STUDY ON PUBLIC ACCEPTANCE OF EVTOL: SAFETY & NOISE

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Abstract

Urban Air Mobility (UAM) has emerged as a promising solution to address the complex challenges inherent in urban transportation systems providing innovative aerial mobility options within cities. However, the successful integration of UAM critically hinges upon public acceptance of electric Vertical Take-Off and Landing (eVTOL) vehicles flying in urban environments. This work briefly presents the outcomes derived from two extensive surveys on the acceptance of UAM and eVTOLs. The survey on UAM is carried out across mid-sized cities in Europe. The primary objective of this survey was to identify key concerns and barriers associated with UAM adoption. The emphasis is particularly on eVTOL safety levels and noise disturbance, which were identified as the most significant concerns among respondents with a share of 65% and 64% respectively. The survey targeting eVTOLs is conducted on a continent-scale, highlighting the international relevance of the findings initially obtained in Europe. Subsequently, these concerns are addressed during the eVTOL conceptual design phase to improve safety levels and reduce noise disturbance from the very beginning and, thus, enhance acceptance. On the one hand, a preliminary safety assessment is conducted to mitigate the potential risks posed by eVTOLs during both airborne and ground operations. This assessment is accomplished through a combination of the Specific Operational Risk Assessment (SORA), as stipulated by the European Union Aviation Safety Agency (EASA), and a Bayesian Networks approach. This approach can handle multistate variables extending the safety assessment beyond the conventional binary states. The incorporation of multistate variables encompassing recovery actions is discussed, thereby enhancing system reliability and safety with fewer mechanical alterations of the eVTOL architecture, and thus, saving costs and reducing take-off mass. This is demonstrated through the application of the proposed safety assessment to the total loss of the eVTOL avionic system. The reliability outcomes are compared between a standard scenario (i.e., without any operational mitigation) and a scenario involving a successful emergency landing at a recovery site (i.e., with the recovery action). The results show that the probability of total failure with a recovery action is 100 times lower than the standard scenario. This indicates that including recovery actions makes the system less prone to failures and could be considered safer in terms of failure frequency. On the other hand, the investigation is augmented by findings from studies on noise disturbance, incorporating psychoacoustics. This aspect aims to decrease the sound disturbances generated by eVTOLs, thus enhancing the overall urban soundscape quality.

With the aim to develop safer and quieter eVTOLs during the initial design stages, the acceptance of eVTOL technology is increased, paving the way for seamless integration of UAM into future transportation services.

Keywords

UAM; noise; psychoacoustics; safety assessment; SORA; public acceptance; eVTOL

NOMENCLATURE

Parameters

L_{AE}	A-weighted sound exposure level	dBA
lambda	failure rate	failures/FH
omega	angular velocity	rad/s
P	Probability	
R	Rotor radius	m
V_{ht}	Blade tip speed	m/s

Abbreviations

ARC	Air Risk Class
BN	Bayesian Networks
BPF	blade passing frequency
BTL	Bradley-Terry-Luce Model
COL	Cooling System
CPT	Conditional Probability Table
CSS	Cooling System Controller Sensor
EASA	European Union Aviation Safety Agency
eVTOL	electric Vertical Take-Off and Landing aircraft

doi: 10.25967/610319

f	failure(s)
FHA	Failure Hazard Analysis
FTA	Fault Tree Analysis
GA	And-Gate
GO	Or-Gate
GRC	Ground Risk Class
MGO	Modified Or-Gate
N	Number of survey respondents
OSO	Operational Safety Objectives
SAIL	Safety Assurance and Integrity Level
SORA	Specific Operational Risk Assessment
UAM	Urban Air Mobility

1. INTRODUCTION

Electric Vertical Takeoff and Landing (eVTOL) aircraft, characterized by their vertical lift capabilities and electric propulsion systems, represent advancements in the field of aviation [1–6]. These aircraft have garnered significant research interest as a potential enabler of Urban Air Mobility (UAM) [7–9]. The convergence of eVTOL technology with the concept of UAM entails alleviating urban congestion, shortening travel times, and redefining urban transportation networks [3, 5, 10, 11]. Thus, the entry into service of these novel aircraft offers the potential for reshaping urban mobility towards a sustainable and efficient aerial transportation system. However, the effective integration and widespread adoption of UAM critically depend on the acceptance of the general public [4, 5, 11–15]. In section 2 of this work, the findings derived from a survey on UAM acceptance conducted across mid-sized European cities are summarized. Mid-sized urban centers, characterized by their amalgamation of cultural, lifestyle, and urban structural diversity, provide a means to assess the feasibility of UAM on a broader scope. While large cities attract significant attention due to their size and impact [16–18], mid-sized cities often serve as early adopters of emerging technologies. Their natural ability to adopt new ways of thinking allows them to quickly adjust, providing valuable insights that are relevant to a wide range of different city types [6, 7, 19]. The conducted survey was designed to scrutinize the current public's perception towards UAM and, in turn, of eVTOLs flying above cities [19]. In addition to that, the results of a second survey targeting eVTOLs flying in cities are briefly presented. The insights gained from the European survey have proven to be relevant and meaningful not just within Europe but also on a worldwide scale. This demonstrates that the attitude toward eVTOL adoption is a topic of global significance, transcending regional boundaries and necessitating international attention. The primary emphasis was to elucidate the factors influencing the acceptance of UAM, with a specific focus on concerns related to eVTOL safety levels and noise disturbances, which have been identified as primary concerns among survey respondents [19]. By addressing these concerns at the conceptual design stage, the development of the UAM system and related eVTOLs can be tailored to conform with community needs.

Consequently, this work focuses on a two-pronged concerns-related study that aims at presenting the approaches applied to improve safety as well as reduce noise and thus, improve public acceptance [4, 5, 14, 15]. First, section 3 is dedicated to the safety assessment of unmanned eVTOLs. Rather than using the conventional aircraft-based approaches [20], such as the ARP 4761 in [21], the safety level of an eVTOL is assessed by adding a Bayesian Network (BN) approach to the Specific Operational Risk Assessment (SORA) issued by the European Union Aviation Safety Agency (EASA), as suggested by Denney et al. in [22, 23]. This is done, on the one hand, to quantitatively support the qualitative approach proposed by SORA and, on the other hand, to explore not only the eVTOL system from a technical perspective, which is represented by binary states - i.e., 1 (intact) or 0 (failed) - but also from an operational perspective, i.e., including mitigation measures [24–27]. These measures constitute a third state for the system and they are put in place to increase system safety. In fact, the approach with BN can take into account the third state assigning to it the probability of mitigation being successful [26, 28]. The results illustrate the improved system reliability achieved through the introduction of a recovery action as a third state, such as an emergency landing, without necessitating mechanical modifications, e.g., additional system redundancies. Redundancies can provide an additional layer of safety but they are typically designed for specific failure modes and may not cover all possible failure scenarios. Instead, operational mitigations offer a more adaptable approach to enhancing eVTOL safety [29]. Second, section 4 is devoted to the noise. Annoyance due to the acoustic signature that eVTOLs emit is already well known by General Aviation as a massive factor affecting acceptance. Future eVTOL concepts will operate not only closer to people but also the flight schedule is expected to be more frequent. This entails that the perceived disturbance may cover the entire day, and thus, the acoustic optimization for eVTOL is extensively relying on psychoacoustics analysis targeting the human hearing sensibility (see e.g. [30] for the European regulation for the psychoacoustics of eVTOL). Hence, the application of psychoacoustics and the analysis assessing the ability of different norms/versions of loudness, sharpness, and tonality in predicting eVTOL noise is presented. After overview sections - dedicated to safety and noise considerations respectively - the overall conclusion centers around the potential for conducting safety assessments and noise evaluations during the conceptual design phase to enrich the understanding of eVTOLs and impact the level of acceptance toward UAM.

