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A Regulatory Analysis and Process Improvement Decision Support Framework for Unmanned Aerial System (UAS) Noise Certification

Session: UAS/UAM Noise Regulations

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Abstract

The rapidly growing Unmanned Aerial Systems (UAS) vehicle category with applications across various configurations and mission profiles introduces challenges in ensuring that applicable noise certification regulations are met. A framework is proposed for assessing regulatory compliance to noise standards and analyzing the process effectiveness and outcomes of noise testing campaigns for UAS. This framework is enabled by a Model-based Systems Engineering (MBSE) workflow for creating verification models that represent requirements derived by applicable regulations under the CFR Part 36 noise certification. As a digital thread-enabled approach, this environment allows for tracking and assessing adherence to noise regulatory practices through mapping noise data flows from test campaigns to metrics of interest as part of the verification of meeting regulatory noise requirements. Moreover, the environment allows for the assessment of the certification process eliminating unnecessary redundancies. The assessment of improvement strategies and selection of testing procedures is demonstrated through an integrated decision support dashboard for a small multi-rotor electric Vertical Takeoff and Landing (eVTOL) vehicle operated for a package delivery mission.

Keywords: UAS; MBSE; eVTOL; noise; regulation;

1. INTRODUCTION

The burgeoning field of Emerging Technology Aircraft (ETA) spans from UAS for package delivery applications to Urban Air Mobility (UAM) vehicles set to radically transform the transportation (“Urban Air Mobility (UAM) Concept of Operations”, 2023) as we know today. Noise remains the second top concern of the public from this new category of vehicles as learned by the studies (“Study on the societal acceptance of Urban Air Mobility in Europe”, 2021) commissioned by the European Aviation Safety Agency (EASA). National Aeronautics and Space Administration (NASA) identified in a technical publication (Rizzi et al., 2018) the current practices, gaps, and recommendations in the areas of ground and flight testing; regulation, and policy; among other subject areas pertaining to ETA. International Civil Aviation Organization (ICAO)’s Committee on Aviation Environmental Protection (CAEP) meeting held in 2022 observed in a working paper (“U.S. UPDATES ON ETA NOISE CERTIFICATION”, 2022) that the generally applicable noise rules for ETA require a base of data generated from common test environments for all the relevant ETA.

Generally applicable rules for noise certification of a variety of aircraft configurations ranging from transport jets to general aviation aircraft to helicopters are encapsulated (“NOISE STANDARDS: AIRCRAFT TYPE AND AIRWORTHINESS CERTIFICATION”, 2024) in Code of Federal Regulations (CFR) Title 14 Chapter I Sub-chapter C Part 36. However, the Federal Aviation Administration (FAA) has released Rules of Particular Applicability (RPA) for multiple UAS category vehicles (“Noise Certification of UAS/AAM using Rules of Particular Applicability”, 2023; “Noise Certification Standards: Matternet Model M2 Aircraft”, 2022) that are majorly based on the Appendices G, H and J of Part 36, which cover the noise standards for general aviation aircraft, large and small helicopters respectively, with several appropriate changes made to address the UAS vehicles.

It is of interest to the FAA to explore the possibility of generally applicable rules to the extent possible for the UAS category vehicles. For instance, EASA released generally applicable rules (“Part 13 - Noise Test Code Annex to Delegated Regulation (EU) 2019/945”, 2024) for small UAS vehicles weighing below 25 kg that are operated in the “open” category with “low risk”. It is worth noting that the EASA small UAS noise rules don’t specify a noise limit and the noise test code refers applicants to adhere to the ISO 3744-2010. EASA also provides generally applicable guidance for the submission of noise test data voluntarily for UAS vehicles weighing below 600 kgs operating in a “specific” category with “low” and “medium” risk (“Guidelines on Noise Measurement of Unmanned Aircraft Systems Lighter than 600 kg Operating in the Specific Category (Low and Medium Risk)”, 2024). Recently, the International Standards Organization (ISO) has also released a test standard for UAS vehicles weighing below 150 kg (“ISO 5305:2024 Noise measurements for UAS (unmanned aircraft systems))”, 2024) which provides various alternative testing procedures including indoor (Anechoic wind tunnel) and outdoor testing alternatives.

This study recognizes that an effective standard-setting process for noise certification of UAS vehicles involves primarily the analysis of available and any newly proposed alternatives for regulatory effectiveness and further understanding the ramifications the corresponding certification test processes entail. The next section describes firstly the formulation of certification testing alternative methods in the context of UAS noise standards followed by the definition of regulatory effectiveness metrics such as technical achieveability and verifiability etc. Further, the modeling approach utilized to capture the probabilistic nature of the test processes and the resulting overall metrics, for example, cost and time, to quantify a given alternative process efficiency are detailed. These two analyses form the regulatory framework that generates the insights necessary to conduct informed decision-making for an effective standards-setting process.

2. METHODOLOGY

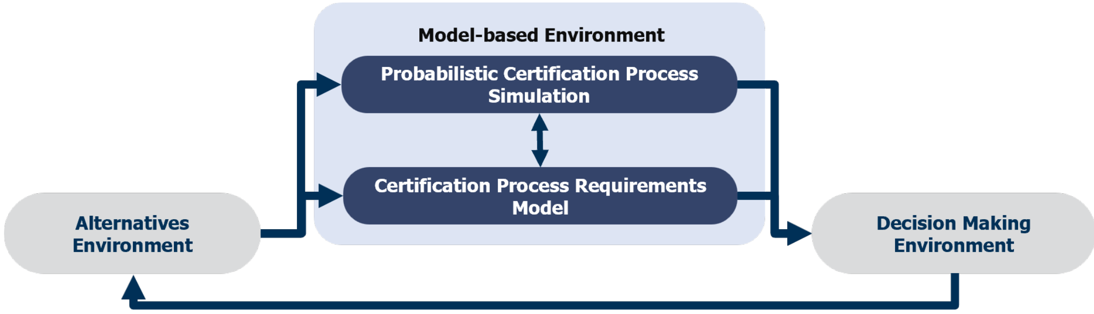

Figure 1: Certification Framework High-Level Architecture

Figure 1 illustrates the high-level architecture of the model-based certification framework proposed. The key analytical environments are housed in the middle whereas the alternatives environment and subsequently the decision-making environment are at each end of the framework. (Ravikanti, Ali, Balchanos, Harrison, & Mavris, 2024) and (Balchanos, Mali, Rameshbabu, Harrison, & Mavris, 2024) highlight the utility of the certification process requirements model and probabilistic simulation model respectively in isolation. This paper integrates the methods described in the two studies in a single framework to holistically address the effectiveness and economic viability of the potential alternatives.

