Global sensitivity analysis of the Doc. 29 aircraft noise model

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Abstract

Aircraft noise contours are a commonly used tool in land use planning. Several best-practice aircraft noise models are available to predict such contours. Among them, the ECAC Doc. 29[1] model is widely used both for regulatory purposes within the EU and for research purposes. However, two challenges arise in the application of the model: first, the model provides only guidelines for certain modeling features, such as the consideration of turns within the aircraft trajectory, but no clear rules. Thus, a certain modeling uncertainty needs to be attributed to the results obtained. Second, the input data used to compute the noise contours inherently includes uncertainties. Both model and parameter uncertainties affect the computational results and need to be accounted for when applying the model. This contribution aims to address the influence of these uncertainties by performing a global sensitivity analysis on the Doc. 29 model. This method can support quantifying the influence of these aspects on the model output and thus could provide valuable insights into the reliability of the model. Moreover, guidelines for the model application could be derived and approaches for a model improvement could be identified.

Framework

Within the course of research project A2.4 of the Cluster of Excellence "Sustainable and Energy-Efficient Aviation" SE^{2}A, the Doc. 29 aircraft noise model was implemented as an in-house research code and verified with the provided test cases [2]. To calculate the sound exposure level of specific flight events (take-offs or landings), several inputs are needed. To generate these inputs, two in-house tools were developed. The Flight Performance Calculator computes the flight profile based on equations provided by Doc. 29, while the Ground Track Generator was developed to produce ground tracks in a Doc. 29 compatible format. These tools were integrated into a comprehensive framework (see figure 1), allowing the model to be run repeatedly with variations in both the input data and specific model features. The resulting outputs are then used to calculate the sensitivity indices. In the following section, the input parameters are discussed in more detail.

Input parameters

The flight profile provides information about the altitude of an aircraft during its trajectory as well as its thrust level and velocity. The aerodynamic and thrust equations necessary to calculate this profile for typical standard procedures as defined by EASA are provided by Doc. 29. However, two uncertainties have been identified within this calculation and will be addressed within the sensitivity analysis. Firstly, when calculating take-off profiles, the maximum take-off mass (MTOM) of the aircraft is required. This mass is typically estimated based on the length of the trajectory and the aircraft type. According to [3], this estimation can be expected to have an error of approximately 4.3 %. Additionally, it is up to the user to decide whether the effects of turns should be considered in the flight performance calculations [2].

The ground track represents a projection of the aircraft's trajectory onto a horizontal plane. To comply with the Doc. 29 calculation procedure, it must be

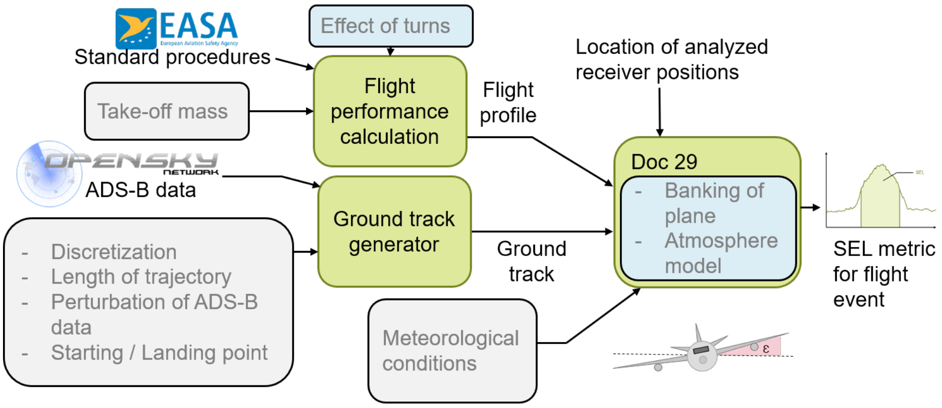

Figure 1: Overview of the Modeling framework

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[1] ECAC Doc 29 4th Edition; Report on Standard Method of Computing Noise Contours around Civil Airports; Volume 2, 2016