2. ASSESSMENT OF ACCEPTANCE

The successful adoption of UAM relies on public acceptance. This section presents briefly the findings of a survey conducted in nine mid-sized cities[1] across Europe to investigate the public acceptance of UAM serving as a driver for this work. A comprehensive description of the survey structure and results is discussed by Babetto et al. in [19]. To enhance the robustness of the findings initially obtained within the European context, a supplementary survey on eVTOL acceptance was conducted across multiple continents, including Europe, America, and Asia. The results from this additional survey conform with those from the European survey. This second survey serves within this paper to validate and reinforce the insights gained within Europe by suggesting consistency and relevance on a global scale. This international alignment strengthens the case for addressing the identified challenges associated with UAM and eVTOLs.

2.1. Survey on the acceptance of UAM

The performed survey aimed to capture the opinions and perceptions of residents concerning UAM across mid-sized cities in Western and Central Europe[2]. A structured questionnaire was designed to encompass various aspects related to UAM, including perceived benefits and concerns. To ensure representative results across diverse demographics, a random sampling approach was employed and the target sample size of N = 371 respondents was calculated through the online tool provided in [31]. Data collection was conducted through a combination of online and paper-form questionnaires. A total of N = 384 responses was collected at the time of this manuscript. Statistical analysis, quantitative coding techniques, and qualitative assessment were utilized to derive meaningful insights from the gathered data.

The survey unveiled varying levels of awareness of UAM among respondents. While a share of 59% of the participants demonstrated familiarity with UAM and its potential benefits, a significant proportion of 41 % exhibited limited knowledge. The perceived benefits of UAM encompassed reduced traffic congestion (i.e., this option was voted by 68 % of the respondents), shorter travel times and deliveries (52 %), and improved coping with urgency, i.e., time-critical situations (57 %). However, these perceived benefits were often overshadowed by concerns related to safety and noise disturbance of eVTOLs, which were picked by a respondents' share of 65 % and 64 %, respectively. Safety emerged as the primary concern that might impede public acceptance of UAM. Participants expressed apprehensions regarding vehicle reliability, autonomous flight, and overall airspace management. Moreover, respondents stressed the need for robust safety regulations and comprehensive risk assessments to ensure a high level of safe operations. Among the participants, 74% emphasized that ensuring a high level of safety and reliability contributes to their acceptance of UAM. Hence, addressing this safety concern was deemed important to instill public confidence and trust in eVTOL operations.

Noise disturbance emerged as another major barrier to UAM acceptance in the public. Respondents expressed concerns about potential noise emissions resulting from UAM operations, which could adversely impact residents' quality of life and well-being. In fact, a quieter noise disturbance was recognized by 65% of the participants as a factor capable of positively impacting UAM acceptance.

2.2. Survey on acceptance of eVTOLs

The attitude towards eVTOLs was investigated in a novel study with N = 578, equally distributed across continents (Europe, Asia, and America), age groups (18-32, 33-47, 48-62), and gender (male, female). The study was conducted digitally via a smartphone app with subjects/respondents from the field of paid crowd-sourcing. As context, a situation of parcel delivery with eVTOLs in a city was given. It is worth noticing that the term "drone" is generally well-understood by the general public, and the term is widely recognized. Whereas, the term "eVTOL" is more technical and might not be as universally familiar. Consequently, in this survey, the term "drone" is primarily used to refer to eVTOLs, simplifying the terminology for broader comprehension. A questionnaire by Aalmoes et al [32] was used, with the scales slightly adapted (yes/ no; very much/somewhat/rather not/not at all):

1) Do you own a drone? [yes/no],
2) Have you ever seen a drone in reality?
3) Have you ever (outside of this research) heard the sound of a flying drone in reality?
4) Have you ever (outside of this research) seen a drone flying in reality?
5) When you HEAR a flying drone, how much does this noise bother, disturb, or annoy you?
6) When you SEE a flying drone, how much does this noise bother, disturb, or annoy you?
7) How much does the idea of the use of more drones in future bother, disturb, or annoy you?

As visible in Fig. 1, around 15% of the respondents do own a drone, which is lower than in other studies, such as Lidynia et al [33]. Also, wide experience with electric drones was found: a share of 90% of the respondents have seen a drone, 83% have heard a drone flying in reality and 88% have seen and heard a drone flying in reality. This harmonized with the findings

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[1] Each selected mid-sized city has approx. 200.000 inhabitants.

[2] The selected cities are: Aachen (GE), Padua (IT), Odense (DN), Liège (BE), Eindhoven (N), Lille (FR), Cadìz Bay (ES), Milton Keynes (UK), Porto (P).

of Stolz [34], who also reported respondents who were well-informed.

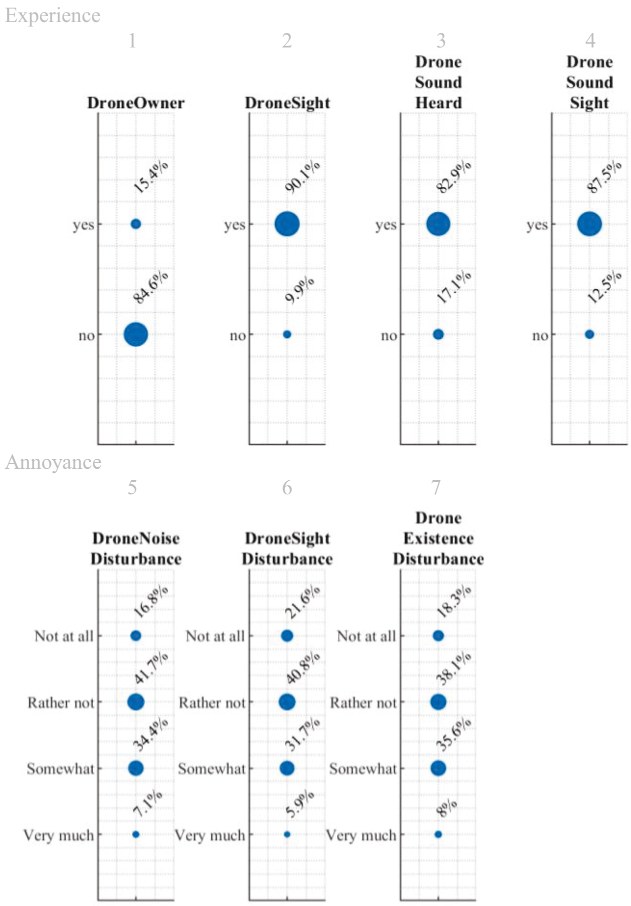

FIG 1. Experience and attitude towards electric drones using a questionnaire by Aalmoes et al [32] of an international, digital user study: Wide experience of subjects and slightly positive attitude towards electric drones is found.

Regarding annoyance, a widespread from "very much annoyed" to "not at all annoyed" can be observed among respondents. Quite similar distributions are visible for acoustic and visual annoyance, as well as annoyance due to the existence of electric drones. This highlights the importance of improvement in multiple disciplines, e.g., safety, along with acoustics. When separating the answers into positive (not at all, rather not annoyed) and negative (somewhat, very much annoyed) groups, the slight majority tends to have a positive attitude towards electric drones: 59% are rather not or not at all annoyed by hearing, 63% feel comfortable by seeing drones and a share of 56% is not concerned by the use of more drones in future.

Overall, these findings underline a slightly positive attitude toward drones. However, it has to be mentioned, that nearly half of the respondents express concerns about the viability of drones in future. All this conforms with the results found by Babetto et al. [19] for European mid-sized cities and it highlights the international applicability.

