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Novel Approach to assess the link between engine design parameters and noise perception

Session: Human Response to Urban Air Mobility (UAM) Noise

David Straub, DLR* Institute of Data Science, Germany, david.straub@dlr.de
Stephen Schade, DLR Institute of Propulsion Technology, Germany, stephen.schade@dlr.de
Rahman Al Mahmudur, DLR Institute of Data Science, Germany, al.rahman@dlr.de
Susanne Bartels, DLR Institute of Aerospace Medicine, Germany, susanne.bartels@dlr.de

Recently, distributed electrified propulsion systems are being developed to power a new generation of aircraft. Here, the noise emission of the distributed propulsion system results from the noise emissions of the individual propulsors, their number as well as position. Thus, acoustic effects such as interferences, modulations and shadowing might significantly impact the noise characteristic. Therefore, on the listener's side, the specifics of the human auditory system lead to more complexities to perception of this noise. As a result, acceptance and annoyance due to a sound are not only associated to mere physical metrics (such as the EPNL) but also to psychoacoustic metrics (such as fluctuation strength and sharpness). In order to address this problem, we are developing a mobile app that will allow a large and diverse number of people to, firstly, set the engine parameters; secondly, hear the corresponding auralized sound; and thirdly, rate it using a standardised questionnaire. The goal is to uncover relationships between parameter configurations and psychoacoustic properties, allowing us to infer guidelines for the low-noise and perception-based design of new types of propulsion systems.

Keywords: Technology Acceptance, Research App, UAM, Electrified propulsion system, Noise

1. Introduction

Urban and advanced air mobility (UAM, AAM) represent a new form of transportation, enabling connections to locations with limited (airport) infrastructure and taxi operations close to settlements Rizzi (2020). Small aircraft could take over the role of such air taxi. Traditionally, those small aircraft are powered by no more than two engines. More recently, distributed electrified propulsion systems are being developed to power a new generation of

*German Aerospace Center

aircraft (Greenwood et al., 2022). Here, the noise emission of the distributed propulsion system results from the noise emissions of the individual propulsors, their number and position.

Generally, urban air mobility creates a new type of aviation noise. For instance, more engines are used compared to conventional aircraft, the sound source is considerably closer to the affected population and thus atmospheric attenuation effects play a minor role. This requires innovative technological solutions for the minimization of pollutant and noise emissions. Similar to drone noise, UAM noise therefore sounds unfamiliar and potentially unpleasant, so that the success of UAM vehicles strongly depends on the public's acceptance of the associated noise (Rizzi, 2020). Resulting acoustic effects include interference, modulation and shadowing (Pascioni & Rizzi, 2018; Guérin & Tormen, 2023), as well as the excitation of additional sound sources through boundary layer ingestion. On the listener's side, the specifics of the human auditory system (on an anatomical, neurofunctional and psychological level) lead to more complexities to perception of this noise. As a result, acceptance of and annoyance due to a sound is not only associated to mere physical metrics (such as the SEL [1]) but even more to psychoacoustic metrics. For example, highly fluctuating noise is rated as less acceptable at the same sound pressure level (Moorhouse, 2011). In studies on drone noise with multiple rotors, loudness and sharpness and again fluctuation strength have been reported to have an impact on psychoacoustic annoyance (Gwak et al., 2020). However, psychoacoustic findings from one type of aircraft - be it multicopter drones, conventional passenger aircraft or passenger aircraft with distributed electric propulsion systems - cannot easily be generalized to another. Significant differences might occur with regard to noise perception and noise annoyance. For instance, at the same sound pressure level (LAeq [2]), recorded sounds from conventional aircraft were reported to be less annoying than recorded (hovering) multicopter drone sounds (Gwak et al., 2020). Such differences in annoyance are often attributed to higher energy content in high frequencies and resulting higher sharpness in the sound of drones (Gwak et al., 2020; Torija & Clark, 2021; Lotinga et al., 2023). A major reason for less high-frequency band energy in conventional aircraft sound at an observer's position and comparably higher high-frequency energy in drone sounds is the distance of the vehicle from the observer and the more or less occurring attenuation of high frequencies due to the atmosphere (Torija & Clark, 2021; Lotinga et al., 2023). Assuming lower flight altitudes of UAM vehicles, psychoacoustics, above all sharpness, may play a larger role for the perception of UAM sounds. Such effects have already been investigated for UAM vehicles (Boucher et al., 2024; Schade et al., 2024) and drones (Torija & Clark, 2021; Lotinga et al., 2023; Schäffer et al., 2016). Nevertheless, to date, knowledge on the effect of psychoacoustic metrics (loudness, sharpness, roughness, fluctuation strength and tonality on annoyance due to drones and UAM as a total is limited an inconsistent. For instance, contrasting prior studies, a listening test using auralized UAM sounds did not find a significant association between sharpness and annoyance (Boucher et al., 2024). Moreover, listening test most often comprise rather small samples (e.g. 40 to 50 participants).

