 1 and 4 degrees of freedom at the significance level 0.05 $F_{crit} = 7.71$ and at level 0.01 $F_{crit} = 21.20$. Only in three cases, marked with an asterisk, H_0 should be rejected, with respect to P03 the rejection is at significance level 0.01 (Table 4).

The absolute values of b_1 for P03 and P10 do not exceed ±0.2 dB/year, which means a change of ±1.0 dB for five years 2014 - 2019. For P04, the slope reaches -1 dB/year, which means a decrease of 5 dB over 5 years. In other cases, there are no grounds for rejecting H_0, which indicates the invariability of $L_{\bar{E}}$ over the period under examination.

15.5. Sound exposure levels of approaches and departures for daytime and nighttime

15.5.1. Number of approaches and departures day and night

For a more detailed picture, the sound exposure levels were divided into daytime and nighttime and approaches and departures. According to the preference of runways, most of the approaches and departures take place over P01 - P08 - P10 and P03 (Table 5). Departures prevail over P01 and P05, and approaches over P03 and P04, which corresponds to the wind rose for Warsaw [10].

During normal use of runways (years 2015 - 2018), the number of approaches over subsequent monitors on the P01 - P08 - P10 track is decreasing, which is due to the branching of the exit tracks. Changes in the number of approaches during the night are small, from 0.0 to -0.4 App/day.

An analogous phenomenon occurs in relation to departures, with a stronger impact of branching flight tracks. In the years 2014 and 2019, when the runway repairs were carried out, these patterns have changed (Fig. 3).

Table 5

Daily mean number of approaches and departures $\overline{N}$ in daytime and nighttime

App.	Day						Night					
	P01	P08	P10	P03	P04	P05	P01	P08	P10	P03	P04	P05
2014	41.6	39.3	14.0	66.3	0.7	11.3	3.2	3.3	1.6	10.9	0.1	2.8
2015	44.0	42.1	29.1	79.6	0.5	1.2	5.8	5.7	5.4	9.4	0.2	0.5
2016	49.4	46.7	39.8	94.2	1.0	2.2	5.9	5.9	5.7	10.3	0.3	0.8
2017	49.3	47.2	45.8	95.6	5.3	1.4	5.5	5.5	5.4	10.5	0.8	0.7
2018	69.5	65.0	59.6	111.9	0.3	2.1	7.7	7.6	7.5	11.6	0.02	0.8
2019	33.2	30.6	28.6	130.4	0.1	12.0	3.3	3.3	5.0	14.1	0.02	2.2

Dep.	Day						Night					
	P01	P08	P10	P03	P04	P05	P01	P08	P10	P03	P04	P05
2014	34.6	31.8	12.8	18.4	0.6	30.4	1.4	2.1	1.2	3.9	0.1	6.3
2015	72.7	63.1	46.0	14.9	0.2	8.2	6.7	6.2	4.1	3.2	0.1	1.4
2016	84.4	69.6	49.4	5.5	1.6	11.4	8.6	7.6	4.9	3.4	0.6	1.9
2017	103.5	84.8	65.4	5.7	3.0	10.5	10.8	9.5	6.7	2.8	0.3	1.9
2018	97.2	79.5	57.6	9.9	0.1	10.5	9.8	9.2	6.5	4.8	0.1	1.8
2019	76.6	60.7	45.3	7.2	0.1	47.6	7.5	7.3	9.4	3.6	0.04	6.4

