FORMULATION AND IMPLEMENTATION OF A GENERIC FLEET-LEVEL NOISE METHODOLOGY

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FORMULATION AND IMPLEMENTATION OF A GENERIC FLEET-LEVEL NOISE METHODOLOGY

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To my beloved wife Laura, and our beagles, Patas and Della:
Every day we are together is a good day.

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Two roads diverged in a yellow wood,
And sorry I could not travel both
And be one traveler, long I stood
And looked down one as far as I could
To where it bent in the undergrowth;

Then took the other, as just as fair,
And having perhaps the better claim
Because it was grassy and wanted wear,
Though as for that the passing there
Had worn them really about the same,

And both that morning equally lay
In leaves no step had trodden black.
Oh, I marked the first for another day!
Yet knowing how way leads on to way
I doubted if I should ever come back.

I shall be telling this with a sigh
Somewhere ages and ages hence:
Two roads diverged in a wood, and I,
I took the one less traveled by,
And that has made all the difference.

\- *Robert Frost, 1916*

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NOMENCLATURE

ACARE	Advisory Council for Aeronautical Research in Europe
ACRP	Airport Cooperative Research Program
ADVENT	Adaptive Versatile Engine Technology
AEDT	Aviation Environmental Design Tool
AEE	Office of Environment and Energy
AEM	Area Equivalent Method
AIRE	Atlantic Interoperability Initiative to Reduce Emissions
ANCA	Airport Noise and Capacity Act
ANGIM	Airport Noise Grid Integration Method
ANOPP	Aircraft Noise Prediction Program
ASPM	Aviation System Performance Metrics
AST	Advanced Subsonic Transport Noise Reduction Program
CadnaA	Computer Aided Noise Abatement
CCD	Central Composite Design
CI	Cohesion Index
CLEEN	Continuous Lower Energy, Emissions, and Noise
CO	Carbon Monoxide
CO_2	Carbon Dioxide
dB	Decibels
DeI	Depth Index

DetI	Detour Index
DI	Dispersion Index
DNL	Day-Night Average Level
DoD	Department of Defense
DOE	Design of Experiments
DSI	Detour Spin Index
EAC	Equal Area Circle
ECAC	European Civil Aviation Conference
EDMS	Emissions Dispersion Modeling System
EDS	Environmental Design Space
EIS	Environmental Impact Statement
EPA	Environmental Protection Agency
EPNL	Effective Perceived Noise Level
ERA	Environmentally Responsible Aircraft
F	Correction factor for pure tones
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FW	Fixed Wing Project (Formerly Subsonic Fixed Wing)
GA	Generic Airports
GI	Generic Infrastructure
GiI	Girth Index
GREAT	Global and Regional Environmental Aviation Tradeoff tool
GUI	Graphical User Interface

GR	Generic Runways
HEETE	Highly Efficient Embedded Turbine Engine
INM	Integrated Noise Model
JPDO	Joint Planning and Development Office
LHC	Latin Hypercube
MAGENTA	Model for Assessing Global Exposure from Noise of Transport Aircraft
MFE	Model Fit Error
MRE	Model Representation Error
N	Designation of the current generation of aircraft
N+1	Designation of aircraft one generational cycle from the present
N+2	Designation of aircraft two generational cycles from the present
N+3	Designation of aircraft three generational cycles from present
NARDP	National Aeronautics Research and Development Plan
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NCA	Noise Control Act
NCP	Noise Compatibility Plan
NEM	Noise Exposure Map
NextGen	Next Generation Air Transportation System
NOx	Nitrogen Oxides
O_3	Ozone
OMB	Office of Management and Budget
ONAC	Office of Noise Abatement and Control

P_0	Reference sound pressure
$P_A^2(t)$	A-weighted pressure squared, as a function of time
PARTNER	Partnership for AiR Transportation Noise and Emissions Reduction
PI	Proximity Index
PNL	Perceived Noise Level
PNL_{max}	Maximum PNL during flyover in dB PNL
QAT	Quiet Aircraft Technology
QC	Quota Count
QTD2	Boeing Quiet Technology Demonstrator Two
R&D	Research and Development
RCEE	Revolutionary Configurations for Energy Efficiency
RMSE	Root Mean Squared Error
SESAR	Single European Sky and Air Traffic Management Research
SEL	Sound Exposure Level
SI	Spin Index
SILENCE(R)	Significantly Lower Community Exposure to Aircraft Noise
SO_2	Sulfur Dioxide
SPL	Sound Pressure Level
SvNEF	Single Value Noise Exposure Forecast
SWAN	System-Wide Assessment of Noise methodology
t_0	Reference time
t_{10}	Duration in seconds of the noise level within 10 dB of peak PNL
TAF	Terminal Area Forecast

TFMSC	Traffic Flow Management System Counts
TRL	Technology Readiness Level
USAF	United States Air Force
WBCSD	World Business Council for Sustainable Development
YDNL	Yearly Day-Night Average Level

SUMMARY

The expected rise in aviation demand requires the reduction of the environmental impacts that impede this desired growth, such as fuel burn, emissions, and airport noise. A number of current technology programs attempt to identify, evaluate, and select the environmental technology solutions for the coming decades. Fleet-level evaluation will be essential to deciding between various technology options because it provides a system-level assessment that clarifies the effect of operational and policy variables. Fleet-level modeling in general, introduces various complexities, and detailed fleet-level models require significant time and computing resources to execute. With a large number of potential technology options available for assessment, a full detailed analysis of the technology space is infeasible. Therefore, a simplified fleet-level environmental evaluation methodology is required to select scenarios to carry forward for detailed modeling. Capabilities such as the Global and Regional Environmental Aviation Tradeoff (GREAT) tool, have achieved rapid simplified fleet-level analysis for fuel burn and emissions, but currently lack a satisfactory generic framework to evaluate fleet-level noise.

Fleet-level noise modeling is a particularly difficult problem due to the spatial nature of airport community noise exposure. Other aviation emissions, such as carbon dioxide, are measured in quantities of mass. The total number of flights can therefore be used to easily scale these measures to the fleet-level. Noise, by contrast, is measured by evaluating the Day-Night Average Level (DNL) 65 dB contour. Noise contours are

spatial representations of noise distribution about an airport. Because each airport produces a unique noise contour, the noise at a single airport or for a single flight, cannot easily be scaled to the fleet-level. To measure fleet-level noise, it is necessary to calculate airport-level noise for all airports in a given study. The need to introduce each airport's unique spatial characteristics, however, gives rise to numerous problems and complications. The current state-of-the-art rapid fleet-level noise models simplify the process by defaulting to a single-runway airport configuration. Consequently, noise contour shape is sacrificed. The exclusion of shape is due to an inability to rapidly model airport noise contours while retaining shape characteristics, the uniqueness of airport operational and infrastructure characteristics, and the lack of metrics to objectively discuss and compare consequent impacts to contour shapes. By forcing the exclusion of contour shape from the problem, these shortcomings affect prediction accuracy and ignore a defining facet of airport noise.

The primary objective of this research is to formulate and implement a generic fleet-level noise methodology that allows decision makers to analyze the fleet-level impact of many technology scenarios on the quantity of noise, and also its distribution about certain airport types. This information can be leveraged to provide screening assessments of technology impacts earlier in the decision-making process, reserving more sophisticated modeling techniques for the most promising scenarios. The capability gaps identified are addressed by the development of a rapid generic fleet-level noise model that captures basic airport noise contour shape and contour area under simplifying assumptions, a categorization of airports with respect to their operational and infrastructure characteristics, and the development of shape metrics that enable rapid classification and comparison of contour shapes.

The rapid generic fleet-level noise model operates under the assumptions of straight ground tracks and standard sea-level atmosphere. By simplifying these variables, a fleet of aircraft-level noise grids can be computed off-line using state-of-the-art detailed noise modeling software. These single events can then be recombined as necessary utilizing logarithmic addition, geometric translation, and rotation to yield a set of runway-level noise grids. Due to the isometric transformation of the runway-level grids, these could be interpolated to a reference grid and summed to provide an airport-level noise grid that captures the basic shape of the noise contour. The model was then validated by comparing results to equivalent detailed models in which the main basic assumptions were violated, examining the effect on contour area and shape accuracy. The results of the validations suggested while shape could be greatly affected by deviation in ground tracks, the basic contour structure shape could be retained. With respect to area, the ability to retain this basic contour shape allowed the area to continue to provide accurate estimates when compared to a state-of-the-art detailed model.

Airport categorization was achieved by de-coupling the operational and infrastructure characteristics of airports. This approach was necessary due to the lack of correlation between these variable types at various airports. Operational characteristics of a sample set of airports were statistically clustered by total number of operations and distribution of aircraft by seat class. The resulting groupings were termed Generic Runways, and were verified against detailed operations of the sample airports. Generic Runways were also validated by assessing their ability to scale with future operations while retaining accuracy and trends. The positive results validate the variables considered for grouping. Geometric characteristics were qualitatively grouped based on reduced runway layouts, termed 'effective' runway layouts, inferred by examining typical resultant noise contours at the sample airports. These reduced layouts were used to generate baseline Generic Infrastructures, which were then compared to the resultant fleet-level noise response of the unique sample airport geometries. A configuration exploration experiment was performed to uncover the relationship between airport geometric variables and contour area, using this information to calibrate the Generic Infrastructures to the sample set. The resultant Generic Runways and Generic Infrastructures were combined to yield 21 Generic Airports, which demonstrated accuracy at the fleet-level and across the unique airport space provided by the sample set. The ability of Generic Airports to accurately provide representative characterizations of airport operational and geometric characteristics validates the approach of de-coupling the two variable types at the outset.

Contour shape metric development consisted of requirements analysis and definition, search for existing metrics, and evaluation of these metrics to meet the requirements. Through qualitative observation of airport-level noise contours, it was determined that they are generally characterized by the total number of contour lobes, and the distribution of those lobes about the central airport structure. A hypothesis was developed stating that if a metric could scale with contour lobe number and lobe distribution about the airport central region, then the necessary requirements defined for the metric would be satisfactorily met. A subset of the collected metrics was able to scale sufficiently with the total number of contour lobes, but none of these provided a scaling with lobe distribution under all conditions. A linear summation of the two best performing metrics was attempted, yielding a Detour-Spin Index which mixes the characteristics of both. The combined metric provides improved correlation with total number of lobes, and satisfactory lobe distribution. The resulting metric was found to meet all of the requirements within a satisfactory tolerance. Some difficulty was still observed in categorical segmentation of differing complex geometries, but most geometric categories were differentiable. Therefore, the resulting metric is applicable for rapid fleet-level scenario comparison of contour shape.

Once the capability gaps were addressed, the resultant System-Wide Assessment of Noise (SWAN) methodology was implemented via use cases to demonstrate the application of the methodology, examining the introduction of a set of possible near-term (N+1) future technologies into the forecast. Forecast year 2018 was evaluated at a 50% insertion of technology infused vehicles into the entire fleet. The minimum insertion required to meet aircraft-level fleet-level noise reduction goals was then assessed, also at year 2018. Finding this scenario feasible, the minimum insertion required to meet fleet-level noise reduction goals using only N+1 technologies was analyzed for forecast year 2025. While these examples are simplified and notional, they demonstrate the types of analyses and investigations that can be performed with the SWAN methodology.

The development, verification, validation, and demonstration of these capabilities complete a framework for evaluating fleet-level noise at the screening-level that retains the ability to capture and effectively discuss shape information beyond the capability of current screening-level noise evaluation techniques. By developing a rapid generic fleet-level noise model, a set of Generic Airports, and metrics that objectively quantify and describe shape, decision-makers can access greater levels of information, including the critical facet of contour shape in fleet-level airport noise.

CHAPTER 1

INTRODUCTION

The demand for air travel has increased significantly over the last decade, establishing growth trends that are expected to continue multiple decades into the future. A variety of entities including government agencies, aircraft manufacturers, and airlines have produced a number of projections that suggest this growth is inevitable. Although each projection exhibits subtle variations, they all agree in one respect: air traffic will increase to many times what it is today. As a result, the challenges of maintaining and operating a working air transportation system will increase significantly. Among these challenges will be the spacing and routing of so many aircraft, the allocation of airspace, and the environmental impact of this increase in demand.

One of the ways in which a growth of aircraft operations will increase the environmental impact of aviation, is airport community noise. Airport community noise is already a major concern for today's airports, and increasing the capacity at many national airports will only serve to exacerbate this issue. Airport operators are extremely concerned about airport noise in the near and long-term, currently managing the issue in the near-term through federal noise abatement initiatives. Although airports potentially can have significant negative environmental impact, they are also often critical components of many communities, economic structures, and the mobility of the population. Airports enable tourism, create jobs, and provide many amenities and services to would-be travelers. At the same time, however, airport noise footprints are inching further into the surrounding communities which at best will create a slew of incompatible land-uses, and at worst negatively impact the population in communities near the airport with respect to health economic factors.

In response to these issues, several national and international initiatives, along with various supporting technology development programs, are examining potential technologies that will allow aviation operations to increase without a significant negative effect with respect to the noise exposed population. Technology investment decisions are inherently expensive and risky, and thus a decision-maker benefits from the capability to evaluate as many potential scenarios as possible at the fleet-level earlier in the decision process. Evaluating more scenarios with capable tools increases knowledge of the problem, and performing evaluations at the fleet-level provides knowledge relevant to overall system performance, rather than specific aircraft performance. Current detailed noise modeling tools, however, require too much time and information to define and model a given scenario, while lower-fidelity methods lack accuracy, noise contour shape fidelity, and a true fleet-level approach. A generic framework for evaluating fleet-level environmental impacts, currently in development, is intended to match the requisite fidelity for such long-term projections, while improving calculation time. The main benefit of a generic approach is that the wide range of aircraft can be represented with a much smaller set of generic aircraft. The subject of this research project is to make possible the evaluation of fleet-level scenarios with respect to noise within the generic framework. These challenges are achieved by addressing observed capability gaps and demonstrating the utilization of the resultant methodology via use cases.

1.1 A Response to Rising Demand

The landscape of air transportation in the United States and Europe is currently undergoing substantial changes, including numerous current and planned upgrades and improvements. The Next Generation Air Transportation System (NextGen) program in the United States and the Single European Sky and Air Traffic Management Research (SESAR) in the European Union, both aspire to bring aviation in these regions to the present and future successfully. The need for these changes is driven by the outdated technology and procedures current air transportation systems utilize, which are not commensurate with the capability and technology that is available cheaply even at the consumer level. According to the National Aeronautics Research and Development Plan (NARDP),

> "the [National Airspace System] NAS's operating procedures were originally designed around technologies now considered antiquated, yet these procedures remain largely unchanged despite new concepts of operation afforded by current and near-term technologies…" [1]

As a result, NextGen is partially "a leveraging of technologies that already exist", at least in the short-term, shifting to a satellite-based navigation system among other incorporations of current technologies [2]. Integration of such technologies is a relatively simple task in even certain complex systems such as personal motor vehicles, which compared to aircraft, have short design-cycles, and large production quantities. In the case of aviation, however, standards for certification are much stricter, weight is at a premium and the level of interoperability with the current system is paramount to safety and efficiency.

The current air transportation system is close to reaching its capacity in terms of operations volume, due to the observed trends in rising demand, providing the impetus for updating the system [2]. Not only has demand risen in the recent past, but forecasts from a variety of different entities in the field project that it will continue to rise. By 2015, it is expected that the number of yearly passengers will reach one billion, and could double or triple by 2025 [2]. According to the Federal Aviation Administration (FAA), "domestic capacity is projected to grow at an average annual rate of 2.1 for the remainder of the forecast period." [3] As can be seen in Figure 1.1, global Boeing and Airbus projections aviation will grow at a steady rate in the near future [4]. The market, in the face of rising demand, must capitalize by meeting this demand.

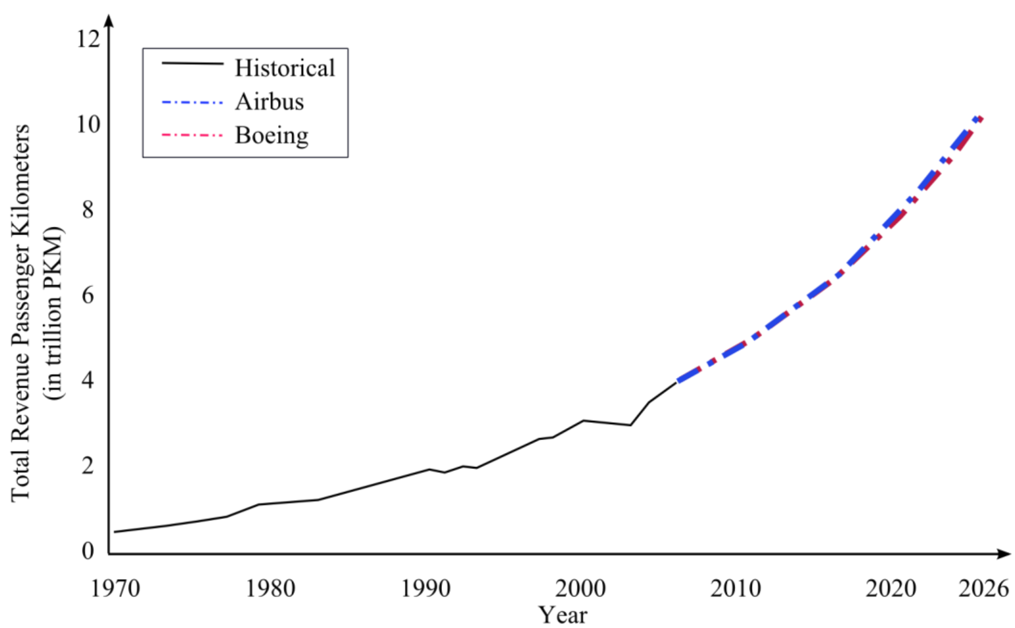


Figure 1.1: Demand projections concur on a long-term increase [4].

This increase in air traffic will require modifications to the air traffic system to manage the number of flights and passengers that will be departing and arriving from many of our nation's airports. A major issue, which has already caused significant concern in the general community, is the environmental impact of aviation. Research into air travel demand, for example, suggests that aviation demand could increase enough in some countries to account for a three or five-fold increase in carbon dioxide emissions [5]. NextGen is, therefore, equally responsible for the development of methodologies, systems, and procedures that will achieve the environmental challenges posed by the future of aviation [2].

1.2 The Environmental Effects of Aviation

The effects of aviation on the environment are numerous, including but not limited to Carbon Monoxide (CO), Carbon Dioxide (CO_2), Nitrogen Oxides (NO_x), Ozone (O_3), Particulate Matter, Sulfur Dioxide (SO_2), general fuel burn, and noise pollution [6]. These effects can be viewed at the aircraft-level and the system-level. At the aircraft-level, those that are of particular interest are fuel burn (measured in volume), CO_2 emissions (measured in weight or concentration), NO_x emissions (characterized by weight or concentration of nitrogen-oxygen compounds) and noise in Effective Perceived Noise Level (dB EPNL) [7] – [9]. The environmental effect of aviation, however, cannot be considered solely at the aircraft-level. The true effect of a technology-infused aircraft on aviation environmental emissions will depend on how such an aircraft is used, the demand situation, and relevant policy scenarios [10]. The effect of designing a more fuel efficient aircraft, for example, is negligible if the manufacturer cannot make the aircraft economically viable, or if the market is uninterested in adopting the novel design. The same logic applies to any potential environmental benefit provided by an aircraft equipped with new technologies. This broader scope of effect is commonly termed the "fleet-level effect" and it is a more appropriate descriptor of the environmental cost of aviation [10], 0.

Ultimately, the effect of increased air traffic will not only affect the quality of the air, but also the quality and quantity of the sound around airports. Sound can be associated with acoustic energy from almost any source while noise, on the other hand, is considered any "unwanted sound." [12] It has also been defined "as sound that produces adverse effects." [13] The range of potential adverse effects is varied, and can constitute a threat to public health and welfare as well as other social systems.

1.3 Negative Effects of Noise

The effects of airport noise can have multifaceted harmful effects to society. Many airports are already struggling to maintain compatible land-uses around their borders with the current demand situation, and noise is considered by most airport operators at the busiest U.S. airports to be a major concern in both the near and long-term future [14]. In fact, noise was ranked as the primary concern by over half of these airports [14]. The increase in demand, coupled with ever-growing surrounding communities, is a chief issue for airport operators with respect to increasing noise, which in turn translates to increasing noise complaints and increased incompatible land-uses.

The impacts of noise can be categorized a number of ways, often divided into noise-related health effects, sleep disturbance, speech interference, negative effects to learning, negative effects to wildlife, and negative effects to the economy [15]. For simplicity, these will be categorized here as direct health effects of noise, the effect of noise on the human environment, the effect of noise to the non-human environment, and the effect of noise on the economy. Although the first consideration is given to direct health effects, it is important to note that the Noise Control Act (NCA) of 1972 charged the Environmental Protection Agency (EPA) with protecting the nation's public health *and welfare* which goes beyond the direct effects on the population's health [16], [17].

1.3.1 Direct Health Effects of Noise

The most obvious concern regarding aviation noise is the potential direct effects to the health of the population. These can be characterized by cardiovascular effects, effects specific to children, effects on hospitals, and noise that causes permanent hearing damage. Research in these areas is still ongoing, and because of their relatively low public profile and high prevalence of confounding factors within the population, there have been a large variability of results [15]. Nevertheless, a recent Airport Cooperative Research Program (ACRP) study found that there was "sufficient scientific evidence that noise exposure can induce hearing impairment, hypertension, and ischemic heart disease." [15], [18] Another potential negative effect is an increase in the likelihood of coronary heart disease [15], [19]. The effects on children are often analyzed separately from that of adults because of their developmental status, and researchers fear that excessive exposure to noise can impact their progress at home and in the classroom. Poustka et. al. found that while there was no link between noise and psychiatric disorders within children, that there was a relationship between parameters such as heart rate and muscle tension [20]. The effects of noise on health care facilities can often be related to general annoyance, as noise is the "the first or second source of complaints by patients and staff" in hospitals [12], [21]. Furthermore, cases in which noise can negatively impact a patient's wellbeing have also been found, particularly in a 1979 study by de Camp of hospitals in Berlin [12], [22]. While hearing impairment or raised hearing thresholds are not generally considered a danger for communities exposed to aircraft noise, there can be significant damage caused to those who are exposed to much higher noise levels due to their occupations (i.e. pilots, air traffic controllers, aircraft marshals, etc.) [15], [23] - [26].

Noise can also disturb the sleeping patterns of people who live near airports. Research shows that the effect of "…chronic sleep deprivation induces marked tiredness, increases a state of low vigilance, and reduces both daytime performance and the overall quality of life." [15] As demand, and therefore nighttime events, increases, the population exposed to a noise level capable of causing sleep disturbances will also increase.

1.3.2 Noise Detrimental to the Human Environment

Noise can have negative effects in the living and working environment as well, beyond direct effects on human health. The two major subjects of research are in speech interference and the learning of children. Noise that frequently causes speech interference can lead to annoyance, complaints, and a shift in the activities that are continually affected by noise [15]. The effect on the children's learning is usually studied through opportune closings and openings of airports around the world. Using this method, researchers have been able to assess the effect of airport noise on the “reading, motivation, language and speech acquisition, and memory.” [15], [27] The results presented by Hygge, conducted on children in Munich near the closing and opening of airports, suggested that noise had negative effects on recall and recognition capabilities [15], [28]. Children who are affected by airport noise can be at a significant learning disadvantage, and a major concern of the general community is that ‘high noise pathways’ might be imposed on those with fewer means or capability to self-advocate. Awareness of the potential for abuse of indigent persons will hopefully help to avoid a situation such as the one in which a strict economic analysis led to the national interstate system passing through neighborhoods of lower socio-economic status[1] [29].