To overcome these drawbacks, we are developing a mobile app which can be used to conduct psychoacoustic analyses for user acceptance research in an economical, valid and flexible manner. This app combines a strong user experience with a high fidelity representation of the propulsion systems and their acoustics. Particularly, the method enables users to vary design parameters of the propulsion system, listen to the resulting noise and submit their auditory impression. The app allows a large number of people to be actively involved in the early stages of propulsion system development by contributing their evaluations of particular configurations. Since human auditory preferences are currently not often consid-

[1] Sound Exposure Level

[2] A-weighted, equivalent continuous sound level

ered in the acoustic design process, our motivation is to establish a database which we can use to examine links between the design of the propulsion system and the subjective sound perception (design-to-perceived-noise). This linkage is achieved through a physics-based and analytical process that involves: a) prediction of the engine noise sources, b) propagation of the noise emission through the atmosphere, c) auralization and d) evaluation of noise perception.

In the following section, we will introduce the theoretical foundations of and arguments for the app (over, for example, a conventional laboratory study).

1.1 Mobile Apps as a Research Method

Our motivation was to create a research method that allows listening tests and psychoacoustic assessments to be fast and easy to conduct and that allow the analysis of a large, representative sample of the population. The potential of involving citizens in the plannings of urban air mobility and transportation using mobile phone apps, e.g. via Participatory Noise Sensing, to achieve a high acceptance of UAM has been highlighted before (Eißfeldt, 2020).

One of the biggest challenges in the development of the app is to reach the largest possible representative sample of human participants and to design the app's functions and interface in such a way that various user groups would enjoy using it several times. The ubiquity of personal computers or smartphones has made possible study designs that engage a larger audience via non-monetary incentives. These designs often achieve a much larger and diverse sample (e.g. Spiers et al. (2023)), gain more public interest, and even become a long-term pastime for many participants (e.g. Foldit, Koepnick et al. (2019). They can be split into two main categories: studies in which the participants themselves are the objects of research, and those in which participants contribute their time, skills and access to locations to the research of other objects. Examples for the first category are The Music Lab, a website where anyone can participate in ongoing auditory psychological research (e.g. on people's ability to infer the addressee of speech samples, Hilton et al. (2022)) or Sea Hero Quest, a viral mobile game which assessed spatial navigation ability across many age groups to further dementia research (Spiers et al., 2023). We consider the present study to fall into this category, but also consider valuable insights from the second category. This includes citizen science projects such as Foldit (Koepnick et al., 2019), in which participants solve protein folding problems in a puzzle-like application, or *Undercovereisagenten*, in which locals submit drone photographs of their region's geography to improve models for the detection of permafrost thawing (Mueller et al., 2023). The methods these studies use to interest and engage their participants are as varied as their topics, such that some of them may look like games (e.g. Spiers et al. (2023); Brown et al. (2014)) others like lab studies, but on the internet (e.g. Hilton et al. (2022)) and yet others almost like the professional software the researchers themselves would use (e.g. Koepnick et al. (2019)). Either way, the goal is to create content and interactions that intrinsically motivate to use the app. Following self-determination theory, content and interactions achieve this when they meet users' basic psychological needs - autonomy, competence and relatedness (Ryan & Deci, 2018). Users may experience autonomy if the app gives them creative choices and uses non-controlling incentives (as opposed to e.g. appealing to users' conscience to "do their duty" or arbitrarily restricting app functions). Competence may be experienced in solving a challenging task and by learning about topics of interest, relatedness by connecting to other contributors via social features. As a result, the app may attract users that would not participate in a laboratory experiment, and it might retain them for longer than a one-time monetary reward would.