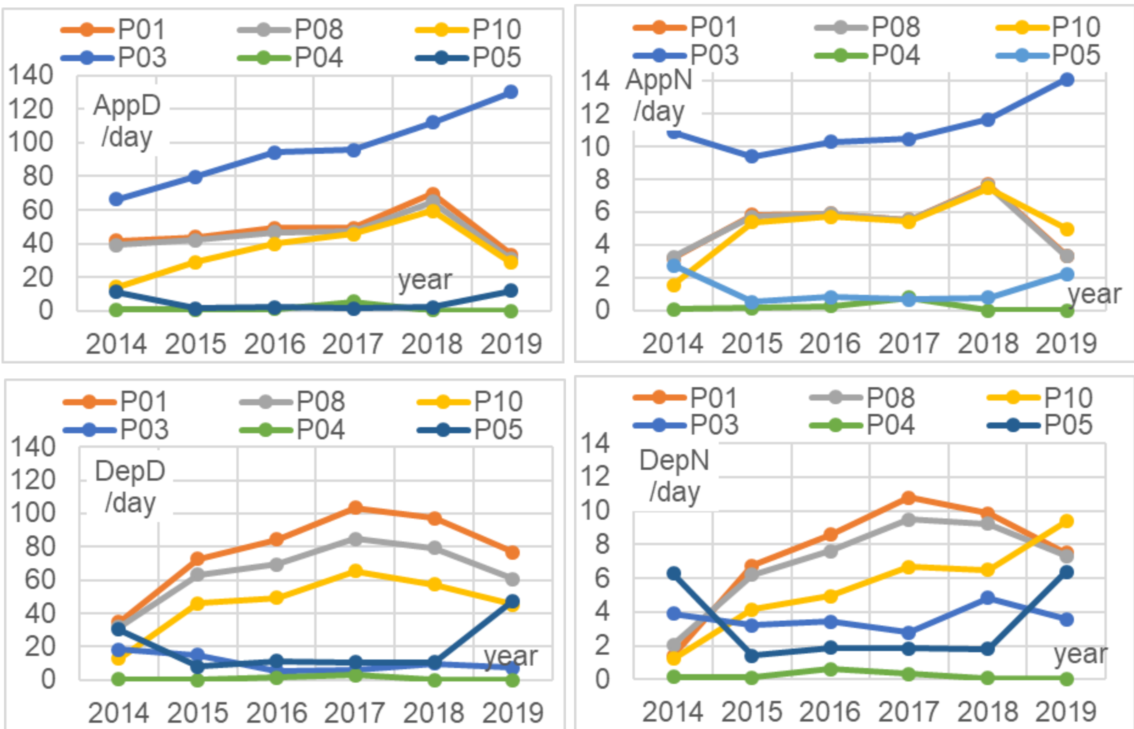

Fig. 3. Mean number of events per day: daytime (left) and nighttime (right), approaches (top) and departures (bottom)

Rys. 3. Średnia liczba zdarzeń na dobę: w porze dnia (po lewej) i w porze nocy (po prawej), przylotów (u góry) i odlotów (u dołu)

There was a transfer of operations from P01 and P08 over P05. In addition, there were aircrafts over P08 and P10 that were not over P01. An almost equal number of arrivals over P10, P08 and P01 at night indicates that almost all the planes heading for runway RWY 11 are heading in this direction at least from P10. Before 2017, some planes entered the landing direction between the P10 and P08 at daytime.

15.5.2. Sound exposure levels of approaches and departures during daytime and nighttime

Table 6 and Fig. 4 give the sound exposure levels $L_{\bar{E}}$ broken down into approaches and departures and daytime and nighttime.