1.3.3 Noise Detrimental to the Wildlife Environment

While mankind stands to suffer many disadvantages as a result of encroaching airport noise, the effect is not limited to our species alone as it can also negatively affect wildlife. Wildlife exposure to noise can result in a disability to hear auditory signals, cause stress, effect behavioral changes, and “in extreme cases, potential extinction.” [30] The effect of noise can vary widely depending on the species. In many situations, aircraft noise can cause animals to leave their current surroundings and can even affect the reproduction rates of certain species [15], [31]. Although evidence has been found that pregnant humans may not be exposed to sufficient noise to suffer negative effects to

[1] During discussions at the UC Davis Aviation Noise & Emissions Symposium (March 2012), members of the symposium discussed issues of equity during the final discussion session, raising concerns that while progress is beneficial, it must not be applied inequitably.

prenatal offspring, studies have suggested that noise exposure can affect the development of animals in the womb (mainly characterized by birth weight) [15], [31], [32].

1.3.4 Noise Detrimental to the Economy

Airport noise can also impact the economy and make-up of the geographical areas around it, be it through land-use decisions, policy, or effects on property values. One of the dilemmas faced between airports and their surrounding communities is that communities generally thrive in many ways because of the draw of the airport, and it often acts as a major component of the local economic engine. On the other hand, the environmental effects, particularly noise, can make it difficult for homeowner's to sell their property at the value that it was purchased [15]. This effect is mostly imposed on a property owner who made the purchase prior to a significant exposure of noise in the area [15], [33]. The effect can sometimes be mitigated by the perceived value of being near the airport, which in many cases is a major business center [15], [34]. Nonetheless, with the projected increase in air traffic, the possibility of affecting many housing markets for the first time in a generation or more is a real possibility.

Noise itself is also financially expensive to control and/or mitigate after the design stage. It is currently estimated that the United States spends approximately $500 million dollars annually in noise mitigation via insulation or land acquisitions [35]. Funds are provided through the FAA Federal Aviation Regulation (F.A.R.) Part 150 program, which will be described further in this chapter. This money is ultimately generated from the collective federal taxes paid for by United States citizens. Furthermore, airports are entitled to collect funds from state and local governments as well as from passenger facility fees [16]. These fees, imposed by airport operators, make flying more expensive to the consumer. In 1996 for example, an estimated $1.1 billion dollars in passenger facility fees were collected [16].

Airport noise has been a consequence of aviation for some time, and is not a novel issue. While increased noise looms on the horizon, it is beneficial to examine how the problem has developed over time, bringing to light the significant factors affecting airport community noise.

1.4 The Context for Airport Noise

Airport community noise has been an issue of concern for over fifty years. It is beneficial to understand the path that noise mitigation has taken to this point, to provide context for the noise-related problems the future will provide. Therefore, a brief summary of the history of aviation noise, and the metrics traditionally used to describe it for selected purposes, are presented here.

1.4.1 The Early Days of Airport Noise

In the earlier days of aviation, aircraft were significantly louder than they are today, but very little concern was originally given to the noise emitted by aircraft. From a standpoint of control, all responsibility for jurisdiction and mitigation was left to the municipalities in which airports resided per the Air Commerce Act of 1926 [16], [36]. Then, from the Civil Aeronautics Act in 1938 to its replacement, the Federal Aviation Act of 1958, "complete and exclusive national sovereignty in the air space" was granted to the federal government by Congress, while maintaining local government control over rules and regulations [16], [37]. The latter act created the FAA, which is still in existence today. The FAA obtained through this act the "authority to control and regulate the use of navigable airspace and aircraft operations." [16], [38] The main issues of concern at this time, however, still did not lie with noise or other environmental concerns but rather with safety and economics [16], [38]. In these early days of commercial aviation, the majority of noise control was achieved through harmonic cooperation between aircraft & engine manufacturers, airlines, and airport operators [16].

As commercial aviation grew, however, noise propagated to the forefront as a significant issue, which prompted congress to amend the Federal Aviation Act in 1968 to enable the FAA to institute noise considerations in the approval process of airframe and engine designs [16], [39]. The amendment was known as the Control and Abatement of Aircraft Noise and Sonic Boom Amendment. As part of the amendment, the FAA issued F.A.R. Part 36. F.A.R. Part 36 accomplished [16], [40]:

- Creating a system for measuring aircraft-level noise
- Establishing maximum noise output levels for new and older aircraft
- Created stages of aircraft based on aircraft size and number of engines

The aircraft stages delineated acceptable noise levels within each category. Stage 1 aircraft were defined as being louder than Stage 2 aircraft and so on up to Stage 4 [41]. One of the drawbacks of F.A.R. Part 36, however, was that it only applied to aircraft whose certification applications were submitted after December 1, 1969, grandfathering in the majority of the fleet, which consequently did not meet the new relatively stringent requirements. The measurement scale identified to measure aircraft noise was the Effective Perceived Noise Level (EPNL dB). At the time of the introduction of the

EPNL metric, it was deemed a "single number evaluator of the subjective effects of aircraft noise on human beings." [42] For a brief description of the general technical concepts of environmental acoustics, the interested reader is directed to Appendix A.

1.4.1.1 Effective Perceived Noise Level (EPNL)

EPNL is an exposure based metric that is a modification of the Perceived Noise Level (PNL dB) metric. The PNL was developed by K.D. Kryter in 1959 [43]. The need for the PNL arose from the fact that people perceived jet aircraft to be noisier than propeller aircraft even at the same Sound Pressure Level (SPL dB). The cause for this was the variations in the frequency spectrum of the two engine types. Kryter used this information to create perceived decibel levels based on the frequency of the signal. The adjustment within EPNL incorporates the tone components present in the broadband noise of an aircraft and the duration of the noise [43]. Armed with a metric that better approximated the human response to a jet aircraft event, certification guidelines were standardized to enable aircraft manufacturers to better design for noise. It has been used for aircraft noise emission certification since 1969, and continues to be in use today [12]. It is defined by Equation 1.1 [43]:

$$EPNL_{dB} = PNL_{max} + 10\log_{10}(t_{10}/20) + F \tag{1.1}$$

PNL_{max} – the maximum perceived noise level during flyover in PNL dB

t_{10} – duration in seconds of the noise level within 10 dB of the peak PNL

F – correction factor for pure tones

1.4.2 Noise Becomes a Primary Concern

Soon after certification requirements for aircraft were established, issues concerning noise beyond that of just aviation were directed to the EPA by congress in 1970. Congress charged the EPA with conducting studies regarding the "effects of noise on public health and welfare". [16] This was achieved through the EPA's Office of Noise Abatement and Control (ONAC) [16], [44]. The results of these studies were significant as they suggested that noise was in fact a serious issue, reporting that approximately 40 million people were exposed to noise that could result in hearing loss [16], [45]. Furthermore, the studies concluded that transportation and aviation noise had negatively impacted the property values of over 44 million people [16], [45]. The results of these investigations led to the establishment of the Noise Control Act in 1972 [17]. The main purposes of this act were to [16], [46]:

- Establish a means of coordinating federal research and activities with respect to noise control.
- "Authorize establishment of federal noise emission standards." [16]
- Provide the public with noise-related information and product characteristics.

Finally, the Noise Control Act called for the EPA to evaluate the adequacy of the FAA noise regulations in place, such that new regulations could be proposed as deemed necessary by the EPA to protect public health and welfare [16]. As a result of the 1972 Noise Control Act, EPA produced a document "developing and publishing criteria with respect to noise." [12], [17], [47] The document, among other achievements, codified the measurements for the impact of community noise, established through metrics generally referred to as equivalent (or equivalency) sound metrics [12]. Equivalency metrics, unlike metrics such as EPNL, "average the intensity [of sound] over a given period of time." [43] Two examples are the Sound Exposure Level (SEL dB) and the "major environmental noise metric" used for airport community noise evaluation, the Day-Night Average Level (DNL dB) [12]. Again, the interested reader is directed to Appendix A for a brief description of the technical concepts of environmental acoustics.

1.4.2.1 Sound Exposure Level (SEL)

The SEL is an equivalency exposure metric that represents a single-event by expressing, in decibels, the sound exposure level as if the entire event occurred in one second of time. The entire pressure signal is integrated with respect to time over the duration of the event and the decibel level is then calculated using a reference time of unity [48]. The SEL is often used to describe the noise for a single aircraft event at an airport because it takes into account the total noise experienced by an observer due to the entire aircraft event without having to necessarily define at what specific point in time the observer became exposed to a certain level of noise. Therefore, whereas the EPNL is useful for calculating noise at specific points, the SEL is useful for characterizing the entirety of the aircraft noise signature at an airport. It is calculated using Equation 1.2 [48]:

$$SEL_{dB} = 10\log_{10}\left\{\left(\int_{t_1}^{t_2} P_A^2(t)dt\right)/P_0^2 t_0\right\} \qquad (1.2)$$

P_A^2 (t) – is the A-weighted pressure squared, as a function of time

P_0 – the reference sound pressure (20 μPa)

t_0 – is the reference time of unity

1.4.2.2 Day-Night Average Level (DNL)

The DNL is an airport-level equivalency-exposure-metric that attempts to characterize the 'soundscape' of an environment over the course of an entire day. It is calculated by combining the noise energy of all events occurring throughout the day, applying penalties for events occurring during sensitive hours (night-time) and averaging this energy over 86,400 seconds (the number of seconds in a day). The original requirements for the metric included that:

> "*1. The measure should be applicable to the evaluation of pervasive long-term noise in various defined areas and under various conditions over long periods of time*
>
> *2. The measure should correlate well with known effects of the noise environment on the individual level and the public.*
>
> *3. The measure should be simple, practical and accurate. In practice, it should be useful for planning as well as for enforcement or monitoring purposes.*
>
> *4. The required measurement equipment, with standardized characteristics, should be commercially available.*
>
> *5. The measure should be closely related to existing methods currently in use.*
>
> *6. The single measure of noise at a given location should be predictable, within an acceptable tolerance, from knowledge of the physical events producing the noise.*
>
> *7. The measure should lend itself to small, simple monitors that can be left unattended in public areas for long periods of time.*" [12]

It is defined by Equation 1.3 [48]:

$$DNL_{dB} = 10\log_{10}\left\{\sum_{i=1}^{n} 10^{0.1SEL_{dB}(i)} + \sum_{j=1}^{m} 10^{0.1(10+SEL_{dB}(j))}\right\} - 49.4 \qquad (1.3)$$

$SEL_{dB}(i)$ – the SEL level in dB of the i^{th} daytime flight,

$SEL_{dB}(j)$ – the SEL level in dB of the j^{th} nighttime flight.

The constant term is derived from the averaging of the sound pressure over the total number of seconds in a day.

The DNL thus was developed as the main policy metric for airport community noise. There are, and have been many deficiencies of the DNL metric that have been criticized by many in the industry over the years but it has persisted as the main metric of choice in airport community noise [12], [49]. The metric alone, however, is not sufficient to determine, for policy's sake, what is a significant exposure level. In a seminal paper by Schultz, the correlation between annoyance and DNL was examined to define a level of significant exposure [12], [50]. As would be expected, the determination of significant noise is a subjective measure, and can vary significantly between different people. Over time, flaws in the Schultz methodology and resulting correlations were identified and further modified such that the United States Air Force (USAF) later produced modified Schultz curves [12], [51]. Three versions of the Schultz curves can be seen in Figure 1.2. Through these curves, the FAA determined that the DNL 65 dB contour was the level at which a member of the community was considered to be significantly affected by noise.

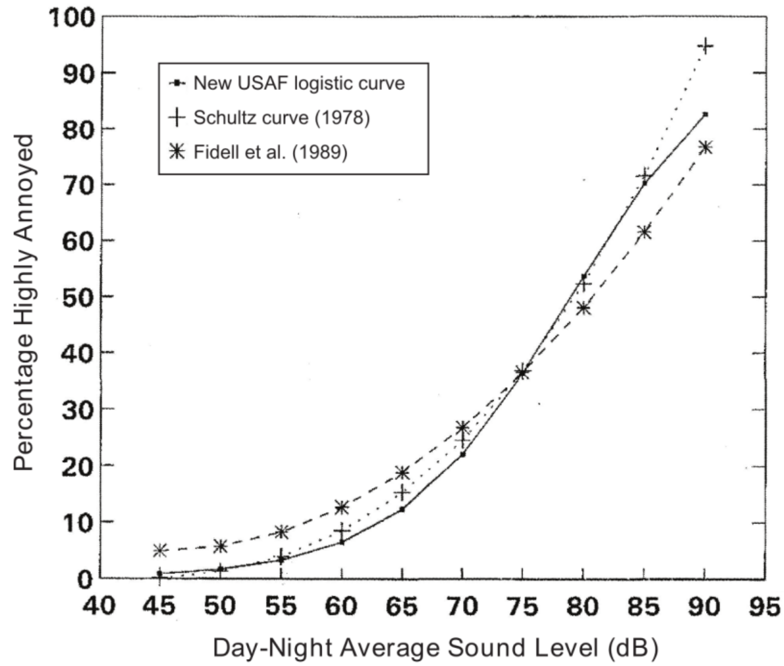


Figure 1.2: Evolution of DNL-annoyance curves [12].

It is important to note that the EPA disagreed on this point and had recommended that the level be lowered to DNL 55 dB. Figure 1.3 demonstrates an example of airport noise contours of various levels overlaid on the geographical representation of the surrounding community. As can be seen, the decision between measuring significant noise at DNL 55-65 dB is significant with respect to the area and to the population exposed as well. Airport noise consists of multiple parts required to measure the environmental impacts including the aircraft-level models, the airport-level model, the threshold of significance, and the geographical context in which the airport resides.

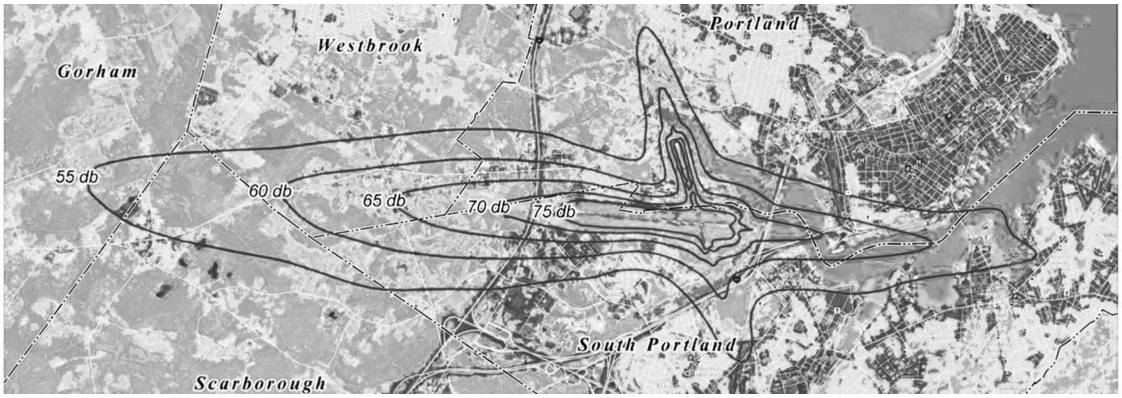


Figure 1.3: Example noise contour overlay on a community [52].

1.4.3 The Evolution of Federal Noise Programs

At this point the EPA and the FAA went in separate directions with respect to noise abatement. In 1976, F.A.R. Part 91 was implemented to restrict the emission of noise by new and old aircraft (retroactively) [16], [53]. This regulation resulted in major pushback from the airline and aircraft industries, which gave rise to the Aviation Safety and Noise Abatement Act of 1979. The main outcome of this regulation was the creation of a single unifying program for measuring noise. In 1981, an interim regulation, F.A.R. Part 150 was established to provide noise compatibility planning guidelines [54]. F.A.R. Part 150 was then made a final rule in 1985 [54]. F.A.R. Part 150 provides many incentives for airports to participate in noise compatibility planning. It allows airports to be granted federal funds for approved Noise Compatibility Plans (NCP). It also forces airports to produce Noise Exposure Maps (NEM) as part of an acceptable plan, which limits the airports liability to noise-related lawsuits. Satisfactory participation in the program preempts any private party from using the noise exposure map against the airport in a noise-related civil case, thereby protecting airports that participate in the program from litigation [16], [55]. The Part 150 program is not mandatory, but all of these benefits have caused most airports with significant noise issues to participate, and it still remains the main form of noise compatibility planning in the United States today.

By contrast, the EPA was authorized through the Quiet Communities Act of 1978 to provide technical assistance to state and local governments to stimulate noise abatement [16], [45]. Unfortunately, many of these programs were ceased when, in 1981, the Office of Management and Budget (OMB) ceased funding for ONAC and thus most of EPA's noise abatement activities. The lack of funding notwithstanding, to this day EPA is still responsible for enforcing regulations under the Noise Control Act of 1972.

In 1991, congress enacted the Airport Noise and Capacity Act (ANCA), with the intent being to homogenize the large number of individual noise restrictions that had developed as a result of predominantly state and local government control of airport noise abatement. Within this act, F.A.R. Part 161 was instituted to implement the provisions of ANCA, which "emphasized a national noise policy." [16] It also provided a plan to phase out Stage 2 or below aircraft and replace them entirely with quieter Stage 3 aircraft by the year 2000.

As is demonstrated by the history of airport noise in the United States, the nature of airport community noise exposure is that it is very dependent on the metrics chosen for evaluation, which are subject to disagreement, revision, and change as more knowledge and understanding is gained. It is important to consider the policy and measurement systems that are relevant to airport community noise measurement when developing systems to evaluate noise at the fleet-level.

The demand projections made by several entities around the aviation industry agree that growth will steadily increase in the long term. This demand presents an opportunity for the business of aviation to expand, innovate, and carry a larger percentage of the transportation economy. This opportunity is threatened by looming environmental concerns, which will only continue to grow as operations expand. The population exposed to noise may increase dramatically as metropolises expand and airports increase operations to meet demand. At some point, the environmental consequences of aviation growth will become constraints that hamper the ability for aviation to move forward and evolve. Still, noise is not a new concern, and measures have been taken in the past to improve aircraft noise performance. As the system grows more complex, however, a generic fleet-level approach will be required to evaluate future mitigating measures, some of which are already underway.

CHAPTER 2

BACKGROUND

2.1 Noise Control in the Next Generation

From the time that noise from aviation was recognized as a significant issue, a number of programs have been initiated and successfully completed to improve engineering noise controls at the vehicle-level. The success of these programs are important, considering that in a 2004 report to congress, the FAA reported that there had been "…a 95% reduction in the number of people affected by aircraft noise in the past 35 years." [12], [35] In 2000, however, "…500,000 people were exposed to a DNL of more than 65 dB and approximately 5 million people were exposed to a DNL of 55 dB." [12] When recalling that the EPA originally recommended that the DNL 55 dB level was the appropriate level at which to demarcate significant exposure, this number becomes more alarming.

Regardless of how significant noise exposure is measured, it is inarguable that significant progress has been made. These major improvements were achieved through a number of technological and policy developments. The two institutions, which are largely responsible for research and development with respect to aircraft and airport noise, are the National Aeronautics and Space Administration (NASA) and the FAA. Although they work separately, a large amount of cooperation is also involved.

> "*The FAA focuses on the impacts of noise on communities, while NASA focuses on noise at its sources – namely aircraft engines, and airframes.*" [12]

Both approaches are required to develop mitigation strategies to address the impending noise concerns. Although many programs have been completed, such as NASA's seven-year Advanced Subsonic Transport (AST) Noise Reduction Program, initiated in 1994, there is still much work to be done [12]. This program achieved many benefits, yet they are expected to be offset by the increase in operations and the relative lack of speed at which "introduction of new noise reduction technologies into the fleet…" occurs [12]. Therefore, the benefits of current noise technologies will probably serve to maintain a status quo for several years but airport noise will "thereafter begin to increase." [12] Another completed noise technology development effort is the Quiet Aircraft Technology (QAT) program, which completed the goal of reducing airport level noise by 10 dB by 2007, using 1997 levels as the baseline [56]. QAT provided research in areas of "aircraft source noise reduction…community noise impacts reduction…and interior [cabin] noise reduction [56]. The Boeing Quiet Technology Demonstrator Two (QTD2) was recently testing multiple technologies to reduce cabin and community noise as well [57]. In response to the current projected rise in demand, which is expected to ultimately nullify and reverse the effects of noise reduction programs already completed, a multitude of programs have been tasked with developing technologies not only for noise but all critical environmental factors.

NextGen is the main air space renovation initiative in the United States; created to evolve the national air space from a "radar-based air traffic control system…to a satellite-based system" of air traffic management, while increasing safety and reducing aviation's environmental impact [58], [59]. NextGen is a Joint Planning and Development Office (JPDO) program concerned with restructuring a system that will certainly reach its limits within the next decade or less. Within NextGen, a barrage of components is required, but with respect to the environment specifically, NextGen's mission is "to develop environmental protection that allows sustained aviation growth." [2] NextGen has taken what it calls a "portfolio-based management approach" to integrate the "development and implementation of a wide range of technologies and programs." [2] As a result, the NextGen initiative is supported by a number of technology development programs that are studying *how* NextGen will be achieved with respect to operational capacity, performance, and the environment. The programs that support NextGen are mainly concerned with bridging the expensive maturation gap between Technology Readiness Levels (TRL) 3-7[2].

One such program is the FAA's Continuous Lower Energy, Emissions, and Noise (CLEEN) program [60]. The purpose of this program is to "bring to maturity new technologies to reduce fuel burn, emissions, and noise" and it is focused on producing technologies for the N+1 aircraft timeframe [1], [61].[3] CLEEN's goals with respect to noise are to "demonstrate … certifiable aircraft technology that reduces … noise levels by 32 EPNdB cumulative, relative to Stage 4." [8] Technologies that are at TRL 3-4 will be brought to TRL 6-7 such that industry can more feasibly absorb these technologies [8]. Such programs are necessary because developing a technology from TRL 3-4 to 6-7 is where the largest expenses and risks must be undertaken by a private developer. These

[2] The Technology Readiness Level (TRL) was developed by NASA to describe the stage of development of a technology.

[3] The N+ nomenclature is utilized to describe the number of out-generations by which an aircraft is expected to be developed, with respect to the current baseline. Therefore an N+1 aircraft refers to an aircraft of the next generation, while an N+2 aircraft refers to those from the second generation and so on [1].

are the TRL levels that require laboratory testing, validation in a "relevant environment", and prototype creation for "implementation on full-scale realistic problems." [62] For example, the European SILENCE(R) program was a six year 112 million euro initiative, spread out over 51 collaborating partners from the industry, research, and academic fields [12]. The EnVIronmenTALly (VITAL) Friendly Aero Engine program is another large technology initiative, costing approximately 90 million euros intended to integrate the results of the SILENCE(R) program with the results from other environmentally friendly technology programs [12]. Therefore, in order to develop the SILENCE(R) technologies and integrate them with other emerging technologies, the total cost is approximately 200 million euros. This effort required the participation of many various entities to pool resources and capabilities. At these costs it is obvious that investing in future technologies can carry significant economic risk. This situation makes it very unlikely that private industry would be able to risk significant investment in this TRL region when current aircraft designs are still performing profitably.

Another similar program initiated by NASA is the Environmentally Responsible Aviation (ERA) project. ERA's main goal is also to mature environmental technologies in support of NextGen [1], [61]. The technologies that ERA is exploring are intended to be used on N+2 vehicles and focus on significant reduction of fuel burn, noise, and emissions with a proposed noise reduction of 42 EPNL dB relative to a Large-Twin-Aisle reference configuration [61]. ERA technologies must reach "a TRL level of 6 by 2020" to be considered 'enabling technologies' [61]. Again, this goal implies that ERA will be bridging the gap that is most difficult and expensive with respect to technology development.

Yet another NASA technology development program that functions in support of NextGen is the Fixed Wing (FW) Project (previously also referred to as the Subsonic Fixed Wing project), which is geared towards major reductions in noise, emissions, and fuel burn for N+3 aircraft [63], [64]. The N+3 goals consist of a reduction of 71 EPNL dB in aircraft noise relative to Stage 4 levels. The main goal of FW with respect to the environment is to reduce noise enough that the envisioned tripling in throughput of the air transportation system will produce at worst no change, or at best, a reduction in overall airport noise footprints [64]. Another primary concern of FW is to "accurately predict system-level changes in noise…as a function of changes in parametric design space." [63] This goal requires a change in the way fleet-level noise is modeled, as will be discussed below.