defined as a series of straight segments. To obtain the aircraft trajectory, ADS-B data or radar tracks are typically used. This study examines the case of using open source ADS-B data from the OpenSkyNetwork [1]. In order to convert the ADS-B data into a series of straight segments, the user must make several decisions, including the desired level of trajectory discretization (which determines the length of the segments), the length of the trajectory and the take-off and landing points. Estimating these points is crucial because the OpenSkyNetwork generally does not provide ADS-B data below a certain altitude for the analyzed airport, making it difficult to ascertain the take-off or landing points based solely on the data. Instead we estimated these points based on typical take-off and landing positions for the investigated airport. There is inherent uncertainty in this estimation, as individual flight operations can lead to deviations in actual take-off and landing positions. The range of this uncertainty (range A/D position) was estimated based on plausible deviations associated with the specific runway examined. Furthermore, we analyze how a perturbation of the Doc. 29 data, specifically displacements in x and y direction, impact the uncertainty of the modeling output. It is expected that 95 percent of all ADS-B data points fall within a 30 m range of the original trajectory [4]. Therefore, we examine a perturbation of up to 30 m.

Within the Doc. 29 noise model, the banking of an aircraft can be taken into account in the calculation of the lateral noise. Additionally, the document presents two possible atmospheric models for modeling atmospheric absorption during sound propagation from the source to the receiver. It also provides recommendations on when to use each model [2]. We therefore analyze the effects of varying the atmospheric model. The meteorological conditions (temperature, air pressure and relative humidity) are needed as inputs to calculate this atmospheric absorption rate and also to calculate the acoustic impedance correction factor. In practice, it is common to use annual averages for these values. In this sensitivity analysis, we examine how deviations from these average values impact the uncertainties of the model output.

In table 1 an overview of the uncertain parameters is given along with the variation range.

Table 1: Overview of the uncertain parameters and the variation ranges

Parameter	Variation
MTOM	±4,3%
Segment Length	[500 m, 5000 m]
Trajectory Length	[15 km, 30 km]
Temperature	[1 °C, 19°C]
Pressure	[100.6 kPa, 101.6 kPa]
Relative Humidity	[70%, 90%]
Range A/D Position	±450 / ±300m
Displacement x/y	±30 m
Effect of Turns	Considered or not considered
Bank Angle	Considered or not considered
Atmospheric Model	SAE AIR-1845 or SAE ARP-5534

Method

To conduct the sensitivity analysis, we employ a variance-based global sensitivity analysis method, specifically using Sobol indices. The first-order index S1 quantifies the contribution of an individual parameter to the variance of the output while keeping all other input parameters fixed. Its value can be used to identify which factor should be prioritized to reduce the uncertainty of the output. The total-order sensitivity index ST quantifies the overall contribution of an input parameter (both its individual effects and its interactions with all other input variables) to the output variance and can be used to determine which factors can be fixed without significantly reducing the uncertainty of the output [5].

Furthermore, we apply the Saltelli sampling method to sample the input space with a uniform distribution for continuous variables, binary variables are represented as 0 and 1. To determine the appropriate amount of samples for robust analysis, we conducted a convergence study for one of the analyzed trajectories. Based on the results that are visualized exemplarily for one trajectory and two measurement locations in figure 2, we concluded that N=256 samples are sufficient for this analysis.

For the sampling and the calculation of the Sobol Indices, we used the SALib toolbox in Python [6].

Analyzed Trajectories

This study examines the sensitivities of parameter variations on the noise exposure levels for individual flights, using Hannover Airport as a case study. It is planned for future work to compare modeling results with actual noise recordings, so we selected the actual measurement positions from the Hannover aircraft noise monitoring system (see figure 3) as receiver positions for the calculation of the sensitivities. We modeled noise emissions of three exemplary flights in 2022, with the trajectories of three flights shown in figure 3 and details on aircraft type, operation, and estimated take-off weight provided in table 2.