The alternative environment generates alternative certification procedures through a morphological matrix composed of various levels of regulatory elements starting from a given regulatory standard to detailed means and methods of compliance and their potential alternatives. For this study noise testing campaigns conducted by Blue Ridge Research and Consulting (BRRC) at the Causey airport (James, Salton, Johnson, Downing, & Calton, 2021) and Volpe Center at Joint Base Cape Cod (JBCC) (Cutler-Wood et al., 2022) had to be resampled to maximize the number of available test conditions to analyze on. For example, a given test condition that was repeated “n” times was resampled to create all possible sizes of data sets from “n-1” to 2. This process was repeated for all the test conditions available in the original dataset. This is then followed by considering metrics of interest such as Sound Exposure Level (SEL) or Equivalent A-weighted noise Level as applies to the regulatory paragraphs being analyzed. Further details of this process in addition to its interfacing with the model-based certification process requirements and simulation are discussed in the following sections.

2.1 Regulatory Effectiveness Analysis of Alternatives

Proposing alternative procedures is aimed at alleviating the certification burden and improving the regulatory effectiveness of current noise certification standards thereby bridging the gap between them and the UAS certification needs. The scope for alternative generation starts from the noise standards at a higher level and extends downstream to the means and methods of compliance. The alternative spectrum may include anything from different noise metrics to microphone setups, to additional flight tests that better capture the specific mission profile of the UAS, etc. Such alternatives are surveyed from the literature on noise standards provided mainly by the FAA, EASA, and ISO noise standards.

The evaluation criteria for the proposed alternatives are broadly represented by certification burden and regulatory effectiveness. On the one hand, the certification burden relates to the economic and time efficiency and the complexity of the alternatives; it will be discussed further in the next section. On the other hand, regulatory effectiveness is indicative of the technological practicability of the alternative including metrics such as technical feasibility, verifiability, etc. Consequently, assessing the regulatory effectiveness of alternatives requires data for verification. To this end, data provided by the Causey UAS Acoustic Measurements campaign conducted by the FAA, Volpe, and BRRC was leveraged to conduct the analysis provided in this study (James et al., 2021). The objective of the testing campaign was to “gather certification quality data in compliance with the UAS noise regulations specified in 14 Code of Federal Regulations (CFR) Part 135” (James et al., 2021). Figure 2 below illustrates the Causey testing campaign layout.

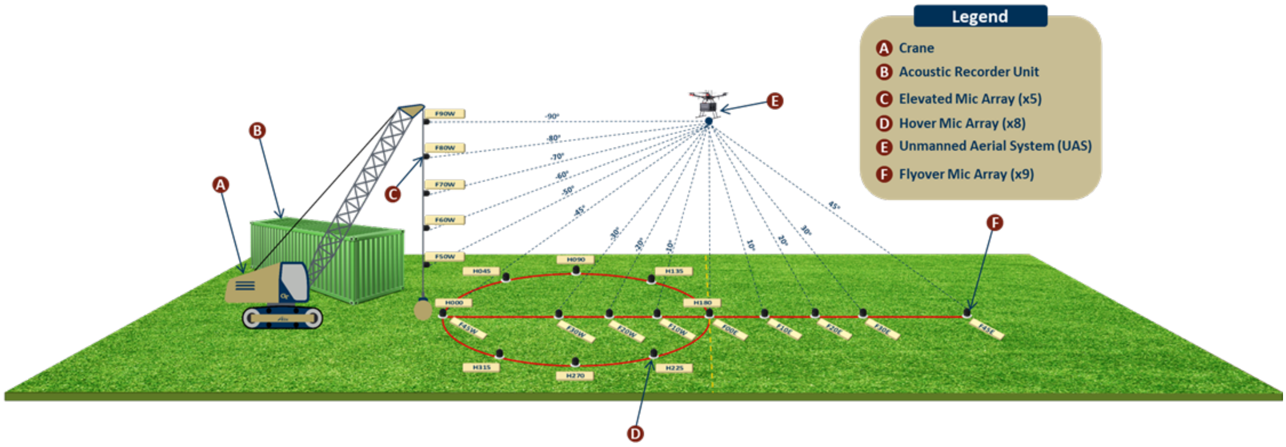

Figure 2: Causey Test Campaign Concept of Operations

The Causey campaign provided noise measurements for three UAS including the Flytrex FTX-M600P, Volansi VOLY C10, and DJI m210. In addition, the test campaign conducted three groups of “test points” including level flyover operations, hover operations, Idle, takeoff, landing, and flyover operations at operational altitude for all three UAS (James et al., 2021). These test points are also conducted based on various combinations of weight, speed, and altitude.

The experimental data provided by the Causey campaign was inclusive of sound pressure-time history for each test point, weather measurements (temperature, humidity, wind speed, and direction), and test metadata including UAS weight, speed, and heading direction. The sound pressure-time history was utilized to calculate two noise metrics prescribed by UAS RPAs: Sound Exposure Level (SEL) for the flyover test and Equivalent Sound Level (L_{eq}) for the hover test (“Noise Certification Standards: Matternet Model M2 Aircraft”, 2022). Re-sampling of the available experimental test data was necessary to overcome the limitation of data scarcity. The Causey experimental data is utilized as input to conduct a comprehensive regulatory analysis of requirements. As proof of concept, the confidence interval requirement from paragraph 26 of (“Noise Certification Standards: Matternet Model M2 Aircraft”, 2022) which requires a “90 percent confidence limit that does not exceed ±1.5 dB(A)” was investigated (“Noise Certification Standards: Matternet Model M2 Aircraft”, 2022). Further detail on the proof of concept is provided in the following sections.

Moreover, a requirement verification model for noise certification of the Matternet M2 was developed in MagicDraw (“MagicDraw - CATIA”, 2023). The MBSE framework ensures consistency and traceability between regulations and the certification database. It consists of requirement blocks and flight test procedures. Requirement diagrams detail regulations using requirement blocks, which specify the regulations, and constraint blocks, which verify if test data meets the requirements. Constraint blocks attach to requirement sections like branches, with each section containing several requirement blocks and each requirement block having multiple constraint blocks.

2.2 Probabilistic Process Modeling and Simulation

Noise testing can be represented as a stochastic process comprised of a sequence of steps or tasks to be conducted. As a sequence of probabilistic events, different sources of uncertainty can emerge as the success of certain steps can be affected by factors such as human error, unstable weather conditions, equipment malfunction, unsatisfactory measurements, and so on. Therefore, the uncertainty associated with such a process needs to be properly captured by identifying all potential outcomes of each step as well as their likelihood of occurrence. This process can be modeled using Markov Chains in conjunction with Graph Theory and Monte Carlo simulations. In this graphical representation, each node in the chain corresponds to a step of the process, and the nodes are connected by edges that represent the different potential paths. Each path has a probability of occurrence such that the probabilities corresponding to all the edges originating from a node need to add up to 1.

Based on previous noise testing campaigns conducted by BRRC at the Causey airport (James et al., 2021) and Volpe Center at JBCC (Cutler-Wood et al., 2022), a typical layout for noise testing can be developed, as shown in Figure 3, and it comprises five phases: test site inspection, test site preparation, flight test, data analysis, and a potential additional day of testing for additional measurements if necessary. Moreover, the flight test day can be divided into three sequential sub-phases: the pre-test procedure during which all equipment including the microphones and windscreens are installed, tested, and calibrated prior to the flight tests, and the weather conditions checked to ensure proper flight conditions. Flight test procedure can then be initiated such that the noise measurements are taken and checked with a possibility of microphone re-calibration, or battery replacement and maintenance between flights whenever necessary. Once all measurements are collected, the microphones are re-calibrated and all equipment collected marking the end of the third testing phase.

