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Assessing the influence of street canyon shape on aircraft noise: Results from measurements in courtyards near Amsterdam Schiphol Airport

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A B S T R A C T

Aircraft noise is a major stressor for communities in the vicinity of airports. Aircraft noise prediction models omit the built environment, based on an implicit assumption that the impact of buildings on the propagation of aircraft noise is neglectable. In this article a study is presented in which aircraft noise levels were measured near walls facing towards and away from aircraft flyovers in an urban test environment near Amsterdam Schiphol Airport. The test environment comprises three adjacent courtyards, each enclosed by stacked shipping containers. To examine the influence of street geometry on aircraft noise, specifically for slanted roofs and building insets, the shipping containers were stacked in a different pattern around each courtyard. In total, sound levels for 2383 aircraft flyovers were analysed across five months at ten microphone positions within the courtyards, for both arrivals and departures. Depending on the geometry of the courtyards, mean differences ($L_{A,max}$) between facades with- and without a line of sight towards the aircraft ranged between −1,3dBA and 5,0dBA for arrivals, and 8,7dBA and 13,6dBA for departures. SEL values ranged between between −0,8dBA and 4,3dBA for arrivals, and 8,1dBA and 11,6dBA for departures. The results suggest that slanted roofs perpendicular to the flight direction deflect incident sound, substantially reducing the sounds levels inside courtyards. Contrarily, building insets at building sides facing away from the flight paths did not reduce sound levels underneath the overhangs significantly. The findings stress the importance of architectural and urban design to mitigate aircraft noise.

1. Introduction

Aircraft noise causes stress-related complaints and has a negative impact on the well-being of residents living close to airports [1,2]. To protect people from excessive noise exposure, noise contours are a commonly used policy instrument, which restrict and regulate the expansion of urban areas where the noise levels exceed the legal thresholds [1]. Within the EU, contours are calculated on the basis of the European Noise Directive (END), which maintains that noise levels are based on the weighed equivalent sound levels (L_{den} and L_{night}) [3–5]. However, sound exposure does not automatically lead to annoyance, but rather is the consequence of reciprocal processes between exposure, context and response [6–9].

Literature on the annoyance-reducing effects of quiet building sides show the importance of context for the level of noise annoyance. For road traffic noise, a quiet building side is defined as a facade without a direct line of sight to the noise source (*n*LOS from now on), where the L_{Aeq} is < 45 dB(A), or where the relative difference with the exposed façade (*d*LOS) (ΔL_{Aeq}) is > 10 dB(A) [10–15].

The shape and surface characteristics of buildings and streets can abate sound levels around or between buildings to meet the criteria for quiet facades (for example see Refs. [16–18]). Roof shape, (green) cladding, urban density and building dimensions scatter, diffract or absorb sound, as the sound energy decays due to reflections and diffraction over ridges and protrusions [17–25].

Since the noise-reducing capacity of smart building designs are largely studied in relation to road and rail traffic, it is uncertain to what extent buildings can reduce aircraft noise as well. Theoretically, the position of aircraft means that sound is dispersed from above, limiting the sound abatement by building edges (see Fig. 1) (see e.g. Refs. [26–28]). Furthermore, the direction from which the source emits noise, in combination with refraction, changes the angle of incidence of the sound waves as they hit a building [29–31]. This can negate or greatly reduce the noise abating potential of buildings and tall barriers (see Fig. 1b) [29,30,32].

For buildings close to the ground track of a flight path, buildings and streets scarcely attenuate any aircraft noise, which means that the sound level near *d*LOS and *n*LOS facades are almost equivalent [33–35]. For buildings at a greater distance from flight paths, buildings seem to act like tall barriers, which leads to a difference between *n*LOS and *d*LOS facades. However, the design of the street canyons around a façade may affect the sound levels. Reflections between buildings can amplify the

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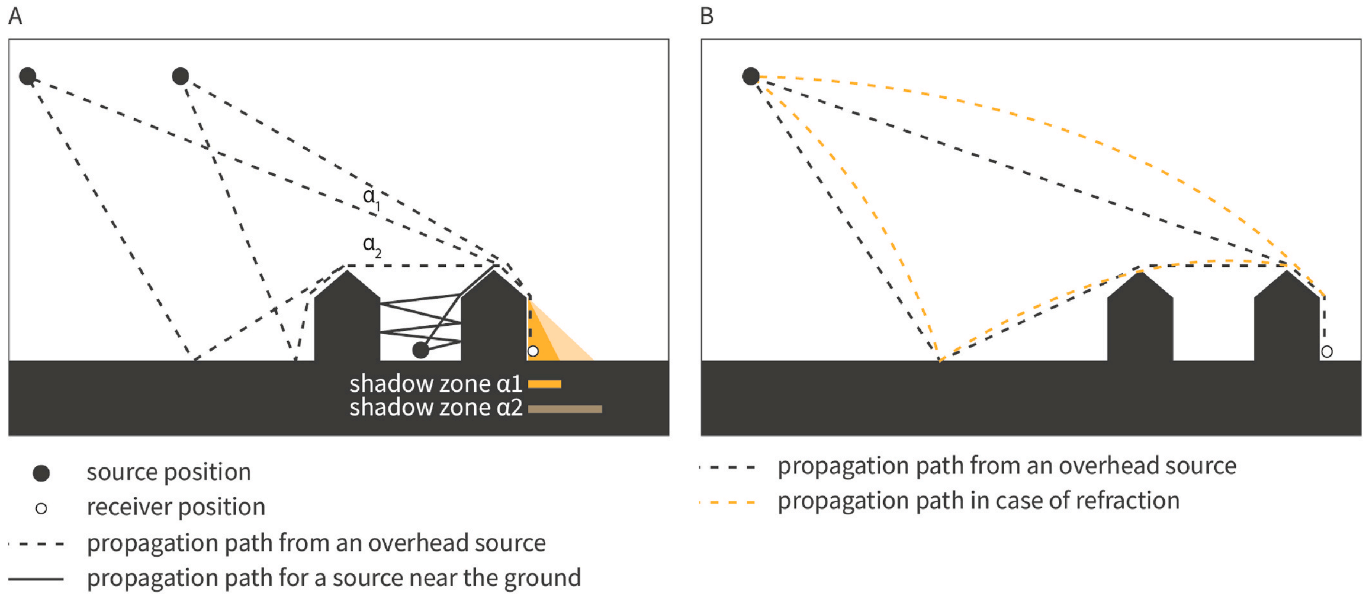

Fig. 1. A) Two source positions with schematic sound paths: being reflected, and diffracted around buildings. B) Schematized effect of refraction versus sound propagation without atmospheric refraction.

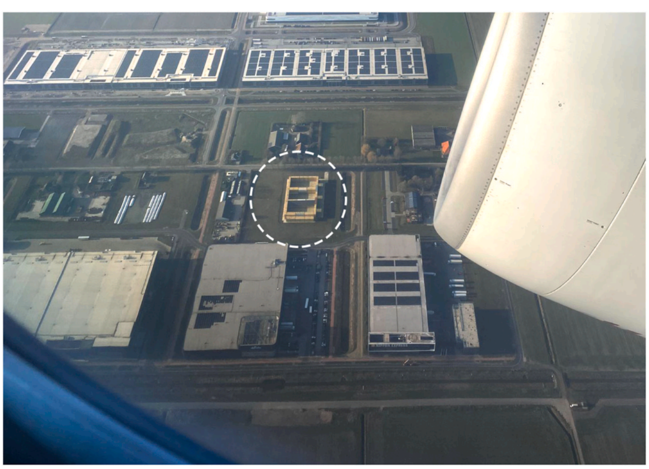

Fig. 2. Aerial image of the field lab as seen from an airplane window.

sound level (i.e. L_{Amax} levels) within streets with buildings on both sides [33,35].