3. SAFETY ASSESSMENT

The conducted surveys highlighted safety levels as the primary concern affecting the adoption of UAM together with noise disturbance. In order to contribute to gaining public acceptance, the following section targets the improvement of an eVTOL safety assessment approach. It deals with the combination of the well-known SORA (in chapter 3.1.1) with BNs (in chapter 3.1.2) that enables including operational mitigations into safety calculations. Including operational mitigations can not only enhance the robustness of the safety assessment but also make the study more reflective of real-world scenarios as it is not just focused on theoretical risks but also addresses practical challenges in actual operations. In fact, people are more likely to accept and support eVTOLs if they perceive that potential risks are being actively managed and mitigated [4, 5, 14, 15, 19].

3.1. Methodology for safety assessment

The safety assessment developed in this work encompasses the SORA combined with BNs. The core of SORA involves a systematic procedure for the comprehensive evaluation and control of risks linked to a specific unmanned eVTOL [35]. While SORA has been undergoing extensive exploration and practical application, its nature in qualitative assessing system failures points to a research area where potential enhancements could be made. BNs offer a suited framework for quantitative safety assessments of unmanned eVTOL integrated into SORA. By integrating BN into the safety assessment process, the methodology gains the capability to model and analyze the probabilistic relationships among different events and components, accommodating multi-state variables and thus, confronting binary states studies of, e.g., the conventional Fault Tree Analysis (FTA) [20–24, 26]. This integration allows for a more comprehensive evaluation of risks, considering technical failure scenarios along with operational mitigations, and their probabilities to occur and be put in place, respectively. Assuring comprehensive safety assessments and risk mitigation measures in technology and operations for new transportation modes fosters confidence, making people more open to embracing the concept [4–6, 14, 15].

3.1.1. SORA

SORA[3] is a systematic methodology that provides a structured - mostly qualitative - approach to assess and manage the risk associated with a given eVTOL operation in the *Specific* category [36]. Initially developed by the Joint Authorities for Rulemaking on Unmanned Systems (JARUS) in 2018 [37], it was later adapted and introduced by EASA [38]. Through SORA, the eVTOL operators can determine the Assurance and Integrity Level (SAIL) enabling them to prepare the necessary documentation and implement mitigations to reduce the level of risk. In SORA's

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[3] The SORA v2 published in 2019 is the focus of this work.

terminology, the SAIL indicates the robustness of the implemented mitigation measures [29, 35, 39, 40]. To begin the SORA process, a detailed Concept of Operations document (ConOps) is required in the first step. This document serves as the foundation for the success of the application. The information provided in the ConOps is then incorporated into the initial risk assessment [41, 42]. Eventually, two parameters for the mission are determined: the Ground Risk Class (GRC) and the Air Risk Class (ARC). The GRC evaluates the risk to uninvolved people or objects on the ground based on factors, such as the operating environment, the dimensions of the eVTOL, and the kinetic energy of an impact at ground level. On the other hand, the ARC quantifies the risk of a collision in the air with a piloted aircraft or other unmanned eVTOLs, considering the type of operational airspace and the specified flight altitude [20, 29, 35, 39, 40]. Once the risk classes are determined, the operator can apply mitigations to reduce them. Strategic mitigations involve pre-flight restrictions or operational area designations, while tactical mitigations are implemented after the eVTOL is launched, such as an emergency landing [38]. To find the SAIL, the combination of the final ARC and GRC is mapped in a pre-defined table delivered by the SORA documentation [23, 36, 38]. The final step involves the identification of Operational Safety Objectives (OSOs), which concern the mission, eVTOL design, operations, and human factors. Given an eVTOL operation, a robustness level for each OSO is determined using the SAIL and is categorized as *low, medium,* and *high.* This robustness level defines the required qualitative standard to be matched to assure sufficient confidence that the respective OSO is fulfilled [36]. Generally, the OSOs defined in SORA represent top-level events at a high system level [20], while the mitigations in SORA serve as predefined barriers that block the path from the top-event to an incident. Additionally, the determination of appropriate levels of robustness for OSOs can be associated with the FTA methodology, wherein factors, e.g., reliability and failure rates, can serve as indicators of robustness levels. For instance, #OSO 5, as the main focus of this work, asserts that *"unmanned eVTOL is designed considering safety and reliability"*[4] [36, 38]. This OSO signifies that safety and reliability must act as design drivers in the eVTOL design process. Consequently, it has to be ensured that the occurrence of any system failure does not result in a fatal outcome, which also aligns with the expected results of an FTA. Although SORA has been widely investigated and effectively used, as demonstrated in the works of Capitan et al. [39], Janik et al. [40], Terkildsen et al. [29] and La Cour-Harbo et al [35], the uncertainties arising from its qualitative-based core in evaluating system failures highlight a specific research domain with potential for enhancement. Furthermore, no explicit guideline is outlined to quantitative assure OSO robustness [23]. In order to address this gap during the initial design phase, the focus of this work is then on proposing an additional quantitative approach for assessing reliability and risk encompassing preventive measures and/or mitigation strategies. By starting with the SORA's results described by Babetto et al. in [41], the proposed approach incorporates BNs to merge mechanical events (i.e., component failure) and operational measures into a unique safety assessment. This approach employs probability (in terms of failure rate for components and the likelihood of being successful for an operational measure) to offer a quantitative approach to ensure an appropriate level of robustness that matches the qualitative SAIL-derived standard.

3.1.2. Bayesian Networks

BNs have emerged as a powerful framework for modeling and analyzing risk in various domains, such as maintenance, finance [43], and image processing [44] among many others [45, 46]. The objective of this chapter is not to delve into the mathematical bases of Bayes' Theorem and the probability theory of BNs, which are detailed in Statistics literature, such as Hoff's publication in [27]. Instead, this chapter provides a brief introduction to the concept, emphasizing BNs' advantages in safety assessment for unmanned eVTOLs compared to traditional methods.

In the context of risk assessment for eVTOLs, BNs stand out first for the valuable advantage of representing multistate variables going beyond the conventional FTA [24, 26]. Unlike traditional FTA, which typically considers binary states of "intact" and "failed" for system components, BNs allow for the representation of an arbitrary number of states per node, i.e., system component states. This means that, instead of simply categorizing a component as either *functioning properly* or *not working*, BNs can model various intermediate states that represent different levels of performance or degradation of the component, e.g., "partially functional", "degraded performance" or "intermittent failure". This capability of BNs in handling multistate variables lies in the Conditional Probability (CP) Tables (CPT) associated with each node (see Appendix 7.1). These tables contain probabilities that describe how the state of a node depends on the states of its parent nodes [24, 26–28]. The considered probabilities are, on the one hand, the failure rate of components and, on the other hand, the probability of successful implementation for an operational measure. By adjusting the probabilities in the CPT, i.e., by adding a new state with the corresponding probability, the probabilities of different outcomes for a node can be influenced, thereby propagating through the network and affecting the top-event of a given system (i.e., "the top-node" that corresponds to the SORA's OSO).

For the population of the BNs presented in this work, the failure rate λ_i (failures/FH) of a i-component is

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[4] The official document employs the term "Unmanned Aerial Systems" (UAS). In order to maintain consistency, this study adopts a modified terminology.

transformed into a failure probability $p_i(t)$ per flight hour using Eq. 1 [26–28].

$$p_i(t) = 1 - exp^{-\lambda_i * t} \tag{1}$$

The assumption of small and constant failure rates ($\lambda_i << 1$) and short maintenance or monitoring intervals allows the direct calculation of $p_i(t)$ for t = 1 as $p_i(t) = \lambda_i * t$ [25]. In this case, the specified failure rates directly correspond to the probability of failure. This way, by introducing the states for a node and appropriately setting the probabilities in the CPT, the BNs can capture the probabilistic relationships between different components or events in the system [27].
Another key advantage derived from the capability of handling multistate variables is modeling recovery actions as an additional state of a node [27]. Recovery actions refer to the measures taken to mitigate the consequences of a system failure or to restore the system to a safe state after a failure has occurred and thus, enhancing system reliability and safety. For example, if a critical component, such as a propulsion system fails during an eVTOL flight, a recovery action may involve performing an emergency landing procedure. By including recovery actions as node states in the BNs and considering their probabilities of being successful in the CPT, the potential reduction in risk due to these actions on the overall system behavior can be evaluated [24,26,28,46]. This enhances the risk assessment process by considering not only the probability of system failures but also the effectiveness of measures taken to recover from those failures allowing for a more reality-oriented study.