Figure 4 depicts an example of the Markov Chain representation of the process following the layout described above for a testing campaign conducting hover testing as the desired flight profile under three different combinations of weight, speed, and altitude conditions, also referred to as test points such that each test point is typically repeated six times (six test runs).

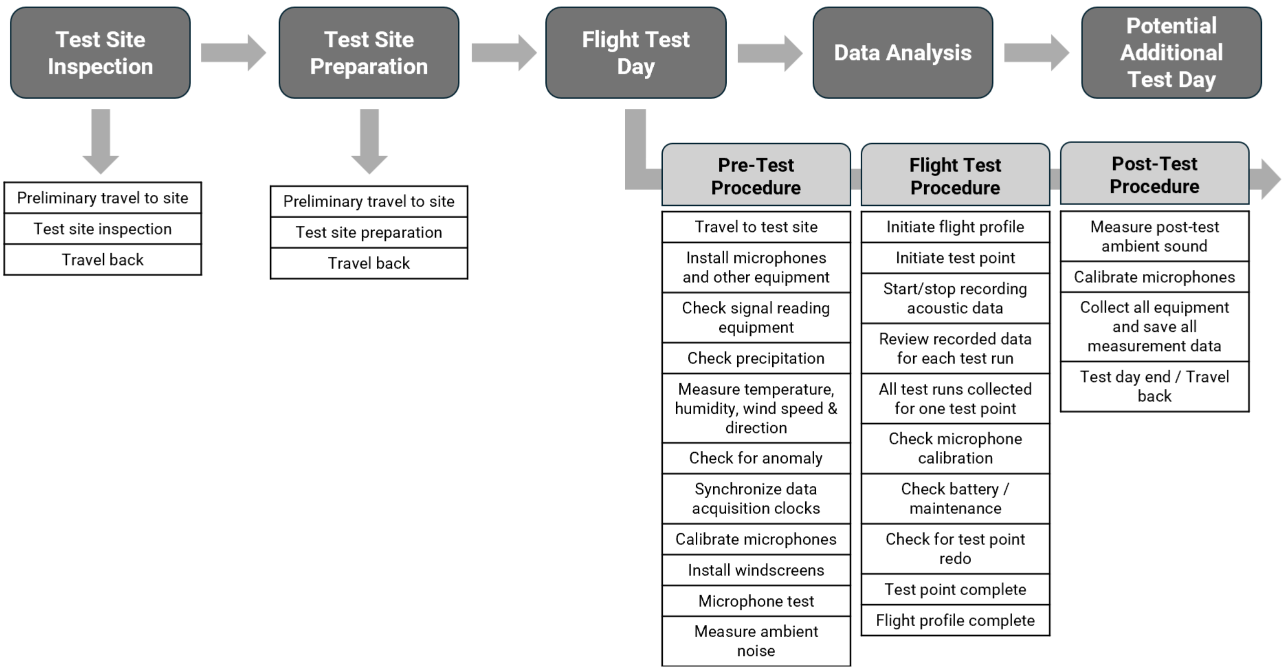

Figure 3: A typical layout of a noise testing process for Unmanned Aerial Systems (UAS)

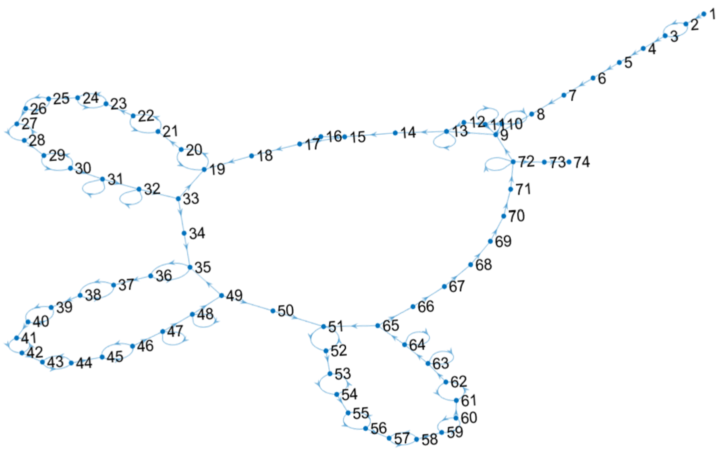

Figure 4: Markov Chain representation of a typical noise testing process

The developed model in Matlab ("MATLAB-R2022b", 2024) enables the simulation of noise testing campaigns of different scales and of different purposes whether they are small-scale testing campaigns exclusively focused on certification, or, in contrast, large-scale campaigns geared towards acoustic research, community acceptance, or environmental studies. Consequently, the framework adapts to the desired testing to better capture the logistics and flight measurements plan based on the available resources including the budget, schedule, and personnel. The model prompts the user to provide two main types of data:

- **Logistics-related data**: the number of personnel involved in each testing phase and the total number of microphones to be used. These two inputs will have direct effects on the duration of the installation and calibration of the microphones as well as the total equipment cost, and the personnel payment.
- **Measurements-related data**: the number and type of flight profiles to be conducted (i.e. flyover, hover, takeoff, and landing), and the number of test points per flight profile. The type of flight profile to be conducted affects the duration of each measurement such that hover measurements typically take around 30 seconds while level flyover measurements take around 24 seconds based on the Causey data that have been provided to analyze and calibrate the model (James et al., 2021). Other trends can also be deduced after processing and analyzing the Causey data. For instance, test points conducted at maximum weight conditions required a much higher number of test runs. Consequently, the model can prompt the user to specify the number of test points performed at maximum weight to further help inform the likelihood of measurement repetitions for those specific test conditions.

Each step of the process is allocated a specific time and cost depending on the logistics and measurement inputs specified by the user. The model tracks the time and cost throughout the process depending on the paths taken by each Monte Carlo simulation. Considering the uncertainty related to the estimates of time and cost of each step, the Design of Experiments (DoE) was set up to capture a wider range of variables and identify the significance of their impact on the overall process. The DoE contains 2000 cases such that each of the variables of each step is varied by factors in the range of [0.4, 4] using Latin Hypercube Sampling (LHS) as the space-filling method of choice. Each DoE case undergoes 10000 Monte Carlo simulations to ensure better accuracy and higher fidelity of the results. Multiple process alternatives can be simulated and compared based on their impact on the certification burden, specifically time, cost, and process complexity.

3. Results and Discussion

The following sections discuss the results generated from the implementation of the methodology described in the previous section with the help of a few illustrative use cases. The case studies are motivated by the study of existing UAS regulations and further considerations of potential alternatives discussed in the previous section. The results are divided into two categories namely regulatory effectiveness which deals chiefly with the technical adequacy of the regulations and secondly, the process simulation which deals with the efficiency of the certification process comparing multiple potential alternatives to a given baseline process.