Indeed, sample sizes are often larger and more diverse than in laboratory studies (Sauermann & Franzoni, 2015; Brown et al., 2014) (in an extreme example, Sea Hero Quest was downloaded 3.9 million times from 63 different countries (Spiers et al., 2023)). A great deal of psychoacoustic research has already profited from being "mobilised" in this way (Hilton et al., 2022; Jimenez et al., 2017; Teki et al., 2016). As novel aircraft will directly impact people in their normal living conditions, this kind of ecological validity is doubly important.

On the other hand, online studies raise concerns about participants' adherence to protocols, the veracity of their statements, distractions and other factors. Similarly, studies with engaging elements, be they colourful graphics, user choices and customization or even game mechanics, are suspected to lead to dubious contribution. Another concern is whether the device is even able to represent the research object (in our case, the acoustics of propulsion technology) with sufficient fidelity.

App design, research goals and engagement features all vary between studies, such that it is difficult to give a final verdict to these concerns. Nevertheless, reviewers have tested the validity of different apps on desktop browsers, mobile phones or other hardware (Gundry & Deterding, 2019; Belisario et al., 2015; Woods et al., 2015). Moreover, features that can threaten or improve validity have been identified (Gundry & Deterding, 2019; Keusch & Zhang, 2017). For example, scoring systems can lead users to perform the task quickly and without diligence in order to maximise their score Gundry & Deterding (2019).

Still, many questions about the effects of engagement features remain unanswered, and findings from past studies may not be easily applicable to our kind of app. In the following method section, we will show how we approached these concerns in practice.

2. METHODOLOGY

2.1 Auralization

A major requirement for this targeted app is the capability to auralize sounds resulting from different propulsion configurations and even small changes in their parameters. For this purpose, an analytical noise auralization framework is developed by the DLR Department of Engine Acoustics in order to support psychoacoustic studies and to examine how changes in the design of future aircraft engines may affect the human sound perception and annoyance (Moreau et al., 2023).

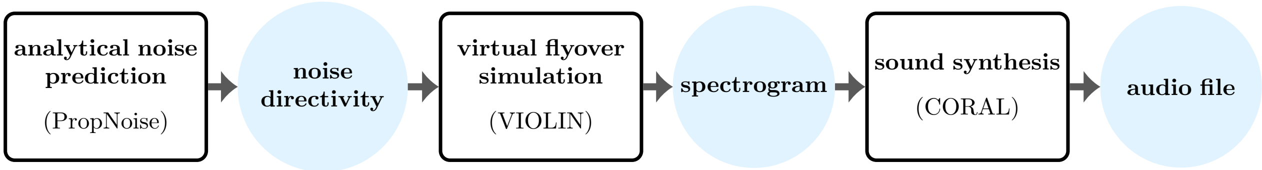

Figure 1: Tool chain for the simulation and auralization of aircraft noise emissions.

The auralization process is used to generate a data set of audio files for subsequent use within the app. A main advantage of the auralization framework is that the entire process is based on analytical models and thus, very short turnaround times are realized (≈ 5 minutes from source prediction to audio files). This allows to perform detailed parameter studies in affordable times and to provide comprehensive data sets for psychoacoustic studies. In particular, the auralization framework enables to investigate new propulsion systems and those designs that are still at an early stage within the development process.