Early research by Bobbio et al. in 1999 explained a straightforward process of converting an existing Fault Tree (FT) into a BN by creating a node in the BN for each block (i.e., primary event or system component) of the FT [28]. Subsequently, corresponding nodes in the BN are created to represent each gate of the FT (i.e., AND Gate and OR Gate), and the CPT is determined. Lastly, the nodes of the BN are interconnected following the underlying structure of the FT. At this point, supplementary node states encompassing mitigations together with the corresponding probabilities of success can be added [24,26,45,46].
The mathematical foundation proposed in [28], along with a variety of available algorithms, has led to the development of a novel BN-based approach implemented into a tool for quantitative risk assessment. A Matlab-based tool was developed capable of solving BN given a system architecture, a top-event (which is a system failure), and the corresponding FT drawn to outline the event dependencies (as suggested in [28]). Hence, the transformation of the overall architecture into a BN enables fast quantitative analyses.

3.1.3. Application

The study involves examining an unmanned eVTOL, namely a hexacopter configuration with coaxial rotors, for cargo delivery service in the urban environment and its avionic system in an early-stage design. In a previous work presented by Babetto et al. in [41], the SORA framework was applied to the selected unmanned cargo eVTOL configuration, yielding insight regarding operational safety levels. The study highlighted that the calculated SAIL for the case study signaled a *high* degree of robustness for the OSOs. In this work, #OSO 5 (*unmanned eVTOL is designed considering safety and reliability*) is further investigated. A *high* degree of robustness implies any *Catastrophic* or *Hazardous* event is deemed intolerable and must be extremely improbable. Therefore, according to the AMC RPAS-1309 in [47][5], any *Catastrophic* or *Hazardous* event must have an occurrence probability lower than $p = 1 * 10^{-8} failures/FH$ and $p = 1 * 10^{-7} failures/FH$, respectively.
The subsequent step of the application focuses on #OSO 5 at (sub)system level and it involves delving deeper into the avionic system architecture. This system has been chosen as the riskiest component of an unmanned eVTOL [22, 23] demanding a safe and reliable design to ensure the overall safety and reliability of the eVTOL, conforming with #OSO 5 at system level.
The exploration of reliability and safety aspects entails the utilization of BNs to analytically resolve the network of probabilistic failure events associated with the avionic system architecture. Within this network, the incorporation of a recovery action is considered, in the case where its execution proves successful. This approach allows for the evaluation of the recovery action's impact and efficacy, enabling a comparison with the scenario where such a proactive measure is not applicable.

- **Avionic system architecture**

The avionic system is categorized into six main subsystems, which are arranged and interconnected as depicted in Fig. 6 in the Appendix 7.2. This architectural layout is derived from a prior Functional & Product (i.e., Component) Analysis. The selection of individual physical components and the resulting system architecture conforms with the requirements and guidelines for unmanned eVTOLs outlined by the British Ministry of Defence [48] and other relevant scientific papers available in [8, 9, 11]. As from Fig. 6, each of the four main subsystems, namely the "Sensor Array System", "Propulsion System", "Data Communication System", and the "Flight Management System" is linked by two redundant power and data buses, respectively. The "Electrical Power System" provides the necessary electrical energy for the operation of the two power buses, while the "Power Distribution System" facilitates the flexible allocation of energy from

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[5] The document was deemed the most valuable as at the time of this manuscript it was the only available source of (as consistent as applicable) information.

at least one of the two battery systems to the bus systems. The internal bus systems are indicated by dashed lines. For clarity, only the main system components are considered in this study.

- **Failure assessment**

A (sub)system is assumed to fail if all corresponding redundancy units of the same type experience malfunction. Furthermore, a system failure is also deemed to occur if the feeding bus systems fail. For simplicity, each of the six "Engine Nacelle Systems" comprises a redundant system consisting of two "Electronic Speed Controllers (ESCs)" and two "Motor Units", as shown in Fig. 6. It is presumed that, for this system, one of the two available subsystems is allowed to fail while still maintaining safe flight conditions for secure operation. The "Propulsion System" is a critical component in ensuring the effective and reliable operation of the eVTOL, and, as one of the four main subsystems of the avionic system, is further considered in this work. The top-event selected is then *"Loss of required propulsion"*. The assessment of the Propulsion System's failure probability involves integrating all subordinate failure cases that contribute to the occurrence of the top-event across the avionic system architecture. Figure 6 illustrates the entire avionic system together with the interdependence of the "Propulsion System (PS)" with the "Electrical Power System (EPS)", "Power Distribution System (PDS)", and "Flight Management System (FMS)". Additionally, the FMS relies on data from the "Inertial Navigation System (INS)" and "GPS System", which, along with the sensor controller, form the "Sensor Array System (SAS)" and play a role in navigation and control. The "Main Data Bus System (MDB)" and "Main Power Bus System (MPB)" are essential for data signal exchange and electrical energy distribution, respectively, and are integral components of the overall avionic system. If any of these seven subsystems experience a total failure, the loss of monitoring of the "Propulsion System" and, in turn, the loss of the eVTOL, will occur.

- **Top-event evaluation**

In a previously conducted Failure Hazard Analysis (FHA) at (sub)system level, the top-event *"Loss of required propulsion"* is classified as a *Catastrophic* event. This top-event might occur when either the Cooling System (COL) or the Cooling System Controller sensor (CSS) or both subsystems fail. In addition, the Recovery Action, namely *Reaching a Recovery Site for an emergency landing*, is available in the event of a "failed Cooling System". In the absence of any other system damages, the eVTOL can attempt to approach an emergency Recovery Site, thereby preventing the *Catastrophic* outcome of the top-event. The introduction of the Recovery Action, as a barrier or mitigation, results in a third system state no longer immediately causing a *Catastrophic* event, which would entail a loss of the eVTOL. Through the incorporation of multistate variables within the BN, the system state severity of *Catastrophic* can be reduced to the severity of *Hazardous*. Consequently, the tolerable outcome severity through a successful Recovery Action, namely the successful landing at the Recovery Site, is classified with a probability of $p = 1 * 10^{-7} failures/FH$ instead of $p = 1 * 10^{-8} failures/FH$ [47].

- **Bayesian Networks conversion**

By combining the Functional & Component Analysis and the FHA previously performed as the foundation for this work, the resulting FT is depicted in Fig. 7 in the Appendix 7.3. Following the mathematical mapping suggested by Bobbio et al. in [28], the BN is constructed as an aggregation of root nodes (representing the failure of individual components) and intermediate nodes (representing the gates of the FT). In the subsequent step, the root nodes are assigned the names of the associated components derived from the system architecture in Fig. 6 of the Appendix 7.2. Intermediate nodes are labeled with the prefix "G" for Gate, followed by the type of node (O: OR-Gate and A: AND-Gate) so that each node has a unique identifier. For the population of the BN presented in Fig. 8, the failure rates of each component, summarized in Tab. 1, are transformed into failure probabilities using Eq. 1. The numerical values are taken from the "Component Reliability Data for Probabilistic Safety Assessment" database by the International Atomic Energy Agency [49]. These values from the year 1988 provide a baseline for conservatively quantifying the system architecture. In addition, despite its age, the majority of required reliability data was available in the 1988 document: utilizing reliability data from the same source maintains consistency across all components.