Table 6

$L_{\bar{E}}$ of approaches and departures during daytime and nighttime

App.	Day						Night					
	P01	P08	P10	P03	P04	P05	P01	P08	P10	P03	P04	P05
2014	94.3	83.3	77.4	82.7	93.0	82.9	95.3	83.8	77.7	83.4	89.6	82.4
2015	94.0	83.3	77.0	82.9	86.5	84.0	95.4	83.9	77.3	84.0	86.6	80.0
2016	94.3	83.3	77.8	82.8	87.0	83.9	95.9	83.9	78.0	84.2	86.0	80.9
2017	94.4	83.3	77.9	83.0	87.5	82.6	95.5	83.8	77.8	84.2	88.3	81.1
2018	94.5	83.1	77.6	83.3	85.8	84.9	95.8	84.0	78.2	84.3	83.6	80.7
2019	94.5	83.2	78.0	83.6	86.1	84.0	95.5	83.9	78.4	84.6	86.8	84.3
Dep.	Day						Night					
2014	91.8	84.5	81.0	81.7	84.2	87.4	91.4	83.2	79.7	82.4	83.1	86.9
2015	91.8	84.8	81.0	81.4	85.1	86.3	91.4	83.5	80.2	82.2	85.4	83.7
2016	92.2	84.1	79.8	82.0	87.2	87.0	92.0	82.9	79.1	81.6	85.9	84.4
2017	92.4	84.2	79.7	82.0	87.3	86.1	92.0	83.3	78.5	81.6	85.9	80.8
2018	92.6	84.0	79.4	81.8	82.2	87.1	92.6	83.5	79.0	81.1	82.3	84.4
2019	93.2	84.3	79.3	82.1	83.8	87.7	92.4	83.0	78.9	81.9	77.9	87.3

As for all events together, $L_{\bar{E}}(y)$ for monitors P01, P03, P08, P10 show no significant fluctuations, or at most a small upward or downward trend.

$L_{\bar{E}}(y)$ runs in P04 for arrivals show an initial decrease of 6.5 dB by day and 3.0 dB by night (2014 - 2015), followed by a linear trend with less fluctuations by day than by night. $L_{\bar{E}}(y)$ in P04 for departures indicate a slight ascending linear trend (2014 - 2017), followed by a jump in the daytime or linear decline at night.

$L_{\bar{E}}(y)$ in P05 for arrivals at daytime shows only fluctuations around the average. $L_{\bar{E}}(y)$ in P05 for arrivals at night has a starting (2014) and ending (2019) value similar to that of the day, and a decrease of $L_{\bar{E}}$ between 2015 and 2018 of about 3 dB.

$L_{\bar{E}}(y)$ in P05 for departures during the day show slight fluctuations, without a clear trend. For departures during the night, the nature of $L_{\bar{E}}(y)$ is similar to that of arrivals at night, i.e. a reduction in the years 2015-2018 of about 3 dB from the value in 2014 and 2019. In addition, in 2017 there was a reduction of 4 dB.