However, as turnaround times of a few minutes are too long to integrate the auralization in a mobile app, the sounds are pre-generated, meaning that for every possible set of design parameters the auralization process is executed and the audio files are stored in a database. The design parameters (e.g. number of blades), which can be varied later in the app, are defined beforehand. For this purpose, the value interval and the step sizes are specified and physical relationships between different design parameters are taken into account. A variation matrix is then created from all design parameters, including intervals and step sizes, and an audio file is generated for each entry in the matrix (i.e. each design configuration) and stored in a database. The database is then made available to the app. This procedure also allows that further design parameters and additional audio files can be added easily by updating the database.

The general process chain of the auralization framework is shown in Fig. 1. The process chain consists of three steps: (1) analytical noise prediction with PropNoise (Propulsion-Noise), (2) virtual flyover simulation with VIOLIN (Virtual Acoustic Flyover Simulation) and (3) noise synthesis with CORAL (Aircraft Engine Noise Auralization).

PropNoise (Moreau, 2017), in its stand-alone version, provides an aerodynamic and an acoustic module. The aerodynamic module is based on a meanline approach to determine the steady and unsteady aerodynamic quantities, as for example pressure fields, wakes and turbulence. These aerodynamic flow perturbations are responsible for the generation of aeroacoustic noise sources inside the engine. Radial distributions of these aerodynamic quantities serve as an input for the acoustic module. The acoustic sources are then determined based on analytical models that rely on the Acoustic Analogy for both tonal and broadband noise sources. Afterwards, a module accounting for the propagation of sound through the engine and its radiation from the entry and exit planes calculates the noise directivity patterns for each source.

VIOLIN (Moreau et al., 2023; Dang, 2022; Prescher et al., 2023) uses the noise directivity patterns as an input to perform virtual acoustic flyover simulations in which the noise is propagated to specified observer positions. Besides the directivity patterns, the tool requires the specification of the airplane trajectory, the weather conditions as well as the engine and microphone positions. VIOLIN uses a frequency-domain approach to propagate the sound through the atmosphere and to determine the noise immission. Thereby, VIOLIN accounts for the Doppler frequency shift, atmospheric absorption as well as the reflection and attenuation of the sound waves on the ground. As a result, at each specified microphone, the spectrograms are determined for each noise source containing the frequency- and time-dependent sound pressure amplitudes.

CORAL (Moreau et al., 2023) allows to make the acoustic results audible and thus, provides a sound synthesis based on the spectrograms determined with VIOLIN. This means that the frequency- and time-dependent sound pressure amplitudes are converted into one-dimensional time series which are saved as Waveform Audio (.wav) files. CORAL offers a binaural noise synthesis meaning that one time series is determined for each ear, respectively.

Moreau et al. (2023) initially validated the noise auralization process by comparing the results of synthesized turbofan sounds with actual flyover measurements and Schade et al. (2024) initially applied the auralization framework to assess sound quality metrics for a distributed propulsion system equipped with 26 low-speed, ducted fans.

2.2 App Design

This section will describe the three base components of the app: the aircraft (propulsion system) configurator, the sound player and the rating scale. Together, they constitute a two-step interaction loop: the user acts by setting the engine parameters, the system reacts by playing the corresponding sound and prompting the user to rate it. Afterwards, the user acts again (rates the sound) and the system reacts again (provides positively reinforcing feedback, i.e. “Thank You” message) and finally the system state is updated and the user’s configuration and rating are saved.

On startup of the app, the user is presented with the “hangar” containing a list of already created aircraft configurations and buttons that respectively take the user to the aircraft configurator (“New Aircraft”), a detailed “expert”-view of the existing aircraft (wrench and screwdriver), the sociodemographic questionnaire (“Tell us about yourself”) and the progress screen (“Achievements”) (Fig. 2).