Other programs focused on minor reductions with respect to noise include the Department of Defense's (DoD) Highly Efficient Embedded Turbine Engine (HEETE) and the Adaptive Versatile Engine Technology (ADVENT) programs that focus on N+2 technology development in support of NextGen [61], [65], [66]. Beyond the N+3 timeframe, the DoD is also conducting the Revolutionary Configurations for Energy Efficiency (RCEE) program, which includes minor considerations for noise and emissions [61], [67]. A hierarchy of the specific programs discussed for the United States can be seen in Figure 2.1.

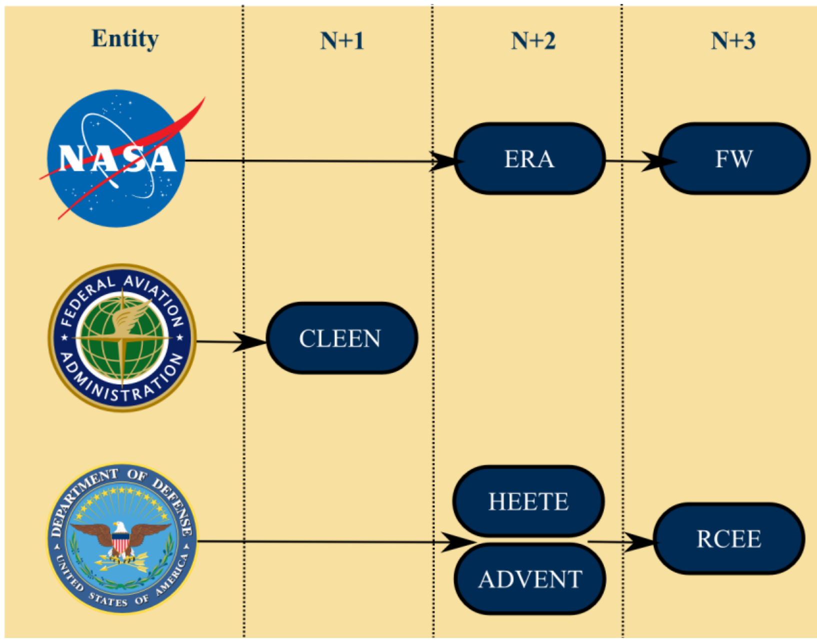


Figure 2.1: Summary of U.S. technology programs supporting NextGen.

In Europe, similar programs are underway, under the umbrella of the Single European Sky Air Transportation Management Research (SESAR) initiative. SESAR is the European Union's equivalent to NextGen, as it focuses on modernizing the currently fragmented European airspace "supported by state-of-the-art and innovative technologies." [68], [69] With respect to environmental technologies, the Atlantic Interoperability Initiative to Reduce Emissions (AIRE) and the CleanSky program are the main technology development programs supporting SESAR [70]. AIRE includes FAA involvement and thus also supports NextGen development while focusing mainly on technologies that require little or no R&D [71], [72]. The effects of noise, while not at the forefront of AIRE, are still considered as a secondary goal. CleanSky is designed to "identify, develop, and validate the key technologies necessary to achieve major steps towards the ACARE [Advisory Council for Aeronautical Research in Europe] environmental goals for 2020.” [70] With respect to noise, these goals include a 50% reduction, by 2020, in perceived external noise with respect to levels in the year 2000 [70].

The challenges facing such programs, with respect to technology assessment and selections, are multifaceted. In summary, it is difficult and expensive to develop technologies for the long term, modeling and predicting technology benefits is expensive and introduces varying levels of uncertainty, and technologies with positive benefits in certain areas can have negative effects in others. Particularly in the aerospace industry, the situation is such that technologies “readily available for implementation in the system…may be obsolete when the system is actually fielded.” [73], [74] If technology selection is not considered early in a design or decision process, it will require ad hoc redesigns or adjustments later in the process and could have significant cost implications [73]. The altruistic benefits of NextGen and SESAR notwithstanding, the ultimate price tag of these national and multi-national programs, as well as those that support them are naturally very large. NextGen is estimated to cost between $14-22 billion dollars [2]. SESAR is estimated to require a 30 billion euro investment in total [69]. The CLEEN program alone is expected to cost “$110 [million dollars]” between 2010 and 2014 [8]. ERA is yet more expensive at approximately $300 million dollars over the lifetime of the program, which currently is funded between 2010 and 2014 [61].

2.2 Fleet-Level vs. Vehicle-Level Evaluation

Since the development expense of technologies is a long-term and expensive process, the strategic decision regarding which technologies to pursue is critical so as to maximize the investment to reduce aviation's environmental footprint.

While addressing these issues is a challenge at the aircraft level, even further challenges are introduced at the fleet-level, particularly with respect to noise. The fleet-level effect of technology infusions must be considered, since the "environmental… impact of new aircraft is a function of both the aircraft performance and the airline's use of new and existing aircraft." [58], [75] The fleet-level consists of a myriad of variables, such as the distribution of aircraft in the fleet, the total number of operations at various airports, the retirement and replacement of aircraft over time, the effects of policy, etc. With respect to noise, matters are further complicated because of the inherent uniqueness of airports in the network. The fleet-level problem, therefore, quickly balloons into a large combinatorial space of variables.

Evaluating the fleet-level effects of potential technologies in detail, including the competing effects of technologies on the various environmental metrics is an expensive modeling process and would be infeasible to examine all possible options due to time constraints. Furthermore, this level of detail would be inappropriate for strategic decision-making at this early stage of the process. At the same time, these early decisions are those that are likely to have the greatest impact on the rest of the program or process, and are thus critical decisions. Among the enabling factors driving this research, the primary fundamental development is what has been characterized as a "paradigm shift" in the way design and decision-making is executed [76], [77]. One of the key characteristics of this paradigm shift involves bringing more knowledge and capability normally associated with 'detailed design', earlier into the design process (i.e. 'conceptual design'). This information, if packaged and leveraged appropriately, can be utilized to gain more insight about a problem earlier in the process, strengthening the foundation on which crucial decisions are made.

Selecting preliminary technology packages based on factors including long term fleet-level implementation impact is a prime example of propagating detailed modeling information into a phase of the project where there is still significant uncertainty about the problem. To date, the state-of-the-art has adopted this concept to a high degree with respect to vehicle-level design, leveraging the physics-based capabilities of detailed codes and methodologies often reserved for latter stages of the design process. To achieve this modeling capability, certain simplifying assumptions must be made, to match the fidelity of the inputs to the knowledge available to the designer early in the process. The benefit is a faster modeling capability that allows for more comprehensive design-space explorations. At the fleet-level, however, there still remains significant work to be done, particularly with respect to noise.

One of the primary enablers that facilitate fleet-level analysis is the Environmental Design Space (EDS), which provides a "capability to estimate source noise, exhaust emissions and performance parameters" for existing and potential future aircraft designs "under different policy and technological scenarios, along with capturing the interdependencies between these outputs." [78] A linkage to the Aviation Environmental Design Tool (AEDT) is utilized to provide thorough assessment of aviation environmental effects [78]. AEDT is a detailed fleet-level evaluation methodology and tool suite that enables a widespread evaluation of environmental metrics including noise. According to the FAA, "AEDT is a software system that dynamically models aircraft performance in space and time to produce fuel burn, emissions, and noise. Full flight gate-to-gate analyses are possible…ranging from a single flight… to scenarios at the regional, national, and global levels." [79] AEDT is intended to absorb, improve upon, and replace the Integrated Noise Model (INM) and other environmental modeling tools. AEDT will serve as the next generation of environmental consequence modeling superseding the Emissions Dispersion Modeling System (EDMS) and the Model for Assessing Global Exposure from Noise of Transport Aircraft (MAGENTA) [79], [80]. In order to link EDS to AEDT, EDS models must be developed for any given engine/airframe combination, which is a significant investment in time and computer resources [78]. To address this need, the concept of a surrogate fleet, or generic vehicles was generated from the "observation that a great deal of similarity exists among certain classes of aircraft." [78] This concept allows the entire fleet to be characterized by only a handful of representative aircraft, significantly reducing the workload required to model the fleet. The generic approach is a significant enabler in that it effectively reduces the dimensionality of the fleet-level problem, making it tractable and flexible.

Some strides have been made in leveraging the generic vehicle approach with respect to fuel burn, which is proportional to CO_2, and NO_x emissions predictions in a larger fleet-level environmental trade-space [79]. These capabilities were combined to include traffic demand modeling and replacement strategy definition capabilities to analyze the multiple parameters that affect the projected fleet-level environmental impact within the Global and Regional Environmental Aviation Tradeoff (GREAT) tool. The vision for GREAT is to create "an interactive environment that will allow for infusion of new technologies and propagates the results to assess the fleet-level implications." [82] The purpose of GREAT is to be utilized as a screening tool to evaluate and trade between a large number of potential technologies, implementation strategies, and policy scenarios to identify a subset suitable for analysis with higher fidelity tools. By allowing decision-makers to analyze a large number of technology packages early in the development process, the strength of the strategic decisions is reinforced, hopefully leading to more efficient technology gains. A generic fleet-level noise evaluation methodology would be similarly beneficial to provide rapid and simple screening capabilities to ensure that all aspects of the technology design space are adequately examined, including tradeoffs between environmental benefits. In fact, GREAT currently lacks a generic fleet-level noise evaluation capability to provide results with respect to this important dimension of aviation's environmental impact. Providing a framework for generic fleet-level noise analysis that can be absorbed by GREAT is a major motivator of this research.

There are a number of challenges responsible for the lack of a simple and rapid noise methodology. In the case of fuel burn, CO_2, and NO_x emissions, for example, these are calculated by volume or mass; easily scalable parameters [7] – [9]. Therefore, the effect can be scaled up or down depending on the number of flights of a given aircraft to provide a single number for a fleet if ideal atmospheric conditions are assumed. While this is a slight oversimplification of the process, it captures the basic concept of integrating from the vehicle-level to the fleet-level. On the other hand, the effect of noise from an environmental impact perspective is significantly more complicated because it is inherently spatial and temporal. There is no 'mass-equivalent' metric for community noise, as will be described later, and there is no value in such a type of metric with respect to noise. The extensive metric for noise would be energy. This energy, however, is a property of the source alone and would be a useless exposure metric. Fleet-level community noise, from a systems perspective is really a function of the source, the medium through which the sound travels, and the receiver. Technologies not only hope to reduce noise, but can also have an effect on how the noise signature propagates spatially, which necessarily includes modeling characteristics of the medium and the receiver. Noise is ultimately concerned almost as much with *where* noise is occurring as it is with *how much* of it is occurring. Furthermore, the fleet-level environmental impact of noise, not being measurable in units of mass, volume, or concentration, is ultimately defined by the loss of quality of life by the ecological systems affected by it, as defined by an appropriate governing body. The operative example is the selection of the DNL 65 dB contour as the metric for significant exposure, which is based on subjective research regarding the population's annoyance via the Schultz curves.

While other environmental metrics can be scaled directly from the vehicle-level, noise modeling, being inherently spatial and temporal, necessarily introduces an extra level of progression: airports. A logical progression, therefore, is to first integrate from the aircraft-level to the airport-level, and finally to the fleet-level as can be seen in Figure 2.2. Since airport noise is definitively a function of the airport characteristics, particularly from the standpoint of shape, these effects must be considered. The temporal aspects, meanwhile, are managed via equivalency metrics such as SEL and DNL, which average the temporal response over a certain reference timeframe.

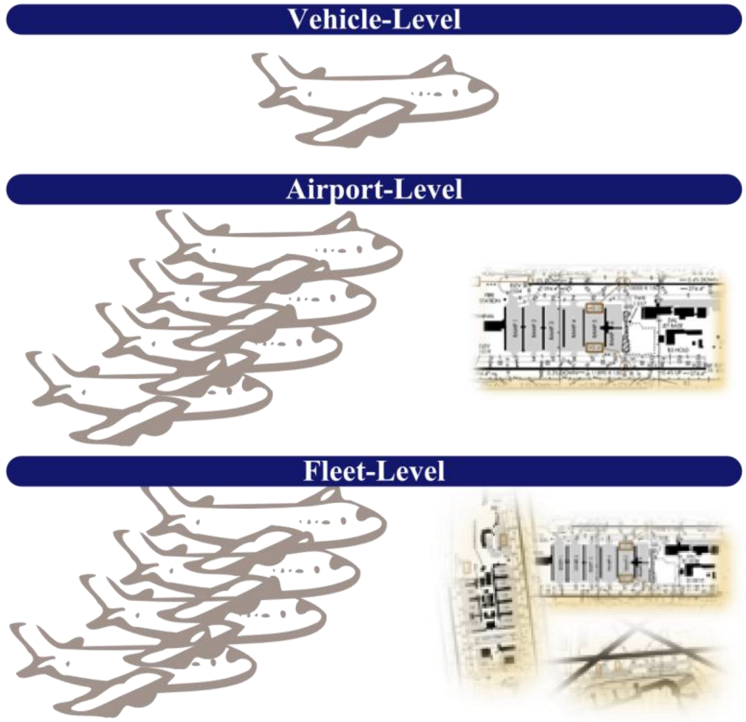


Figure 2.2: Spatial nature of noise invokes airport-level evaluation.

The large number of potential airports involved in a given analysis, such as 382 primary commercial service airports in the United States alone, introduces an even further complication of variables with respect to a fleet-level analysis [83]. These variables can range from the airport configurations, operational characteristics, runway utilization, weather conditions, elevation, terrain, and special local procedures. While modeling noise in detail is a common capability, the complexity of aircraft and airport noise modeling yields a large number of factors that can potentially affect noise, some of which may be more important than others with respect to a rapid preliminary fleet-level evaluation. It is these extremely detailed variables that hamper rapid evaluation of noise at the fleet-level, and that furthermore increase the time required to provide fleet-level analyses at the detailed level.

A generic fleet-level noise evaluation methodology is required to address these issues, but only serves as a high-level general description of what needs to be achieved. In order to present a plan to address this need, a more concrete description of the problem is necessary. One way to examine the anatomy of the problem is to step through a notional noise evaluation framework for a technology and demand scenario, identifying where the gaps exist to achieving a generic fleet-level noise methodology. Using this approach, the scope of this research can be appropriately and clearly defined.

2.3 A Generalized Framework for Evaluating Fleet-Level Noise

In order to better illustrate the capability and knowledge gaps that must be filled to fully assess the fleet-level noise space, a general framework of steps is stipulated, to serve as an organizational structure for the conversation. By stepping through the process, the gaps, combined with the issues motivated through the literature search, can be used to generate targeted research questions and hypotheses to address the problem.

The notional process is based on the comparison of a technology demand scenario to an appropriate baseline, because this is a cross-section of what the rapid fleet-level analysis must be able to achieve. The main difference is that instead of comparing a single scenario, a variety of scenarios must be comparable within an acceptable analysis time and accuracy. The basic general steps of a methodology to evaluate noise technology scenarios will remain constant, with small variations required for specific problems. The steps are presented here purely for a procedural purpose, as different infinite frameworks could be argued for various problem-types. For the purposes of this research, those arguments will be considered trivial. As such, the process will consist of the framework presented in Figure 2.3. The data, tools, and methods utilized to execute these steps can also vary. While some of these areas are well-defined, or considered to be in sufficient progress, others will be found to be lacking. To simplify the discussion, they will be grouped into the concepts of fleet and operations definition, scenario and forecast building, fleet-level noise modeling, and contour comparison as shown in Figure 2.4.

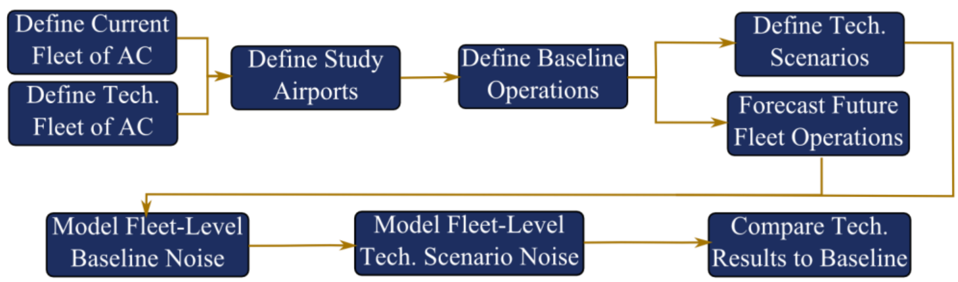


Figure 2.3: Generalized framework for evaluating fleet-level noise.

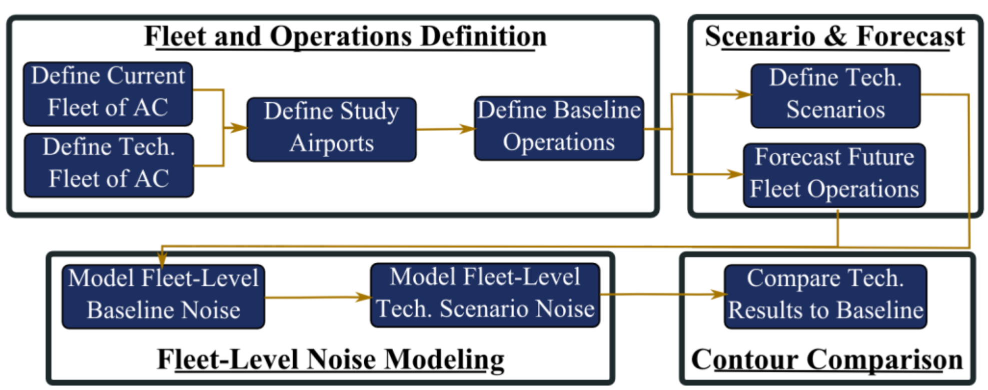


Figure 2.4: Core concept-categories.

2.3.1 Fleet & Operations Definition

The definition of the current fleet can be done in a number of ways, and is usually dependent on the dataset that is chosen. For example the Traffic Flow Management System Counts (TFMSC), produced by the FAA can be used to define the fleet of aircraft that will be utilized in an analysis [84]. Similarly, the vehicles used for detailed F.A.R. Part 150 noise studies at any given airport could be chosen. Another potential option is to leverage the generic vehicles developed by Becker [9]. This latter option is particularly useful because it reduces the amount of computation time required. In any case, various avenues of research with respect to defining and simplifying the fleet are under way, and validation of any of these is outside the scope of this research.

Similarly, the technology fleet refers to aircraft that will be introduced over time into the system that have been infused with technological capabilities. Again this can be done a number of ways, including through the use of EDS [85]. Other aircraft design tools that allow for technology-effects modeling can also be implemented to achieve this, but regardless, are all examples of vehicle-level modeling. Vehicle-level modeling concepts and challenges are beyond the scope of the proposed work. Fleet operations can be defined by simply selecting from appropriate available datasets.

The definition of the fleet airports, on the other hand, is an issue that requires further exploration and development for the purposes of creating a generic fleet-level noise analysis capability. As described earlier, the airport-level is critical in arriving at fleet-level estimates with respect to noise. With the large number of potential airports of interest with unique operational, infrastructure, and atmospheric characteristics, there is major need to reduce the computational load via categorization. Such groupings have been employed at the vehicle-level in the past, such as those utilized to create generic vehicles and groupings generated by Isley that combine aircraft into 'families' [9], [86]. While runtime is a major factor in reducing the number of airports required to execute a comprehensive study, there can also exist political sensitivities invoked by the use of specific airport names or characteristics to perform noise studies not authorized by those airports. The large variety of unique airport characteristics, while appropriate for detailed studies, like Part 150 Noise Compatibility Plan (NCP), is restrictive with respect to analyzing a large number of potential technology combinations at the fleet-level for an entire system of airports. By categorizing airports and making them generic, a large amount of information can be obtained about the generic classes, which can be used to infer similar relationships to the unique airports. Using general classes reduces the workload and improves the amount of valuable information that can be derived from a certain amount of modeling effort. A generic approach is therefore critical to enable the rapid tradeoff of solutions, not only for noise, but in the context of other environmental metrics as well. In fact, this is not the only situation in which useful airport categorizations have been developed. While they vary in methodology and function, they can be used to guide the process to create noise-related groupings.

Many airport groupings exist that are used for a variety of different reasons. Among them are the Aviation System Performance Metrics (ASPM) 77 airports, of which the JPDO assigned a subset of 35 airports to represent the space of significant aircraft activity in the United States [87], [88]. Together the 35 airports encompass over 70% of the air transportation passengers and serve major metropolitan areas. The

MAGENTA distinction of 95 airports is comprised as those airports that account for 90% of the population exposed to DNL 65 dB noise [89], [90]. The FAA also provides hub-size groupings defined based on the total percentage of U.S. enplanements handled by a given airport. Within these types of categorizations it is noted that they "are mainly based on passenger numbers and mostly restricted to qualitative statements rather than quantitative air traffic characteristics." [91] As a result, these grouping types are not well suited for modeling because they do not provide the appropriate input definition information for different airport categories.

Airport groupings also exist from a generalization perspective, which aim to describe a large number of airports with a relative few, through technical similarities. This approach is better suited for generating inputs to a model, because objective technical characteristics are tracked. These have been developed specifically to improve the efficiency of airport capacity impact assessments, and to study the feasibility of noise trading schemes [91], [92]. While the concept and even some of the methods for grouping are compatible, or even ideal for generating airport groups suitable for fleet-level noise modeling, there are a number of unique issues with the current problem that require a separate approach. For example, the work done with respect to airport capacity impact assessment considers many variables that are either irrelevant or too detailed for the level of analysis with respect to generic fleet-level noise, as listed in Table 2.1 [92]. In many cases, the variables are not appropriately stated with respect to noise modeling, but do begin to describe the problem quantitatively.

Table 2.1: Parameters relevant to airport capacity impact management [92].

Airport Process Chain Element	General Parameters (Procedures and regulations)	Airport Infrastructure Parameters	Air Traffic Parameters
General	• Characteristics of the other operation aircraft	• Navigation Aids	• Traffic Demand • Traffic mix
Final Approach	• Final approach procedures • Separation regulations	• Final approach routes	• Arrival share
Runway System	• Landing procedures • Runway coordination regulations	• Runway system layout • Runway exit positions	• Runway usage
Departure	• Departure procedures • Separation regulations	• Departure routes	• Departure share

With respect to analyses utilized to evaluate noise trading schemes, the grouping strategies are very useful, but there is no concern for the geometry of the airports with respect to their effect on predicted contour area [91]. Other groupings, based on airport capacity management impact assessments, do consider runway layouts, but the infrastructure variables that determine a noise contour shape are different than the ones relevant for airport capacity modeling [92].

While these grouping techniques provide a sufficient methodological background on which to build, there is still a lack of noise-specific groupings for the purposes of reducing fleet-level noise analysis prediction runs. Groupings with respect to noise must consider the infrastructure shape, but also in the context of the resultant contour shape. In many cases, runways can be sufficiently close together that it cannot be inferred from the resulting contour that two runways are in operation instead of one. Situations such as these are not captured in the current literature, and a noise-specific categorization would be beneficial for the purposes of reducing screening-level modeling runs.

2.3.2 Scenario and Forecast Building

Scenario and forecast definition are concepts that can be handled a number of ways, one of which is the GREAT tool described above. GREAT incorporates forecasting methods along with available datasets to provide operations forecasting, and also allows for aircraft retirement and replacement definition. Research in these subjects is beyond the scope of generic noise modeling and will be considered sufficiently mature for the purposes of this research. In any case, the methodology developed should be independent of the forecast or scenario, allowing for flexibility between different datasets at different entities.

2.3.3 Fleet-Level Noise Modeling

There are a number of detailed and lower-fidelity noise modeling tools that can potentially be used to achieve the tasks required for fleet-level noise modeling. While the nature of vehicle and airport-level modeling at the detailed level is satisfactory, there are significant challenges for integrating to the fleet-level, especially when using simplified models. Lower fidelity tools with sufficient accuracy are necessary to enable the rapid tradeoff of a large number of technology, policy, and demand scenarios. To assess the state-of-the-art in these areas, a benchmarking exercise is necessary.