3.1 Regulatory Effectiveness

Figure 5 shows a model-based representation of a regulatory paragraph that ensures end-to-end traceability in the broader regulatory context. This allows us to keep track of critical dependencies and relationships between various elements of a regulatory hierarchy. The representation in the SysML environment allows automatic requirement verification of the resampled test data previously alluded to.

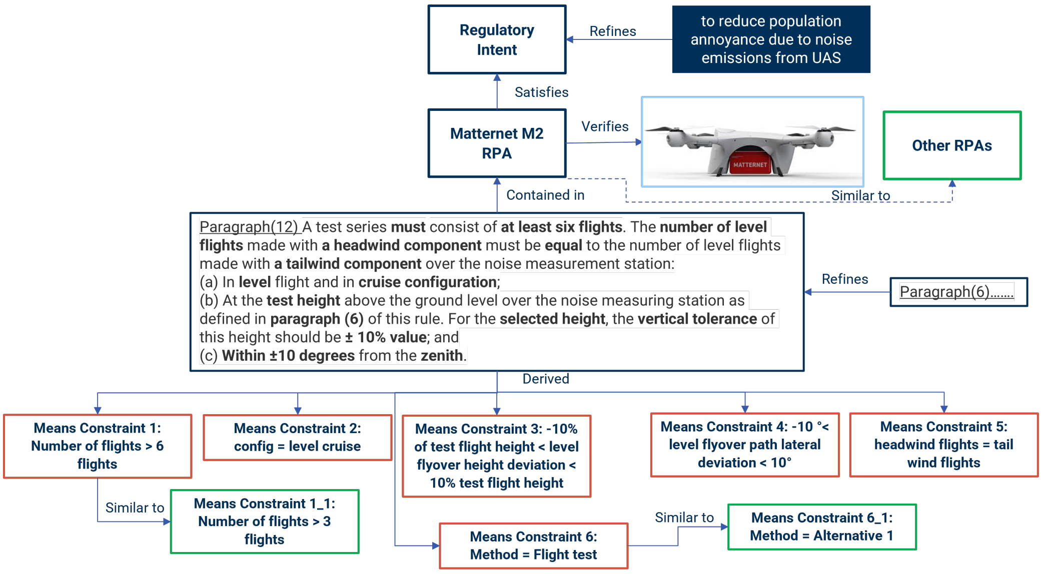

Figure 5: Model Based Certification Requirements Representation (Regulatory Paragraph from ("Noise Certification Standards: Matternet Model M2 Aircraft", 2022))

An analytical example that illustrates one of the many benefits of automated requirement verification is illustrated in Figure 6. The requirement identifications shown on the X-axis are assigned to various direct or derived means and methods of compliance from a process such as depicted in Figure 5. The data from the resampled original test data (as described previously in section 2) is methodically fed to appropriate model elements and the verification success of each element is presented on the Y-axis. It is seen readily that requirements that are below certain predetermined verification success criteria such as 50% as in the case illustrated can be further investigated to determine whether an available applicable alternative formulation may improve the verification success appropriately.

Consider for instance the confidence interval requirement from paragraph 26 of ("Noise Certification Standards: Matternet Model M2 Aircraft", 2022) to further illustrate how a potential alternative is investigated for improved verification success. All noise measurements made in a given test campaign must be able to establish the confidence interval of ± 1.5 dBA. Figure 7 shows the average confidence interval achieved for the equivalent A-weighted sound level with respect to the number of repeated measurements. Furthermore, various trends show the location of the microphone where the measurement has taken place in terms of emission angle for the source, and the "W" indicates west of the flight center line. The weight of the test vehicle is also mentioned for all the trends. It can be said that the majority of heavier flight measurements require more repeats to establish the confidence interval and measurements at some emission angles (for example 90 degrees at lighter flight configuration) require fewer repeated runs to establish the confidence interval in comparison to measurements at other emission angles (for example 50 degrees at lighter flight configuration). This form of analysis informs regulatory paragraphs that prescribe the noise metric to be reported and the flight profile and vehicle configuration to be followed for certification tests. This process was repeated for other microphone locations that were installed on the ground while considering different noise metrics such as SEL and A-weighted maximum sound level etc.

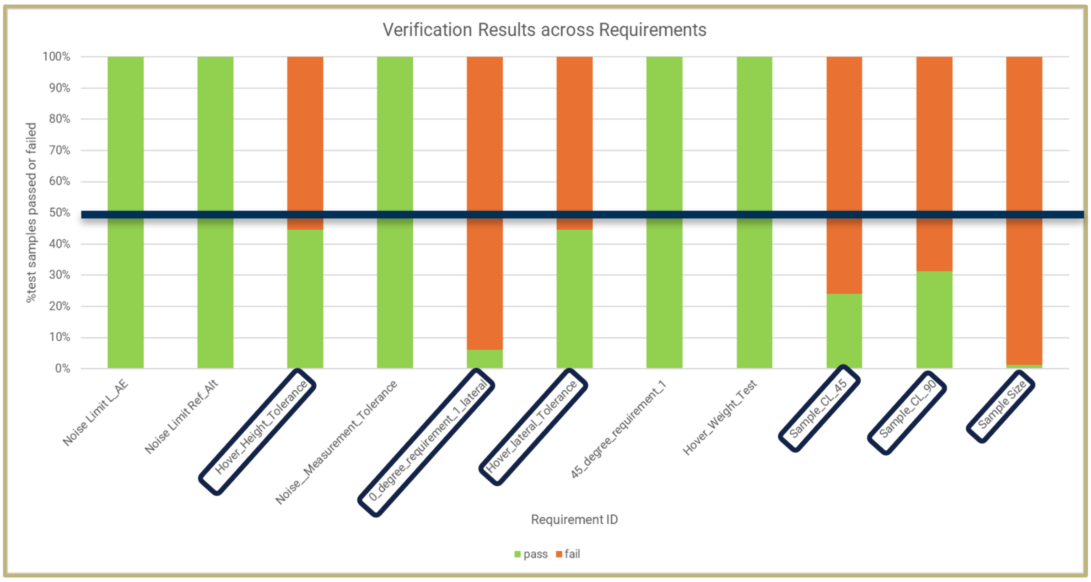

Figure 6: Model Based Certification Requirements Verification and Analysis

3.2 Process Simulation

As a demonstration of the capabilities of the process simulation and evaluation model, a case study has been formulated. Within the RPA set by the FAA for the Matternet M2 Aircraft ("Noise Certification Standards: Matternet Model M2 Aircraft", 2022), specifically in the section concerning hover noise testing, the FAA requires the aircraft to fly at different spatial locations relative to one microphone with the intent of reducing the number of microphones and their subsequent cost and workload associated with using more microphones. It's worth mentioning that the RPA issued for the Matternet M2 only requires a flyover test, but it also prescribes a supplemental hover test that will not be used to evaluate the applicant's compliance with noise standards rather it will be used to collect noise data that will inform the generation of generally applicable noise standards for UAS by the FAA ("Noise Certification Standards: Matternet Model M2 Aircraft", 2022). In contrast, Bell Textron Inc. proposed the use of more microphones for hover as a means to decrease testing time while enhancing testing efficiency.