This is different for sites at the flanks of a flight path, where the horizontal distance between the ground track of an aircraft flyover and a building is larger. For example, a computational study comparing twenty urban locations located less than 1000 m from a flight path (altitude: 100–200 ft (30–60 m)) found differences up to 4.6 dB between the individual locations[27]. In a different computational study, it was found that canyons with slanted facades and building insets yield a greater sound reduction near *d*LOS facades compared to canyons with straight facades [36]. The results from both studies suggest that urban and architectural shape may reduce aircraft noise in such areas. The results are not backed by measurements or follow-up studies, and atmospheric effects were not, or only rudimentarily, considered. This raises the question as to what extent the design of street canyons influences aircraft noise based on measurements.

This article presents the results of a study which examines this question, based on measurements near Schiphol airport in Amsterdam, the Netherlands. The study which is presented in this paper had two objectives:

- To examine if sound levels vary around buildings exposed to aircraft noise, and to what extent this leads to a ‘quiet’ building side.
- To examine if the variance in sound levels is linked to the shape of buildings, in particular slanted facades and building insets.

The aim of the study was to identify the impact of the shape of buildings on aircraft noise for low-rise residential areas. In the context of this study, low-rise residential areas correspond to buildings similar to a height up to three building storeys.

2. Method

2.1. Site description

To examine the impact of building geometry on the propagation of aircraft noise, a full scale ‘field lab’ was built close to Amsterdam Schiphol Airport, see Fig. 2. The lab is formed by three courtyards which are enclosed by ‘walls’ comprised of shipping containers. Each shipping container is 12,2 m (m from now on) in length, 2.6 m in height, and 2.4 m in width, made from corrugated steel slabs. Despite its resemblance of buildings and walls, corrugated steels slabs reflect, and scatter incident sound waves differently compared to traditional building facades comprising concrete, masonry and/or glass, especially for mid and high frequency sound. In this, we assume that the facades are basically flat, not having large structural elements such as balconies or balustrades. The shipping containers are placed atop a concrete surface, consisting of concrete tiles each 2 m by 2 m. Each courtyard has a different geometry, as shown in Fig. 5. The design of the three courtyards, including the slanted facade and building insets, was loosely based on a previous computational study [36,37].

The slanted roof consists of corrugated sandwich panels, 72 cm thick, 100 cm wide and 750 cm long, comprising PIR-insulation wedged in between two thin textured aluminium coated steel plates. The total load of the panels is around 10–12 kg per m^2. The panels rest on horizontal rafters, formed by three wooden beams affixed on top of the shipping containers touching the panels. The panels and rafters were connected to the shipping containers with clamps and bolts, stabilizing and fixating the roof.

The field lab is located near Schiphol’s runways (*Kaagbaan*), which is one of the airport’s most frequently used runways. Depending on wind direction and route preferences, the runway is mostly used for

Fig. 3. Close-up of microphone 4 in front of a shipping container.

departures. Most flights take place between 7am and 11pm local time, albeit that there also flight during the nightly hours.

The location of the field lab, runway, and ground tracks of flights for a representative day are shown in Fig. 4.

2.2. Equipment

In the field lab, sound levels are measured with ten microphones, all placed near facades facing either towards, or away from, the nearest flight route. The position of the microphones is shown in Fig. 3 and Fig. 5 and designated within *mic 1* to *mic 10*. The microphones are placed 20 cm away from the facades, each 1.5 m above the ground surface, except for *mic 2* and *mic 6* which are each 3.9 m above the ground surface. This height corresponds to a first storey eye level position. Microphones were placed on the centre line of the courtyards, except for microphone 3 and 7, which are placed near corners. As the microphones are positioned away from the shipping containers and concrete slabs, the sound signal is subject to interfering (reflected) sound waves. This leads to a destructive interference at about e.g. 400 Hz. Although circumventable by mounting the microphones straight on the walls, the aim of this study was to assess shielding effects inside street canyons, at positions where, in theory, people can stand or sit. As, in theory, this can be at any position in space between the wall and ground surfaces, it was decided to affix the microphones always at equal distance from walls. Besides, interference patterns depend on source-receiver distances and wave directionality, which vary during, and between, individual flyovers. To smoothen out these effects, first data was processed per flight, which output data was aggregated for further analyses (see section 2.5). Class II microphones were used (NP2 series), provided by Munisense, equipped with a porous water repellent wind screen.

The microphones sit in a thermoplastic waterproof box, which is connected to the electricity grid. The microphones also have a built-in battery, which can provide electricity in case of power cuts. Acoustic data is stored as WAV files on a flash drive on site, and remotely on a cloud server through 4G. Sound pressure levels (SPL) in third octave bands are recorded every 0.125 s and uploaded on the cloud server. The acoustic data is matched with a time stamp, linked to a calibrated clock on the server.

2.3. Sound sources

The microphones record the SPL on a 0.125 s interval, which is the accumulated sound from various sound sources around the field lab. The field lab is situated near a road, relatively close to a motorway, and surrounded by three farmhouses and warehouses. The road, farms and warehouses mainly produce sound during daytime, while passing cars

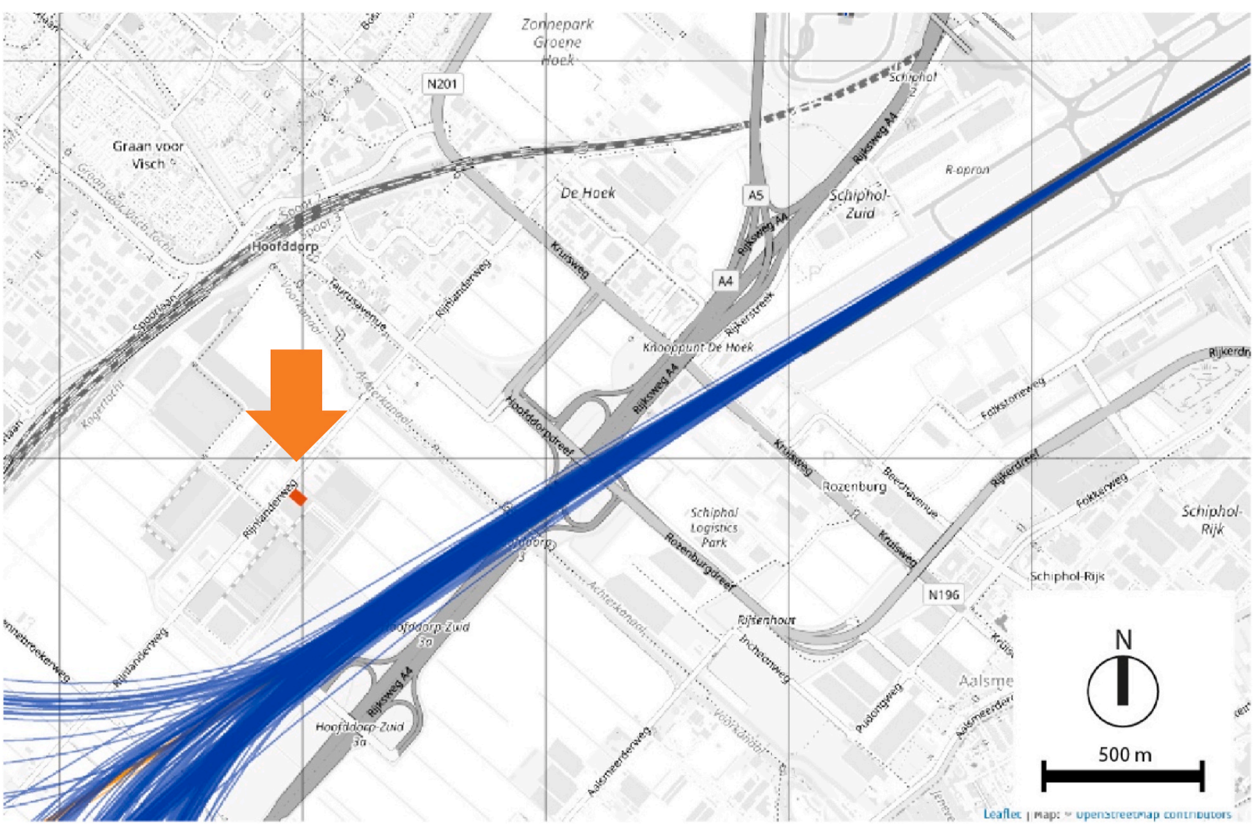

Fig. 4. Map showing ground tracks of departures from Schiphol's Kaagbaan runway (in blue) on March 1st, 2022 and the location of the field lab (in orange, below orange arrow). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