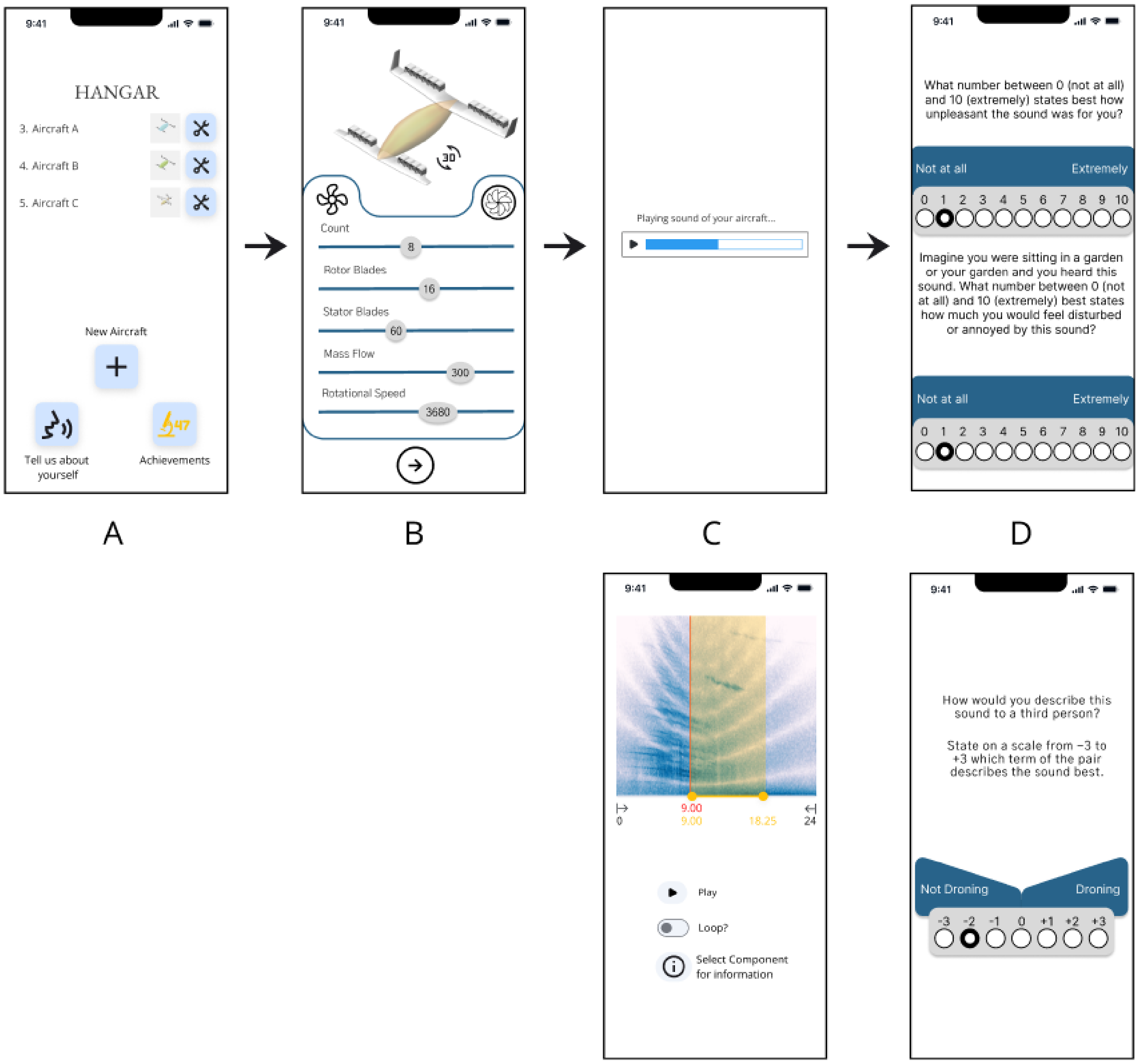

Figure 2: Overview of the app. Arrows denote the interaction flow from one section to the next. From left to right: home page, aircraft configurator, sound player (normal and detailed version) and part of the sound rating scale (sound annoyance, sound unpleasantness and one example for a sound quality item). Design study, subject to change.