2.3.3.1 Detailed Modeling Methodologies and Tools

There are a variety of detailed methods and tools available for airport and fleet-level noise modeling. The main detailed airport noise evaluation methodology in the

United States was created to accompany the F.A.R. Part 150 program administered by the FAA. This regulation includes the procedures for setting up, executing, and submitting an NCP as outlined by the FAA, and thus serves as the national standard for airport noise evaluation methodologies. The modeling tool required for any Part 150 NCP is INM, developed by the FAA [93], [94]. A summary of the relevant aspects of the Part 150 evaluation methodology will be provided first, as they provide insight into the modeling capabilities within INM and most other detailed noise models, while highlighting the effort required in completing a detailed noise study.

The F.A.R. Part 150 program provides a number of details about how a given airport should go about constructing an NCP. The NCP has two important aspects: the Noise Exposure Map (NEM), which is a spatial representation of the noise 'footprint' of the airport, and a descriptive list of steps the airport has taken and plans to take with respect to noise abatement [94]. It also defines the A-weighted frequency metrics to be utilized to correlate noise levels with "surveyed reactions of people to noise." [54] For a more complete description of the development of A-weighted noise levels, the interested reader is directed to Appendix A. The regulation designates the DNL metric as the system "for evaluating the cumulative impacts of multiple noise events." [54] The regulation also provides standardized compatible land uses in areas of varying noise exposure, and requires INM as the modeling tool to be used in development of NEM's. In the interest of providing inputs that appropriately and consistently represent the noise impact of an airport, the regulation also defines what relevant information should be gathered and the appropriate level of detail. F.A.R. Part 150 calls for a Yearly Day-Night

Average Level (dB YDNL)[4] and thus a significant amount of operational data must be collected that:

> "*will indicate, on an annual-average-daily-basis, the number of aircraft, by type of aircraft, which utilize each flight track, in both the standard daytime…and nighttime…periods for both landings and takeoffs*." [94]

Depending on the operation, flight profiles and subsequent engine power levels required to fly those profiles must be documented [94]. Similarly, the weight of the aircraft must be tracked either through actual takeoff weight or a surrogate such as the stage length designation listed in Table 2.2 [95].

Table 2.2: Departure stage lengths utilized by INM [95].

Stage Number	Trip Length (nmi)
1	0-500
2	500-1000
3	1000-1500
4	1500-2500
5	2500-3500
6	3500-4500
7	4500-5500
8	5500-6500
9	>6500

Furthermore, topographical information or restrictions to the airspace specific to a given airport must be included if they impede the use of certain tracks [94]. Finally, the airport elevation and temperature must be provided, as these metrics affect the atmospheric absorption and propagation of sound from a source [94]. As can be expected

[4] The YDNL is similar to the DNL except that the averaging-time is on the yearly scale instead of daily.

from the detail required for a Part 150, the result is a commensurately detailed noise exposure map of the status quo noise situation. Then, applying any changes to "…land use, airport operations, plus any improvements…from noise mitigation actions…" a noise exposure map is generated to predict the noise exposure in five years [54].

INM is designed to meet the requirements for submitting successful NCP's. This detailed tool has a Graphical User Interface (GUI) which allows the user to select an airport for study, and input the information detailed above. INM includes the ability to change the standard conditions to include humidity, headwinds, and changes in temperature and pressure. From the interface, the user also defines detailed flight tracks across all airports and then inputs flight schedules that describe which aircraft, at how many operations, at what general time of day are flying at a given track. As such, the setup required to conduct an airport Part 150 study is significant and includes data collection, sorting, and input. The result, consequently, is that INM can provide a host of useful metrics, beyond just the required measure of YDNL. INM provides contours, and allows users to define terrain characteristics, population densities, map overlay, and the definition of locations of interest.

INM is also database driven, so while the large amount of data required can be input through the GUI, it is also possible to input the information directly to the database files in the INM folder. The runtime of INM is reasonable for a detailed model, but is significantly affected by the number of aircraft in the fleet, the variety of tracks, the number of runways at the airport in question, and the grid defined for calculation. Depending on the type of output desired, an INM run can take hours to weeks to execute. Including the setup time, the time required to turn around detailed studies is too restrictive with respect to evaluating a multitude of strategic noise mitigation options at a fleet-level. Moreover, it is more difficult to automate INM and execute large numbers of evaluation scenarios without a user-in-the-loop. The Air Force also has a noise exposure program, NOISEMAP, utilized to model noise at military air bases. It is qualitatively similar and shares some compatibility with INM [95], [96].

F.A.R. Part 150 and the INM are designed to "promote a planning process through which the airport operator can examine and analyze the noise impact created by the operation of an airport, as well as the costs and benefits associated with various alternative noise reduction techniques…" [94]. They are well suited to such airport-level problems which occur in the relative short term and include significant local and state-level impact. As such, they provide the operator the ability to include a significant amount of detail that is valuable when dealing with specific sensitive land-use and community noise issues. Unfortunately, they are ill suited to long term fleet-level noise mitigation strategy assessments. The immense detail available to the user is not as effectively leveraged when considering noise evaluations at the fleet-level decades into the future. At this stage, specific airport short-term operational characteristics and land use details are not necessarily relevant to the overall problem at hand. For example, the particular temperature or pressure at a given airport is probably a variable of lesser consequence when considering a fleet-level approach because it only serves to introduce uncertainty due to what are random variables that impair the user's ability to evaluate the direct benefit of a scenario across different airport types. While such a study in variability due to atmospheric factors is valuable, it is infeasible to execute it at the fleet-level for a myriad of technology combinations. Ultimately, much of the detail provided is incongruent with the level of detail provided by technology and demand models early in the strategic decision-making process, resulting in a fidelity mismatch. Furthermore, describing technology modified aircraft is cumbersome and difficult in INM. The definition of a dynamic fleet of technology modified vehicles in INM would be a significant effort, let alone a fleet-level evaluation of the many possible technology package combinations.

Nonetheless, the modeling capabilities in INM are certainly desirable in many ways, and in fact, the basic modules of INM are included in the FAA's comprehensive Aviation Environmental Design Tool (AEDT). While AEDT provides an improved fleet-level capability that enables the detailed examination of technologies, operations demand, and policy, the time to execute such a tool suite is similarly large and would not enable an exhaustive search of the design-space. That is to say, the generic screening capability desired to down-select the best performing technology packages would not preclude the use of AEDT, but rather precede it, aiming to improve the focus, efficiency, and value of a more detailed and higher fidelity AEDT study.

Other detailed tools of increasing capability have been developed recently as well. While INM is still the standard noise calculation tool for Part 150 studies, capability improvements have been achieved in other detailed tools which are predominantly used overseas. For example, the Computer Aided Noise Abatement (CadnaA) software package is a detailed model that includes broad community noise mapping, not necessarily confined to airport noise [97]. The airport noise components have the capability to calculate noise in accordance with European Civil Aviation Conference (ECAC) Doc 29 (the same standard methodology utilized by INM and recognized by most nations) as well as other methodologies [95], [98]. Competitors of CadnaA, include the Predictor-LimA Software Suite, developed by Brüel & Kjær, which also allows for broad-scale community noise analysis, and IMMI, developed by Wölfel, which allows for noise calculations at airports using various methodologies while linking airport operations data gathering and management (significantly reducing setup effort) [99], [100]. Again, these tools provide a splendid level of detail, targeted at improving the accuracy of airport noise exposure predictions that will enable airports to better inform the public, and avoid damaging public situations with respect to airport noise. This level of detail is not without a significant runtime cost of course, and again, the detail required from the inputs is inherently inappropriate for fleet-level projections twenty or thirty years into the future, with relatively substantial uncertainty accounted for by more general variables.

2.3.3.2 Lower Fidelity Methods/Tools

Lower fidelity methods, on the other hand, have struggled to achieve sufficient fleet-level accuracy and have been unable to sufficiently leverage the detailed modeling capabilities earlier in the decision process. The most established screening-level methodology is the Area Equivalent Method (AEM), also developed by the FAA. AEM is a "screening procedure used to simplify the assessment step in determining the need for further analysis with the Integrated Noise Model... as part of Environmental Assessments and Impact Statements…and Federal Aviation Regulations…Part 150 studies." [101] AEM is a spreadsheet based model that estimates the change in area of an airport contour with respect to operations [101]. AEM is utilized to determine whether or not an

Environmental Impact Study (EIS) is required or not, by establishing a decision criterion of 17% increase in the DNL 65 dB contour area to define 'significant' change. "AEM determines the DNL noise contour area in square miles for a mix and number of aircraft types by using linear regressions that relate DNL noise contour area as a function of the number of annual daily average operations." [101] Use of AEM assumes that similar runway and flight track utilization will be maintained through the baseline and the subsequent alternative [101]. Furthermore, AEM assumes a single runway and one-way traffic flow, and thus cannot be used to evaluate any scenarios that would change "the general shape of the contour." [101] While AEM does provide a methodology for generating regression parameters, it requires a separate noise modeling of aircraft (required if using technology enabled vehicles). AEM results are only considered to be valid for binary decision-making, depending on whether or not there will be a 17% increase in DNL 65 dB contour area.

Dikshit and Crossley also developed a simplified fleet-level noise model for use in a fleet-level environmental assessment [10], 0. The main concept was to utilize the aircraft noise certification points (measured in EPNL), pictured in Figure 2.5, to build a linear regression model to estimate the area dominated by the DNL 65 dB contour 0. The regression is a function of the operations volume at a given airport. To build the regression model, the Indianapolis and Buffalo airports were utilized to gather experimental runs and then the Least Squares method was used to compute the regression coefficients. Two common tests for regression models are model fit error (MFE), and model representation error (MRE). The former refers to the ability of the model to predict the data that was utilized in its creation [102].

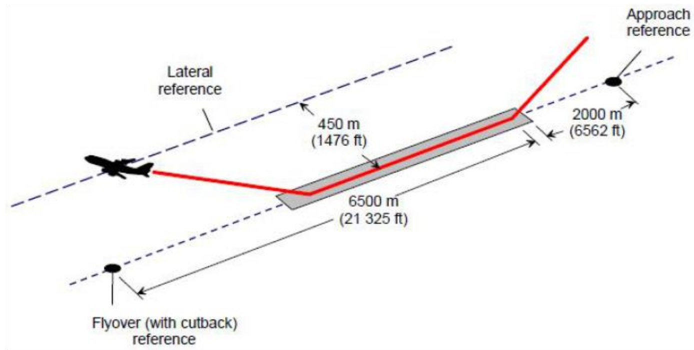


Figure 2.5: Location of noise certification points 0.

The latter refers to the ability of the model to predict results of cases that were *not* used in developing the regressions [102]. While this particular model performed admirably with respect to the MFE, it was not successful with respect to the MRE as can be seen in Figure 2.6 0.

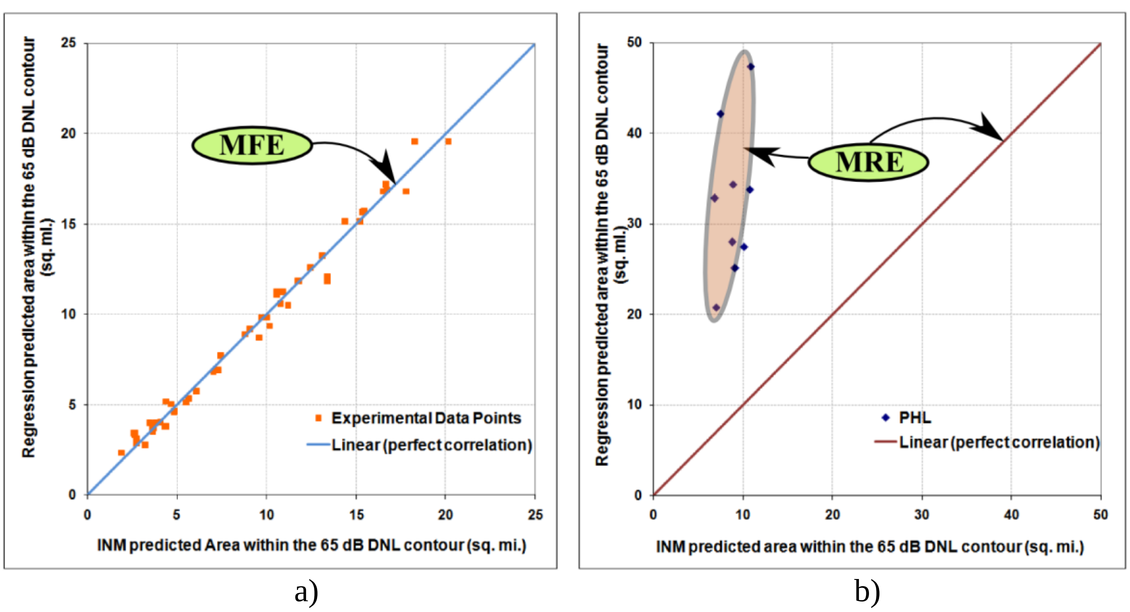


Figure 2.6: a) MFE suggests good model; b) MRE contradicts model effectiveness (Adapted from [11]).

The relative inability of the model to predict results of cases not used to create the model make its widespread applicability at the fleet-level questionable. This discrepancy was attributed to a lack of certain aircraft-type operations at the airports utilized to create the regression model 0. Although not explicitly mentioned, it is possible that some error is contributed by the lack of contour shape capturing ability. This particular work also expounded upon the characteristics desired within a screening fidelity fleet-level methodology. While not necessarily relevant to the benchmarking effort, insight into the requirements set forth by the authors could be beneficial in guiding further developments. The authors put forth that the method must have the flexibility to include new or technology-infused aircraft, be single valued, "[be] rapidly computable, have a simple formulation, and be well correlated with a standard noise model." 0, [58] A similar approach was utilized by Hollingsworth and Sulitzer, which mirrors the approach of Dikshit and Crossley, but instead of being based upon EPNL certification data, the British Quota Count (QC) system was utilized 0, [103].

Another method, considered by Dikshit and Crossley for fleet-level noise analysis, is the Single-valued Noise Exposure Forecast (SvNEF) 0. The SvNEF is a single-valued metric that utilizes the aircraft certification data at all three pertinent locations. Correlation studies between the SvNEF and INM DNL 65 dB contour area showed acceptable correlation but "in certain scenarios, a large increase in the exposed area will only correspond to a small change in SvNEF and vice versa." 0 The drawback to the SvNEF, from the author's perspective, is that it did not consider the differences between aircraft, such as their size, beyond the EPNL certification values. Nevertheless, the model did serve as the foundation for the model created by Dikshit and Crossley, which was constructed as an improvement upon the SvNEF formulation to include some consideration for the differences between aircraft 0.

2.3.3.3 Critical Analysis of Existing Methods

The methods described above have all made advancements at varying levels in the development of fleet-level noise models, but each has certain drawbacks. Before critically discussing these, however, a basic set of guiding requirements should be identified. Recalling that Dikshit and Crossley developed what could be considered preliminary requirements for their work in Ref. 0, these will serve as an appropriate foundation on which certain necessary adjustments or clarifications can be made.

As previously mentioned, the capability to include new aircraft and technology infused aircraft is critical to predicting future fleet-level noise responses. Including future aircraft for the purposes of a long-term fleet-level prediction is almost more important than current aircraft, since in the long term, a majority of the fleet would supposedly consist of next generation aircraft and beyond. Speed of computation is an important but somewhat ill-defined requirement. Speed is a relative term, and the speed of computation must be measured with respect to an otherwise capable alternative. In this case, the alternatives are the detailed airport or fleet-level noise models available. Correlation, agreement, or validation with an industry standard is also desired, within reason, to lend credence to a simplified solution. Although the level of reasonable accuracy must still be specified, a sensible agreement with standard methods is necessary to provide confidence in the generic fleet-level method as a decision-support tool. At some point, if the time saved by executing a lower fidelity method is insufficient for a given loss of accuracy, then a detailed model would serve the purpose better. Therefore, combining the speed and accuracy criteria provide a comparable measure of efficiency. A simple formulation is also heavily desired to avoid a "resource allocation problem." 0 A 'simple formulation', however, is a poor requirement and really constitutes a subjective constraint intended to mitigate the loss of rapid computability in more complex scenarios. The simplicity should be re-stated as full automation and comparatively short setup time. After all, one of the main stated drawbacks of detailed models, such as INM, with respect to rapid screening fidelity fleet-level analyses is that they "require…too much user interaction and input." 0

The fifth requirement proposed by Dikshit and Crossley is that the model should be single-valued, or provide only one metric output; namely the DNL 65 dB contour area. The airport noise exposure system is, again from a systems perspective, an interaction between a source, its path, and the receiver(s) at the end of that path [12]. Calculating solely the DNL 65 dB contour area provides no information about where the receivers of that level of noise are located. To put it differently, the contour area provides no information by which the user can predict how that area will be distributed about an airport. This extra information is a critical piece in terms of evaluating future noise emissions because recent demand forecasts suggest that at some point, the expected increase in demand will not be adequately counterbalanced by noise reduction technology [12]. Since the end goal is to minimize the population exposed to airport noise, the problem cannot be entirely governed by reduction in contour area but must also incorporate noise allocation. Noise allocation refers to *where* noise is designed to occur around a given airport. Consider a simple example where a single-runway airport has a

DNL 65 dB contour distributed over the surrounding population as shown in Figure 2.7-a. Now consider the airport in Figure 2.7-b, which has the same DNL 65 dB contour area, but in the second case affects a significantly smaller portion of the notional population and occupies a completely different geographical space. Although this example is an oversimplification, it is a useful illustration that reveals the value of determining not only the areas of noise contours but also shape.

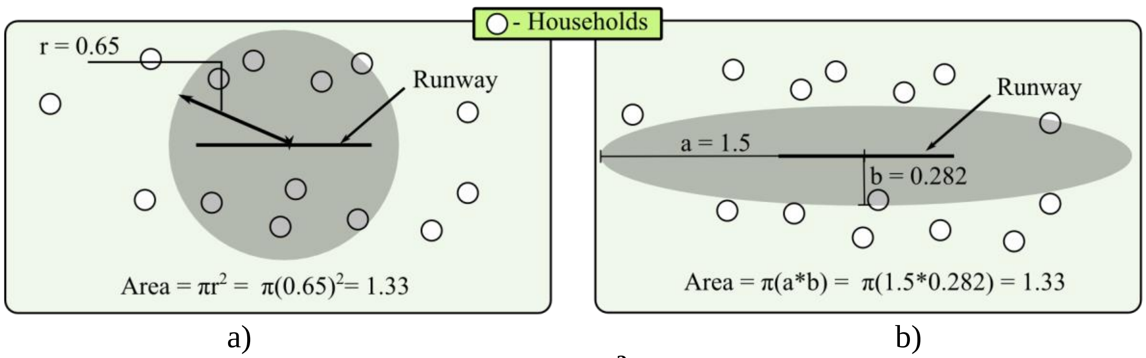


Figure 2.7: a) Circular contour of 2.8 units^2; b) Elliptical contour of equal area.

With a more accurate representation of shape, only a well estimated population density model is required to predict the number of households affected. Therefore, a single-value output for a noise methodology, is not necessarily an excellent requirement, considering that airports vary greatly in size, shape, and utilization. Area only really provides a direct measure of size. To better estimate the total areas exposed to significant noise, some capacity to describe contour shape can be very beneficial, and subsequently also serves to increase the likelihood of an accurate contour area estimate. Capturing the shape of a contour also enables the sensitivities of infrastructure-related fleet-level variables that affect the distribution of airport noise to be examined.

Having established a baseline of what is desired from a fleet-level analysis model, a qualitative evaluation of the detailed and lower-fidelity methods discussed above can be performed. For example, AEM lacks sufficient accuracy, cannot model runway utilization, cannot model different aircraft weights, and is difficult to combine with technology-infused vehicles. While it is very simple and quick to execute, it does not provide any information about contour shape. On the other hand, the simplicity of the input format is attractive for a generic method. The other methods, which can be characterized as regression methods, have certain accuracy issues as well and also cannot capture any information about shape. These methods are, however, capable of including technology infused aircraft within the model and can also be used in a larger fleet-level environmental study as shown by Dikshit and Crossley 0. A summary of the desired features and characteristics are listed in Table 2.3.

Table 2.3: Desired features for a generic fleet-level noise model.

Desired Characteristics
1. Easily incorporates new and tech. modified aircraft
2. Computational speed with respect to detailed models
3. Acceptable accuracy with respect to detailed models
4. Simple-to-manage inputs
5. Full automation
6. Contour area *and* shape information captured

2.3.4 Contour Comparison

The final step, naturally, consists of comparing the result of the technology scenario with the baseline to analyze benefits and drawbacks of a potential option. As mentioned earlier, carrying information about airport noise contour shape is beneficial for examining the large variety of different airport configurations that exist. Contour shape agreement, however, can span the spectrum of qualitative and quantitative measures, and appropriate means of describing contours with respect to their shapes is noticeably lacking. While visualization is a very important aspect of strategic decision making, there are also shape metrics that could be applied to airport noise contours, to support the evaluation of differently shaped contours. The current methodology of describing contours simply by the DNL 65 dB contour areas, as demonstrated above, is not sufficient to project information about the shape of a contour and is thus only part of the total description. Implementation of shape metrics would allow the shape effects imposed by different scenarios to be tracked and evaluated between many scenarios whereas visual techniques can become impractical as the number of scenarios increases. Shape descriptor metrics would provide the ability objectively define the impacts of technology scenarios on different airport types. At the fleet-level, however, it is difficult to select a metric that appropriately describes the different possible shapes that could be encountered.

2.4 Capability Gaps

The general process presented above to complete an evaluation of technology scenarios with respect to noise can be achieved through a multitude of diverse methods and tools which can be employed to complete a given step, some of which were enumerated and described herein. These give rise to a morphological analysis of capabilities that can be mixed and matched to accomplish a fleet-level assessment and comparison. A morphological analysis is a decomposition method that "…help[s] structure the problem for the synthesis of different components to fulfill the same required functionality" that can be compiled into a morphological matrix to communicate the results in a structured manner [104]. Based on the literature search and benchmarking performed above, a morphological matrix of the capabilities available was constructed, and is listed in Table 2.4, to visualize the options and determine the shortcomings in the current state-of-the-art.

Table 2.4: Options to perform fleet-level technology scenario evaluations.

Define Baseline Fleet	Define Techs.	Define Airports	Define Baseline Ops.	Define Tech. Scenarios	Forecast Future Ops	Model Fleet-Level Noise	Compare Results
TFMSC	CLEEN	MAGENTA 95	TFMSC	CLEEN	TAF	AEDT	Area
Part 150	ERA	OEP 35	Historical	ERA	Boeing	INM	Population
Generic Vehicles	FW	ASPM 77	Real-time	FW	Airbus	Cadna-A	
Seat Class	HEETE	OPSNET 45	Part 150	HEETE	Historical	LimA	
	ADVENT	Core	Other	ADVENT	Other	AEM	
	RCEE	TAF		RCEE		IMMI	
		INM				SvNEF	
						M-SvNEF	

Various options are available for each step, but it is important not to confuse the number of options available with the quality or ability with which those options perform the intended function. Analyzing the morphological matrix in conjunction with the analysis provided above shows that the main capability gaps for the desired generic fleet-level noise methodology exist in defining the fleet airports, modeling fleet-level noise rapidly while including technology infused vehicle models, and in metrics used to describe different contour shapes. A summary of the status quo analysis methodology as compared to the desired generic approach can be seen in Figure 2.8.