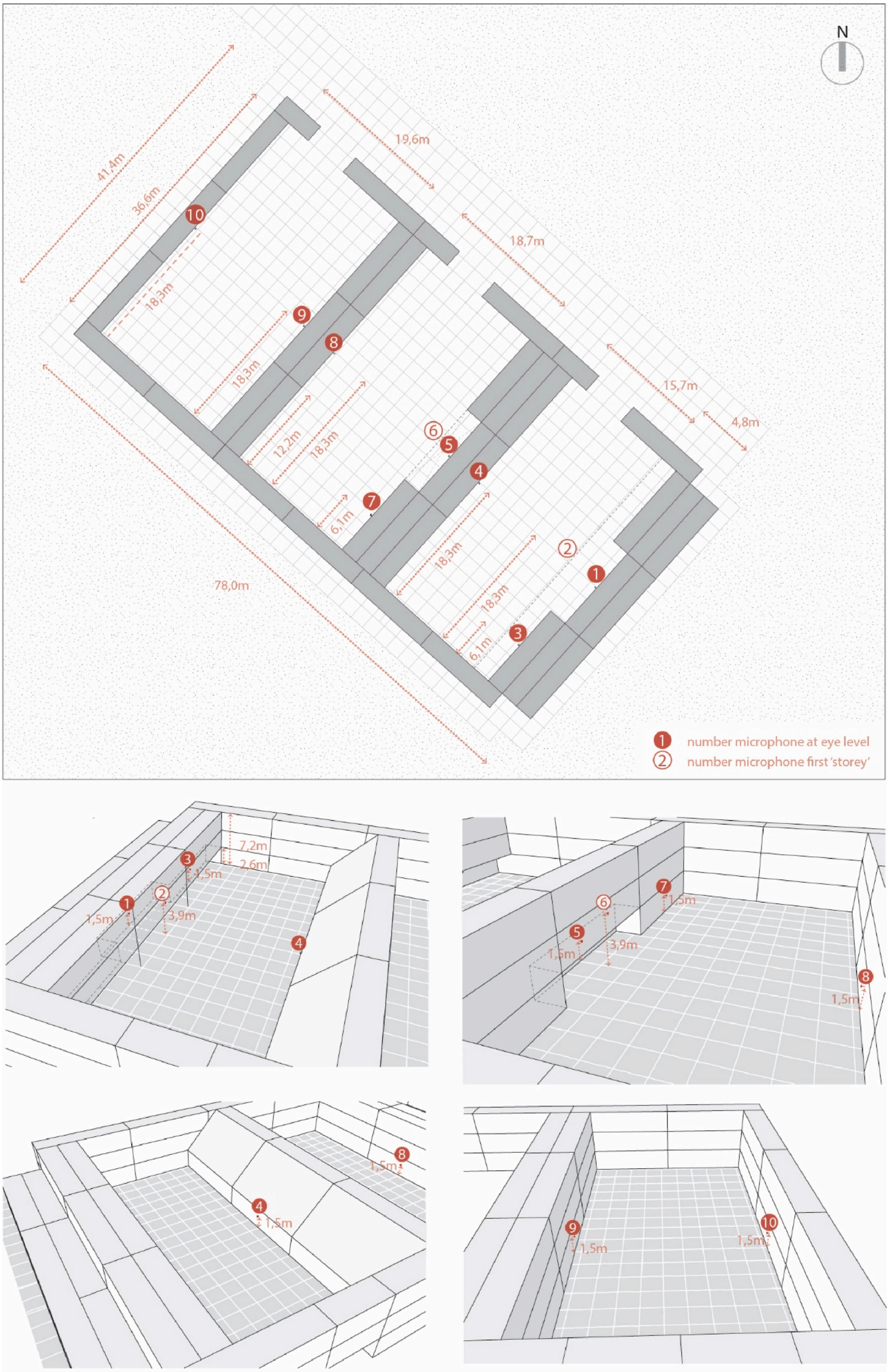

Fig. 5. Top view and closeups of the courtyards and microphone positions.

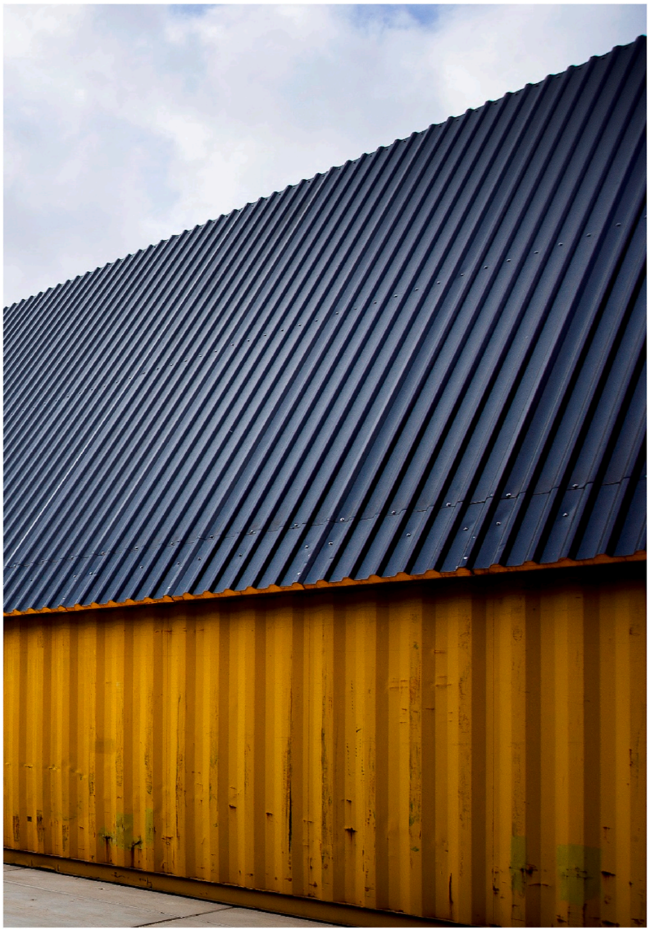

Fig. 6. Corrugated sandwich roof panels and shipping containers (detail).

driving on the motorway emit a constant hum. To reduce the risk that the sound data for the aircraft flyovers is contaminated, the field lab's courtyards are fenced off on all sides. This reduces sound levels from road traffic inside the courtyards, which makes it easier to detect and isolate sound emitted by aircraft flyovers. Also, the risk of contamination of the dataset was further limited as good as possible by only processing data between 9pm in the evening and 7am in the morning. As the location of the field lab is relatively close to a runway, the sound pressure level (SPL from now on) substantially increases during an aircraft flyover, compared to the normal SPL in between aircraft flyovers. Schiphol's radar system was used to retrieve information about all airplanes flying in the proximity of the field lab. Besides information about the flight number, aircraft type and routing, the radar data contains information about the altitude and geographic coordinates, with a resolution of 4 s.

2.4. Meteorological data

Weather data was retrieved from a weather mast on the airport's premise, operated by KNMI (Royal Dutch Meteorological Institute). The distance between the field lab and the weather mast is approximately 5500 m. The local surroundings near the weather mast are comparable with the area around the field lab in terms of the ground surfaces (grass fields) and density (limited buildings). This means that the surface roughness will likely be comparable (see also [38]). The weather data is publicly accessible, with the wind and the temperature sensors at a height of 10 m and 1.5 m above the ground surface. The wind velocity, temperature, humidity, and pressure levels are averaged for each hour.