2.2.1 Aircraft Configurator

Although, strictly speaking, users only configure propulsion systems, we present this module as an aircraft builder. Users set parameters of the propulsion system using sliders (see screen B from Fig. 2). For example, users can adjust the number of propulsor units and this change will also be visible on the 3d model of the aircraft. The configurator only allows technically possible settings. For example, rotational speed cannot go over a certain limit. Furthermore, certain parameters are causally linked - such as rotational speed and mass flow - such that setting one automatically also changes the other. While the exact list of available parameters is yet to be determined, the user will be able to choose among both propeller and ducted fan models with various possible settings.

2.2.2 Sound Player

After users finish one configuration, the corresponding sound is retrieved from our database and the resulting (auralized) sound is played automatically. The user cannot progress before having heard the full sound to ensure a uniform listening experience. The sound player is displayed as a simple progress bar to avoid confounding by any complex visual elements (see screen C, top from Fig. 2). However, in a section separate from the configuration workflow, we offer a more feature-rich audio player, allowing for example the selection of subsections of the sound to loop through them specifically, and visual exploration of a spectrogram (see screen C, bottom from Fig. 2).

2.2.3 Sound Rating Scales

Our rating scales are based on previous work on the valence and quality of aircraft sound and assessments include aspects of both annoyance and unpleasantness (as distinguished by Torija & Clark (2021)) as well as sound quality. The user rates a) how unpleasant the sound was using a numerical 0-10 scale b) how annoying the sound would have been in an outdoor home environment using a modified question and scale proposed by Schäffer et al. (2016) (see screen D, top from Fig. 2 and c) how the sound could be described to another person using a semantic differential as proposed by Schütte et al. (2010) (see screen D, bottom from 2). As a consequence of displaying them on smartphone screens, only 2-3 items can be displayed at the same time and the descriptors of the semantic differentials do not fit on either side of the selectors. In order to nevertheless emphasise that the descriptors are meant to be extremes on a descriptive continuum, we gave the UI elements ascending edges.

2.2.4 Engagement Features

We follow self-determination theory's prediction that people engage in activities when they feel that their basic psychological needs are met (Ryan & Deci, 2018). To support autonomy, we add a "workshop" space that is accessible after the creation of an aircraft providing options to individualize the created aircraft in terms of e.g. color and name. To support the need for competence, this "workshop" also gives the users the opportunity to re-listen to the sound with the aforementioned feature-rich audio player. Explanatory texts inform about the design of electric aircraft, the physical origins of the sounds and how they were simulated. The 3d model of the concept aircraft displayed in the configurator similarly serves to increase users' sense of understanding and competence and increase their immersion (Agrawal & Bech, 2023) in the task. We also account for self-determination theory's predictions about the positive and negative impacts of intrinsic and extrinsic rewards. The included progression system awards badges at specific milestones which are not communicated beforehand - only that such milestones do exist. For example, a badge is awarded for completing 5 noise ratings. This makes the rewards surprising and unrelated to a strict performance metric. It minimizes the incentive to make fast and careless ratings in order to receive more rewards, and avoids shifting away attention from the main task (Ryan & Deci, 2018). We decided against adding other extrinsic rewards like high scores or monetary compensation, as these could actually harm intrinsic motivation by shifting attention towards these new features Ryan & Deci (2020).

2.2.5 Data Validation Features

The perception of a sound, especially in terms of annoyance has been repeatedly shown to be influenced not only by acoustic but also by personal and situational aspects (Bartels et al., 2022). The app therefore includes an optional sociodemographic questionnaire which asks for age, gender, attitudes towards aviation, circumstances under which the app was used, and more. The users can decide to answer as little or as many questions as they want and are rewarded with a badge accordingly. We opted for this optional approach to avoid drop-out of users overwhelmed with the lengthy questionnaire, which would lead to fewer aircraft configurations. We also plan to ask the users to allow us their device's microphone to classify (but not store) the acoustic context in which they use the app (e.g. at home, with people present, in traffic...). This would allow us to consider distractions in our later analyses. The app also checks whether headphones are plugged in or not. Headphones are essential for an accurate listening experience; the sound will not be played without them.