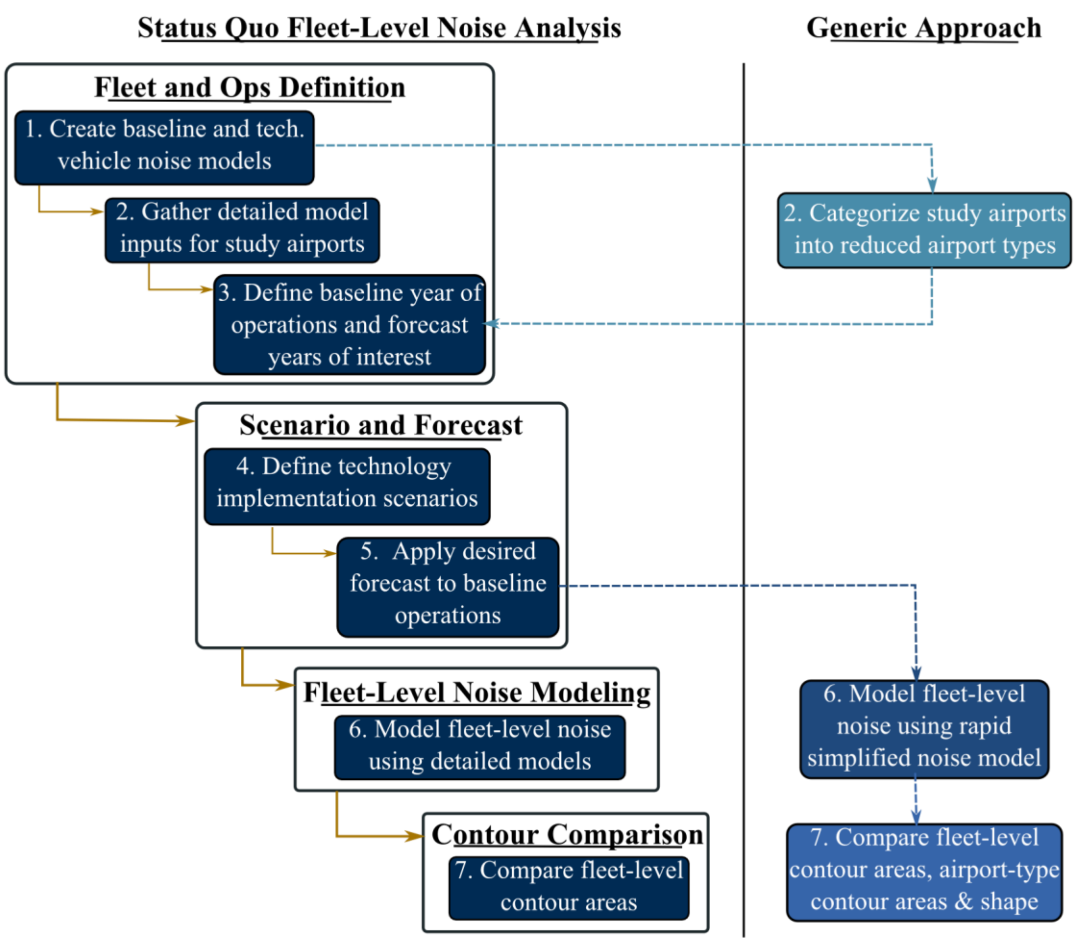


Figure 2.8: Comparison of status quo and desired methodologies.

The three capability gaps, summarized in Figure 2.9, can be considered as three separate opportunities for development. The combination of the three will enable the implementation of a generic fleet-level noise methodology. The definition of an airport database, which could potentially be very large, introduces a cumbersome multiplication to the number of cases that must be executed to achieve a fleet-level estimate. If every airport must be calculated, the process will naturally become slower. With respect to noise modeling, the issue with detailed methods, such as INM or AEDT, is that they are time and effort intensive to setup and run, and therefore limit the ability to examine the large combinatorial space of technologies sufficiently. A capability that can run a large number of cases in a relatively short period of time is absolutely necessary to enable satisfactory strategic down-selection of the best performing technology combinations with respect to noise.

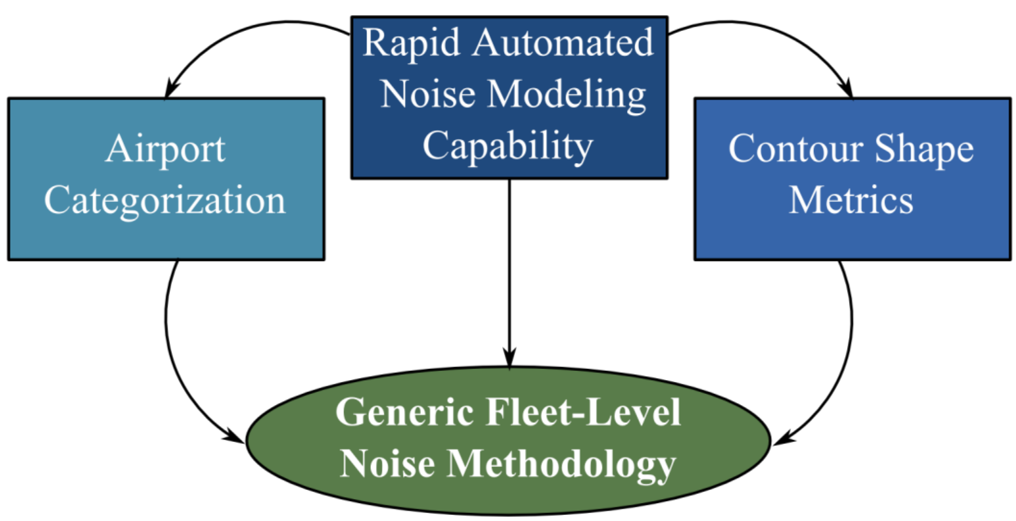


Figure 2.9: Areas of assessed capability gaps.

Simplified models, on the other hand, currently do not provide sufficient accuracy with respect to detailed methods to be applied to the generic approach, and only consider the DNL 65 dB contour area. These models lack the ability to capture contour shapes, which are most appropriate when evaluating the environmental impact of a spatial problem. Consequently, metrics for communicating contour shapes are not available or widely used, and limit the quantitative characterization of a contour beyond simple contour area.

These capability gaps, once sufficiently fulfilled, will enable desired analyses at the fleet-level motivated by the background and literature search. Hence, sufficient gap fulfillment can give rise to use cases that assess the fleet-level noise impacts of different technological infusions with respect to their impacts on contour area and shape. The overarching research objective can therefore be stated:

> *Research Objective: To develop a generic fleet-level noise methodology that supports the generic framework for fleet-level environmental analyses and enables rapid evaluation of technology response scenarios with respect to contour area and shape impacts.*

Satisfactory development of such a generic fleet-level noise methodology would provide answers to the research questions:

> *R.Q. - How do technology infused aircraft impact the contour area and shapes of airports in the context of total forecasted operations, and fleet mix?*

The hypothesis that addresses this research questions is inspired by the literature search performed, uncovering the importance of contour shape characteristics to fleet-level noise analyses. Whereas in the past, improvements could be measured by area reduction, as airport noise has been reduced, it is more important to address the spatial nuances of the problem as early as possible. The overarching hypothesis is thus:

H - If technology infused aircraft are applied to a fleet of operations via a forecast, their impact will not be uniform across all airport types, and will not be restricted to reductions in contour area only, but also to impacts to the airport noise contour shapes, which may impact the ultimate measured benefit of a given set of technologies. These impacts at the screening level will be more appreciable in a generic framework as opposed to the cumbersome and time consuming detailed approaches currently available.

This research questions can be addressed when a generic fleet-level noise methodology is enabled by first addressing the capability gaps summarized above. Once an approach is developed to fulfill these areas, the generic fleet-level noise methodology can be constructed and implemented to provide answers to the research questions.

CHAPTER 3

APPROACH

In order to structure a research plan that will effectively address the issues presented in the background literature search and gap analysis, it is important to formally state the problem via research questions. This process ensures that the stated issues will be addressed in a structured manner. Once the research questions are presented, hypotheses can be generated based on the background literature search that will ultimately be tested via experiments. This chapter will serve as the roadmap for the dissertation, detailing the research questions, the subsequent hypotheses, and the designing of the experiments that will provide answers to those questions. Within this chapter, the methods, processes, and techniques relevant to the project will be presented and justified from a technical and programmatic standpoint. Once the capability gaps are addressed, the generic fleet-level noise methodology will be explicitly described prior to the description of several use cases that can be leveraged to answer the overarching research questions.

3.1 Rapid Fleet-Level Noise Modeling

The capability gap of greatest importance is the lack of a rapid fleet-level noise modeling tool that can produce a high volume of scenario evaluations. While detailed models provide the technical capability, the relative runtime and lack of simplified automation make such studies impossible. Simplified models, on the other hand, do not consider the shape of the contours, struggle to include technology infused aircraft, and suffer with respect to accuracy under varied scenarios. Not only is a rapid fleet-level noise modeling process required to produce results, but it is imperative to the success of the remaining capability gaps. Functioning as a virtual test-bed, the potential to examine a large number of cases in a relatively short period of time with total automation enables the formulation of a plan to address the other capability gaps. In order to create a modeling capability that achieves the characteristics defined in Chapter 2, a number of research questions must be addressed:

I. *What are the important variables to consider for a generic fleet-level modeling tool?*

II. *How can detailed tools be leveraged to provide noise information for a simplified fleet-level modeling capability?*
   a. *What simplifying assumptions can be made to speed up the process?*
   b. *How can contour shape information be retained?*

III. *What are the sources of error in such a model?*

The main capabilities missing within the available generic methods, as described by the benchmarking exercises in Chapter 2, are general accuracy across multiple airport types and some capture of shape information. The two are somewhat coupled, however, as shape accuracy should by extension imply improved area accuracy. The lack of shape capture has likely hampered the ability to accurately predict contour area, especially in the existing regression methods that typify the currently available generic options.

3.1.1 Variables of Importance

The first research question, regarding the variables of importance, will ultimately define the capability of the resultant model. The assumptions made with respect to this question, will determine under what conditions it may be used, and what behaviors can be observed through its application. Therefore, the logical place to begin is by collecting a broad set of variables that are known to affect airport-level noise. From this set, assumptions, and determinations can be made to reduce the number of variables to only those that are most relevant to the problem. Once the variables that are required to achieve a desired level of accuracy and detail are selected, the process for creating a model that incorporates these variables can be described.

In order to collect an encompassing list of variables from which to select, the variables utilized in detailed noise models can serve as a reasonable baseline. Since these are the variables used by industry-standard models from which policy is derived, it can be assumed that they constitute a complete picture of the important factors affecting airport community noise. Variables such as the total number of runways, the relative spatial orientation of the runways, the utilization of each runway, the direction of traffic, the total number of operations, the types of aircraft flying those operations, the terrain characteristics of the airports, the environmental characteristics, and even the populations that surround these airports can all affect the resultant noise contour and its significance. They should not all be included in a rapid fleet-level model, however. It is important to recall the overall goal of providing a model to examine fleet-level trends and interactions of noise due to future technology packages. Some especially unique variables, such as terrain features for example, are outside the scope of this research and assumed to be too detailed for the purposes of the analysis. These types of variables are appropriate for detailed methods, but only serve to confound results when the goal is to isolate fleet-level impact due to a number of technological scenarios. Others are atmospheric variables that can also mask the important trends, since details such as varying temperatures, pressures, or headwinds can vary over time, even at the same airport. The non-exhaustive list of the variables used by the detailed models benchmarked in Chapter 2 that conform to the international standards agreed upon at the European Civil Aviation Conference (ECAC) are provided in Table 3.1 [98]. Examining the variables identified in Table 3.1, they can be characterized by four types: operational characteristics, geometric characteristics, atmospheric characteristics, and population characteristics, as shown in Table 3.1.

Table 3.1: Variables affecting airport-level noise.

Variable Name	Category
Total Ops	Operational
Fleet Mix	Operational
Fleet Distribution	Operational
Number of Runways	Geometric
Runway Configuration	Geometric
Runway Utilization	Operational/Geometric
Trip Length	Operational
Traffic Direction	Operational/Geometric
Terrain features	Atmospheric/Geometric
Temperature	Atmospheric
Pressure	Atmospheric
Headwind	Atmospheric
Humidity	Atmospheric
Special procedures	Operations
Airport Elevation	Atmospheric /Geometric
Runway end elevation	Atmospheric /Geometric
Approach glide slope	Operational
Taxi/Run-up Maneuvers	Operational
Ground tracks	Operational
Aircraft banking angle	Operational

Grouping the variable types is an approach similar to that used by Bock and Schinwald, which allows for assessment of the critical variables at a higher level [92]. Operational characteristics include details such as the total number of operations, the types of aircraft in the fleet, the distribution of flights amongst aircraft, the types of operations, and the number of nighttime operations. Geometric characteristics include the number of runways, their length, width, and location. The flow of traffic and the utilization of the runways are examples of the interrelationship between operational and geometric characteristics as these variables can be dependent on aircraft size or the time of day. Atmospheric characteristics include the temperature, pressure, wind characteristics, terrain features, airport elevation, runway-end elevation, etc. These characteristics are can vary significantly between airports and are too detailed for the intended fidelity level of the results. These types of variables can be modeled at the vehicle-level to assess the atmospheric impact on a given technology performance level, while the fleet-level assessment can concentrate more on the relative effects of introducing that technology in certain quantities to the fleet. Population characteristics, while extremely unique in their own way, are very difficult to include, and ultimately necessary to provide affected population estimations. The development of generic populations is beyond the scope of this work, although it must eventually be addressed.

The remaining important variables are operational and geometric (or infrastructure) characteristics, and these are considered to be the most relevant to provide the level of detail desired for a rapid fleet-level noise model. The major variables considered for modeling are listed in Table 3.2.

Table 3.2: Variables to be carried through for modeling

Variable Name	Category
Fleet Mix	Operational
Total Operations	Operational
Trip Length	Operational
Fleet Distribution	Operational
Traffic Direction	Operational/Geometric
Day/Night Ratio	Operational
Approach/Departure Ratio	Operational
Total Number of Runways	Geometric
Runway Configuration	Geometric
Runway Utilization	Operational/Geometric

3.1.2 Enabling Rapid, and Automated Fleet-Level Noise Modeling

Keeping in mind the operational and geometric variables that must be captured, a model must be developed that leverages detailed methods, retaining the accuracy provided by such models while simplifying the setup, execution, and automation. The developed model must behave as a surrogate, fixing certain variables as discussed above, while allowing the factors of interest to vary. The underlying concept behind detailed noise models is to compute noise at multiple observer points for each flight segment, integrating these to yield a flight-level grid [95]. This summation is performed for each flight in the study, and the resulting noise levels are summed to yield an airport-level noise grid, which is then converted to DNL values [95]. Therefore, the airport-level result can be viewed simply as logarithmic additions of all the sound exposure level (SEL) events occurring within a given flight schedule, as demonstrated via Equations 3.1 and 3.2 [95].

$$SEL_{apt} = 10\log_{10}\left(\sum_{i=1}^{n} 10^{\left(\frac{SEL_i}{10}\right)}\right) \tag{3.1}$$

$$DNL_{apt} = 10\log_{10}\left(\frac{10^{\left(\frac{SEL_{apt}}{10}\right)}}{86{,}400\ seconds}\right) = 10\log_{10}\left(10^{\frac{SEL_{apt}}{10}}\right) - 49.4 \tag{3.2}$$

SEL_{apt} – The airport-level SEL grid

SEL_i – The flight-level SEL grid of the i^{th} flight

n – Total number of flights

DNL_{apt} – The airport-level DNL grid

86,400 – The number of seconds in one day

Note that penalties for nighttime flights were omitted for simplicity, but must also be included in converting from SEL to DNL noise. Given this simple relationship, it is possible to pre-calculate a large number of generalized single-event situations and recombine them as required to approximate a full airport study using the same mathematical concepts. With the final airport-level noise grid, contours can be drawn, and areas calculated. In order to capture the airport-level geometric characteristics, the summation of aircraft-level noise grids can be done to the runway-level, as shown in Equation 3.3.

$$DNL_{rwy} = 10\log_{10}\left(\sum_{i=1}^{n} 10^{\left(\frac{SEL_i}{10}\right)}\right) \tag{3.3}$$

DNL_{rwy} – the runway-level DNL grid

SEL_i – the flight-level SEL grid for the i^{th} flight on the runway

Then, the resulting runway-level grids can be translated and rotated based on their relative spatial positions, and interpolated to a reference grid using the nearest-neighbor method. For more information regarding the interpolation of scattered data, the interested reader is referred to a review of several methods by Franke in Ref. [105]. The resulting runway-level grids can then also be logarithmically summed to yield an airport-level grid using Equation 3.4.

$$DNL_{apt} = 10\log_{10}\left(\sum_{j=1}^{n} 10^{\left(\frac{DNL_j}{10}\right)}\right) \tag{3.4}$$

DNL_{apt} – the airport-level DNL grid

DNL_j – the runway-level DNL grid for the j^{th} runway

n – the total number of runways at the airport

The runway-level geometry, however, must sacrifice certain detail. While the runway locations can be set, the lengths and widths cannot be allowed to vary, as this would preclude the ability of accurately overlaying single-event grids. By executing a large number of detailed aircraft-level noise models off-line, the computation time of airport and ultimately fleet-level noise contours can be decreased dramatically. This approach allows for the inclusion of sophisticated detailed noise modeling methods earlier in the analysis process, retaining the ability to model airport-level noise while using the best available methods to provide the aircraft-level responses given certain assumptions. The formal hypotheses can be stated as:

I. *If aircraft-level grids can be pre-calculated, leveraging detailed noise modeling methods, then the logarithmic addition of these grids can approximate a runway-level grid with acceptable accuracy with respect to a detailed model.*

II. *If runway-level grids can be calculated using pre-calculated aircraft-level grids, the runway-level grids can be translated, rotated, interpolated, and summed to approximate an airport-level grid within acceptable accuracy and significant time savings with respect to a detailed model.*

The detailed assumptions of the proposed modeling process are described below, followed by a description of the validation test cases that will address the hypotheses and provide quantification of the sources of error.

3.1.2.1 Assumptions

Although the concept can be stated in simple terms, the creation of such a model requires certain assumptions and management of challenges that must be discussed first. For example, any operation at a given runway, at a given airport, can be characterized in an infinite number of ways with respect to ground track, heading, etc. Again, since the concept of the proposed method is to provide a rapid and simplified process, it is expected that acceptable compromises must be made with the detail normally provided by industry standard models. By making several simplifying assumptions, a manageable number of generic pre-calculated single-event noise grids can be obtained and stored for future use. These assumptions include:

1. Only two operation types will be considered: approach and departure. Approach and departure operations account for the majority of airport noise as opposed to flyover and touch-and-go operations, which are less common and related to training exercises reserved for smaller airports or emergency situations [106].

2. All operations are straight-in and straight-out, with an eastern heading, and are thus aligned with the runway axis as can be seen in Figure 3.1. This assumption can greatly affect the shape of a contour, but by capturing the airport geometry, the basic shape characteristics of the contour can be retained. The diversity in ground tracks are the major driver for computation time through detailed models, because of the repeated computation of aircraft-level noise under different geometric conditions.
3. The noise response of a single event is symmetric about the runway and ground track axes. This assumption, in conjunction with the second assumption, allow for the pre-calculation of only one half of the single-event noise grid, thereby reducing storage and computation requirements by a factor of two.
4. No terrain or environmental effects or deviations are considered beyond the defaulted 'standard day' settings used to obtain the pre-calculated events. However, the goal is to compare a baseline versus a technology scenario such that the effects on both cases would cancel, retaining the effect of the technology scenario.
5. Airport and runway elevations are assumed to be sea level.
6. All airport runway lengths are fixed at two nautical miles to ensure that all aircraft can be pre-calculated regardless of weight. This runway length is utilized in the notional single-runway airports pre-loaded in INM. In practice, any length could be selected, as long as these are consistent between aircraft-level grids.
7. Aircraft flight distance will be modeled through the discrete stage length parameter utilized in INM, which acts as a surrogate for departure weight [107].

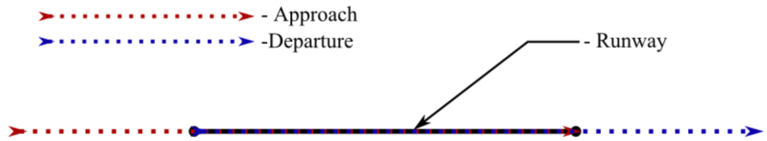


Figure 3.1: Notional single-runway airport.

These assumptions allow for the generation of a pre-calculated database of noise responses for each aircraft in the fleet, leveraging mature vehicle-level noise modeling capabilities. Each can be defended based on the nature of the fleet-level technology evaluation problem. The straight ground-track assumption is particularly critical, as it can affect the overall accuracy of the final contour shape, as can be seen in Figure 3.2.

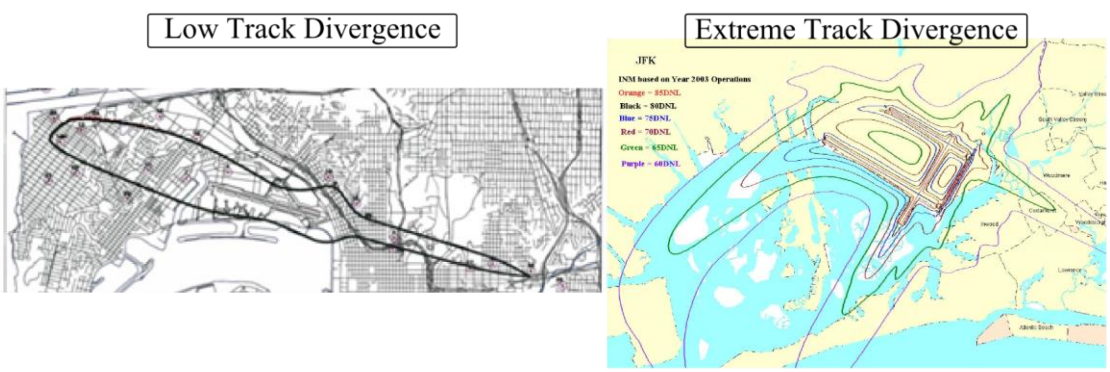


Figure 3.2: Effects of ground track divergence [108], [109].

While airport track operations can have a significant effect on airport noise contours, these ground tracks are very difficult to forecast as they are within the discretion of local airports and are heavily tailored to the surrounding communities. Furthermore, incorporation of different tracks and procedures, while an involved process, is a short-term implementation project as compared to aircraft technologies [110]. The straight ground-tracks also allow for the assumption of longitudinally symmetric noise responses, an extension of the assumption of a longitudinally symmetric aircraft, which reduces the database storage capacity and algorithm work-load by a factor of two. For the described model to include specific ground tracks, it would require each vehicle to have a pre-calculated noise grid for each possible ground track in the analysis, significantly increasing the storage and runtime required to generate an airport-level noise contour, and reducing the generality of the aircraft-level noise responses. Furthermore, the effect of the ground track is expected to be relatively minor within the boundaries of the DNL 65 dB noise contour. Nonetheless, opportunities for calibration can be explored in the future, applying spatial surrogate modeling methods to predict the effect of ground track dispersions.

Environmental factors such as weather and terrain effects are important to noise, and therefore also to the effect of noise technologies. These are, however, uncontrollable variables that cover a wide range of possibilities at a given set of airports. Therefore, the value of including them in a generic process for screening out the strongest technology packages is very limited at the early stages of the strategic decision-making process. As mentioned previously, these performance metrics can be analyzed at the aircraft-level using current methods. The effect of airport elevation, while certainly important to noise, again only serves to include detail not beneficial in the early screening process. Furthermore, analyzing the distribution of airport elevations in the United States in Figure 3.3 reveals that approximately 80% of these airports are in the range of 0-1000 feet of elevation [93].