Table 2: Overview of the analyzed trajectories

Nr.	Aircraft type	Type of operation	MTOM
1	A321-232	Take-off	77100 kg
2	EMB175	Landing	38950 kg
3	737400	Take-off	65090 kg

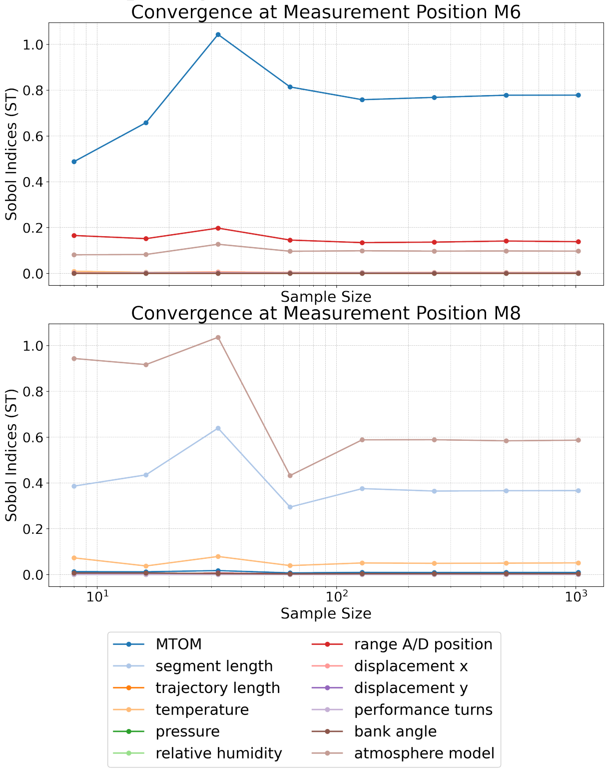

Figure 2: Convergence study of the sensitivity analysis framework for an exemplary trajectory at two measurement positions

Results

To perform both a Factor Prioritization and a Factor Fixing study, it is essential to analyze both the S1 and ST indices, as outlined in the method section. However, the ST values exhibit only minor differences from the S1 values (with a maximum difference of 0.06), and the ranking order remains consistent across the three analyzed trajectories. This indicates that there are only minor interactions between the variables. Therefore, this paper documents only the ST values of the analyzed trajectories. Thereby, a color code marks the sensitivity with darker color indicating a higher sensitivity. The measurement positions in the tables represent the assumed most critical points for the analyzed trajectory.

In the analysis of trajectory 1 (see table 3), we observe that for measurement point 6 the MTOM and the take-off position range are the most sensitive input parameters. This makes sense, as this point is situated close to the runway and, consequently, near the aircraft's take-off position. At this location, the aircraft is at a relatively low altitude, meaning that variations in altitude due to the aircraft's mass have a large impact. For the other two positions, the atmospheric model is the most sensitive input due to the greater distance between the measurement point and the aircraft and thus the greater propagation distance during this segment of the flight. Furthermore, for position 8, the segment length is the second most sensitive input. This makes sense as well because this point is near the curve, so the degree of discretization has a large effect on this position. Across all measurement positions, the model is not sensitive to the perturbation of the ADS-B data, the bank angle, the effect of the turns on the performance calculations, the atmospheric pressure or the trajectory length.

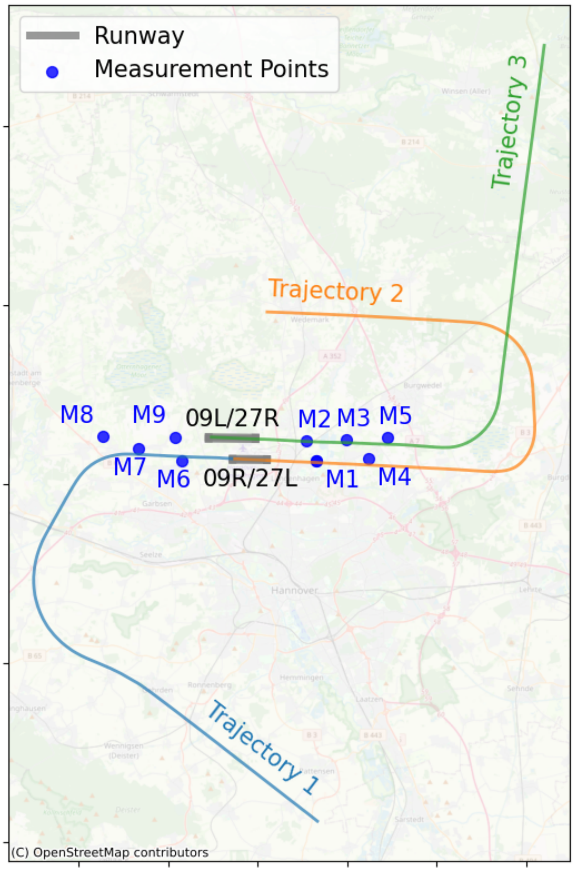

Figure 3: Trajectories at the Hannover airport that were utilized for sensitivity analysis

In the analysis of trajectory 2 (see table 4), across all measurement positions, the atmospheric model is the most sensitive input. In contrast to the other two trajectories (see tables 3 and 5), we can observe that the displacement in y direction is a sensitive input to two of the measurement positions (M1 and M4).