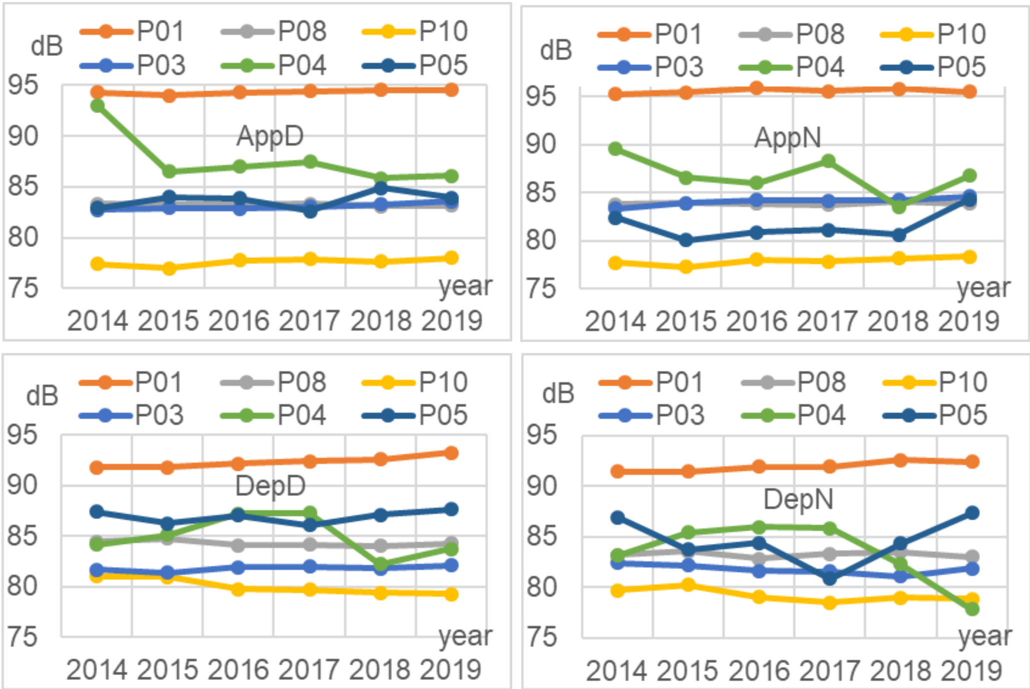

Fig. 4. Sound exposure level $L_{\bar{E}}$: daytime (left) and nighttime (right), approaches (top) and departures (bottom)

Rys. 4. Poziom ekspozycyjny $L_{\bar{E}}$: w porze dnia (po lewej) i w porze nocy (po prawej), przylotów (u góry) i odlotów (u dołu)

Regression analysis confirmed the linear trend $L_{\bar{E}}(y)$ (Table 7) in five cases. In P01 for departures $L_{\bar{E}}$ increases in the daytime by 0.28 dB/year and in the nighttime by 0.24 dB/year. In P08, the growth rate for arrivals is 0.16 dB/year during the day and 0.20 dB/year at night. However, in P05 there was a downward trend, which is statistically significant only for departures. For arrivals F did not exceed the critical value, although the occurrence on P05 of negative coefficients b_1 with similar values for the time of day and night, which differ from the pairs on other monitors, suggests the non-random cause.

Table 7

Calculated linear regression coefficients $\widehat{b_1}$ in dB/year for $L_{\bar{E}}(y)$ together with empirical F

	App/Day		App/Night		Dep/Day		Dep/Night	
	$\widehat{b_1}$	F	$\widehat{b_1}$	F	$\widehat{b_1}$	F	$\widehat{b_1}$	F
P01	0.08	5.30	0.06	0.94	0.28	59.91**	0.24	23.90**
P08	0.16	27.46**	0.20	19.88**	0.10	4.50	-0.18	3.53
P10	-1.03	4.24	-0.60	1.70	-0.30	0.34	-1.02	2.41
P03	0.18	0.84	0.33	0.77	0.08	0.26	0.01	0.00
P04	-0.03	3.46	0.01	0.28	-0.08	1.93	-0.02	0.06
P05	0.14	4.30	0.16	6.49	-0.39	26.66**	-0.25	4.38

* indicates significance at 0.05

** indicates significance at 0.01

15.5.3. ANOVA calculations

ANOVA calculations were performed in the Analysis ToolPak in MS Excel [13]. Two-way ANOVA with replication was used. The Sample factor had App (Approach) and Dep (Departure) levels. The Columns factor had Daytime and Nighttime levels. The replications were $L_{\bar{E}}$ values for the years 2014 - 2019.

The critical value for 1 and 20 degrees of freedom at the significance level $\alpha = 0.05$ is equal to $F_{\text{crit}} = 4.35$ and at $\alpha = 0.01$ $F_{\text{crit}} = 8.10$.

Tables 8 - 13 provide summary data and results. The significance of the influence of both factors and interactions is marked with asterisks.