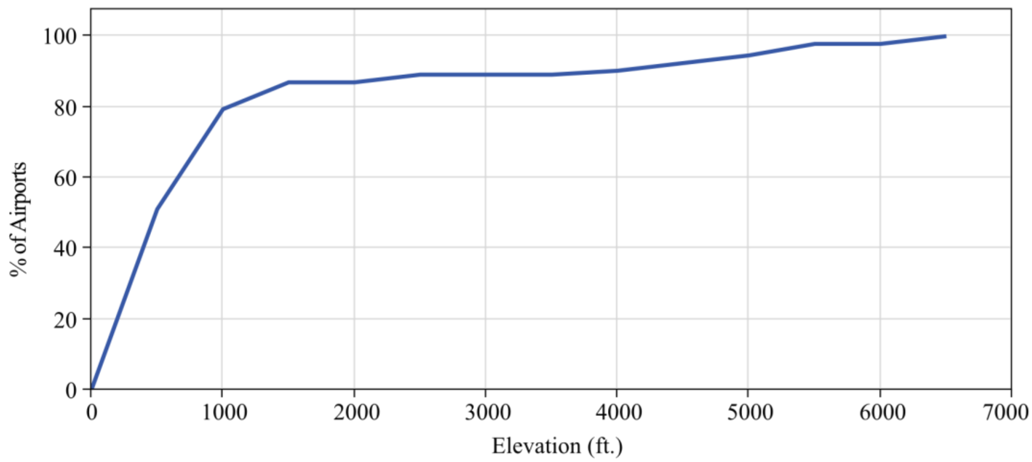


Figure 3.3: Cumulative distribution of U.S. airport elevations [93].

The average point-to-point grid error, for example, for an airport at approximately 1,000 feet of elevation is 0.43 dB DNL. While the effect will be more significant at especially high altitudes, the effect of altitude on noise propagation is relatively well understood, and can possibly be applied à-posteriori if necessary, via calibration factors. The specific steps of the process can be seen in Figure 3.4, and are explicitly outlined in Appendix A. To measure the effectiveness of this model, a verification and validation plan was devised to compare the results to those of a detailed airport noise model.

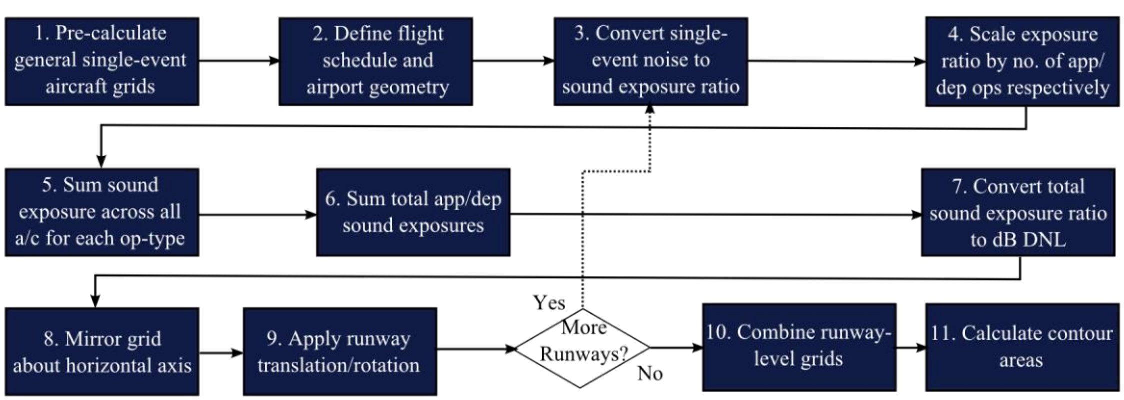


Figure 3.4: Modeling process.

3.1.3 Verification and Validation Tests

In order to test the methodology described above, and thus address the hypotheses, a validation plan must be defined. The comparisons must be done with respect to accuracy and runtime of a “gold standard” detailed model. For the purposes of this research, the detailed model of choice is INM, since it is the industry standard, is already available, and is accessible. INM has certain limitations with respect to the grid resolution that it can provide on a personal computer. In order to maximize the amount of information that can be compared, the grids used for validation will be 70 x 30 nautical miles with a horizontal spacing of 0.4294 nautical miles, and a vertical spacing of 0.0920 nautical miles. The absolute size of the grids is chosen conservatively, to ensure that plenty of comparable information is provided.

The two major assumptions that must be tested are the integration of aircraft-level grids to runway-level grids and the integration of runway-level grids to approximate airport-level grids, addressed by Hypotheses I and II respectively. In order to address these assumptions, tests will be defined that add progressive levels of complexity, finally culminating in system-level tests. Finally, the assumptions regarding fixed atmospheric variables, fixed runways lengths, and straight ground tracks can also be tested. Using the information from these results, the expected sources of error can be confirmed and some information regarding the appropriate envelope of use of the model can be defined. Accuracy will be measured via point-to-point comparison of the grids, contour area precision, and shape error for the DNL 65 dB contour.

In order to objectively determine the accuracy of the method, a review of the literature was utilized to set an appropriate benchmark. These reviews included several reports in which aircraft and airport noise values were reported, as well as the error ranges suggested in Ref. [98], which was intended for "organizations making aircraft noise contour calculations" [98]. These ranges, while provided for manifold situations, were used along with corroborating information in the literature to set the tolerance range at +/- 1.5 dB DNL [98], [101], [111], [112]. For contour area and shape tolerance, the comparison was achieved by subtracting and adding the point-to-point tolerance from all grid points of INM, and re-calculating the contours based on these adjusted grids. This method allows for the creation of tolerance bands by which area and shape can be compared. These tolerances will be used throughout the experiments defined below.

3.1.3.1 Experiment I: Aircraft-Level to Runway-Level Integration

The first hypothesis is relatively simple to test, as it only requires a single experiment (E-I). Because only the aircraft-level to runway-level aspects of the process are being compared, the airport configuration for both the simplified model and INM will be a single-runway with a length of 2 nautical miles and uni-directional traffic flow. Uni-directional flow is required because the simplified model could only capture cross-flow using two runways that occupy the same geographical space. This configuration would introduce error due to interpolation and summation of runway-level grids to airport-level grids. For this test, only a small set of aircraft will be selected, which sufficiently represent the type of aircraft currently in operation. The number of operations will be set to 1000, all day-time, using a flight schedule as listed in Table 3.3. The detailed noise model will be set to standard acoustic day conditions, such that all assumptions of the simplified model are obeyed in INM, allowing for isolated testing of the aircraft-level to runway-level integration. The point-to-point error between the simplified model and the INM grids will be tracked along with the area of the 55-70 dB DNL contours (in increments of 5 dB DNL). The shape of the contours will also be tracked qualitatively along with the imposed tolerance defined previously.

Table 3.3: Flight distribution for E-I.

Aircraft Name	INM Model	Engine Model	Approach	Departure
CRJ-900	CRJ-9ER	CF348C5	50	50
737-800	737800	CF567B	200	200
767-300	767300	2CF680	120	120
777-200ER	777200	GE90	100	100
A380	A380-841	TRENT9	30	30

The only error expected is due to numerical precision error caused by the computer transforming from a logarithmic to a linear scale. This error is expected to be minor and well within the imposed tolerances.

3.1.3.2 Experiment II: Runway-Level to Airport-Level Integration

In order to test the assumption of integrating from the runway-level to the airport-level, two test cases are required. The set of cases presented for this experiment will attempt to present the extremes of the interpolation situations that could occur in practice. The point-to-point error between the simplified model and INM grids, the contour area error of the 55-70 dB DNL contours, and the qualitative shape of the contours will be tracked for all cases in this experiment.

3.1.3.2.1 Case 1: Single Runway Configuration, Cross-Flow Traffic

The first case (E-II.1) to verify the integration of runway-level grids to airport-level grids is conducted using identical settings from the single-runway experiment detailed above. The only difference being that half of the operations are assumed to have a westward heading, while the other half maintains their eastward heading, using the operations listed in Table 3.4. The effect is such that while the airport configuration is still that of a single-runway, the generic method must model these as two runways that occupy the same geographical space.

Table 3.4: Flight distribution for E-II.1.

Aircraft Name	INM Model	Engine Model	App East	App West	Dep East	Dep West
CRJ-900	CRJ-9ER	CF348C5	25	25	25	25
737-800	737800	CF567B	100	100	100	100
767-300	767300	2CF680	60	60	60	60
777-200ER	777200	GE90	50	50	50	50
A380	A380-841	TRENT9	15	15	15	15

In this, and all subsequent cases, only the intersection of the interpolated grids will be compared with respect to INM, as the points outside the intersection cannot be used to predict noise responses. Furthermore, any perimeter points of the intersection are also discarded because they will be prone to large error due to extrapolation rather than interpolation. While these error points are well beyond the contour levels of interest, it is important to be rigorous for the purposes of reporting overall point-to-point accuracy. The main new error source expected for this experiment is due entirely to the interpolation and summation of points, which is dependent on the granularity of the aircraft noise grids.

3.1.3.2.2 Case 2: Cross-Runway Configuration, Departures Only

The second case (E-II.2) to investigate runway-level to airport-level interpolation consists of a cross-runway configuration as shown in Figure 3.5. This case uses 2000 total operations, which are all day-time departures. Two INM aircraft models are used in the schedule: a Boeing 737-800 and a Boeing 747-400.

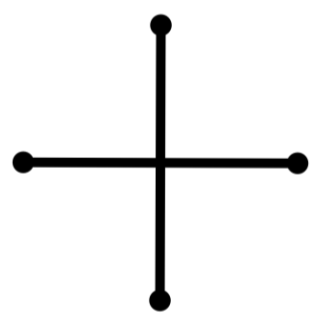


Figure 3.5: Cross-runway configuration.

Each flies 1000 operations, with the former flying in an eastern heading on the horizontal runway, while the latter flies in a southern heading on the vertical runway. This case tests a difficult interpolation of a rotated runway. The cross runway represents the most extreme rotation of a runway. Moreover, by including only operations of the departure type, the roughness of the contours near the break-release caused by ground-based directivity can be used to further stress the interpolation of the runway-level grid to an airport-level grid [95].

3.1.3.3 Experiment III: System-Level Verifications

Once the specific unit-level tests demonstrated that the model was working as intended, a set of system-level tests were devised to examine the entirety of the model functions in conjunction. This experiment presents more nuanced cases, including runway rotations, multi-runway airports, large fleets of unique aircraft, nighttime flights and un-even traffic flows in one case. The point-to-point error between the simplified model and INM grids, the contour area error of the 55-70 dB DNL contours, and the qualitative shape of the contours will be tracked for all cases in this experiment.

3.1.3.3.1 Case 1: Single Rotated Runway Configuration Cross-Flow

The first case (E-III.1) compares a single rotated runway configuration in cross-flow in INM with a similar case using the simplified modeling approach. The runway configuration is angled at approximately 346 degrees from the horizontal axis, as can be seen in Figure 3.6, and all assumptions are set to obey the assumptions of the simplified model. The INM model was provided by the FAA Office of Environment and Energy (AEE) as a pre-configured study, consisting of 153 unique aircraft flying approximately 530 operations split between approach and departure.

Figure 3.6: Single rotated-runway configuration.

Nighttime events accounted for 11% of the total operations. The traffic predominantly pursues a northwesterly heading but a minority percentage of the traffic pursues a southeasterly heading. It is important to note that these are representative scenarios of airport traffic, and not necessarily designed to model a specific day. This case introduces rotation of an entire airport runway as well as a diverse mixture of aircraft that typically fly at an airport of this type and size.

3.1.3.3.2 Case 2: Four Parallel-Runway Configuration, Cross-Flow

The final runway-level to airport-level experiment consists of a four parallel-runway airport, with cross flow traffic, as shown in Figure 3.7.

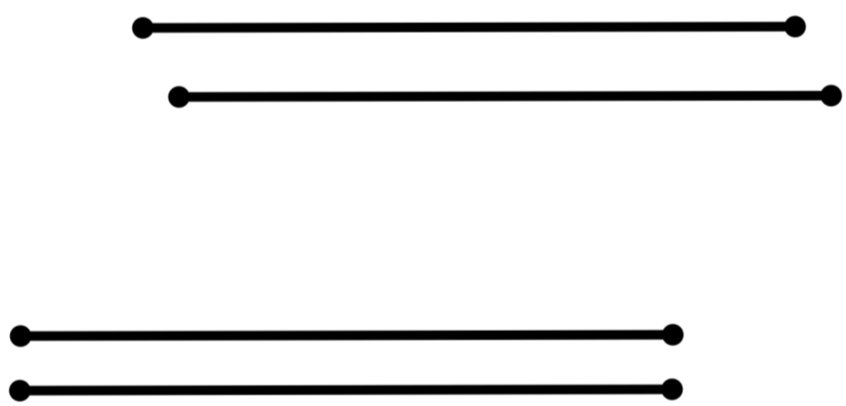


Figure 3.7: Four parallel-runway airport configuration.

This INM model was also provided by AEE, and consisted of 163 unique aircraft flying approximately 2,650 operations split between approach and departure, 9.30% of which were nighttime events. Again, the INM model is configured to conform to the assumptions of the simplified model. Due to the cross-flow configuration, the simplified model actually treats this airport as 8 runways: four in east-flow and four in west-flow occupying the same geographical space. This case introduces further aircraft variety, larger operational volume, and a relatively large number of runway-level interpolations required to produce an airport-level grid. The case is meant to represent the potential error increase created by interpolating and summing relatively large numbers of runways.

3.1.3.4 Experiment IV: Robustness to Assumption Violations

Once the simplified model has demonstrated accuracy with respect to a detailed model when the assumptions are obeyed, the limitations of the process can be measured through several cases in which the major assumptions are sequentially violated by the INM models. For this experiment, the simplified model remains identical to E-III.2, while each case compares these results to various different versions of the INM detailed model. The two major assumptions that will be assessed are the atmospheric assumptions, including the elevation of the airport, and the straight ground tracks assumptions. These assumptions are expected to account for the majority of the inaccuracies with respect to detailed models. Atmospheric assumptions affect the modeled propagation of aircraft noise, as well as aircraft/engine performance, while the ground tracks can significantly impact the consequent geometry of a contour, as demonstrated earlier in Figure 3.2. For each of the cases presented below, the four parallel-runway INM study will be utilized.

The point-to-point error between the simplified model and INM grids, the contour area error of the 55-70 dB DNL contours, and the qualitative shape of the contours will be tracked for all cases in this experiment. Since it is expected that more significant shape error will be observed due to the violation of assumptions, a method for objectively determining this error is introduced. The metric consists of a re-parameterization of the contours to a common reference frame: polar coordinates. By calculating the length of the vector (R) at a given angle (θ), a parameterization of the contours can be created that facilitates objective comparison of the resulting shapes. The comparison metric is a logical extension of the contour closure points utilized by Su to compare aircraft-level noise contours [113]. By performing these calculations at fixed intervals of θ along the angular axis, as can be seen in Figure 3.8, a common set of radial contour points is generated.

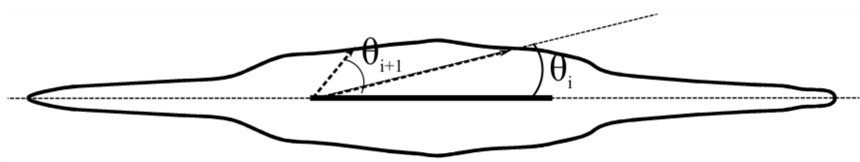


Figure 3.8: Re-parameterization of contour to polar coordinates.

3.1.3.4.1 Case 1: Atmospheric Assumptions Violated

The first case (E-IV.1) consists of violating the sea-level standard acoustic day atmospheric assumptions. The INM model is set to the nominal atmospheric settings, including an elevation of 1,026 feet. While ignoring terrain effects is an important assumption for the simplified model, the nominal INM deck did not include terrain features, and thus this assumption was not tested. Comparisons similar to the previous experiments will be provided, but with the inclusion of radial contour points.

3.1.3.4.2 Case 2: Ground Track Assumptions Violated

The next case (E-IV.2) consists of removing the straight ground-track assumption in isolation of the sea-level and atmospheric assumptions. This assumption is expected to have a significant impact on this particular case because, as can be seen in Figure 3.9, the nominal INM ground tracks for this airport are extremely divergent and varied, whereas the simplified model is represented by only straight ground tracks. The error introduced by the nominal ground tracks is expected to predominantly affect shape, and have a relatively larger impact than the atmospheric assumptions.

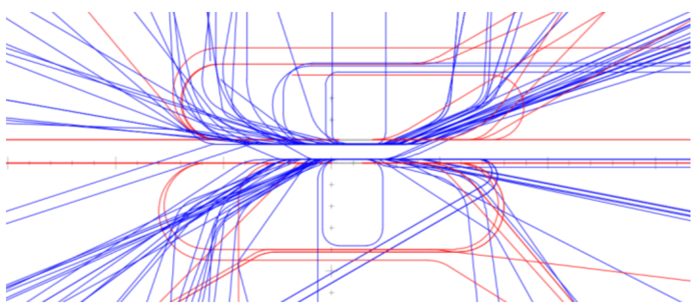


Figure 3.9: Nominal ground tracks for four parallel-runway airport.

3.1.3.4.3 Case 3: Comparison to Full Detailed Model

The final comparison (E-IV.3) is to the full detailed INM model, with all assumptions violated, to characterize the error expected when discussing an airport of this size and type. This case demonstrates the interaction of the atmospheric and ground track assumptions violated in combination, and can represent the type of error that could be expected when calculating contours with the simplified model for an airport with a relatively large operational volume and large aircraft variety. The characteristic effects of these error sources can then be assessed and discussed.

3.1.3.5 Experiment V: Process Evaluation

The final necessary assessment for a rapid noise modeling capability is to compare the speed of execution to the detailed model that it approximates. Whenever possible, the setup and runtime of both will be compared. When coupled with the accuracy assessments from the previous experiments, this information provides a type of accuracy cost for a gain in computational speed and automation.

3.1.4 Summary of Experiments

A summary of the experiment plan can be seen in Table 3.5. These experiments will determine whether the resulting generic noise model is based on the appropriate mathematical foundation regarding the summation of single-event noise.

Table 3.5: Summary of generic noise model experiments.

Exp.	Cases	Objective
E-I	1	Examine validity of aircraft-level to runway-level grid summation
E-II	2	Examine validity of runway-level to airport-level grid interpolation and summation
E-III	2	Examine system-level model accuracy under ideal conditions
E-IV	3	Examine system-level model accuracy under non-ideal conditions
E-V	1	Compare setup and runtime between simplified and detailed model

The experiments will also quantify the error due to grid interpolation and due to the assumptions made as compared to a detailed airport noise model. The resulting generic noise model allows for the modification of certain variables pertinent to airport noise, listed in Table 3.6. In the development of the remaining capability gaps, the generic noise model will be leveraged as a virtual test-bed to enable further explorations.

Table 3.6: Variables and outputs of the generic noise model.

Operations
Aircraft
Total Ops.
Aircraft Distribution
Stage Length
Day/Night Ratio
Approach Operations
Departure Operations
Infrastructure
Number of Runways
Runway End Position
Runway Rotation
Runway Utilization
Number of Runways
Outputs
Contour Points (x,y)
Contour Areas
Airport DNL Grid

3.2 Airport Categorization

Once a rapid simplified fleet-level model is developed, an effective categorization of airports can be addressed to reduce the number of model-runs required to perform a fleet-level study. Much like generic aircraft are desirous in their ability to rapidly define an entire current and future fleet rapidly and with sufficient accuracy, a representative set of airports would be equally valuable with respect to fleet-level noise. Since the airport-level, unlike for other environmental emissions metrics, is a necessary consideration for fleet-level noise, it is a source of great inefficiency that every time a technology scenario is modeled, all airports in the scope of a study must be computed. Detailed methods such as MAGENTA, designed to perform detailed fleet-level analyses, complete it by creating airport-level contours for each airport included in any given study. For MAGENTA, this includes and INM or AEDT computation of the 95 airports that account for 90% of the population exposed to significant noise [89], [90].

Reducing the number of study airports could significantly affect the runtime of a fleet-level study. Moreover, in support of a generic framework, the level of detail provided by unique airports is not particularly appropriate for the available inputs at the early stage of the decision-making process regarding technology package selection. If the generic noise model is used, then its assumptions must also be adopted. Many of these assumptions are designed to strip away the uniqueness of a specific airport. Therefore, modeling unique airports when the unique inputs are not utilized in the model is impractical. A much more efficient process could be developed if airports were grouped by similarity characteristics commensurate with the variables affected by the simplified model, eventually yielding a smaller subset of Generic Airports that would appropriately represent the fleet-level with respect to noise. If a representative set could be used to infer the behavior of the generic class, onto the specific airport, significant analysis and runtime savings can be achieved, while simultaneously matching the fidelity of the inputs and outputs to the model.

In doing so, it is important to consider the number of variables that are important to rapid fleet-level noise, perhaps discounting some of the more esoteric variables that make airports so varied and unique, especially if they cannot be captured by the generic noise model developed. Although conceptually similar grouping exercises have compiled several technical methods to achieve groupings, the process is very application specific, and no such grouping exists for the purposes of accurate fleet-level noise prediction. To formulate the problem properly, the relevant research questions are presented below:

I. *What subset of airports should be considered for grouping?*
   a. *What variables should be considered for grouping?*
   b. *What grouping strategy and techniques should be employed?*

II. *How can the groupings be verified and validated?*
   a. *What is the increase in accuracy versus assuming single-runway airports?*
   b. *How can groupings be made appropriately robust?*

The research questions will be addressed with the appropriate hypotheses and experiments, outlined below. Some of the questions may not require experiments but rather logical decisions regarding how to proceed. The approach to answer these questions will be comprised of several steps, including a selection of a grouping subset, the definition of tools and techniques for grouping, and the verification and validation activities necessary to ensure successful completion of the task.

3.2.1 Defining an Airport Subset

The first step, while seemingly trivial, will have a significant impact on the overall practicality of the groupings developed. Selecting the base collection of airports from which groups will be generated will ultimately impact the final group definitions, and will serve as the general classes to which all other system airports are matched. Therefore, they must constitute a meaningful subset that includes multiple airport sizes and types, and most importantly, must be relevant to fleet-level noise. While a number of sub-categorizations were explored in the previous chapter, the logical choice is the MAGENTA 95 [89][87], [90]. The MAGENTA 95, as mentioned earlier, are the airports that account for approximately 90% of the population affected by significant airport noise [89], [90]. Since this sub-categorization is entirely based on the magnitude of contribution to fleet-level noise of the entire system, it is clear that this collection is the most appropriate to use in developing airport classifications. By using these specific airports instead of a different or random set, the Generic Airports can be assured to reasonably predict noise at the most important set of airports with respect to noise in the United States, thereby improving the utility of the resulting model.

3.2.2 Variables for Grouping

The larger the set of factors that are utilized for groupings, the more diverse the end-state generic airports will become. Without simplifying assumptions to remove some of the unique details about airports, the ideal grouping, at one extreme, would yield one category for each airport, yielding no benefit with respect to modeling speed.

Fortunately, the resultant variables carried through in the development of the noise model can be recycled to identify a logical baseline of variables from which groupings can be generated. Again, this leaves variables of the operational and geometric type. As mentioned previously, since the simplified model was built as a prerequisite to generating Generic Airports, it also follows that Generic Airports must follow the same assumptions since both must work together in the generic fleet-level noise methodology.

Although there is some relation between operational and geometric characteristics, they must be decoupled so that meaningful patterns can be identified. Synthesizing the resultant classifications yields a useful tool for learning about a group of airports by simply examining a generic class. For example, while examining the data-types that define airports operationally and geometrically, it quickly becomes apparent that searching for patterns within both variable categories simultaneously would be inefficient and unlikely to lead to relevant results. The variable types are drastically different, and it is unlikely that the operational characteristics would group along similar lines as the geometrical characteristics. For example, while Los Angeles International Airport (LAX) and Pittsburgh International Airport (PIT) both have four runways, LAX is a major international port with many more operations than PIT. When defining characteristics do not sufficiently correlate with each other, it can lead to difficulty in producing effective groupings.

As a result, it was necessary to employ the variable categorizations established earlier to account for this issue. The approach devised consists of separating the variables by type and grouping airports separately within those types. Therefore, the operational characteristics such as operations volume, fleet mix, and flight distribution constitute a grouping that results in Generic Runway-types. Meanwhile, the geometric characteristics, such as the number of runways and runway orientation, result in Generic Infrastructure-types, hence the second hypothesis:

I. *If variable types are decoupled, groupings for each are facilitated, and the super-position of both groups can be used to predict fleet-level noise.*

The decoupling of these two variable categories is not an entirely exact proposition, but it is a very powerful strategy, because it allows the airport noise contours to be viewed from two very different perspectives. The operational characteristics influence the total noise produced by the airport, dominated by the total number of flights, the types of aircraft operating, etc. The infrastructure characteristics, on the other hand, can be considered influence how the total noise is allocated geospatially. Of course there is some interplay between the two, but for the purposes of grouping they will be assumed to independent. To reflect this decoupling, the following sections will address operational variables, ultimately resulting in Generic Runways, and infrastructure variables, ultimately resulting in Generic Infrastructures, separately, while the combinations of the two will be referred to as Generic Airports. The basic grouping strategy is summarized in Figure 3.10.