2.5. Data analysis

Aircraft flyovers were detected based on four conditions, which are also shown in Fig. 6. Data analysis was carried out through a flow chart written in MATLAB R2018b.

First, sound events were detected based on the acoustic criteria as protocolised in ISO 20906. It was chosen to deviate from ISO 20906, as the statistical descriptor L_{20} was used as the threshold criterion for the detection of airplane flyovers instead of the A-weighted equivalent sound level $L_{Aeq,1s}$. For each day, this step was repeated for all microphones, and for all data collected between 9pm and 7am (the next morning).

Second, an aircraft flyover was identified as such, based on the condition that SPLs had to remain 10 dB (dBs from now on) above the L_{20} for at least 5 s, and no longer than 120 s. This ensured that sounds other than those emanated from airplanes were selected for further analysis. In some cases, SPLs exceed the threshold value for a prolonged period, e.g. in case of engineering works or rain. Based on a first manual analysis of the data, it became clear that the audibility of airplane flyovers was normally not longer than a minute, after which a save cut-off value of 120s was chosen.

Third, meteorological data from the nearby weather mast at Schiphol airport was linked to the measurements. The database contains information about precipitation and wind velocity, which was used to exclude sound events coinciding with rainfall and very strong wind speeds (>17 m/s).

As a final step, the local weather data, flight data and the acoustical measurements were combined. If all criteria were met, a sound event was selected for further analysis, and the maximum SPL (L_{Amax}) during the sound event was calculated. Based on the time stamp linked to the L_{Amax}, the code screened the radar data to see if any flights flew near the field lab within a radius of 1500 m near the time the L_{Amax} was registered.

To perform this step, the resolution of the flight and acoustic datasets was synchronized first, by applying a linear extrapolation of the data between points from 4 s to 1 s. First, the code screened which flights flew within a radius of 15 km around the field lab, and at an altitude lower than 1100 m. If any flight(s) were found, the code checked whether the flight(s) had passed a smaller area close to the field lab around the time a sound peak was registered. The box was based on a square formed by four geo-coordinates, corresponding to a smaller area than the radius of 1500 m used in the first step.

If all conditions were met, for each sound event, a window of ± 30s around the L_{Amax} was drawn. Only the data falling inside this window were analysed, and for each microphone the L_{Amax} and A-weighted

Table 1
Mean values and standard deviation for the flights analysed, based on the distribution of the weather data, and distance to the field lab, and height of airplanes, at the loudest point during a flyover.

Flight procedure		Wind direction (degrees)	Wind speed (meter/second)	Temperature (degrees Celsius)	Air Pressure (Pa)	Humidity (percentage)	Distance (meter)	Altitude (meter)
Arrivals	μ	160.6	2.7	5.3	10249.6	90.0	1360.3	211.6
	σ	123.9	1.6	3.4	122.3	7.9	333.0	25.4
Departures	μ	206.2	5.1	6.6	10167.4	88.0	1067.9	537.3
	σ	55.8	2.8	3.8	127.9	7.6	374.2	119.7

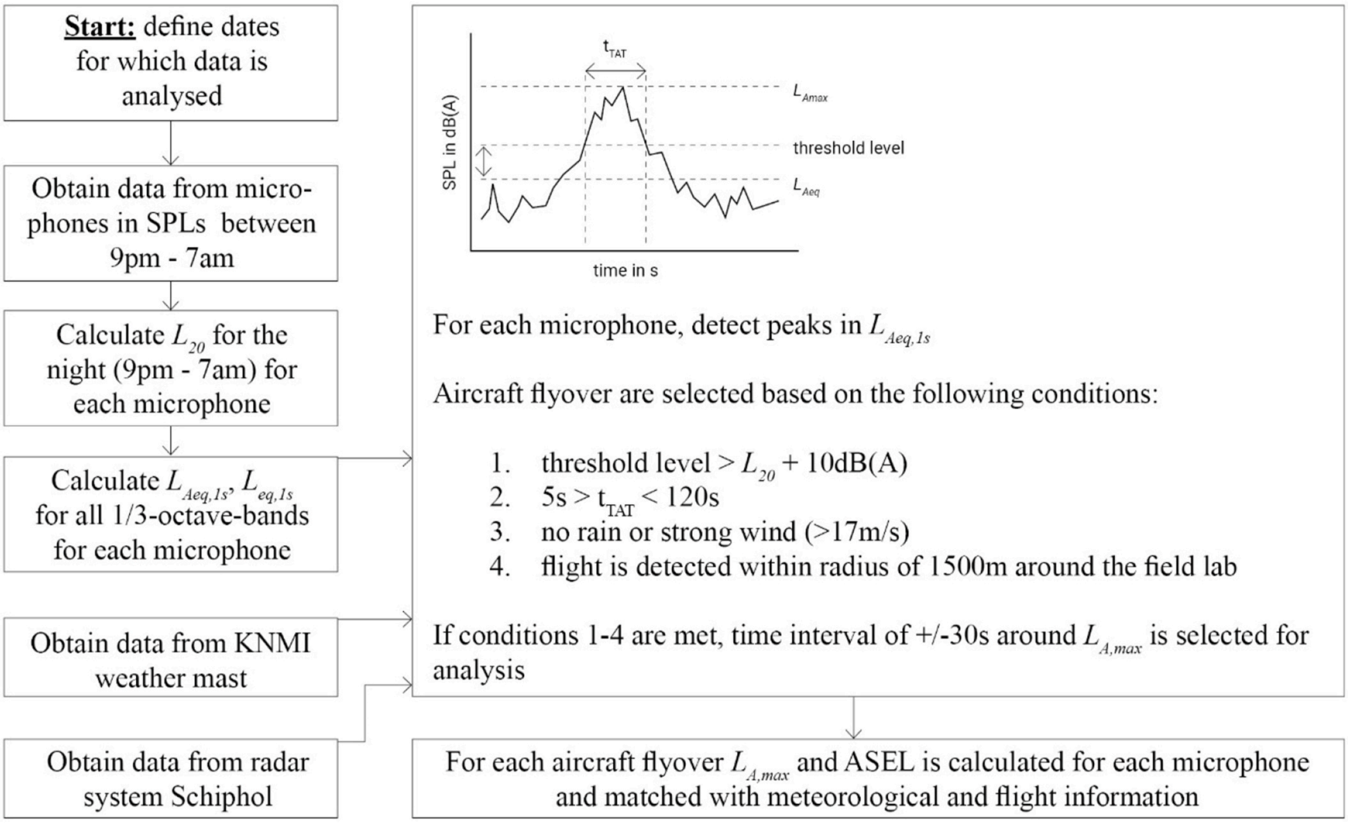

Fig. 7. Diagram showing the different steps of the analyses.

sound exposure level (ASEL from now on) were calculated, aside the L_{max} and SEL values for five octave bands (63Hz, 125Hz, 250Hz, 500Hz, 1000Hz). $L_{(A)max}$ and (A)SEL are common indicators in aircraft noise studies, see e.g. Refs. [7,29] Based on the altitude and geographic coordinates, a slant angle was determined based on the time stamp of the L_{Amax}.

3. Results

3.1. Variation in weather, position, and aircraft types

The data which was analysed for this paper was collected between 27th October 2021 and 3rd March 2022. In total 2383 aircraft flyovers were selected for further analysis, comprised of 508 arrivals and 1875 departures.