This case study models and simulates the single microphone configuration proposed by FAA as a baseline process requiring three different test points as shown in Figure 8, and compares it to an alternative process employing three microphones with only one test point (see Figure 9). As a result of reducing the number of test points in the alternative process, the Markov Chain representation has been significantly reduced from 74 steps to 42 steps as depicted in Figure 10.

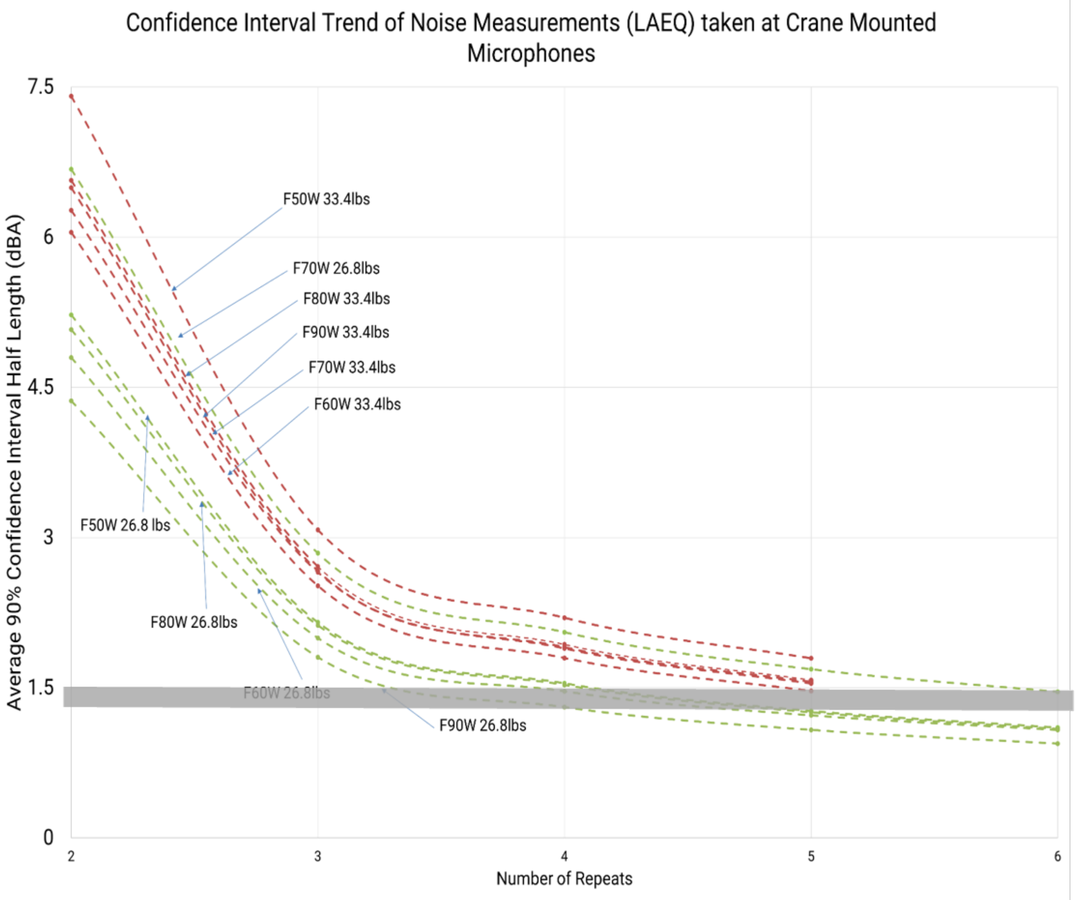

Figure 7: Analysis to Investigate the Regulatory Effectiveness of Potential Alternatives

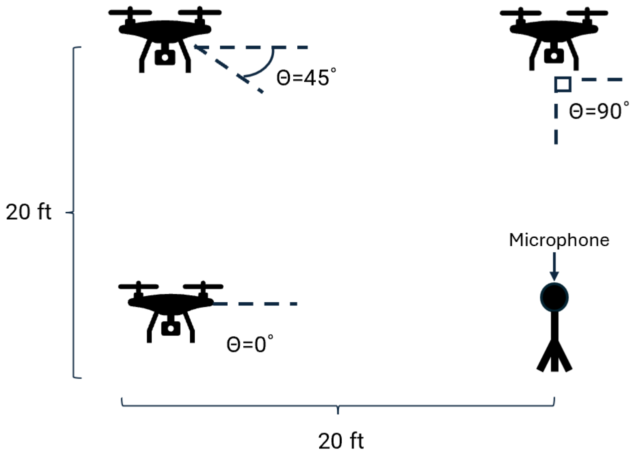

Figure 8: Microphone layout for the baseline process during the hover measurements ("Noise Certification Standards: Matternet Model M2 Aircraft", 2022)

The analysis of the results from both the baseline and alternative processes has been carried out using different visualization techniques including histogram overlays and sensitivity plots. The metrics of interest that were collected consist of mean time and mean cost for each DoE case. Figures 11 and 12 reveal that the baseline process entails lower mean time and lower mean cost, thus making the baseline process the better option in terms of these two metrics. The increased costs in the alternative process is mainly due to the additional microphones and windscreens which increase both the equipment cost as well as the labor cost due to the increased workload for the installation and calibration of the microphones. Moreover, this comparison indicates that the installation time and calibration time of the

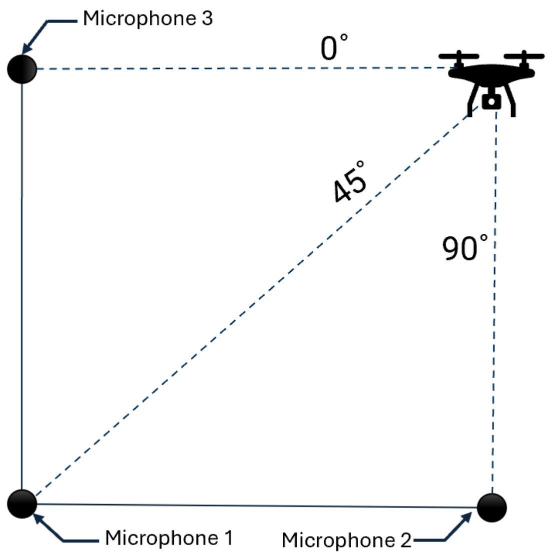

Figure 9: Microphone layout for the alternative process during the hover measurements