2.3 Using the App in Aircraft Design Processes

An app can be easily modified and rolled out to an already existing userbase, making possible an iterative approach to engineering where user acceptance data is continuously fed into the design process as changes to the design are made. The basic process is illustrated in Fig. 3: The current state of the technology (in the present case, propulsor sound emissions) is assessed and entered into the app as data, e.g. sound files. In the app, the data serve as stimuli in its interactive features, e.g. playful exploration or challenging tasks. The user engages with these features and as a result produces data that can be further analyzed to gain additional knowledge with regard to the technology (propulsor sound emission). Using statistical methods, the underlying perceptions and attitudes the user has on the technology can be estimated, which are fed back to inform the design of the technology. Until the technology has reached a satisfactory state (i.e. psychoacoustically optimised sound emissions) the process can be reiterated with its adjusted versions or to investigate a different aspect of acceptance (e.g. in-cabin sound emissions).

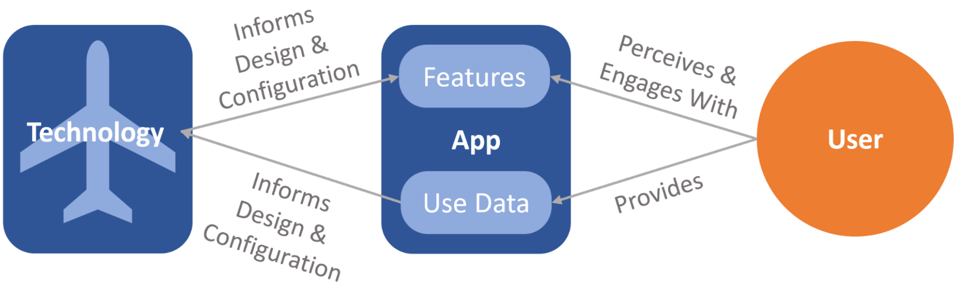

Figure 3: Idealised process for the design of tolerated, accepted and endorsed aircraft.

3. Expected Results and Outlook

The development of the app is currently in progress as described above. In the following, we describe the expected results, how to analyze them and to use our findings in practise, e.g. for future engine development and also for community engagement regarding future UAM planning.

3.1 Intended Statistical Analyses

We will analyze whether the sound variations produced by the available engine configurations lead to a statistically detectable variance in ratings of sound valence and quality. Even if users are able to distinguish the sounds of different configurations, they might rate them similarly. Conversely, users might be unable to consciously distinguish the sounds but still rate them differently.

To test how users interact with an app like this, we will look at the highest-rated configurations and the amount of agreement between raters. For example, users may mostly try out extreme values or adjust in smaller steps to find an optimum. It is also possible that, after producing several configurations, users end up focusing on a subset of parameters they perceive as having the largest influence on the sound.

In Sections 3.1.1 - 3.1.3, three approaches to analyze the collected data are outlined.

3.1.1 Multiple Regression Analysis

The input for the app are selected engine design parameters. The auralization process, outlined in Sec. 2.1, is applied in advance to all possible design parameter combinations and all resulting audio files are stored in a database. This means that each combination of engine design parameters is directly linked to one specific audio file. By exercising in the app, users then provide a subjective evaluation of the sounds of different propulsion configurations. These subjective evaluations can then be classified, for example with regard to a positive or negative rating. By processing this data using multiple regression analysis, a correlation can then be established between the positive or negative rated sounds and certain engine design parameters. This allows to identify design parameters that have a particularly strong impact on subjective sound perception and to derive design principles for future propulsion systems.

In addition, sound quality assessments can be carried out for positive or negative classified sounds and psychoacoustic metrics such as roughness, sharpness or fluctuation strength can be calculated for these noise signals. This allows to additionally link the subjective user preferences with these psychoacoustic parameters. Multiple regression analysis can then be used to establish a correlation not only between the design parameters and the subjective noise ratings, but also between the design parameters and the psychoacoustic parameters.