Table 8

Results of the two-factor ANOVA with replication for the P01 monitor

Summary	App	Dep	Total		App	Dep	Total		App	Dep
Daytime				Nighttime				*Total*		
Count	6	6	12	Count	6	6	12	Count	12	12
Sum	565.9	554.1	1120	Sum	573.4	551.8	1125	Sum	1139	1106
Average	94.32	92.35	93.34	Average	95.57	91.97	93.77	Average	94.95	92.16
Variance	0.041	0.297	1.207	Variance	0.06	0.232	3.684	Variance	0.477	0.281

Source of Variation	*SS*	*df*	*MS*	*F*	*Test F*
Sample	1.136	1	1.136	7.23*	4.351
Columns	46.6	1	46.6	296.4**	4.351
Interactions	4.052	1	4.052	25.77**	4.351
Within	3.144	20	0.157		
Total	54.93	23			

Table 9

Results of the two-factor ANOVA with replication for the P08 monitor

Summary	App	Dep	Total		App	Dep	Total		App	Dep
Daytime				Nighttime				*Total*		
Count	6	6	12	Count	6	6	12	Count	12	12
Sum	499.4	505.8	1005	Sum	503.3	499.4	1003	Sum	1003	1005
Average	83.23	84.3	83.77	Average	83.89	83.24	83.56	Average	83.56	83.77
Variance	0.009	0.07	0.353	Variance	0.01	0.077	0.155	Variance	0.128	0.376

Source of Variation	*SS*	*df*	*MS*	*F*	*Test F*
Sample	0.243	1	0.243	5.88*	4.35
Columns	0.275	1	0.275	6.65*	4.35
Interactions	4.478	1	4.478	108.4**	4.35
Within	0.826	20	0.041		
Total	5.821	23			

Table 10

Results of the two-factor ANOVA with replication for the P10 monitor

Summary	App	Dep	Total		App	Dep	Total		App	Dep
Daytime				Nighttime				*Total*		
Count	6	6	12	Count	6	6	12	Count	12	12
Sum	465.7	480.3	946	Sum	467.4	475.4	942.8	Sum	933.2	955.7
Average	77.62	80.04	78.83	Average	77.9	79.24	78.57	Average	77.76	79.64
Variance	0.133	0.614	1.937	Variance	0.143	0.404	0.733	Variance	0.147	0.64

Source of Variation	*SS*	*df*	*MS*	*F*	*Test F*
Sample	0.415	1	0.415	1.282	4.35
Columns	21.12	1	21.12	65.31*	4.35
Interactions	1.776	1	1.776	5.49*	4.35
Within	6.47	20	0.323		
Total	29.79	23			

Table 11

Results of the two-factor ANOVA with replication for the P03 monitor

Summary	App	Dep	Total		App	Dep	Total		App	Dep
Daytime				Nighttime				*Total*		
Count	6	6	12	Count	6	6	12	Count	12	12
Sum	498.3	491	989.3	Sum	504.6	490.7	995.3	Sum	1003	981.7
Average	83.06	81.83	82.44	Average	84.1	81.78	82.94	Average	83.58	81.81
Variance	0.1	0.068	0.487	Variance	0.173	0.232	1.653	Variance	0.424	0.137

Source of Variation	*SS*	*df*	*MS*	*F*	*Test F*
Sample	1.507	1	1.507	10.51**	4.35
Columns	18.87	1	18.87	131.6**	4.35
Interactions	1.794	1	1.794	12.51**	4.35
Within	2.869	20	0.143		
Total	25.04	23			

Table 12

Results of the two-factor ANOVA with replication for the P04 monitor

Summary	App	Dep	Total		App	Dep	Total		App	Dep
Daytime				Nighttime				*Total*		
Count	6	6	12	Count	6	6	12	Count	12	12
Sum	525.9	509.8	1036	Sum	520.8	500.5	1021	Sum	1047	1010
Average	87.64	84.97	86.31	Average	86.8	83.41	85.11	Average	87.22	84.19
Variance	7.158	4.019	7.027	Variance	4.199	9.703	9.462	Variance	5.354	6.904

Source of Variation	*SS*	*df*	*MS*	*F*	*Test F*
Sample	8.656	1	8.656	1.38	4.35
Columns	55.19	1	55.19	8.8**	4.35
Interactions	0.786	1	0.786	0.125	4.35
Within	125.4	20	6.27		
Total	190	23			