- **Results**

The resulting BN without the Recovery Action is depicted in Fig. 8 of the Appendix (see 7.4), whereas the correction of the original BN with Recovery Action in place after the event "Cooling System failure has occurred" is shown in Fig. 2. A probability of a successful emergency landing at a recovery site is assumed

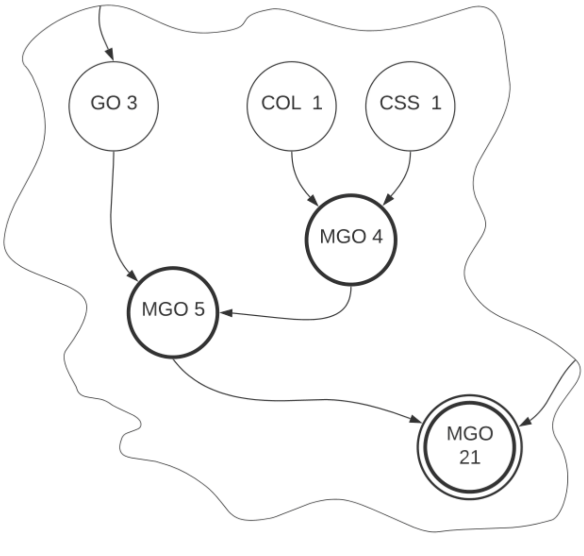

FIG 2. Bayesian Network with mitigation included into node MGO4

ID	**Name** (number of units)	λ [f/FH]
BAT	Battery system (2x)	$8.86*10^{-5}$
PIU	Power Interface Unit (2x)	$6.39*10^{-5}$
PMU	Power Manag. Unit (2x)	$6.39*10^{-5}$
COL	Cooling System (1x)	$4.44*10^{-5}$
CSS	Cool. System Sensor (1x)	$1.45*10^{-6}$
PDS	Power Distr. System (2x)	$6.39*10^{-5}$
MDU	Motor Drive Unit (2x)	$6.39*10^{-5}$
ESC	Elect. Speed Control. (6x)	$4.66*10^{-6}$
MSM	Motor System (12x)	$2.50*10^{-5}$
SCU	Sensor Control Unit (3x)	$6.39*10^{-5}$
INS	Inertial Nav. System (2x)	$4.13*10^{-5}$
BSS	Barom. Sen. System (2x)	$4.42*10^{-6}$
GPS	Global Posit. System (3x)	$1.45*10^{-6}$
VOR	VOR System (2x)	$4.66*10^{-5}$
CAM	Camera System (2x)	$2.07*10^{-4}$
WFA	WiFi Antenna (2x)	$4.66*10^{-5}$
SCA	Sat. Comm. Antenna (2x)	$4.66*10^{-6}$
ADA	ADS-B Antenna (2x)	$4.66*10^{-6}$
GCA	GCS Antenna (3x)	$4.66*10^{-6}$
FCC	Flight Control PC (4x)	$4.76*10^{-5}$
MMC	Mission Manag. PC (2x)	$2.63*10^{-5}$
SCU	Sensor Control Unit (2x)	$6.39*10^{-5}$
MDB	Main Data Bus (2x)	$1.24*10^{-8}$
MPB	Main Power Bus (2x)	$3.2*10^{-7}$

TAB 1. Failure rates of each avionic subsystem

as the third state of the node concerning the Cooling System (COL 1). The gates MGO 4 and MGO 5 serve to transfer this third state to the top-event MGO 21. MGO 4, MGO 5, and MGO 21 are the Modified nodes (i.e., including the Recovery Action) corresponding to GO 4, GO 5, and GO 21 of the standard scenario. The introduction of the Recovery Action has no effect on the *Intact* system status as reported in Tab. 2. However, the total failure of the system is significantly decreased from $p = 4.6 * 10^{-5} failures/FH$ to $p = 5.2 * 10^{-7} failures/FH$ for the realistic scenario (i.e., successful landing at the recovery site).

failure event	**fail** (f/FH)	**intact** (f/FH)
no RA	$p = 4.6 * 10^{-5}$	–
with RA	$p = 5.2 * 10^{-7}$	$p = 4.5 * 10^{-5}$

TAB 2. Failure probabilities of the avionic system architecture including operational mitigations, i.e., Recovery Action (RA).

Both values are greater than the intended value of $p = 1 * 10^{-7} failures/FH$ (for a *Hazardous* event). Yet, the observed decrease in failure probability does not necessitate any technical modifications to the eVTOL. Thus, achieving the desired target failure probability is attainable with notably fewer adaptations of the mechanical system architecture (i.e., fewer redundancies), resulting in cost savings and reduced take-off mass. However, while this measure can reduce the occurrence of the top-event, it cannot reach an acceptable level (from regulatory), unless the severity of the event is reduced to *Minor* to undercut the associated threshold value of $p = 1 * 10^{-3} failures/FH$ (for a *Minor* event) with additional mitigations. Still, the flexible modeling of the BN allowed the simulation of a realistic system highlighting the potential of operational measures in increasing system reliability, and thus, safety. In fact, it demonstrates how a single mitigation can effectively address a potential hazard and it can instill confidence in the operational safety measures to reach the robustness required by the OSO under investigation [22].

3.1.4. Summary of the safety assessment

Overall, the major concern of safety implies significant influence over the feasibility and acceptance of emerging technologies, such as unmanned eVTOLs. However, the integration of safety considerations within the conceptual design phase of unmanned eVTOLs induces complexities. Unlike traditional aircraft safety assessments, eVTOLs encompass several operational mitigations that have an impact on safety studies. Conventional safety assessment methodologies lack to include operational measures, resulting in an inadequate assessment of safety and reliability for eVTOLs.

To address this inadequacy, a novel framework was formulated with the objective of bridging this gap, thereby providing a more comprehensive safety assessment for unmanned eVTOLs. By incorporating operational mitigations into the safety assessments through the implementation of BNs, the SORA approach used for unmanned eVTOLs is augmented in terms of precision and integrity of safety evaluations, aligning more accurately with the realistic operational scenarios. The application of the proposed methodology unveiled a potential for operational mitigations to significantly enhance safety levels, akin to the stringent standards set by conventional aviation protocols, while not only maintaining efficient and lightweight designs but also showing active promptness in handling hazards during real-world operations. This finding has important implications for the acceptance of UAM. By ensuring a significantly high safety standard (i.e., show OSOs' robustness) - already at the conceptual design stage - and quantitatively demonstrating it to authorities to obtain approval to fly, the potential arises to shift safety concerns from obstacles that impede UAM to drivers that motivate greater public acceptance of UAM [16]. In fact, when individuals perceive that a new mode of transportation, such as eVTOLs, has undergone rigorous safety assessments, such as EASA's SORA, to ensure flight authorization and measures have been put in place to mitigate risks both in terms of technology and operations, they are more likely to feel secure and comfortable embracing this new concept, i.e., concerns and skepticism are alleviated. This evolution could lead to the widespread adoption of UAM and its seamless integration into future urban transportation systems.

4. ACOUSTIC OPTIMIZATION

Besides safety, the acoustic signature of eVTOLs is also object of public concern, which is discussed in the following. Many potentials for the acoustic optimization of eVTOLs are known or were recently studied or adapted from helicopter research. A summary of the potential of acoustics optimization is given in Koenig et al. [50]. In addition, according to Brentner [51], key variables for low noise design are among others, larger number of blades, lower disk loading, the reduction/elimination of unsteady aerodynamic interactions and low tip speed V_t (Eq. (2)). V_t includes the forward flight speed V, as well as the rotational velocity of the blade tip calculated with the angular velocity ω and the blade radius R.

$$V_t = \sqrt{V^2 + (\omega R)^2} \tag{2}$$

Ruijgrok [52] discussed the reduction of tip speed in the context of annoyance. Using, for example, lower rotational speed and smaller blade radius - with an increased number of blades to maintain the required thrust - increases the frequencies of the harmonics of the blade passing frequency (BPF). This might reduce the annoyance improvement even at reduced noise levels [52]. Current methods of annoyance assessment use psychoacoustic metrics, which are examined in the next section.