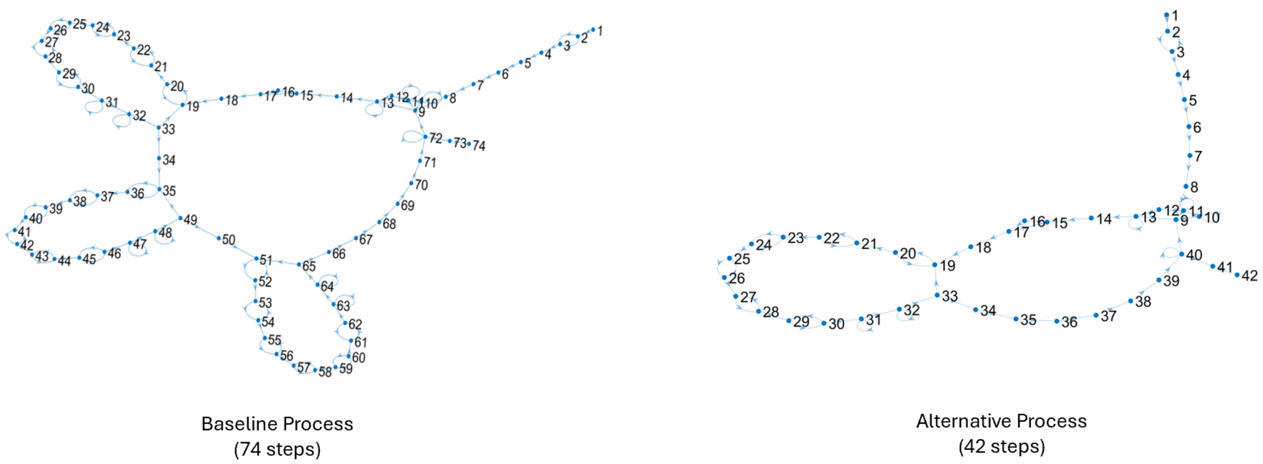

Figure 10: Markov Chain representation for the baseline process (left figure) and alternative process (right figure)

additional microphones in the alternative process outweigh the time spent on taking measurements of the additional test points in the baseline process. Consequently, the baseline process can be considered to be more efficient in terms of time and cost under the current process parameters such as the estimated likelihood of test runs and test points failure as well as the estimated time for the installation and calibration while taking into account the number of personnel on-site. Under certain combinations of these parameters, there might be scenarios in which the alternative process can emerge as a more time-efficient option compared to the baseline process.

In addition to histogram overlays, sensitivity plots have been generated to reveal the variability of the process simulation output metrics with respect to the input time and cost values allocated to each step of the process. Analyzing this variability and its significance allows for a better understanding of how sensitive the process is to certain steps that could be critical enough to create bottlenecks and highly reduce the efficiency of testing if not planned and carried out properly. This sensitivity analysis is conducted using the Prediction Profiler on JMP ("JMP Pro 17", 2023) which enables the dynamic visualization of the variability between the inputs and outputs of the simulation. The prediction profiler consists of multiple plots of the time and cost of each step and their corresponding predicted responses which refer to the total time and total cost of the entire noise testing process. Furthermore, by mapping the inputs to the outputs, surrogate models, also known as meta-models, can be generated to support interactive parametric decision-making. In the aim of finding the most adequate Probability Density Function (PDF) that can properly replicate the Monte Carlo distribution, multiple functions were evaluated.