Table 1 shows the variation of the weather, the distance between the

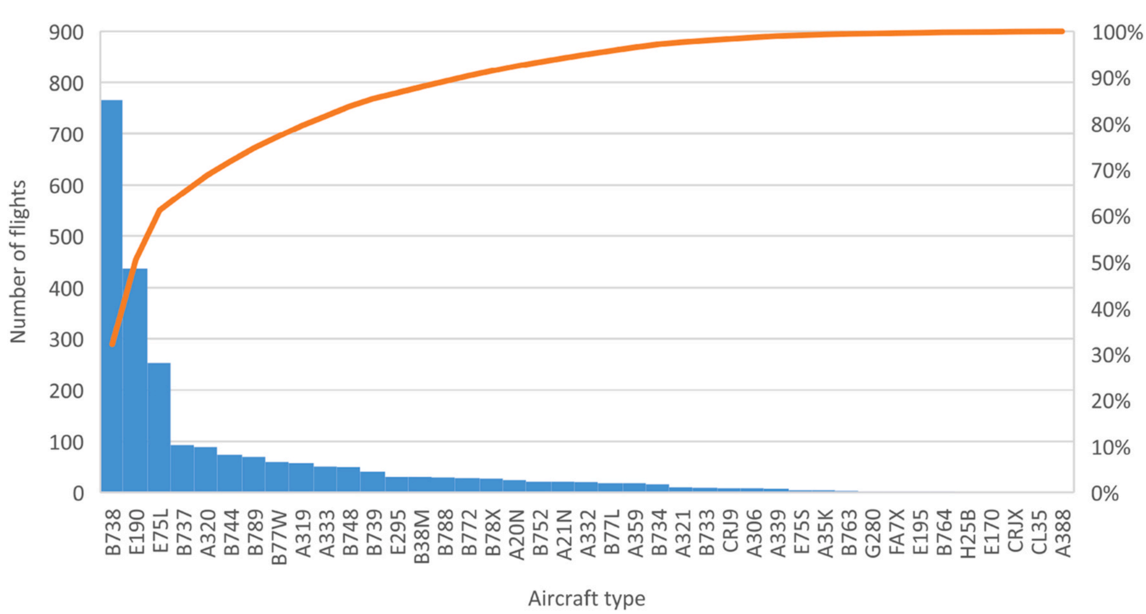

Fig. 8. Distribution of aircraft types for the total 2382 flights that were analysed in this study.

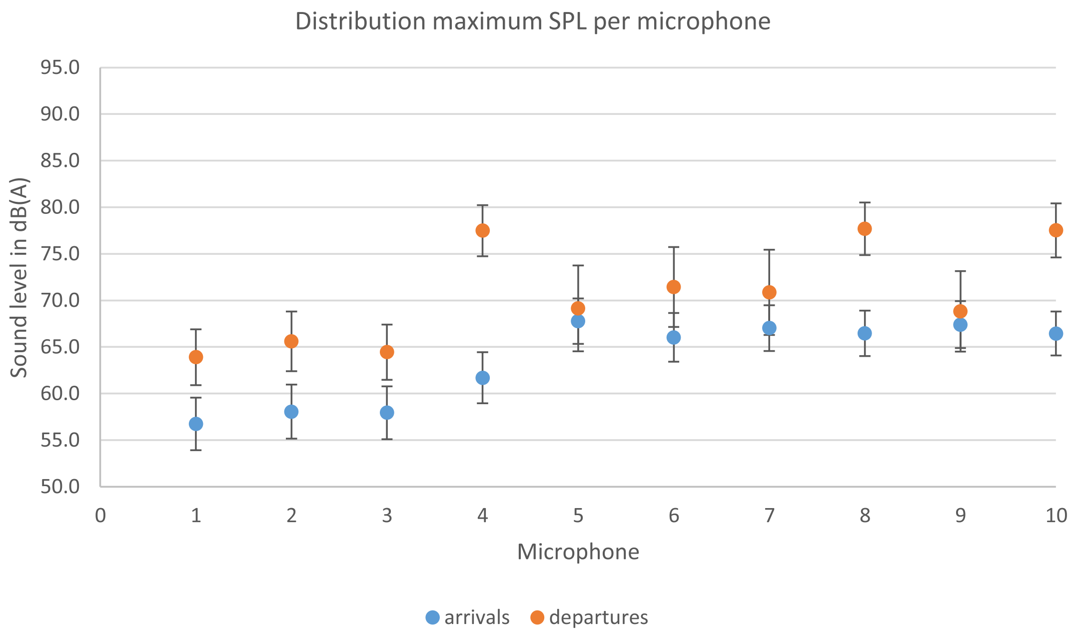

Fig. 9. Distribution of maximum sound pressure level per microphone (A-weighted).

ground paths of the airplanes and the field lab, and the altitude of the airplanes, for all flights that were analysed in this study. Seasonal variations are relevant for the propagation of sound in outdoor settings, as e.g. wind speed, wind direction, and surface-air temperatures affect atmospheric refraction and the normal of the wave front [31,32]. On average, the altitude of the airplanes varied between 537 m for departures and 211 m for arrivals. Ascending airplanes also flew closer to the field lab compared to landing airplanes. Based on radar data, it was found that the most common airplane type was the Boeing 737–800 (B738), followed by the smaller Embraer 190 (E190) and Embraer 175 (E75L) types, see Fig. 7.

3.2. Variation in maximum sound levels and sound exposure levels

Figs. 8 and 9 show the distribution of the A-weighted maximum sound pressure level (L_{Amax}) and ASEL for all flights. The figures plot the mean values, and the standard deviation around the mean value (error bars), separating arrivals and departures. The figures show that generally, courtyard 1 with the slanted roof (*mic 1, 2, 3, 4*) is exposed to less (aircraft) sound than courtyards 2 and 3 with regular flat roofing (*mic 5, 6, 7, 8, 9*). Comparing the results between courtyards, it was also found that for departures, sound levels are lower for microphones which are placed near facades facing away from the airplanes, i.e. *mic 1,2,3,5,6,7,9*. For arrivals, however, the direction in which facades face do not seem to yield a comparable result. Figs. 6 and 7 also seem to suggest that the building overhangs above microphones 1,2 and 5 enhance the level of sound abatement.

The results for the variation in maximum sound levels between the ten microphones were analysed by means of a repeated measures ANOVA design and Bonferroni post hoc tests. It was found that the results between microphones were significantly different ($F(9,23820) = 2560, p < .001, r = 0.70$), except for microphones 1 and 3 ($p = 1.000$), for microphones 5 and 9 ($p = 1.000$), and for microphones 8 and 10 ($p = 1.000$). Separate ANOVAs for arrivals and departures led to slightly different results. For departures, it was found that the results between microphones were significantly different ($F(9,18740) = 5043, p < .001, r = 0.84$), except for microphones 1 and 3 ($p = 1.000$), for microphones 5 and 9 ($p = 1.000$), and for microphones 8 and 10 ($p = 1.000$). For arrivals, it was found that the results between microphones were significantly different ($F(9,5070) = 1744, p < .001, r = 0.86$), except for microphones 5 and 9 ($p = 1.000$), for microphones 6 and 8 ($p = 0.438$) and 6 and 10 ($p = 0.137$), for microphones 7 and 8 ($p = 1.000$) and 7 and 9 ($p = 0.980$) and 7 and 10 ($p = 1.000$), for microphones 8 and 10 ($p = 1.000$), and for microphones 9 and 10 ($p = 0.109$).

In the first courtyard, the largest differences were found between microphone 1 and 4 (13.6 dB(A)), based on the mean values for the maximum SPLs for departures. Under the same conditions, in the second and third courtyards, the largest differences were found between microphone 9 and 10 (8.7 dB(A)). These differences are lower or even reversed for arrivals, respectively 4.9 dB(A) for courtyard 1 (microphones 1 versus 4), and −1.3 dB(A) for courtyard 2 (microphones 5 versus 8).

The shielding effect was further analysed for five octave bands (63Hz, 125Hz, 250Hz, 500Hz, 1000Hz). The mean values and the standard deviations for the $L_{A,max}$ and ASEL are shown in Table 2. The table shows that the differences between courtyards and microphones are largest for higher frequencies compared to lower frequencies. For the 63Hz octave band, the differences between *d*LOS and *n*LOS facades are similar across the three courtyards. The differences are on average smaller than 5 dB(A), based on the $L_{A,max}$. The differences between the three courtyards, based on a comparison of the results of microphones 1–3, 5–7, 9, become clearer for frequencies above 500Hz.