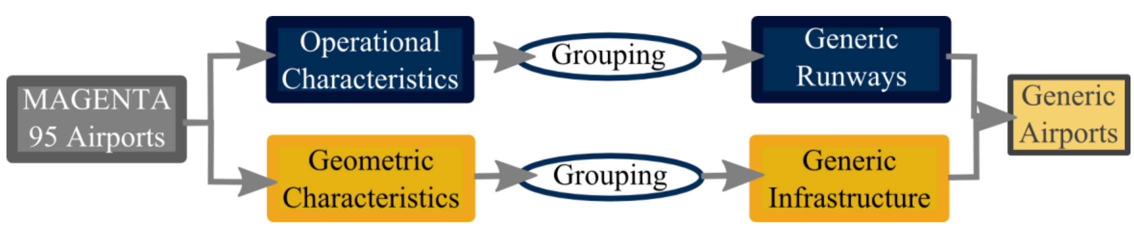


Figure 3.10: Summary of airport grouping strategy.

3.2.3 Operational Grouping

The specific approach for grouping the operational variables consists of several steps. First the appropriate data must be collected, and parsed to identify the appropriate specific variables for grouping. Then grouping techniques must be identified and implemented, yielding a baseline set of Generic Runways. These Generic Runways can then undergo a verification and validation process. Verification will include ensuring that the mathematical theory is working as intended, while validation will include robustness to aircraft variability and flight schedule variability over time. Whenever appropriate, calibrations may be applied to ensure Generic Runways properly represent the operational characteristics of the airport space. A summary of the process can be seen in Figure 3.11.

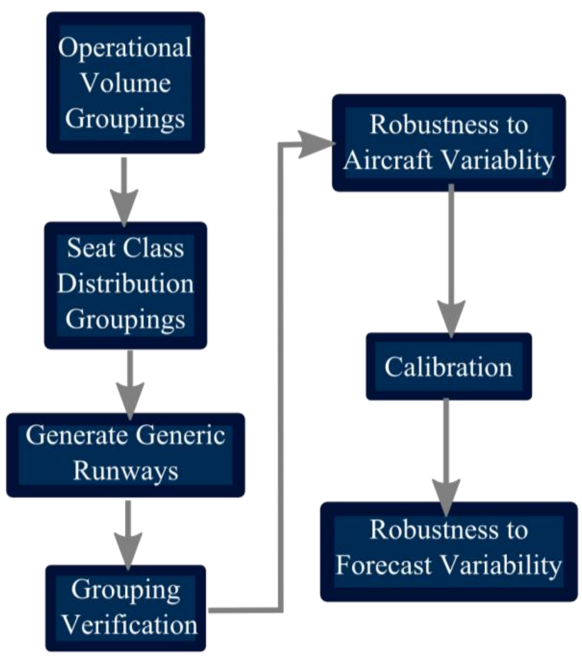


Figure 3.11: Steps of Generic Runway development process.

The overall hypothesis for Generic Runways is as follows:

II. *If the operational airport space can be segmented and clustered, yielding average Generic Runways, and representative aircraft used for the Generic Runways are reasonably average representations of the true fleet, then Generic Runways will be able to accurately predict the fleet-level area due to operational effects only, and will be able to maintain similar accuracy as the flight schedule varies over time.*

3.2.3.1 Data Selection and Collection

In order to perform effective groupings, a useful set of operational data must be collected for all 95 of the MAGENTA airports. There are a number of open data sources available, such as the FAA's Traffic Flow Management System Counts dataset, which includes historical data of operations including equipment type, and other useful information [84]. Another option would be to pull the historical data in real-time from websites that track flight data [114]. A third option is to use a datum set of operations provided by the Volpe National Transportation Systems Center, implemented in the Global Regional Environmental Aviation (GREAT) tool [79], [82], [115]. This baseline schedule of operations defines the operations by origin and destination pair, the aircraft operating the route, the distance of the route, the total number of times per year the operations occur, as well as providing a long term fleet-level operations forecasting capability, which can incorporate official forecasts such as the TAF or a user defined forecast. Since the resulting fleet-level noise methodology will ultimately be paired with GREAT, the capabilities within GREAT should be leveraged to develop Generic Runways [58]. Other datasets could also potentially be utilized, but the 2006 datum operations in GREAT provide the most efficient meshing with the generic framework for fleet-level environmental assessments. Aircraft operations for the datum year in GREAT are categorized by families, developed by Isley, which are derived from similarities within seat classes, listed in Table 3.7 [86]. These categorizations reduce the number of unique records that GREAT must output to produce a forecasted flight schedule.

Table 3.7: Seat class definitions [86].

Seat Class	Pax Range
1	1-19
2	20-50
3	51-99
4	100-150
5	151-210
6	211-300
7	301-400
8	401-500
9	501-600
10	601+

3.2.3.2 Grouping Variables

The purely operational variables can include a number of factors such as the total number of flights, the types of aircraft flying at a given airport, the distribution of the flights across those aircraft, the percentage of approaches and departures, and the percentage of nighttime flights. While approach and departure operations are quite different from a noise perspective, this research will assume that the airport behaves as a control volume in steady-state, where each approach is approximately accounted for by a departure operation. All flights will be considered in daytime, since the datum operations do not specify a time of day. Another variable of potential importance is the stage length distributions of different aircraft at different airports. For example, a regional hub may fly significantly different stage lengths than an international port. Including this variable, however, would introduce a level of complication that could hamper the ability make effective operational groups. For this research, the stage length distributions will not be used for grouping, but will still need to be modeled via an averaging of the constituent airports of each Generic Runway. Therefore, the majority of the variability in the noise response between airport operational characteristics is assumed to be accounted for by the total number of operations and the mix of aircraft that perform the operations. The validity of this assumption will be determined based on the results of validation experiments.

3.2.3.3 Grouping Techniques

While grouping could be performed on the operational volume and aircraft distribution together, it is useful to further separate these characteristics. For example, while two airports may have similar aircraft distributions by percentage, the number of operations could differ by an order of magnitude, which would negatively impact the ability, from a mathematical standpoint, to provide a representative set of operational characteristics. Therefore, the 95 airports must first be grouped by the total number of operations, which can then be followed by a more targeted grouping by aircraft-type distribution.

Another obvious issue is the definition of aircraft types. Analyzing the distribution of flights with respect to specific aircraft flying at a given airport would be infeasible, as there are 452 unique aircraft in the entire set of operations for the

MAGENTA 95 airports in the datum year operations contained in GREAT, even when the aircraft-family groupings developed by Isley are applied [86]. Fortunately, the seat class designations listed in Table 3.7 can be utilized to simplify the aircraft distribution by grouping unique aircraft into seat class types. The consequent assumption is that all vehicles in a certain seat class are reasonably similar. Furthermore it is necessary to assume that each seat class can be reasonably represented by a single vehicle, and that only one vehicle per seat class is necessary to create significant groupings. The operational dataset contains vehicles ranging from seat class 2 to seat class 9. Other aircraft characterizations could be employed to a similar effect, but since the operational data selected is already provided in this format, it is the logical choice for this research. Ultimately, the Generic Vehicles pioneered by Becker, will be utilized to represent the fleet, and groupings based on representative sets is a decision that ultimately supports and can interface with this generic framework [9].

3.2.3.3.1 Statistical Clustering Techniques

In order to generate the airport volume groups and the subsequent aircraft distribution groupings, several statistical clustering techniques were reviewed. The decision to use statistical clustering was based on the fact that the operational data is quantitative and continuous, and therefore it can be difficult to qualitatively or visually assess groupings without certain bias. Since statistical clustering provides an automated, repeatable, and quantitative mode of analysis, this is the most appropriate grouping process to employ. Statistical clustering also contains a large number of options, however, and from these the K-means approach was selected. K-means is "a prototype-based, partitional clustering technique that attempts to find a user-specified number of clusters represented by their centroids." [116] The basic algorithm is known as the Expectation Maximization (EM) algorithm, and defines a prototype in terms of a centroid and subsequently iterates until the prototypes it has placed in the data properly represent the centroids within a certain tolerance, as represented in Figure 3.12 [116]. The only user input required is to define the number of desired clusters.

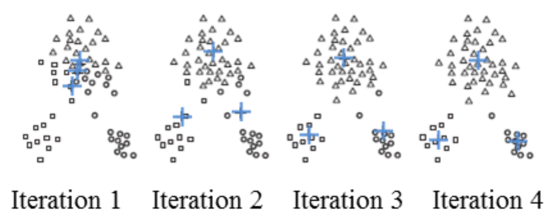


Figure 3.12: K-means centroid convergence [116].

While there is still some subjectivity involved in selecting the total number of groups, the clustering algorithms are repeatable and offer plenty of options which can be compared and contrasted in future work. The only user input required is to define the number of desired clusters. Statistical clustering can also, if needed, include variables of different types, which again may benefit Generic Runway development in the future. These specific trades are outside the scope of this research.

3.2.3.4 Generic Runway Creation

While the groupings provide the technical information regarding which airports can be classified together, it is still ultimately up to the engineer to define the creation of a Generic Runway. For the purposes of this research, and in the context of the tools intended for use, a Generic Runway will be defined by the operational inputs required for the generic noise model developed previously. This includes the representative aircraft that will fly operations, and the amount of flights for each aircraft, generated by applying a flight distribution to the volume of the runway. The representative aircraft will initially consist of the average aircraft within each seat class. In the long term, however, it is important to recall that the development of Generic Vehicles, which will significantly reduce the runtime required for fleet-level noise analysis, will be utilized in lieu of the representative vehicles [9]. The volume will be determined by using the average operational volume of airports in a given group. The distributions will similarly be determined by averaging the percentages by seat class of all airports in the group. While these values are determined mathematically, they may require calibration at some point. Nonetheless, it is important to verify the results *prior* to calibration because if significant bias error is present, any adjustment could over-calibrate, while breaking the mathematical foundation upon which the Generic Runways are built. The split of operations will assume a steady-state control volume model of an airport, therefore having an equal number of approach and departure operations. This assumption suggests that there is approximately one flight departing an airport for each flight arriving; an assumption more or less borne out in the historical data provided in GREAT [117]. Finally, the flights must also be assigned stage length values, and these will be defined by the average stage length distribution of flights for a given seat class across all available stage lengths for all airports associated with a given Generic Runway.

3.2.3.5 Generic Runway Verification and Validation

Once the Generic Runways are defined in a manner that they can be used to compute noise through the generic noise model, it will be necessary to examine their ability to predict the in-group and total fleet-level noise of the actual MAGENTA 95 schedules under various conditions. These tests include verification, where only the representative aircraft are used for both Generic Runway and MAGENTA 95 flight schedules, an assessment of the bias error due to the use representative aircraft, and finally a robustness assessment of Generic Runways as flight schedules evolve over time.

3.2.3.5.1 Experiment I: Baseline Verification

The first test (E-I) of the Generic Runways will be to verify that the mathematical formulation applied behaves as intended, and that no other phenomena are confounding the results. This test will be accomplished by running the baseline Generic Runways through the generic noise model developed above for a single-runway, cross-flow airport configuration, thus removing any geometric bias caused by the different nature of approach and departure contours. All flights for a given seat class in the actual MAGENTA 95 flight schedules will also be flown by the chosen representative aircraft, to remove any bias error caused by using a representative aircraft as a proxy for each seat class group. This configuration of the experiment allows for the isolation of the error due to the assumption that the total operations and aircraft distributions are the primary drivers of the noise response. The actual and predicted total DNL 65 dB contour areas will be collected for the 95 airports as well as for each Generic Runway. The specific

Generic Runway errors will also be analyzed. A summary of the experimental configuration of the generic noise model is demonstrated in Table 3.8.

Table 3.8: E-I experimental configuration.

Operations	MAGENTA 95	Generic Runways
Aircraft	Representative Aircraft	Representative Aircraft
Total Ops.	MAGENTA 95 Datum	Generic Runways
Aircraft Distribution	MAGENTA 95 Datum	Generic Runways
Stage Length	MAGENTA 95 Datum	Generic Runways
Day/Night Ratio	1:0	1:0
Approach Operations	MAGENTA 95 Datum	50%
Departure Operations	MAGENTA 95 Datum	50%
Infrastructure	**Fixed**	
Number of Runways	1	
Runway End Position	Origin	
Runway Rotation	0 degrees	
Runway Utilization	N/A	
Number of Runways	Cross-flow	
Outputs		
Contour Areas	DNL 65 dB	

3.2.3.5.2 Experiment II: Robustness to Aircraft Variability

The second experiment (E-II) will test the ability of the developed Generic Runways to predict the overall DNL 65 dB contour area of the MAGENTA 95 airports with operations flown by the 452 unique aircraft/engine combinations contained the datum schedule, while Generic Runways will continue to utilize the representative aircraft. It is important to assess the bias error due to the use of representative aircraft as opposed to Generic Vehicles, so that calibrations can be performed. A summary of the experimental configuration is provided in . Specifically, the experiment will track the total DNL 65 dB contour area of the 95 MAGENTA airports versus the prediction provided by the Generic Runways, as well as the prediction accuracy of each Generic Runway with respect to its constituents. Any necessary calibrations will then be performed by adjusting the total operations at each Generic Runway.

Table 3.9: E-II experimental configuration.

Operations	MAGENTA 95	Generic Runways
Aircraft	MAGENTA 95 Datum	Representative Aircraft
Total Ops.	MAGENTA 95 Datum	Generic Runways
Aircraft Distribution	MAGENTA 95 Datum	Generic Runways
Stage Length	MAGENTA 95 Datum	Generic Runways
Day/Night Ratio	1:0	1:0
Approach Operations	MAGENTA 95 Datum	50%
Departure Operations	MAGENTA 95 Datum	50%
Infrastructure	**Fixed**	
Number of Runways	1	
Runway End Position	Origin	
Runway Rotation	0 degrees	
Runway Utilization	N/A	
Number of Runways	Cross-flow	
Outputs		
Contour Areas	DNL 65 dB	

3.2.3.5.3 Experiment III: Robustness to Forecast Variability

The final robustness assessment (E-III) for Generic Runways will examine the variability that can occur with respect to a changing forecast. While a forecast may predict certain rises in demand today, there can be no guarantee that the details of this forecast will continue to be the same, or even that the trends could not shift dramatically in terms of volume and the type of aircraft fulfilling that demand. Moreover, different entities employ different forecasting techniques and can often disagree on the methods and results of each. Therefore, it is critical that Generic Runways are capable of performing the same function independently of the forecast applied to the datum operations. This potential variation in forecast was exemplified earlier with the comparison of the Boeing and Airbus differences of forecasted demand.

In order to test this via experiment, again some setup and assumptions are necessary. First, to simplify matters, it is necessary to assume that the forecast can be made to change by varying seat class distributions. This maintains a certain generality, rather than favoring specific aircraft by manufacturer or type, which are not of interest to this specific problem. By using seat classes to simulate several future forecast scenarios, different forecasts that favor different strategies to service the flight demand can be analyzed. Another assumption is that no aircraft will be retired or introduced into the fleet. The purpose of the experiment is to assess the ability of the Generic Runways to retain their baseline accuracy with respect to changes in total demand and seat class distribution in the positive or negative direction. Finally, it must be assumed that the overall change in flight distributions is applied uniformly across all airports in the system. While it is unlikely that all airports would modify their functions in the exact same way due to size or geographical restrictions, this behavior is somewhat captured by the baseline operations at each airport. For example, airports of small size do not often have operations of large seat class aircraft. Therefore, no matter how the number of flights for a high seat class changes, those airports that currently do not accommodate these types of aircraft will not deviate from that behavior. In this way the forecast does not actually change at the same pace at all airports, although changes by seat class are applied uniformly across all airports in the study. Nonetheless, it must still be assumed that the airports that were originally grouped together in the baseline will, more or less, follow the same developmental path over time.

While a completely random variation of the demand and overall seat-class distribution forecast would provide a satisfactory evaluation of the robustness of Generic Runways, it would be a mistake to ignore the baseline data already provided. Since this data is historical, it should be preserved for context, serving as a seed point for the future flight schedules analyzed. Therefore, this research will follow the process outlined by Becker of utilizing composite beta distributions to generate scaling factors that can be applied to the baseline information [9]. This approach allows the baseline to retain a certain influence over the possible future forecasts. These composite distributions are generated by creating a 100 case Latin Hypercube (LHC) Design of Experiments (DOE) of four sets of the beta distribution parameters: α and β. The LHC design is selected because of its relative simplicity and ability capture the interior of an exploration space. In this case, the design space is the range of possible forecast deviations, and a well-represented mixture would require good capture of the interior of the space. By allowing α and β parameters to vary from 1-30, a wide variety of possible composite distribution shapes can be generated [78]. Only 100 cases will be evaluated due to the dimensionality of the problem. Each case must be applied to all 95 MAGENTA airports and to the Generic Runways. As a result, 100 cases require on the order of 10,000 airport-level executions of the generic noise model. On the other hand, this is a useful example that demonstrates the importance of developing the rapid noise modeling capability prior to performing these grouping tasks. Four beta distributions will be summed to provide sufficient articulation in the composite beta distribution to model all eight seat classes. Once the DOE is generated, the four beta distributions will be computed, summed together, and evaluated at evenly-spaced discrete points in the space. Each discrete evaluation represents a seat class. The magnitude of the composite distribution will be scaled to range between 0.5 and 2, yielding a possible maximum of double the baseline operations, and a possible minimum of half the total baseline operations. An example composite beta distribution and its impact to an existing seat class distribution can be seen in Figure 3.13.

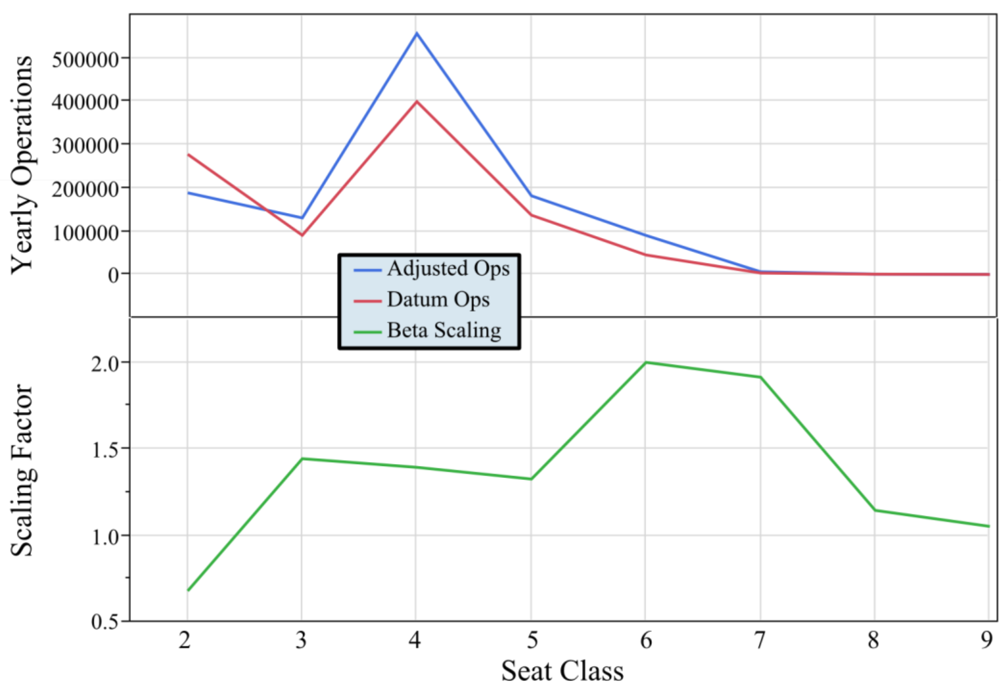


Figure 3.13: Three sample composite beta distributions.

As can be seen from the example, the context of the baseline distribution is retained, even when the composite distribution is skewed towards other seat classes. These scaling factors will be applied to the datum operations of the MAGENTA 95 and executed through the generic noise model. The Generic Runways will then be parametrically varied using the same composite beta distribution scaling factors for each seat class. In this fashion, the baseline information will be preserved, but the Generic Runways can evolve with the overall changing landscape of the forecast. The experimental configuration of the model is summarized in Table 3.10.

Table 3.10: E-III experimental configuration.

Operations	MAGENTA 95	Generic Runways
Aircraft	MAGENTA 95 Datum	Representative Aircraft
Total Ops.	Datum, Composite Beta	Generic Runways, Composite Beta
Aircraft Distribution	Datum, Composite Beta	Generic Runways, Composite Beta
Stage Length	MAGENTA 95 Datum	Generic Runways
Day/Night Ratio	1:0	1:0
Approach Operations	MAGENTA 95 Datum	50%
Departure Operations	MAGENTA 95 Datum	50%
Infrastructure	**Fixed**	
Number of Runways	1	
Runway End Position	Origin	
Runway Rotation	0 degrees	
Runway Utilization	N/A	
Number of Runways	Cross-flow	
Outputs		
Contour Areas	DNL 65 dB	

The experiment will track, for each case, the total DNL 65 dB contour area as well as the scaled prediction of the adjusted Generic Runways. Again, the accuracy within each Generic Runway group will also be evaluated. Some of the error can be quantified by examining the correlation between overall error and the changes in seat class volume. If correlation is observed due to changes in operations by specific seat classes, this would suggest a shortcoming of the representative aircraft chosen, which would ultimately be idealized by the Generic Vehicles. Success of these experiments will determine if the developed Generic Runways can reasonably encapsulate the diverse operational characteristics of the MAGENTA 95 airports.

3.2.4 Geometric Grouping

The overall process for grouping airports by geometric characteristics consists of first collecting and synthesizing the appropriate data, observing the dataset for patterns, and defining several Generic Infrastructures that capture the majority of the airports examined. These Generic Infrastructures can then undergo verification and validation exercises, including a baseline comparison to the actual MAGENTA 95 airport geometries, a configuration exploration to uncover the relationship between the geometric variables and area, and finally a calibration and final comparison of the Generic Infrastructures to MAGENTA 95 airport geometries.

3.2.4.1 Data Selection and Collection

While the operational variable data is largely based in operation counts by aircraft type, the geometric variables require a completely different set of data. These variables pertain strictly to the airports, and are not usefully collected in any one place. Therefore, the raw geometric data has to be gathered and organized manually. The relevant geometric data includes the runway layouts for each airport and a representative contour for each airport. From this information, several other characteristics can be inferred, but these are the fundamental geometric characteristics that must be collected for each airport. Airport layouts can be obtained from open sources such as AirNav [118]. Noise contours can be found through published noise exposure maps from Part 150 and other studies from publicly available data [54]. In many cases, however, these contours are not easy to find, and the runway layouts can sometimes differ from how airports are operated. Another option was to obtain the DNL 65 dB contours for the MAGENTA 95 from the 2009 noise inventory from the FAA Office of Environment and Energy (AEE) [119]. This information provides more specific information as to the runways utilized for noise assessment and the resulting noise contours from each airport. The main benefit of using this dataset is that each contour is from the same timeframe, whereas open source data can provide contours intended for a range of up to two decades from one airport to another. This dataset also provides more explicit runway utilization data, which can be useful when performing groupings.

3.2.4.2 Grouping Variables

Once all the geometric data is collected, it can be manually organized and distilled in matrix format, to provide facilitate further observation. First, the number of actual runways will be tracked, as well as the basic shape of the contour. Each airport will also be defined as operating in uni-directional flow, cross-flow, or semi-cross-flow.