Table 13

Results of the two-factor ANOVA with replication for the P05 monitor

Summary	App	Dep	Total		App	Dep	Total		App	Dep
Daytime				Nighttime				*Total*		
Count	6	6	12	Count	6	6	12	Count	12	12
Sum	502.3	521.7	1024	Sum	489.4	507.6	997.1	Sum	991.7	1029
Average	83.72	86.94	85.33	Average	81.57	84.6	83.09	Average	82.64	85.77
Variance	0.685	0.395	3.331	Variance	2.412	5.626	6.157	Variance	2.658	4.228

Source of Variation	*SS*	*df*	*MS*	*F*	*Test F*
Sample	30.09	1	30.09	13.20**	4.35
Columns	58.72	1	58.72	25.76**	4.35
Interactions	0.058	1	0.058	0.0256	4.35
Within	45.59	20	2.28		
Total	134.5	23			

The effect of Sample was significant at a level at least equal to 0.01, only for P08 at $\alpha = 0.05$. Daytime is not important on P04 and P10, but it is important on $\alpha = 0.01$ level for P03 and P05. Interactions are not significant only in P04 and P05. MS_{within} in P04 and P05 was many times greater than on the other monitors. Since MS_{within} is a measure of the influence of side effects and interfering factors [1, p. 48], this confirms the significant influence of these factors in P04 and P05. Also in P10 MS_{within} indicates greater influence of side effects than in P01, P03 and P08.

15.6. Dependence of sound exposure level on distance

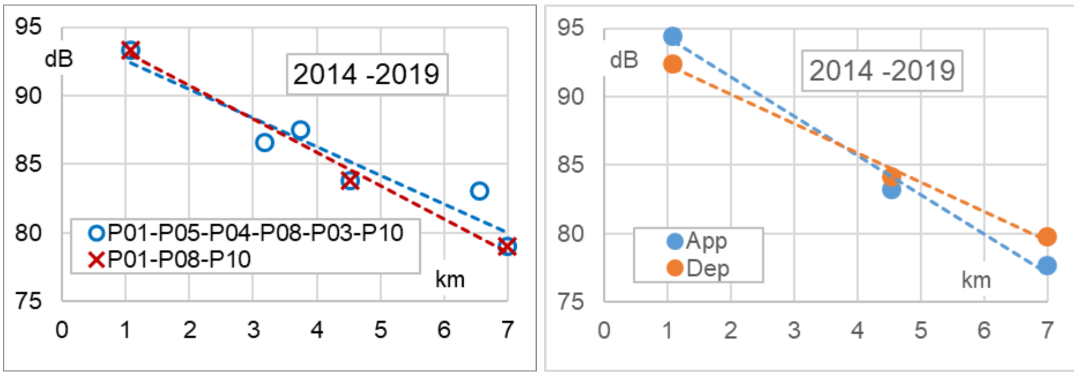

Fig. 5. $L_{\bar{E}}$ versus the distance from the airport. Circles without crosses indicate monitors that do not lie on the P01-P08-P10 track. The red line on the left panel indicates the trend for P01-P08-P10, and the blue line for all monitors

Rys. 5. $L_{\bar{E}}$ w zależności od odległości od lotniska. Kółka bez krzyżyków oznaczają monitory, które nie leżą na torze P01-P08-P10. Linia czerwona na lewym panelu wskazuje trend dla P01-P08-P10, a linia niebieska dla wszystkich monitorów

The data indicate that $L_{\bar{E}}$ decreases as the distance from the airport increases (Fig. 5). The dependence of $L_{\bar{E}}$ for the whole period 2014 - 2019 on the distance from runway threshold is shown for all monitors (left) and only monitors on the same track P01-P08-P10 (right).