3.3. Spectral analysis and differences between microphones

The distribution of sound energy across frequencies was further analysed with spectrograms. Fig. 11 show the spectrogram of a single flight which was randomly selected from the dataset (see Fig. 12).

The SPL per second for the same flight are displayed in Fig. 10. Both the spectrogram and the graph show that sound levels increase for all microphones following a similar trend during the first 10–15 s. After 15 s, sound levels further increase for microphones 4,8 and 10, but stabilize for microphones 1,2,3 and 6, or drop for microphone 5,7 and 9. After 30–35 s, sounds levels steadily decay all microphones. Data from the radar system showed that the airplane flew perpendicular to the field lab around 10:36:35, which corresponds to the sound peaks in Fig. 11. Around this time, the horizontal ground distance between the airplane and field lab was approximately 760 m with a flight altitude around 400 m. This corresponds to a slant angle of ≈26°, which is slightly greater than the threshold angle required to see passing airplanes from the

Table 2
Mean values and standard deviation for the L,Amax (dB(A)) and ASEL (dB(A)) per 1/3-octave band. A: arrivals; D: departures.

			Microphone number									
			Mic 1	Mic 2	Mic 3	Mic 4	Mic 5	Mic 6	Mic 7	Mic 8	Mic 9	Mic 10
63Hz												
ASEL	A	μ	71.3	70.0	72.1	73.3	73.7	71.5	73.8	74.8	73.8	75.0
		σ	3.7	3.4	4.2	3.3	3.3	3.2	3.5	3.1	3.1	3.1
	D	μ	81.4	81.7	81.9	84.4	80.8	80.6	81.1	84.9	81.6	85.4
		σ	3.8	3.8	3.9	4.0	3.8	3.7	3.8	4.1	3.9	4.1
L_{Amax}	A	μ	59.6	58.8	60.4	62.9	62.6	60.0	62.6	63.7	62.6	64.1
		σ	4.4	4.1	5.1	4.1	3.9	3.8	4.1	3.8	3.7	3.9
	D	μ	70.9	70.7	71.1	74.0	69.5	69.5	70.8	74.6	70.3	74.9
		σ	4.4	4.5	4.6	4.5	4.3	4.5	4.5	4.6	4.6	4.6
125Hz												
ASEL	A	μ	70.2	69.5	69.9	70.7	72.5	73.3	72.1	73.1	72.3	73.2
		σ	2.8	2.6	2.8	2.8	2.5	2.4	2.4	2.5	2.5	2.7
	D	μ	79.4	78.6	78.8	85.1	78.5	80.5	79.4	85.1	79.3	84.1
		σ	3.2	3.3	3.1	3.9	3.5	3.7	3.2	4.1	3.2	3.9
L_{Amax}	A	μ	57.7	57.0	57.4	59.7	62.1	63.2	60.9	61.1	61.2	61.5
		σ	3.0	3.2	3.1	3.5	2.8	2.8	2.9	3.1	3.0	3.3
	D	μ	68.9	67.2	67.4	75.7	67.7	70.1	69.2	75.4	68.2	74.4
		σ	3.8	3.7	3.8	4.2	4.4	4.5	4.1	4.6	3.9	4.4
250Hz												
ASEL	A	μ	61.7	64.5	62.5	69.1	66.6	68.0	67.5	69.9	67.1	69.6
		σ	2.3	2.3	2.1	2.3	2.2	2.2	2.2	2.3	2.2	2.3
	D	μ	71.1	73.2	70.5	82.2	72.1	75.0	73.1	82.0	73.5	81.7
		σ	2.9	3.1	2.8	3.2	3.3	2.9	2.7	3.2	3.0	3.1
L_{Amax}	A	μ	57.7	57.0	57.4	59.7	62.1	63.2	60.9	61.1	61.2	61.5
		σ	3.0	3.2	3.1	3.5	2.8	2.8	2.9	3.1	3.0	3.3
	D	μ	68.9	67.2	67.4	75.7	67.7	70.1	69.2	75.4	68.2	74.4
		σ	3.8	3.7	3.8	4.2	4.4	4.5	4.1	4.6	3.9	4.4
500Hz												
ASEL	A	μ	60.0	63.1	60.3	66.6	73.9	72.2	72.2	72.2	73.4	71.4
		σ	2.3	2.4	2.2	2.4	2.5	2.4	2.5	2.3	2.6	2.3
	D	μ	67.1	70.0	66.9	77.9	72.3	74.5	72.8	78.1	72.1	79.1
		σ	2.7	2.8	2.5	3.1	3.7	3.9	4.0	3.3	3.4	3.2
L_{Amax}	A	μ	57.7	57.0	57.4	59.7	62.1	63.2	60.9	61.1	61.2	61.5
		σ	3.0	3.2	3.1	3.5	2.8	2.8	2.9	3.1	3.0	3.3
	D	μ	68.9	67.2	67.4	75.7	67.7	70.1	69.2	75.4	68.2	74.4
		σ	3.8	3.7	3.8	4.2	4.4	4.5	4.1	4.6	3.9	4.4
1000Hz												
ASEL	A	μ	60.7	60.8	61.6	63.6	69.6	68.4	69.7	68.2	69.4	68.6
		σ	2.3	2.4	2.3	2.4	2.2	2.3	2.3	2.2	2.3	2.4
	D	μ	66.4	67.8	64.7	77.0	70.2	71.1	70.8	77.9	70.2	77.5
		σ	3.0	3.1	2.6	3.0	3.5	3.3	3.3	3.0	3.2	3.0
L_{Amax}	A	μ	57.7	57.0	57.4	59.7	62.1	63.2	60.9	61.1	61.2	61.5
		σ	3.0	3.2	3.1	3.5	2.8	2.8	2.9	3.1	3.0	3.3
	D	μ	68.9	67.2	67.4	75.7	67.7	70.1	69.2	75.4	68.2	74.4
		σ	3.8	3.7	3.8	4.2	4.4	4.5	4.1	4.6	3.9	4.4

position of microphones facing towards the flight path (to see the airplane from microphones 4,8 and 10 the slant angle is at least 21°). Till 10:36:30 the slant angle is smaller than 21°, which means that, de facto, none of the microphones has a direct line of sight towards the airplane. However, the figures also show that sound levels near *n*LOS microphones, i.e. microphones 1–3, in courtyard 1 are substantially lower compared to *n*LOS microphones in courtyard 2. The spectrogram for microphones placed in front of *d*LOS facades, namely, microphones 4,8 and 9, clearly show Doppler shifts and tonal components. Although that Doppler shifts and tonal components are also visible in the graphs that display the results for *n*LOS facades, the energy is more spread out across different frequencies, which may be linked to spectral broadening. Especially for microphone 1, frequencies above 300Hz contains less energy compared to microphones 4, 8 and 10. The results in Fig. 10 confirm that the buildings induce a shielding effect across the full frequency range, including lower frequencies. However, the level of shielding depends on the surrounding geometry of the courtyard, with a greater level of shielding in the courtyard with a slanted roof, i.e., for microphones 1–3.

4. Discussion

In this paper, the results of in-situ measurements studying the reduction of aircraft noise in three courtyards were presented. The underlying research objectives were:

- To examine if sound levels vary around buildings exposed to aircraft noise, and to what extent this leads to a ‘quiet’ building side.
- To examine if the variance in sound levels is linked to the shape of buildings.