4.1. Assessment of acoustic annoyance

To describe and assess the annoyance or euphony of sounds, psychoacoustic metrics are being applied. For instance, loudness, sharpness, tonality, roughness, impulsiveness, or fluctuation strength can help to describe how humans perceive noise. Although models combining multiple psychoacoustic metrics have been discussed for a long time, such as the psychoacoustic annoyance PA by Zwicker et al. [53], a further modification adding tonality by More [54] or the sensoric euphony by Aures [55, 56], more basic metrics are applied today in official regulations, e.g., the A-weighted sound exposure level L_{AE} (measured in dB(A)) as reported in the guidelines by EASA [57]. The usefulness of psychoacoustic metrics is often discussed and has not shown a breakthrough in aviation today.

Besides loudness, which is standardized in ISO 532-1, many different versions/norms of the psychoacoustic metrics are applied in the literature. Doing analysis with psychoacoustic metrics, thus, requires choosing a specific version/norm of the metrics in the first place. One possibility is to choose the metrics depending on their capability to predict human annoyance. Some software, such as *Artemis*[6] allows to compare different versions/norms of the metrics. In the following, a comparison of different norms/versions of the psychoacoustic metrics loudness (as defined in ISO532-1 [58] and DIN45631/A1 [59, 60]), sharpness (discussed in DIN45692 [61] and by Aures [62] and von Bismarck [63–65]), tonality (DIN45681 [66]), and tonality based on the hearing model presented by Sottek in [67] is presented via the implementation of *Artemis*.

4.2. Comparison of different versions/norms of the psychoacoustic metrics loudness, sharpness, and tonality

In the survey (in chapter 2.2), samples from measurements in a hover-test-bench and in real flights (4x2 coaxial quadcopter, the *Rubina X8*) were analyzed. Variations of multiple design parameters, such as blade size, number of blades, and ducts, among others, were included at three operation points and payloads. Four flight segments, namely takeoff, flyby, hover, and landing were considered. Empiric annoyance rankings were derived from the survey study (presented in chapter 2.2) calculated with the Bradley-Terry-Luce Model (BTL) using pairwise comparisons.

Linear regression models were employed to evaluate the effectiveness of psychoacoustic metrics in predicting empirical annoyance levels as in Eq.3:

$$f(x_1) = \beta_\mathrm{O} + \beta_1 \cdot x_1 \tag{3}$$

Since the analysis of 10-fold cross-validation showed no impact on the results for the used data, the complete database was used for the fitting and the split into training and test data was not done. Equivalent results were found for the real flights and the hover-test-bench, which is the reason why only the data of the hover-test-bench is visualized in Fig. 3.

The evaluation is shown in Fig. 3. A negative value on the BTL-scale represents higher annoyance; whereas, a positive value means lower annoyance.

To analyze the dependencies, the statistic values, respectively, R^2, indicating to what extent the variation of the data is described, and $p-$ Value, indicating, whether the null-hypothesis can be rejected and thus, the model is significant. Dependencies are marked as follows:

- $R^2 > 0.6$ and $p-$ Value < 0.05 with a blue background represents a strong dependency;
- $R^2 > 0.3$ and $p-$ Value < 0.05 with a grey background represents a dependency;
- $R^2 < 0.3$ or $p-$ Value > 0.05 with no background color as no relevant dependency was detected.

The loudness according to DIN45631/A1 [59, 60] and ISO532-1 [58] shows similar strong dependencies to the empiric annoyance as expected by their nearly equiv-

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[6] Software platform for sound and vibration analysis: https://www.head-acoustics.com/products/analysis-software/artemis-suite

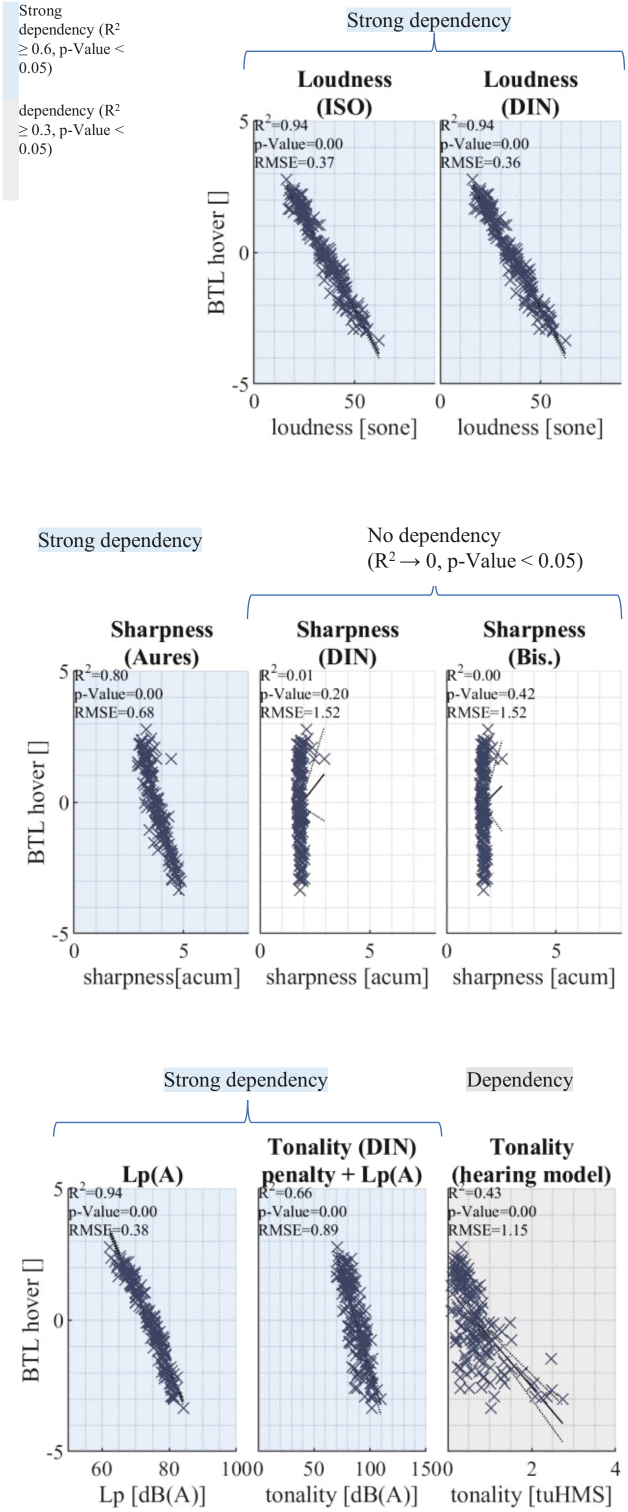

FIG 3. **Evaluation of dependency of different versions of the psychoacoustic metrics loudness (ISO, DIN), sharpness (Aures, DIN, von Bismarck), tonality (DIN penalty only, Lp(A)+ DIN penalty, hearing model) to annoyance. Dependency is rated according to R^2 and $p-$Value.**

alent calculation methods. This is similarly found for the A-weighted sound pressure level $L_\mathrm{p}(A)$.

Regarding sharpness, only the method by Aures [62] shows a strong dependency on the empiric annoyance, while DIN45692 [61] and von Bismarck [63–65] show quite constant values. However, the DIN45692 and von Bismarck have been developed for sounds with comparable loudness[7], which is not considered in this study.

The tonality DIN45681 [66] adds a penalty in decibels (in dB) to the sound pressure level, which in this case leads to a worse dependency to annoyance than $L_\mathrm{p}(A)$ alone. Thus, this metric is not recommended for eVTOL sound evaluation. However, the tonality based on the hearing model Sottek [67] shows a dependency to annoyance with $R^2 > 0.43$ and $p-\text{Value} < 0.05$.