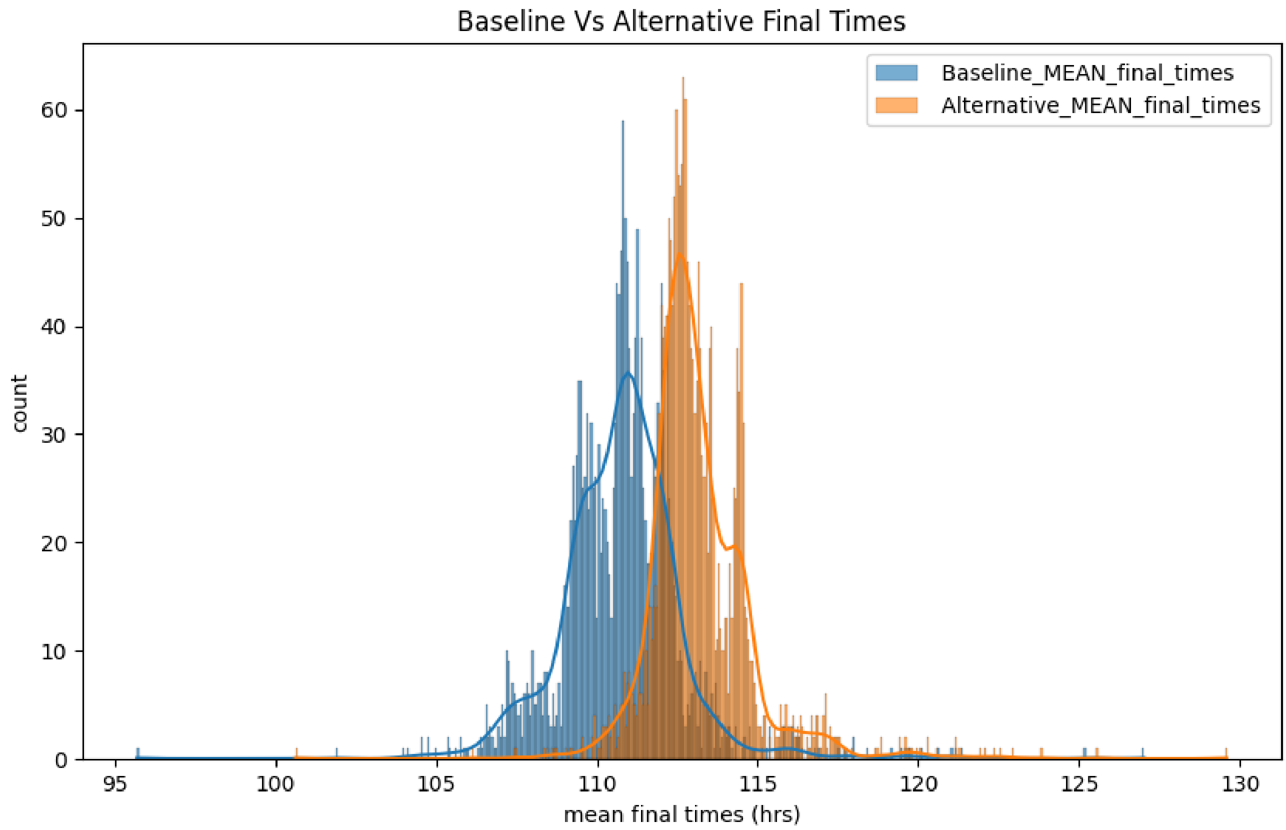

Figure 11: Baseline vs. alternative mean final times overlay

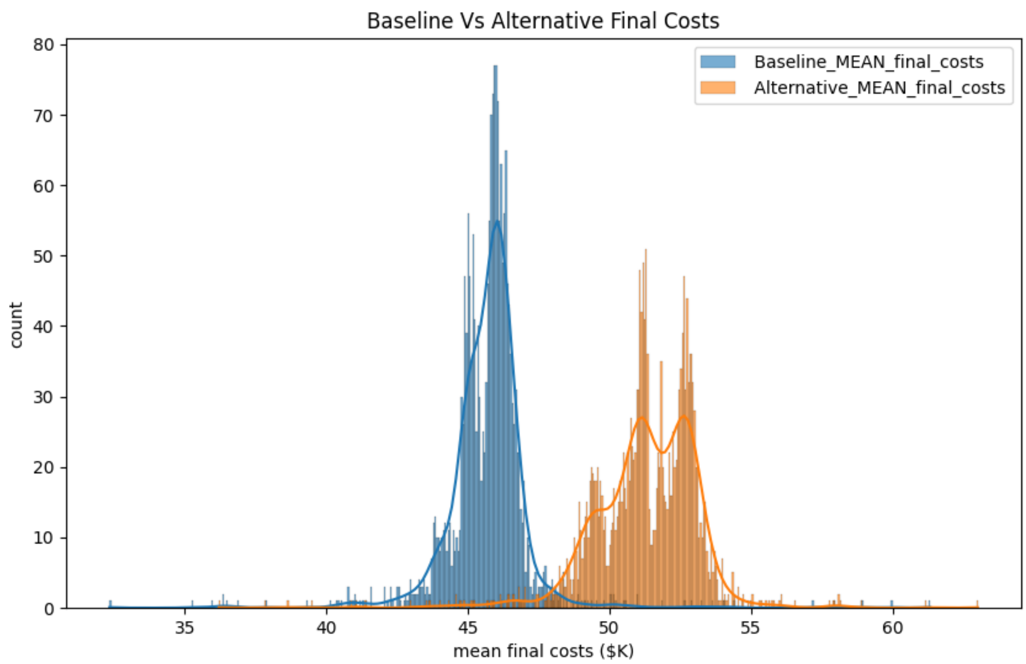

Figure 12: Baseline vs. alternative mean final costs overlay

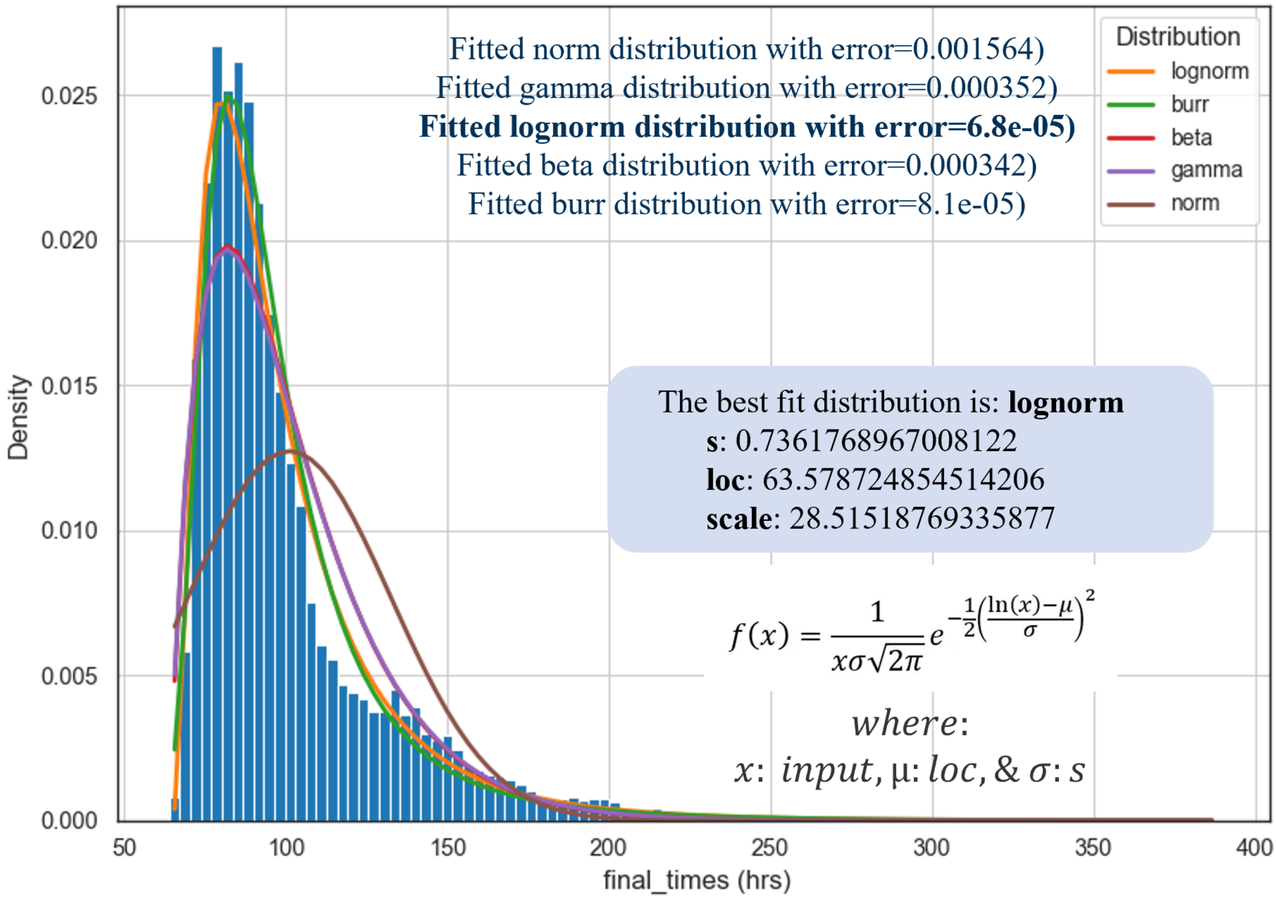

Figure 13: Sample Monte Carlo distribution of a single DoE case

It can be seen from Figure 13 that the most suitable option with the lowest error appears to be the log-normal distribution with the parameters being μ, σ, and scale. Using the log-normal PDF, the parameters were computed for each DoE case and employed as the output metrics of interest to develop the surrogate models and construct the prediction profiler. Figure 14 depicts an example of the prediction profiler corresponding to the location parameter for the time output for the individual times of each step. Furthermore, the significance of the predictor variables can be analyzed (see Figure 15). Based on the order, steps 36 and 12 appear to have the highest statistical significance in predicting the location output metric. To further analyze these two steps, step 12 was held constant while the time associated with step 36 was varied. This resulted in a notable correlation with a direction change. Similarly, the analysis can be applied to the baseline process and a comparison can be conducted. Additionally, the same process can also be repeated for the two remaining parameters as the example above exclusively focused on the location parameter.