4.1. Sound shielding

Firstly, the results show that buildings can reduce aircraft noise, but that the reduction depends on the geometry of the surrounding buildings and the flight procedure. For departures, the results show a clear and significant difference between microphones near facades with (*d*LOS) and without (*n*LOS) a direct line of sight towards the flight paths, for all three courtyards. However, for arrivals, these differences are only significant for the courtyard with a slanted roof, and not for the two courtyards with straight walls. For departures, the relative differences

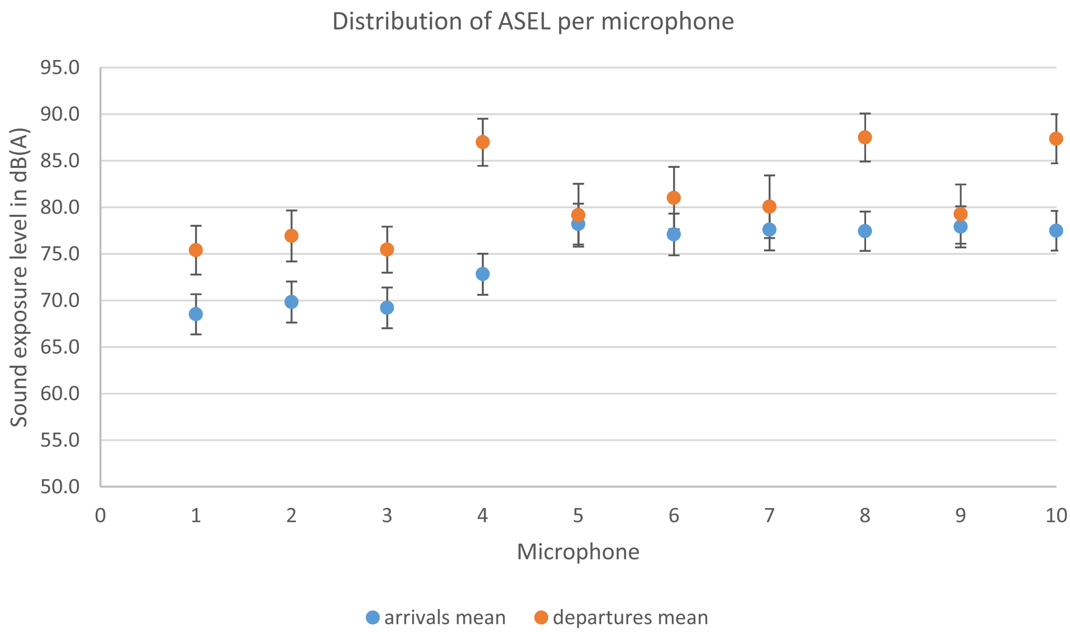

Fig. 10. Distribution of (A-weighted) sound exposure level (ASEL) per microphone.

between *d*LOS and *n*LOS facades well exceeded 10 dB(A), which is seen as an indicator for a quiet building side [10,13]. For arrivals, the relative differences between *d*LOS and *n*LOS facades only exceeded 10 dB(A) if the results between a courtyard with a slanted roof and a straight wall are compared. On the contrary, the sound levels remained similar at both ends of the courtyards, probably because of the shallow angle of the incident sound waves, which means that sound energy reaching the probes emanates from reflected sound waves. The results suggest that the overall sound pressure level around the probes mainly depends on the reflected sound inside the courtyard, and to a lesser extent on the sound that diffracts around the roof edges. This is illustrated by the relatively small differences between e.g. microphones 1 and 2, and microphones 5 and 6, even though the differences are statistically significant.

Compared to a previous study by Flores et al. [34], the shielding effects of buildings presented in this study are substantially greater. These deviations could be explained by the differences between research methods used in this and the study by Flores et al., but also by the relatively great slant or elevation angles. For example, the study reported in this article examined the relative differences between *d*LOS and *n*LOS microphones simultaneously during single aircraft flyovers. Previous studies compared *d*LOS and *n*LOS facades by comparing two datasets with separate results for the relative differences between microphones near a building and a microphone placed away from reflecting surfaces (free field measurement) [34].

4.2. Quiet building sides

It is yet unclear if a reduction of 10 dB(A) or more between *d*LOS and *n*LOS facades leads to a similar drop in annoyance ratings as previously found for road traffic. In terms of annoyance ratings, for most microphones in the courtyard with a slanted roof, the maximum sound pressure levels were lower than 65 dB(A) on average. Aircraft flyovers with a maximum sound level above 65 dB(A) are seen as an indicator for noise annoyance from aircraft flyovers [7]. For departures, sound pressure levels reduced across the five octave bands scrutinized in study, although the reduction becomes larger for higher frequencies. It is however recommended to observe caution in extrapolating these results to other locations. The results depend on flight procedures, e.g. routing and altitude, and meteorological conditions, e.g. wind speed and wind direction.

Aside from the maximum sound pressure levels, the results for the sound exposure levels show that the buildings also reduce the duration of exposure to severe levels of aircraft noise. The spectrograms confirm that near *n*LOS facades the sound energy is substantially lower for frequencies above 200Hz and contains less tonal components compared to *d*LOS facades. The tonality of aircraft noise is seen as a marker for the identification of aircraft noise, and is correlated with the level of annoyance [39].

4.3. Low-rise urban contexts

Secondly, the results show that for low-rise urban contexts, the shape of streets and buildings influences the sound pressure levels near facades. The results show that a slanted roof deflects sound from a courtyard, which leads to sound pressure levels significantly lower compared to courtyards with straight walls, at least, for the case study and site presented in this study. Despite the variance in shielding, this conclusion does not depend on the flight procedure or the angle at which sound enters the courtyards. However, building insets yield no significant reduction of sound levels inside the courtyards. This conclusion is supported by the results from the statistical tests, which showed no significant differences between microphone 1 and 3, and 5 and 9, which are equal for both arrivals and departures. This means that both the inset in courtyard 2, and the inset in courtyard 1, which sits even further pushed back away from the main façade, yielded no clear additional sound abating effects. The outcome of the statistical tests suggest that insets induced no significant additional shielding effect independently from the directionality of incident sound. Further research is recommended on this specific topic, comparing different slant angles, meteorological conditions and canyon configurations.

4.4. High-rise urban contexts

The results of this study do not shed light on the Influence of building density and height. The results show that reflections between the walls negate the differences between the microphones at eye level. Increasing the urban density, i.e. reducing the distance between the walls, will reduce the probability that probes are exposed to direct sound emitted by the airplanes. This may lead to lower sound pressure levels, although