In the analysis of trajectory 3 (see table 5) we have similar results to trajectory 1 (see table 3), which is also a take-off, in the sense that the MTOM and the range of the A/D position are sensitive inputs for the measurement point near the runway (M2). Otherwise, the atmospheric model is the most relevant input for all points.

Based on the analyzed parameters within the range defined in table 1, the most critical parameter for factor prioritization is which atmospheric model is used within the modeling. In addition, the MTOM, the range of the landing point/starting point and the segment length are important inputs for specific measurement points. Factors that can be fixed without significantly affecting the uncertainty of the results

Table 3: Trajectory 1 - Take-off of A321-232 - Sensitivity Index Heatmap (ST)

	M6	M7	M8
MTOM	0.77	0.10	0.01
Segment Length	0.00	0.03	0.36
Trajectory Length	0.00	0.00	0.00
Temperature	0.00	0.03	0.05
Pressure	0.00	0.00	0.00
Relative Humidity	0.00	0.01	0.00
Range A/D Position	0.14	0.01	0.00
Displacement x	0.00	0.00	0.00
Displacement y	0.00	0.00	0.00
Effect of Turns	0.00	0.00	0.00
Bank Angle	0.00	0.00	0.00
Atmospheric Model	0.10	0.85	0.59

Table 4: Trajectory 2 - Landing of EMB175 - Sensitivity Index Heatmap (ST)

	M1	M2	M4
MTOM	0.00	0.00	0.00
Segment Length	0.00	0.00	0.00
Trajectory Length	0.00	0.00	0.00
Temperature	0.12	0.08	0.03
Pressure	0.00	0.00	0.00
Relative Humidity	0.03	0.00	0.01
Range A/D Position	0.12	0.01	0.05
Displacement x	0.00	0.00	0.00
Displacement y	0.07	0.02	0.08
Effect of Turns	0.00	0.00	0.00
Bank Angle	0.00	0.00	0.00
Atmospheric Model	0.75	0.92	0.86

Table 5: Trajectory 3 - Take-off of 737400 - Sensitivity Index Heatmap (ST)

	M2	M3	M5
MTOM	0.39	0.16	0.18
Segment Length	0.00	0.00	0.00
Trajectory Length	0.00	0.00	0.00
Temperature	0.04	0.09	0.10
Pressure	0.00	0.00	0.00
Relative Humidity	0.00	0.00	0.00
Range A/D Position	0.10	0.03	0.01
Displacement x	0.00	0.00	0.00
Displacement y	0.00	0.00	0.00
Effect of Turns	0.02	0.00	0.00
Bank Angle	0.00	0.00	0.00
Atmospheric Model	0.47	0.76	0.75

are the bank angle, the influence of this bank angle on the performance calculations, the perturbation of the ADS-B data in the x-direction, the length of the trajectory and the atmospheric pressure.

Discussion and Outlook

This preliminary study aims to understand how specific model inputs affect the uncertainty of the Doc. 29 aircraft noise model. However, a necessary next step is a similar study for a complex airport scenario for which Doc. 29 is intended to be applied, in order to improve the reliability of the reported sensitivities. In such a case, it would be valuable to investigate the impact of specific uncertainties on the noise contours of such a scenario and, more specifically, to identify the relationship between receiver position and trajectory that must be present to affect the significance of certain parameters. Given that the atmospheric model significantly impacts output uncertainty, future studies could examine the two atmospheric models separately. Comparing model uncertainties with measurement uncertainties might also yield valuable insights. Additionally, the impact of aircraft substitution correction, which is sensitive to uncertainties, remains an open question. Finally, the method used is highly dependent on the range of the input parameters. Therefore, the results of this study refer only to the variation within the specified range.

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