The graph includes arrivals and departures day and night. The trend lines determined by the linear regression method are also shown. The average slope of $L_{\bar{E}}$ with distance for all operations together is $\widehat{b_1}$ = -2.09 dB/km for the all monitors and $\widehat{b_1}$ = -1.87 dB/km for P01-P08-P10. The coefficient of determination is 0.91 for all monitors and 0.99 for P01-P08-P10 only.

The $\widehat{b_1}$ changes in time on the P01-P08-P10 track are shown in Fig. 6, taking into account the type of operation and time of day. Values $\widehat{b_1}$ are negative, which means a decrease of $L_{\bar{E}}$ with distance from the airport. Absolute value $|\widehat{b_1}|$ determines the speed of this decrease in dB/km. With regard to departures, regression analysis showed that the $|\widehat{b_1}|$ increased monotonically in subsequent years by 0.1 dB/year. This trend is significant at least at the level of 0.05. The coefficient of determination for Dep/D was R = 0.95, while for Dep/N R = 0.77. Regression analysis for approaches did not indicate a linear change.

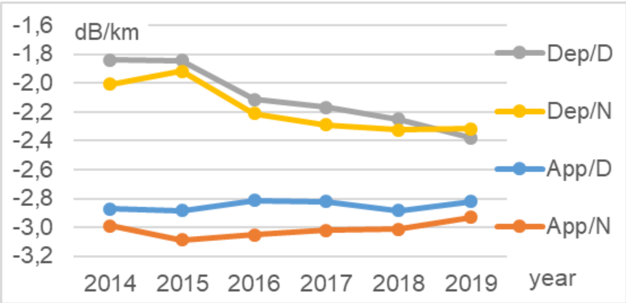

Fig. 6. Values of $\widehat{b_1}$ in dB/km for the track P01 - P08 - P10 in the years 2014 -2019 for different combinations of flight operation/time of day

Rys. 6. Wartości $\widehat{b_1}$ w dB/km dla trasy P01 – P08 – P10 w latach 2014 -2019 dla różnych kombinacji operacja lotnicza/pora doby

The two-factor ANOVA for departures showed a significant impact of the year and no influence of the time of day. With regard to approaches, the situation is the opposite. Important is the effect of the time of day, while $\widehat{b_1}$ for years do not differ statistically.

15.7. Discussion

Sound exposure levels $L_{\bar{E}}$ on noise monitors of Chopin Airport for the years 2014 – 2019 were subjected to analysis. The changes of $L_{\bar{E}}$ in the whole period 2014 - 2019 were not large, as they amounted to about 1 dB. Only on the little used track over the district of Ursynów $L_{\bar{E}}$ decreased by 5 dB in this period.

Changes $L_{\bar{E}}$ over time were different on individual monitors. Some show an upward trend, others a downward trend. Since annual averages are studied and the same aircrafts are flying on all departure and arrival tracks, it is unlikely that the nature of the differences between monitors will be determined by the individual noise characteristics of the aircrafts.

With respect to P01, P08, the regression analysis did not show a linear trend in $L_{\bar{E}}$ fluctuations around the multi-annual average. However, when taking into account the type of aircraft operation and time of day, the regularities became apparent. There was a growing linear trend for departures in P01. This trend concerns both a daytime and a nighttime. The slope of the regression line was 0.24 - 0.28 dB/year, accordingly. Also, for P08 there was an upward trend. It concerns approaches, and the slope of the simple regression is 0.16 - 0.20 dB/year. Both these trends have a significance level $\alpha = 0.01$ and occur during the day and night.

ANOVA for P01 and P08 showed the significance of the differences between $L_{\bar{E}}$ for approaches and departures, daytime and nighttime as well as the significance of interactions between the aircraft movement type and the time of day.