Moreover, the data can be weighted based on the responses to the sociodemographic questionnaire and the device's microphone. For example, a hobby pilot or an airport employee might rate sounds more positively; residents close to airports may have a more negative perception. Younger people, because of their higher acuity for high frequencies, may be more sensitive to changes to parameters that affect those frequencies.

3.1.2 Perception-based Ranking of Propulsion Configurations

As described at the beginning, we do not only intend to use the app to involve several hundred respondents. Respondents are also encouraged to create multiple configurations and evaluate the resulting sounds. Based on theses evaluations of the configured sound across all users, a ranking can be derived with regard to the sound preference of the developed propulsion configurations. By this, citizens are viewed and included as stakeholders in the configuration of modern electrified aircraft and plannings of UAM as a whole. Furthermore, noise perception based rankings enable the selection of certain propulsion configurations among realizable configurations. Thus, noise rankings can be applied as selection criterion besides efficiency and safety aspects.

3.1.3 Data-based Analyses

The human subjects evaluate the sound files using various psychoacoustic parameters. The sound files are labeled accordingly and later categorized based on the sound perception (e.g. pleasant vs. unpleasant). The aim of further data analysis is to use data-based approaches to identify sound components that are responsible for the unpleasant sound perception. For instance, these could be individual frequencies, frequency sequences or frequency combinations. Several methods could be used for the further analysis. Currently, two approaches are considered promising and are therefore listed here: a) data-driven frequency decomposition methods and b) machine learning methods including the explainability of decision making. Particularly, using the spectrograms and the categorized sound perception, a machine learning algorithm could be trained. The trained system would then be able to evaluate new sounds that lie within the spectrum of the training data with regard to a human's sound perception.

3.2 Further Evaluation of the Survey Method and User Behaviour

We validate this novel approach to sound perception measurement by comparing the results from highly controlled focused listening tests in our local facilities. There, participants listen to one aircraft sound, rate it on a desktop computer using LimeSurvey and are then presented with the next sound. The sounds are pre-configured and auralized by us to represent the spectrum of feasible configurations. One important difference is that app users use a wide variety of headphones. Furthermore, app users only rate sounds they themselves created, which might positively bias them. For reasons discussed below, self-created sounds may be less varied than pre-configured ones.

To test how users interact with an app like this, we will look at the highest-rated configurations and the amount of agreement between raters. For example, users may mostly try out extreme values or adjust in smaller steps to find an optimum. It is also possible that, after producing several configurations, users end up focusing on a subset of parameters they perceive as having the largest influence on the sound. Furthermore, even if users are able to distinguish the sounds of different configurations, they might rate them similarly. Conversely, users might be unable to consciously distinguish the sounds but still rate them differently.

3.3 Potential Impact

The app will be publicly available and designed to be usable and attractive to a broad range of users. It will include layperson-level explanations about psychoacoustics and electric aviation. This means that the app contributes to science communication and also serves as a gateway to more information into the DLR's other research efforts. Most important, the app engages citizens in the planning of future aviation scenarios and provides transparency targeting a possibly high acceptance of UAM in the population. At the same time, as users spend time and effort on the app and are exposed to its content, it can increase the acceptance of the innovative product (in our case, UAM and other aircraft with distributed electric propulsion systems) by increasing the perceived control over, understanding of, identification with and emotional proximity to the product, all of which are predicted to be major factors in technology acceptance (Marangunić & Granić, 2015). These effects would be strengthened even further if users could be made aware of changes to the product that happened because of their input.

The project will yield critical insights into which geometric design parameters of propulsion systems contribute to pleasant subjective sound perceptions. Additionally, it will generate valuable and previously scarce audio signal data, which can be utilized for further psychoacoustic analyses. The app will be updated with new configuration options of interest to aeroacoustic research as they become relevant. All in all, we aim to identify crucial acoustic factors in the acceptance of aircraft with distributed electric propulsion systems

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[3] All of the acknowledged made their contributions as members of the German Aerospace Agency's Institute for Data Science.

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