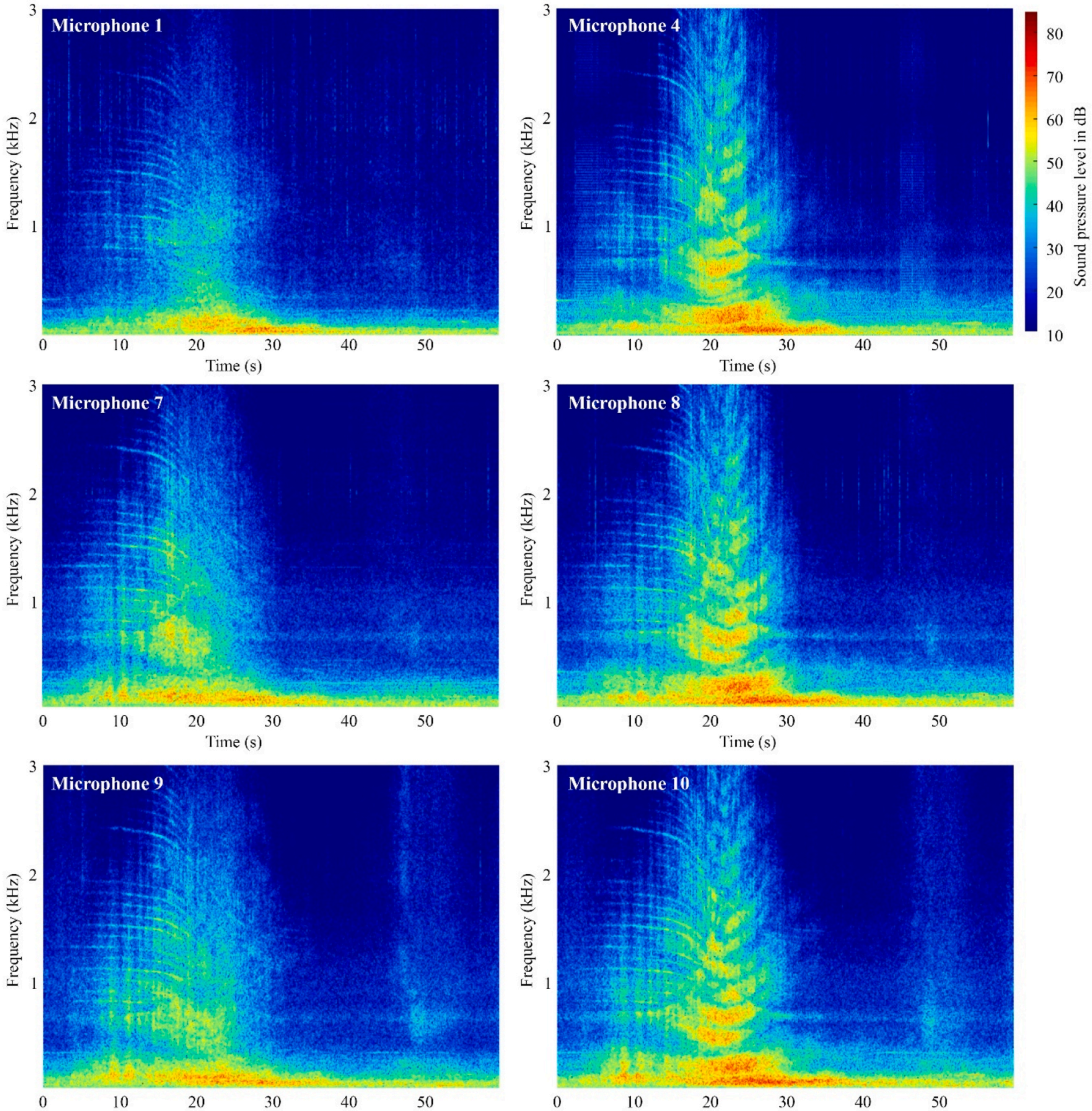

Fig. 11. Spectrogram for four microphones for a randomly selected flight: Boeing 777-200LR, departure time 10:35:51 on March 1st' 2022.

these effects might be partially negated as more narrow walls may keep the sound trapped, prolonging reverberation. This is important to reiterate that the experiment presented in this paper does not give answers to the height-related queries. Further research is also needed to examine if the variance in the measurements relates to weather conditions and e.g. airplane types.

4.5. Other limitations and recommendations for future research

As mentioned before, the results presented in this article relate to the location and context of the experiment, which differs from real urban environments in various ways. First, buildings are rarely made from shipping containers, and the acoustical properties of corrugated steel are different compared to facades comprised of glass, bricks, timber or concrete. It is therefore important to carry out more research on the influence of surface materials and other facades shapes in the light of this study. Second, the experiment exclusively focussed on low-rise urban contexts, while it remains unclear how other urban design variables, such as density and height affect noise shielding properties of buildings. Third, although we compared the results with literature on noise annoyance and quiet building sides, it remains unclear if a relative difference between exposed and shielded facades affect aircraft noise annoyance ratings similarly. The results show that high frequency sound is more effectively reduced than lower frequencies. This means that the

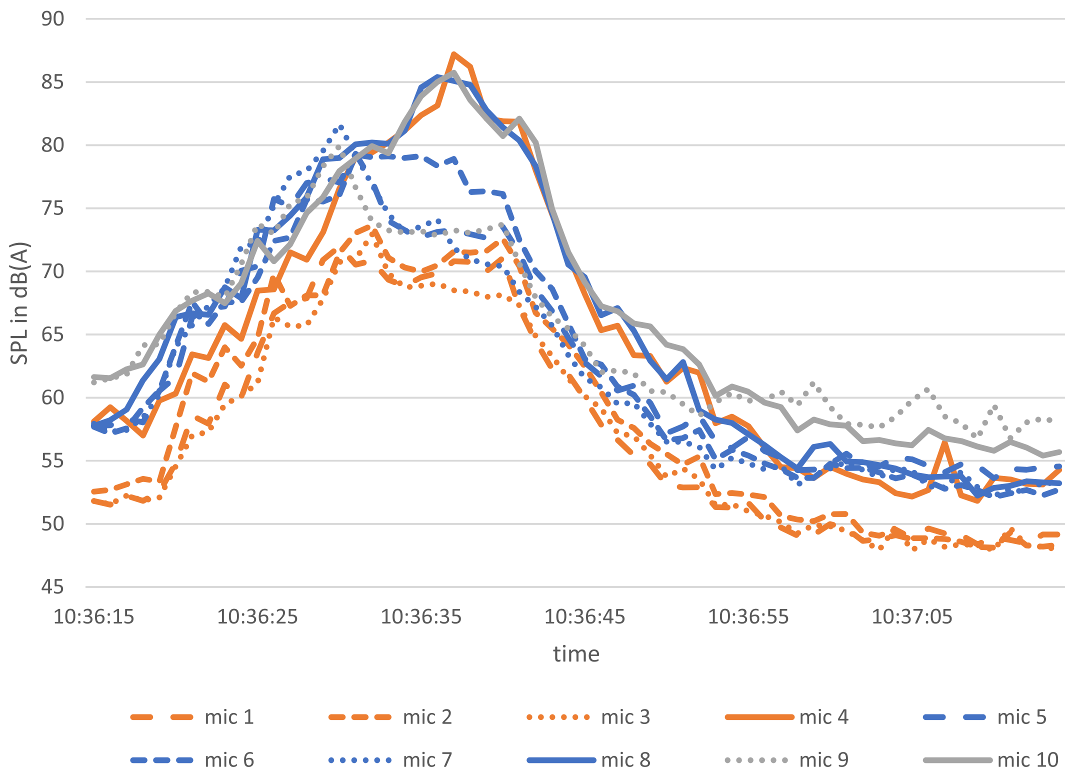

Fig. 12. Sound pressure level for a randomly selected flight: Boeing 777-200LR, departure time 10:35:51 on March 1st' 2022.

characteristics of airplane noise depend on the position in relation to a facade. It is not clear if this changes human perception of airplane noise, which can be studied in controlled settings deploying e.g. listening tests. Based on this study, we also believe that it is necessary to examine how the built environment can be simulated in aircraft noise prediction models. We see this as an important step to assess the influence of urban morphological variables on noise annoyance and (other) health indicators. We believe that these steps are essential before the results can be turned into policies and noise mitigation strategies.

5. Conclusion

To conclude, the results of the study presented in this article show that, for the case study and location studied, a slanted roof deflects incident aircraft noise, significantly reducing sound levels inside courtyards and near façade facing away from the flight paths. The study shows that, within a single street, depending on e.g. sound directionality and the visibility of the source, local differences can be substantial, in some cases >10 dB(A) for departures. Caution must be observed when applying these results to other locations due to the influence of flight-related and meteorological variables.

The results in this study do not support building overhangs or insets as an architectural design strategy to mitigate aircraft noise, at least not at locations similar to the case study location presented in this article. In general, the findings support the argument that the built environment affects the propagation of aircraft noise considerably. The findings also underline the importance to include the built environment in aircraft noise prediction models, . The results stress the important of urban and architectural design, underling the important to develop decision support tools to evaluate the impact of design proposals on aircraft noise exposure in urban areas.

CRediT authorship contribution statement

Martijn Lugten: Writing – original draft, Supervision, Data curation, Conceptualization. **Gustaf Wuite:** Writing – review & editing, Data curation. **Zhikai Peng:** Writing – review & editing, Resources. **Martin Tenpierik:** Supervision.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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