4.3. Summary of the acoustic optimizations

The presented study showed that the choice of norm/version of psychoacoustic metric influences further acoustic results. When employing an empirical annoyance model, it is essential to use the exact identical metric that was utilized in creating the model. As indicated by the results presented above, using a different version or norm of a metric could significantly alter the values within an annoyance model.

Moreover, different results regarding the feature importance of the individual metrics emerge dependent on which version/norm is used. In this specific case study, it may be suggested to incorporate tonality into an empirical annoyance model, particularly if utilizing the version that relies on the Sottek hearing model. However, if the DIN45681 is used, tonality can be omitted, since the result is worse than $L_\mathrm{p}(A)$ alone. Overall, the importance of carefully choosing the psychoacoustic metrics and considering their differences has to be underlined.

5. CONCLUSIONS

The findings from the surveys conducted in European mid-sized cities andat continent-scale on the acceptance of UAM and eVTOLs revealed safety and noise as the predominant concerns among potential users against the adoption of eVTOLs as urban transportation. However, through innovative approaches taken at the conceptual design stage, these critical issues were effectively handled.

In addressing the safety concern, a methodology was proposed, integrating the established holistic but qualitative SORA framework and BNs for a comprehensive quantitative assessment. The importance of including multi-state variables beyond the binary classification of the standard FTA was highlighted. This evolution allowed the incorporation of operational mitigations into the failure probability calculations entailing

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[7] `https://cdn.head-acoustics.com/fileadmin/data/global/Application-Notes/SVP/Psychoacoustic-Analyses-I-02.2018.pdf`

an improvement in safety levels without necessitating architectural modifications that increase weight, size, and costs to the eVTOL. Furthermore, it exemplified a promising strategy for realistically studying and enhancing eVTOL safety while fostering vehicle design efficiency and acceptance of UAM. Overall, by assuring technical and operational safety, positive public perception and trust can drive further development and integration of eVTOLs as urban transportation systems, thereby playing a significant role in enhancing the acceptance and successful implementation of UAM.

Moreover, in the context of the proposed safety assessment, a potential future work includes first the evaluation of "reliability importance measures", e.g., the Critical Importance Factor (CIF). The CIF is characterized as the probability that the component remains operational. This could be further explored using BNs to identify potential architectural enhancements. Notably, when assessing the impact of components on system failure, the CIF suggests optimizations in terms of redundancy reduction. Through the CIF, a considerably low failure probability can be observed in redundant systems indicating the possibility of eliminating one module while preserving a failure probability under the threshold. This modification could yield benefits such as reduced weight, lowered costs associated with electronic components, and decreased maintenance requirements. Second, the inherent safety-related challenge in preliminary eVTOL design lies in the constrained dataset of reliability information available for quantitative assessment of the eVTOL and its components. To address this, synthesizing and quantifying expert viewpoints emerges as a future strategy for overcoming this gap.

The concern of noise, standing out as the second primary concern, was also thoughtfully tackled by analyzing the application of psychoacoustic metrics. The impact of different versions/norms on their ability to predict the human perception of noise was analyzed using empiric annoyance results from an international user study. For the loudness varying sounds, the loudness ISO532-1 or DIN45631/A1, sharpness according to Aures, and tonality based on the hearing model Sottek showed the most promising predictions of the human annoyance of eVTOL noise. In the in-house acoustic database, these versions/norms of the psychoacoustic metrics indicated an improvement of empiric annoyance, when decreasing $L_{\mathrm{p}}(A)$, loudness, sharpness, or tonality. Many measures are currently available to influence the acoustics of an eVTOL in the early design stages. One example is the well-known reduction of the blade tip speed, which can help to decrease the sound pressure levels. In future work, it will be interesting to compare different measures regarding their impact on annoyance. Likewise, the comparison of an empiric annoyance model versus the application of simple metrics, such as $L_p(A)$ alone, will be discussed.

6. ACKNOWLEDGEMENTS

Parts of this research project were funded by the European Regional Development Fund (ERDF) with the funding code EFRE-0801700 (Project URAF).
Sincere gratitude to the diligent contributions of Benedikt Kniebel during the course of this research; his dedication, insights, and hard work have greatly enriched the progress and outcomes of this study. Sincere gratitude also to the advice, expertise and contributions of Michael Fischer, especially in the context of psychoacoustic metrics.

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7. APPENDIX

7.1. Conditional Probability Tables (CPT)

Bayesian Networks are visual representations of dependencies among random variables. The variables represent propositions (or the probability of an event occurring, which can be translated into a state for that variable). Links connect these variables to show the dependency, for example, node B is connected to node A and node C in Fig. 4. B is referred to as a child of A and C, while on the other hand, A and C are parents of B. A Conditional Probability Table (CPT) is given as an example for node B in Fig. 5, where node B has two states, i.e., b_1 and b_2, and it depends on its parents A and C, which have two states, respectively, a_1, a_2 and c_1, c_2. The terms that populate the CPT are the conditional probability, which is defined as in Eq. 4

$$P(A|B) = P(B \cap A)/P(B) \tag{4}$$

This implies that event A and event B are dependent upon each other. A conditional probability for event B given event A is equal to the conditional probability of event A given event B, multiplied by the own state probability for event B and divided by the own probability for event A.

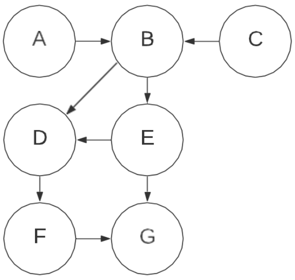

FIG 4. Example of a BN

a_n	$P(A = a_n)$
a_1	0.9
a_2	0.1

A	C	$P(B = b_1 \mid A, C)$	$P(B = b_2 \mid A, C)$
a_1	c_1	0.2	0.8
a_1	c_2	0.9	0.1
a_2	c_1	1	0
a_2	c_2	0.5	0.5