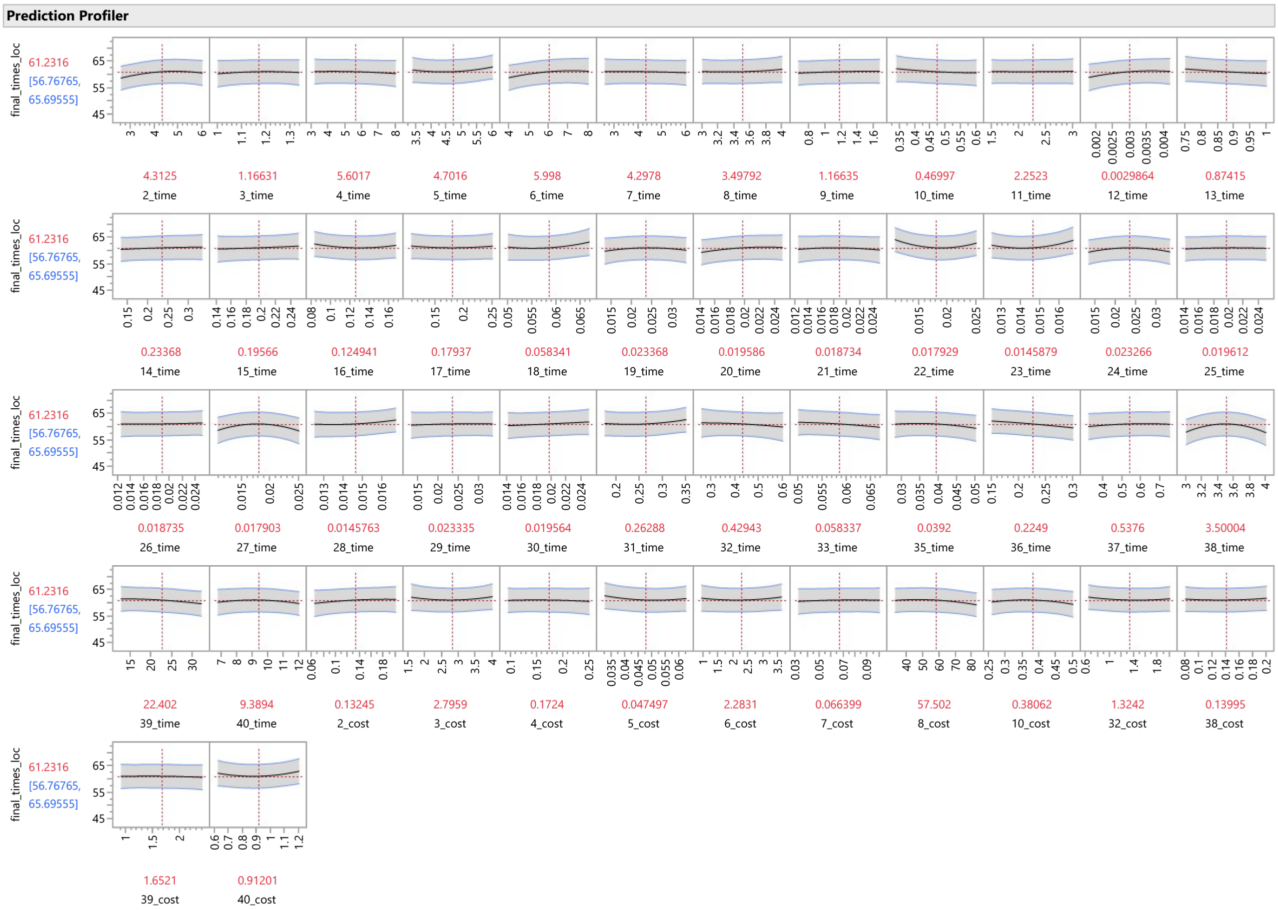

Figure 14: Prediction profiler plot of alternative process time generated using JMP ("JMP Pro 17", 2023)

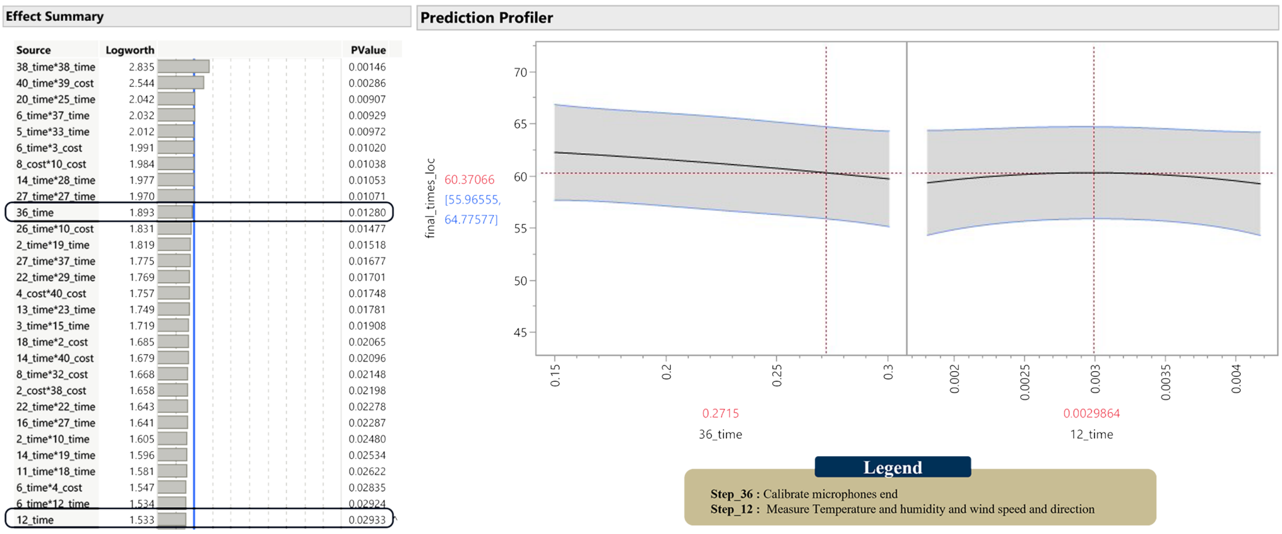

Figure 15: Key steps sensitivity plot generated using JMP ("JMP Pro 17", 2023)

4. Conclusion

This study demonstrates the benefits of an integrated framework that can conduct trades among potential certification procedure alternatives with the technical adequacy metrics and economic viability metrics in tandem. Future work is thus comprised of conducting multiple case studies centered around the incremental changes to regulatory paragraphs similar to those described in this paper. In addition, this method's feasibility remains to be investigated in assessing radical changes to a given certification procedure such as expanding or constraining the range of vehicles it is applicable to.

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16. Abstract

The rapidly growing Unmanned Aerial Systems (UAS) vehicle category with applications across various configurations and mission profiles introduces challenges in ensuring that applicable noise certification regulations are met. A framework is proposed for assessing regulatory compliance to noise standards and analyzing the process effectiveness and outcomes of noise testing campaigns for UAS. This framework is enabled by a Model-based Systems Engineering (MBSE) workflow for creating verification models that represent requirements derived by applicable regulations under the CFR Part 36 noise certification. As a digital thread-enabled approach, this environment allows for tracking and assessing adherence to noise regulatory practices through mapping noise data flows from test campaigns to metrics of interest as part of the verification of meeting regulatory noise requirements. Moreover, the environment allows for the assessment of the certification process eliminating unnecessary redundancies. The assessment of improvement strategies and selection of testing procedures is demonstrated through an integrated decision support dashboard for a small multi-rotor electric Vertical Takeoff and Landing (eVTOL) vehicle operated for a package delivery mission.

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