Linear falling trend $L_{\bar{E}}$ in P10 was not confirmed by significant trends for $L_{\bar{E},\mathrm{App,D}}$, $L_{\bar{E},\mathrm{App,N}}$, $L_{\bar{E},\mathrm{Dep,D}}$ and $L_{\bar{E},\mathrm{Dep,N}}$. Regression analysis results in negative gradients of all four straights, equal from -1.03 to -0.30, but the share of unexplained variance is too high. ANOVA for P10 showed significant influence of interaction between the aircraft movement type and the time of day. The influence of an undefined factor is also possible. P10 is located in an area far from the airport, where runway extensions intersect with other tracks. Minor changes in the actual flight trajectory are possible, e.g. economically dependent.

A similar situation occurred in P03 of a similar location as P10. There was a significant growing linear trend for $L_{\bar{E}}$, and the growing trends were also for $L_{\bar{E},\mathrm{App,D}}$, $L_{\bar{E},\mathrm{App,N}}$, $L_{\bar{E},\mathrm{Dep,D}}$ and $L_{\bar{E},\mathrm{Dep,N}}$. ANOVA showed the significance of the aircraft operation type and the time of day as well as the significance of interaction. Here too, the reason may be an unidentified factor related to the location of the monitor in relation to tracks.

On P04, the highest variability $L_{\bar{E}}$(y) occurred, creating a linear downward trend with a slope of -0.94 dB/year at $\alpha = 0.05$. In addition, $L_{\bar{E}}$(y) indicates two steep drops. The first one in 2015 by about 4 dB and the second one in 2019 by about 3 dB. Due to the small number of sound events in P04, even a small number of disturbances affected $L_{\bar{E}}$. Detailed analysis showed that in 2014 several events with an exposure level of more than 100 dB were recorded during the day and night time. The elimination of such events may have resulted in a decrease in $L_{\bar{E}}$ in the following years.

P04 is located in an area of high population density, where air noise causes complaints. An unusual $L_{\bar{E}}$(y) time pattern compared to other monitors, and especially the steeper drops indicate the influence of an additional non-random factor.

MS_{within} for P04 and P05 is many times greater than the others, which indicates the influence of side effects and interference factors at these measurement points. This is consistent with the visual analysis of $L_{\bar{E}}$ carried out above, indicating the steep drops.

The dependence of $L_{\bar{E}}$ on the distance from the runway threshold showed a decreasing linear trend. This trend is significant on the tracks being the extensions of the runways of Chopin Airport up to 7 km. The decrease with distance is greater for approaches than for departures. Near the airport $L_{\bar{E}}$ is greater for approaches. Over the distance ca 3.5 km $L_{\bar{E}}$ is greater for departures.

In the years 2014 - 2019, the decrease of $L_{\bar{E}}$ with the distance for approaches has not changed. Probably this is due to the constancy of the angle of descent of aircraft on the approach to landing, which is equal to 3°. However, the drop in the level with the distance for departures increased in this period from 1.7 dB/km to 2.3 dB/km, which indicates an increase in the angle of climb.

15.8. Conclusions

The applied method of analysis of data from the Chopin Airport noise monitoring system using the single event sound exposure level allowed for the assessment of air traffic noise without the impact of changing air traffic.

It was found that for five out of six examined noise monitors, the change in the level of exposure for an average single air traffic operation did not exceed ±1 dB for the entire 5-year period. The exception was a monitor on the track with little traffic and high pressure to reduce noise, where the level decreased by 5 dB.

The decrease in the sound exposure level with distance for all operations 2014 - 2019 is 2.1 dB/km, but the decrease is greater for arrivals than for departures. The decrease with distance for arrivals has not changed in the years 2014 - 2019, while the decrease in the level of distance for departures increased from 1.7 dB/km in 2014 to 2.3 dB/km in 2019.

Levels of mean exposure of a single aircraft operation in the years 2014 - 2019 including all aircraft events were subjected to analysis. In order to deepen the analysis, the division of aircraft events into approaches and departures and time of day and night was taken into account. In further research it would be desirable to consider the factor which is the type of aircraft. Moreover, it would be interesting to compare data for different periods of the year and to perform analyses for single events instead of averaged values.

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