c_n	$P(C = c_n)$
c_1	0.55
c_2	0.45

FIG 5. CPT for node B

7.2. Avionic system architecture

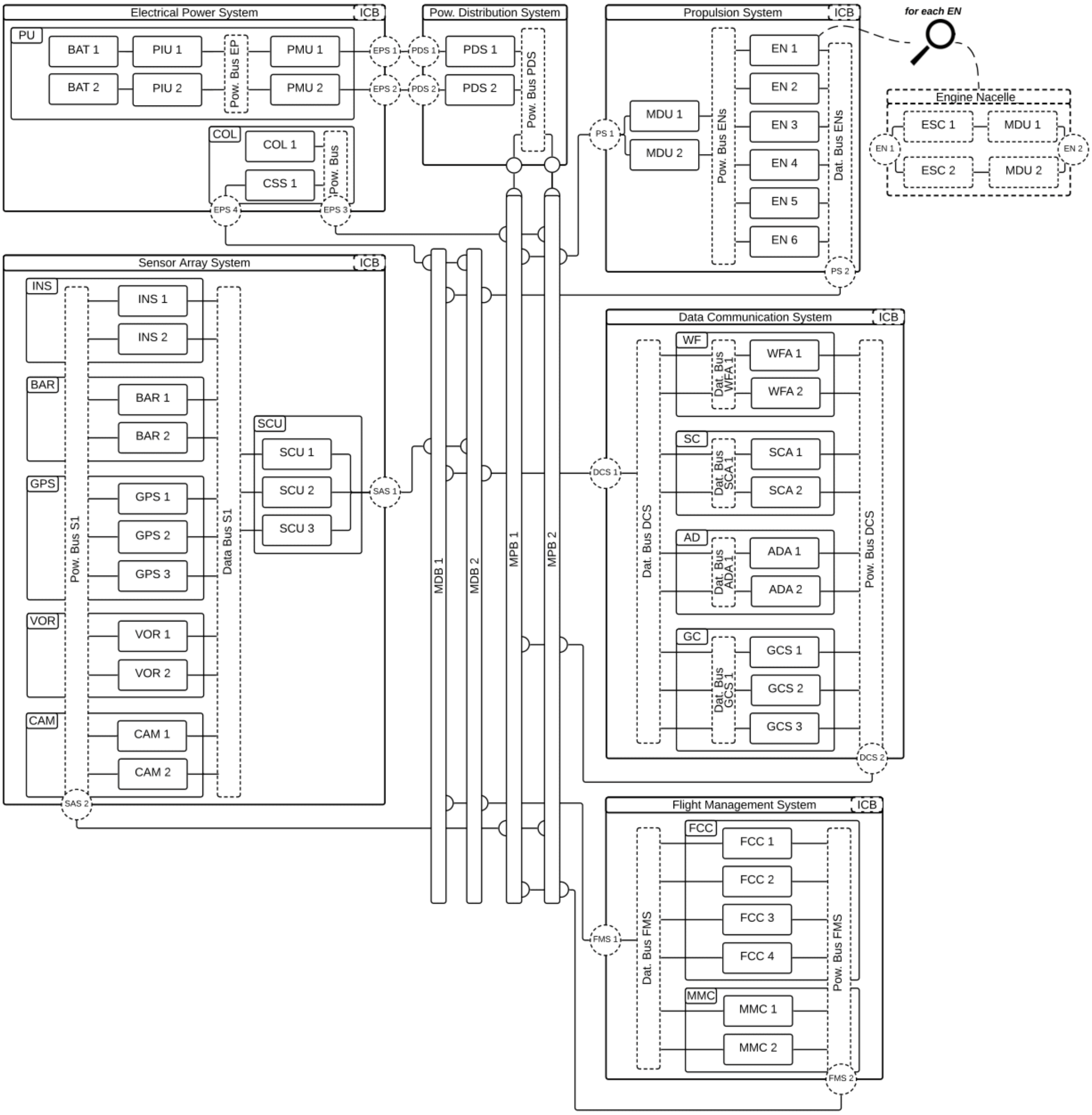

FIG 6. Reference avionic system architecture

7.3. Fault Tree

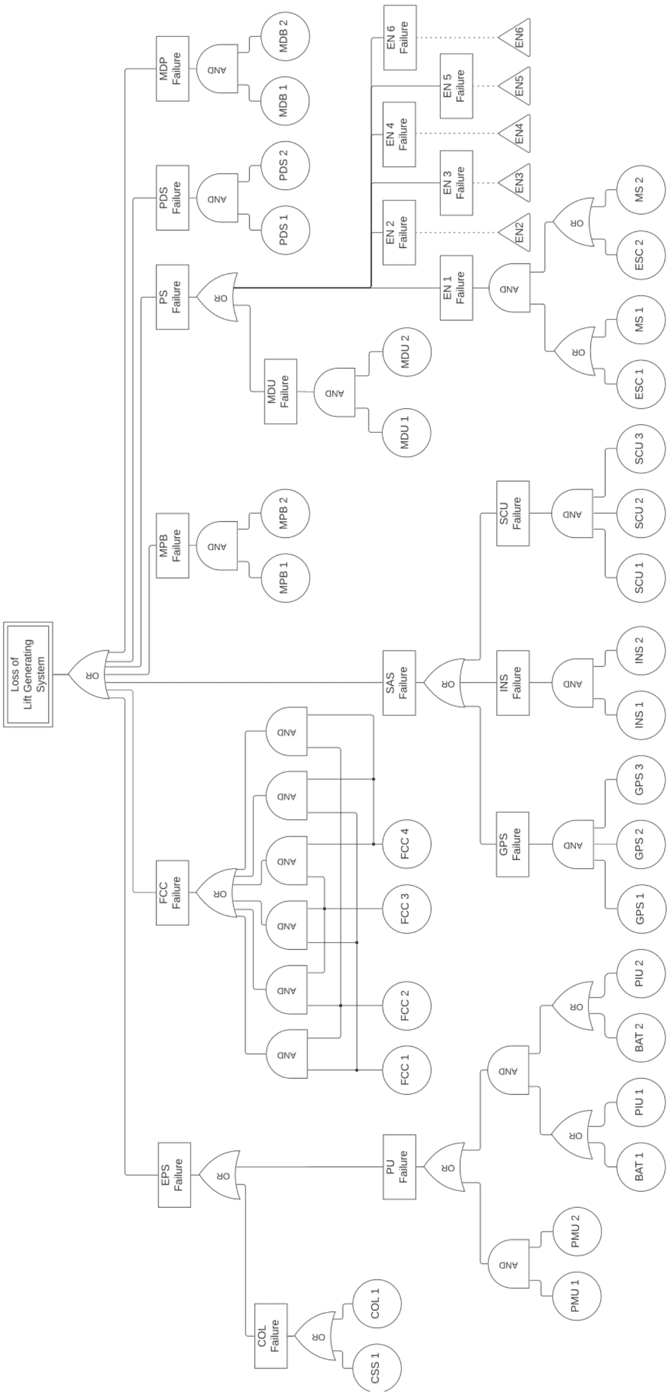

FIG 7. Fault Tree of the avionic system in case of loss of propulsion

7.4. Bayesian Network

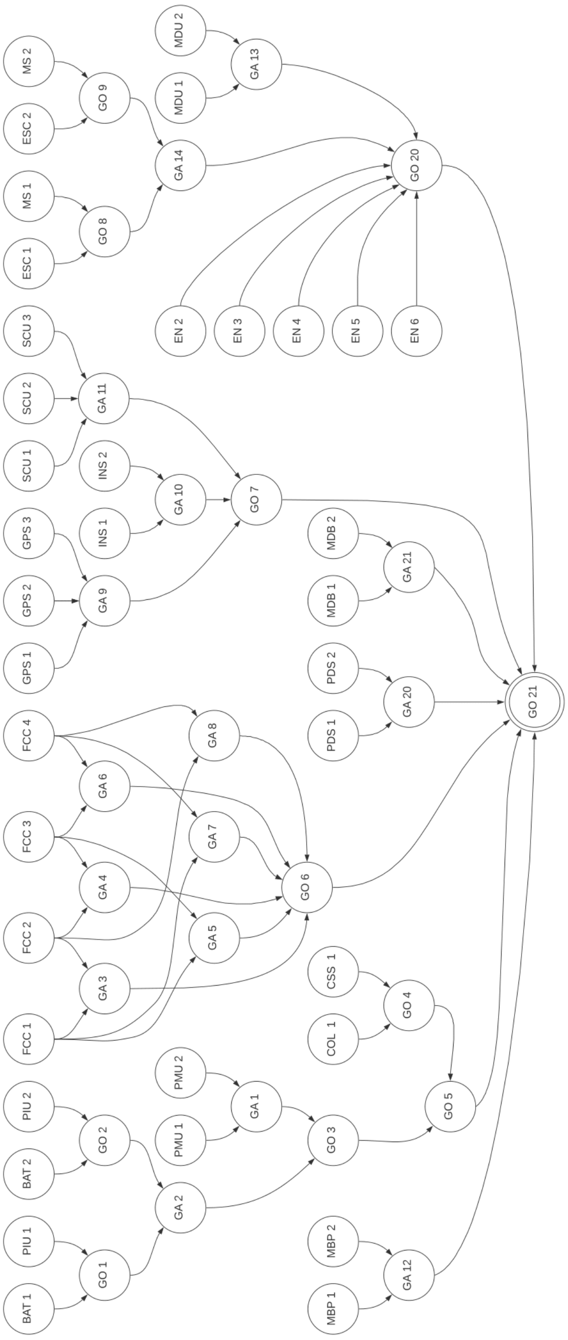

FIG 8. Bayesian Network of the standard architecture