Although a number of characteristics will be tracked to describe the airports, the geometric characteristics that will be considered for grouping consist of the number of runways, the orientation of the runways, and the resulting noise contour. The other variables, while potentially useful, cannot currently be incorporated due to the lack of an objective shape-grouping. Fortunately, since the sample set consists of 95 airports, qualitative grouping is feasible.

3.2.4.3 Grouping Techniques

Airport categorization based solely on the runway layout or the resultant noise contour would provide an incomplete set of information. In many cases the actual runway layout will not map directly to how an airport is operated, or how the resulting noise contour appears. Some airports do not operate on all runways, and often runways can be restricted to general aviation use, specific time-of-day flights, or completely closed to all traffic. Similarly, some runways are so close to each other that they do not produce separate definable contours, behaving as one runway with respect to the contour geometry. Conversely, the contours alone cannot be utilized because some runway information is required to define infrastructures to provide the generic noise model. This situation leads to the introduction of a third representative geometry defined by a set of "effective runways".

Effective runways refer to the runway layout modified by the appearance of the resulting contour, re-structuring the original layout to represent, in a reduced form, a layout that would produce such a contour. A common example is two parallel runways such as those shown in Figure 3.14 [120], [121]. The resulting contour shape will be used to influence how the actual configuration can be simplified into more basic parts. By reducing the runway layouts, the variety of airport geometries can be reduced to a few simple sets, which can be observed and classified via the number and orientation of the effective runways.

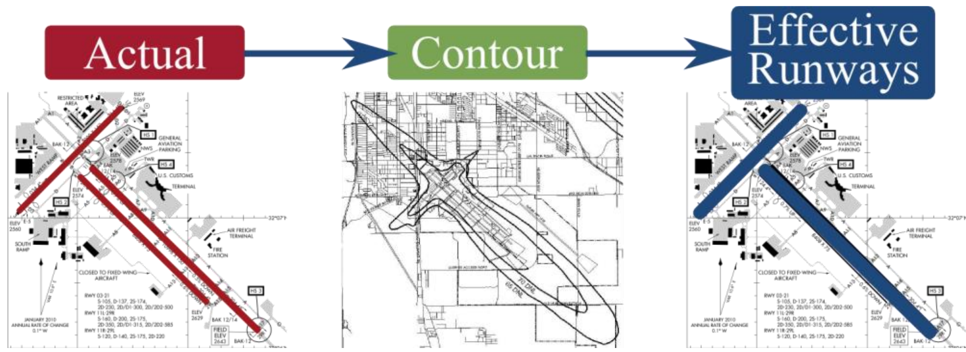


Figure 3.14: Effective runways reduce geometric space (Adapted from [120], [121]).

The operative hypothesis follows:

III. *If runway layouts can be reduced to effective runway layouts using resultant contour information, the qualitative categorization of these layouts will yield an accurate representative average of the geometric diversity present of the MAGENTA 95.*

The goal of Generic Infrastructures is to capture the interplay of the multi-runway airport configurations and their effect on the overall trends of such a contour. Therefore, it is not imperative that a Generic Infrastructure precisely represents each possible airport geometry, but rather that the emergent trends in the general class of airport contour geometries are captured.

3.2.4.4 Generic Infrastructure Creation

The first set of Generic Infrastructures will be determined via observation of the existing geometric structures. Utilizing common infrastructure layouts observed within each category, geometric baselines will be derived. Since groupings will be qualitative, the designer can only guess at first what a representative geometry should look like for each category, although this deficiency will be addressed later. Nonetheless, whenever possible, federal guidelines defining minimum separations or staggers between runways will be implemented to provide a realistic representation of a group [122]. Generic Infrastructures are defined as runway configuration inputs for the generic noise model including the number of runways, the flow of traffic, the location of these runways relative to an arbitrary reference runway, and also the rotations of a given runway relative to the horizontal axis.

3.2.4.5 Generic Infrastructure Verification and Validation

In order to verify and validate Generic Infrastructure groupings, a set of experiments must be devised. These experiments are designed to test and improve the qualitatively defined Generic Infrastructures.

3.2.4.5.1 Experiment IV: Baseline Verification

This experiment (E-IV) will be designed to verify the baseline accuracy of the Generic Infrastructures in predicting the MAGENTA 95 DNL 65 dB contour areas by category and in total. Because Generic Infrastructures were created through qualitative observation, under the advisement of applicable federal guidelines, some error is expected. Yet, the Generic Infrastructures should demonstrate a significant prediction improvement over considering all geometries as single-runway airports as all previously existing simplified noise methods assume, as discussed in Chapter 2. To properly assess this capability, any bias due to operational differences between airports must be removed. Similar to the way geometric effects will be completely excised from the Generic Runways analysis, the operational effects must be removed through appropriate configuration of the generic noise model. Therefore, a fixed operational schedule will be used for all MAGENTA 95 airports as well as all Generic Infrastructures. A summary of the experimental configuration of the generic noise model is provided in Table 3.11.

Table 3.11: E-IV experimental configuration.

Operations	Fixed	
Aircraft	Representative Aircraft	
Total Ops.	1215	
Aircraft Distribution	Datum Average	
Stage Length	Datum Average	
Day/Night Ratio	1:0	
Approach Operations	50%	
Departure Operations	50%	
Infrastructure	**MAGENTA 95**	**Generic Infrastructures**
Number of Runways	INM Definition	Baseline Generic Infrastructures
Runway End Position	INM Definition	Baseline Generic Infrastructures
Runway Rotation	INM Definition	Baseline Generic Infrastructures
Runway Utilization	Uniform	Uniform
Number of Runways	Cross-flow	Cross-flow
Outputs		
Contour Areas	DNL 65 dB	

Finally, it will be assumed that all runways must be 2 nautical miles in length, in accordance to the generic noise model assumption. The total DNL 65 dB contour area for all 95 MAGENTA airports will be compared to the total scaled area produced by the Generic Infrastructures. Similar to the Generic Runway validations, the Generic Infrastructure groups will also be tracked independently and analyzed for deficiencies, determining the direction in which calibration may be applied.

3.2.4.5.2 Experiment V: Configuration Exploration

Once a direction for calibration is determined for the Generic Infrastructures, a configuration exploration can be performed that simultaneously provides the appropriate mode of calibration. While operations can vary greatly, the infrastructures of airports change with much less frequency and, while they may evolve over time, are unlikely to produce geometries much different than those already observed today. Capacity-related expansions are limited to additions of parallel runways [122]. The robustness of the Generic Infrastructures instead must test for the ability of the generated set to represent, on average, the diversity that could potentially exist in the current and future set of airport infrastructures. Furthermore, the configuration explorations must serve as a confirmation that no other significant geometries are contained as subcategories within the observed Generic Infrastructures, at least with respect to the contour area metric. These assessments will be performed only on the Generic Infrastructures that introduce novel runway interactions.

The experiments will involve using LHC DOE's to vary the relevant geometric parameters of a given runway, while keeping the first runway as a fixed reference runway. This configuration allows the number of cases to be reduced and the comparison of results to be made simpler. The DOE will consist of 128 cases, in order to provide sufficiently articulated spacing between the ranges of each geometric variable. The geometric factors will vary between the different generic classes, and thus the variables and their ranges will be specific to each generic class yielding several experiment blocks.

Of the observed categorizations, the particularly interesting ones are the Parallel, Intersecting, Parallel-Intersecting, and Triple Intersecting categories. The Parallel configuration will be demonstrated as an example below, reserving other geometric variable settings for Appendix B.

3.2.4.5.2.1 Parallel Configuration

The Parallel configuration is characterized by airports with varying runway separations and runway offsets. Therefore, assuming the first runway is spatially fixed, as shown in Figure 3.15, the only variables of consequence are the stagger (X_2) of the second runway, and the separation (Y_2) of the second runway from the reference runway.

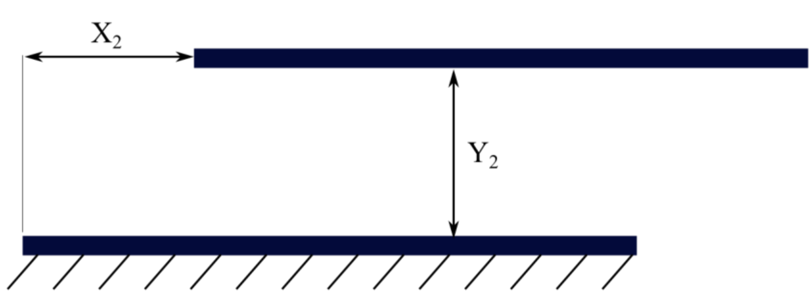


Figure 3.15: Parallel airport geometry.

These variables can be examined by manipulating the Cartesian position of the left-end of the second runway through a DOE of two geometric variables. Ranges for the variables are determined from the observed airports, and specific documents regarding runway separation and offset regulations. The ranges for stagger and separation of the parallel runway are listed in Table 3.12, along with the baseline configuration.

Table 3.12: Variable ranges for Parallel configuration exploration.

	X_2	Y_2
Range	-1.25 – 1.25	0 – 1.6
Baseline	0	0.8

3.2.4.5.2.2 Operational Settings

While geometry is the main factor of interest in these experiments, the geometries are undeniably affected by the operational characteristics applied to the airport. Consistent with classical DOE procedure, however, the operational characteristics are best typified as random variables, to which the infrastructures must be made robust [102]. In order to account for the importance of this effect, a two variable Central Composite Design (CCD) of operational volume and aircraft mix will be augmented to the LHC design, resulting in 9 replicates of each LHC case. The purpose of this augmentation is to capture the basic effect of operations, to ensure that no important behaviors are overlooked as a result of the interaction with operations. As mentioned earlier, while the decoupling of operational and geometric characteristics is necessary to effectively group airports, the two are not entirely independent, and thus significant interactions may occur. Nonetheless, it is expected that the effect of operational characteristics will only serve to exaggerate the effect of the geometrical design variables, which can then be used as a worst-case evaluator of the geometries.

The operational characteristics will consist of operational volumes of 250, 1250, and 2250, and large, medium, and small-skewed aircraft flight distributions, as shown in Figure 3.16.

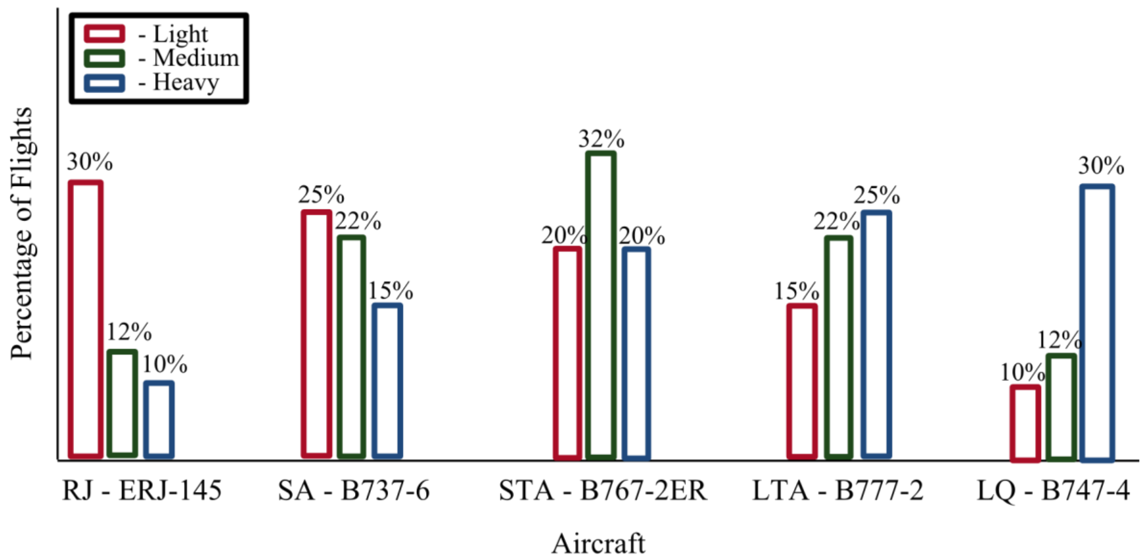


Figure 3.16: Aircraft distributions.

The aircraft were chosen as reasonable representations of the Generic Vehicle classes developed by Becker, to properly cover the range of relevant fleet aircraft [9]. These will include the ERJ145, the B737-6, the B767-2ER, the B777-2, and the B747-4. Since the representative seat class vehicles will not necessarily be defined in the same time frame, this categorization will be utilized instead. The experimental configuration of the generic noise model is summarized in Table 3.13.

Table 3.13: E-V experimental configuration.

Operations	**Fixed**
Aircraft	Representative Aircraft
Total Ops.	3-Level Discrete: 250, 1250, 2250
Aircraft Distribution	3-Level Discrete: Light, Medium, Heavy
Stage Length	Uniform
Day/Night Ratio	1:0
Approach Operations	50%
Departure Operations	50%
Infrastructure	**Varying**
Number of Runways	1-3
Runway End Position	Range Dependent on Geometry
Runway Rotation	Range Dependent on Geometry
Runway Utilization	Uniform
Number of Runways	Cross-flow
Outputs	
Contour Areas	DNL 65 dB

3.2.4.5.2.3 Evaluation of Results

The experiment will track the relationship between the DNL 65 dB contour areas to changes in the geometric characteristics in the context of operational characteristics and examine the results for evidence that the configuration is sufficiently homogeneous. Sub-categories will be identified by a multimodal response of contour area with respect to one or more geometric variables. If a sub-category emerges, the possibility of including this category in the generic classes will be discussed.

3.2.4.5.3 Experiment VI: Generic Infrastructure Calibration and Final Validation

The final assessment of the Generic Infrastructures will be completed after the information gathered from the previous experiments is used to calibrate the baselines. Once calibrated, the ability of the Generic Infrastructures to predict the total fleet-level contour area will be re-evaluated.

The baseline validations can be used to assess the direction required for calibration, while the relationships uncovered by the robustness assessments will provide the proper mode of calibration. The experimental configuration is summarized in Table 3.14.

Table 3.14: E-VI experimental configuration.

Operations	Fixed	
Aircraft	Representative Aircraft	
Total Ops.	1215	
Aircraft Distribution	Datum Average	
Stage Length	Datum Average	
Day/Night Ratio	1:0	
Approach Operations	50%	
Departure Operations	50%	
Infrastructure	**MAGENTA 95**	**Generic Infrastructures**
Number of Runways	INM Definition	Calibrated Generic Infrastructures
Runway End Position	INM Definition	Calibrated Generic Infrastructures
Runway Rotation	INM Definition	Calibrated Generic Infrastructures
Runway Utilization	Uniform	Uniform
Number of Runways	Cross-flow	Cross-flow
Outputs		
Contour Areas	DNL 65 dB	

While Generic Infrastructures could be tuned mathematically using an optimization algorithm to better match the average geometry, it would only provide a Generic Infrastructure tuned with respect to area. In reality, the mean Generic Infrastructure for a given category exists on a Pareto-surface that consists of area *and* shape, which may be described a number of ways. Without this information, however, tuning to area specifically would not necessarily provide a true mean configuration. While this shortcoming is beyond the scope of this thesis, the development of shape metrics that can enable shape optimization in future work will be addressed when the third capability gap is discussed.

3.2.5 Generic Airports

Once Generic Runways and Generic Infrastructures have been developed in parallel, Generic Airports can be generated via a classical Venn diagram combination, linking an operational set to a representative geometry, as can be seen in Figure 3.17. Therefore, one unique Generic Airport will be constituted by a flight schedule input, and a runway configuration input to the generic noise model. While Generic Airports may have similar runway configurations or operations, none will share both simultaneously. Naturally, this will cause the dimensionality of the airports to increase beyond the number of groups identified via operational and geometric classification. Therefore, it is extremely important to bear in mind the ultimate number of Generic Airports to maintain a reasonably low total as compared to the sample set. Considering that other airports, not included in the MAGENTA 95, could become relevant to noise, it is desirable to generate approximately a ¼ - ⅓ of the total MAGENTA 95 airports or fewer to serve as Generic

Airports, thereby dramatically increasing the rapidity by which fleet-level noise can be computed.

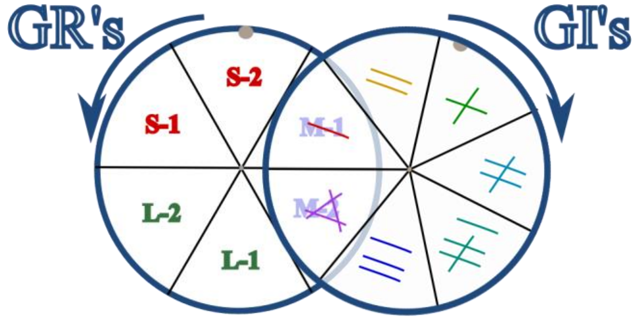


Figure 3.17: Combination of generic components yields Generic Airports.

Finally, it is important to remember that Generic Airports and generic noise methods are not meant to replace more detailed, higher fidelity analysis tools. There is no way that Generic Airports could completely represent every airport situation accurately. These Generic Airports will be intended specifically for use with the generic noise model as part of a larger generic fleet-level noise methodology. While they can be utilized with other models, these may benefit from more or less fidelity in the respective groupings. The true value of these Generic Airports will be in the ability to view operational and geometric trends in a reduced representative set, which can then be inferred onto the unique specific operational and geometric characteristics that form actual airports. In order to determine if the work of grouping airports by de-coupling operational and geometric characteristics is successful, Generic Airports as a whole must be compared to the MAGENTA 95.

3.2.5.1 Experiment VII: Generic Airports Validation

This final assessment of Generic Airports consists of going through the process of calculating each individual Generic Airport, as well as each individual MAGENTA 95 airport using the actual operations and infrastructures, thereby testing the value of the original decision to de-couple the two characteristics. The experimental configuration of the generic noise model is summarized in Table 3.15. Finally, discussions and recommendations regarding the use of Generic Airports will be provided, including a quantification of the time savings, potential improvements, and future developments that could be pursued.

Table 3.15: E-VII experimental configuration.

Operations	MAGENTA 95	Generic Runways
Aircraft	MAGENTA 95 Datum	Calibrated Generic Runways
Total Ops.	MAGENTA 95 Datum	Calibrated Generic Runways
Aircraft Distribution	MAGENTA 95 Datum	Calibrated Generic Runways
Stage Length	MAGENTA 95 Datum	Calibrated Generic Runways
Day/Night Ratio	1:0	1:0
Approach Operations	MAGENTA 95 Datum	50%
Departure Operations	MAGENTA 95 Datum	50%
Infrastructure	**MAGENTA 95**	**Generic Infrastructures**
Number of Runways	INM Definition	Calibrated Generic Infrastructures
Runway End Position	INM Definition	Calibrated Generic Infrastructures
Runway Rotation	INM Definition	Calibrated Generic Infrastructures
Runway Utilization	Uniform	Uniform
Number of Runways	Cross-flow	Cross-flow
Outputs		
Contour Areas	DNL 65 dB	

3.2.6 Summary of Experiments

The experiments presented above are intended to confirm the ability of Generic Runways and Generic Infrastructures to represent the operational and geometric diversity of the MAGENTA 95 with respect to fleet-level noise. A summary of the experimental plan for this capability gap is provided in Table 3.16.

Table 3.16: Summary of airport categorization experiments.

Exp.	Objective
E-I	Verify assumption of statistical clustering based on operations and seat class distribution
E-II	Identify bias error due to use of representative aircraft to represent actual aircraft fleet
E-III	Test robustness of operational models to forecast variability
E-IV	Test baseline Generic Infrastructure models
E-V	Explore the potential space of configurations for significant sub-categories
E-VI	Test calibrated Generic Infrastructures
E-VII	Test ability of Generic Airports to predict fleet-level noise

3.3 Contour Comparison Metrics

The third task that must be completed to provide sufficient investigative capability for a generic fleet-level noise methodology is a metric, or set of metrics, that can be used to compare contours from different scenarios from a shape perspective. While area gives a good explanation of scale, it does not provide any information about shape, and how that area is distributed about an airport. While the length and width of a contour can be measured, the utility of these measures breaks down when dealing with more complex contour geometries, and are not sufficiently descriptive to provide holistic comparative assessments. Furthermore, as was discussed in the Generic Airport development above, objective measures of shape can have multiple applications to improve other aspects of the generic fleet-level noise methodology.

While a shape metric is a useful abstraction, it is difficult to choose a single objective measure that describes shape, which is fundamentally complex. To this point, technology impact assessments have tacitly ignored contour shape, because qualitative assessments would require observation and discussion of every airport in every fleet-level study. To bridge the gap between the subjective descriptions of contour shape to an objective description, a set of research questions are posed, which must be addressed to arrive at a recommendation regarding contour comparison metrics.

I. *What characterizes an airport noise contour shape, as opposed to an aircraft contour shape?*
    a. *What are the general requirements for metrics?*
    b. *What requirements are specific to this type of metric?*

As was discussed by the simple thought experiment in Section 2.3.3.3, the contour area is not a sufficient descriptor of an airport noise contour, but the lack of description provided by area should not mean that 'shape' can only be addressed from a qualitative standpoint, especially if a generic noise modeling capability is available that can capture contour shape. On one hand, the qualitative method can be extremely powerful when used for a small number of cases for a limited number of airports, but when discussing a larger number of cases of fleet-level contours, it would be beneficial to communicate shape information in a simpler context that serves as a sufficient surrogate for the information typically processed subjectively through direct contour visualization.

The most logical place to begin the search for an appropriate metric is by defining what characteristic must be measured. This concept must be specifically defined, not only for the purposes of searching for appropriate metrics, but also to understand what aspects of an airport contour shape are of interest to the problem. Therefore, the methodology will follow a mapping from the qualitative descriptions of an airport noise contour to a quantitative description of what an ideal metric should objectively capture. Once the object of the measurement is more clearly defined, the general requirements for an acceptable metric will be referenced. Combining the two will lead to specific metric requirements pertaining to this problem. Using these requirements, shape metrics can be sought after and pre-evaluated qualitatively to identify the metrics that warrant further quantitative examination. These metrics can then be evaluated using the generic noise model, described above. Once results are obtained, the data for the selected shape metrics can be analyzed with respect to their ability to meet the desired requirements and properly distinguish the qualitative aspects of different airport noise contours. An overview of the methodology to identify and analyze contour comparison metrics can be seen in Figure 3.18.

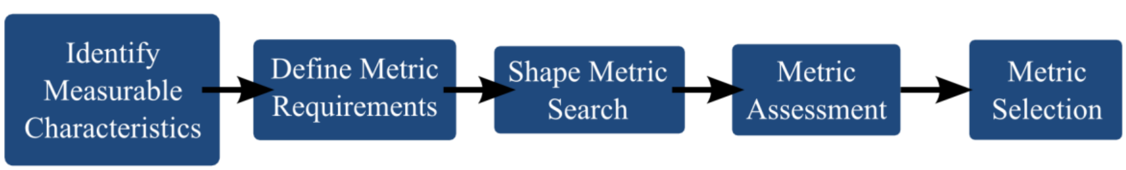


Figure 3.18: Contour shape metric development process.

3.3.1 Qualitative Analysis of Airport Noise Contours

Although qualitative shape descriptors are not necessarily as useful in objectively defining large numbers of contour shapes, the value of well-constructed qualitative metrics should not be overlooked. In order to objectively define what the desired metric must measure, it is necessary to map the observed qualitative differences between airport noise contours to objective measureable characteristics. Such taxonomy of a noise contour is not a new concept. For example, taxonomies exist for aircraft-level noise contours, describing where brake-release occurs, thrust cutback, etc. as can be seen in Figure 3.19 [123]. As can be seen in Figure 3.20, however, this taxonomical construct is not necessarily useful or even applicable for airport-level noise contours. Such qualitative taxonomies, however, do not formally exist for the runway or airport-level where many operations of sometimes varying types are occurring. From observation of various contours, it can be argued that airport-level noise contours are defined by an airport nucleus, and a variety of contour lobes surrounding this central region. The airport nucleus is abstractly defined as the central area from which operations originate, bounded nominally by the runway infrastructure. Mathematically, the airport nucleus is the polygon generated by connecting the runway ends of an airport in a counter-clockwise fashion, such that the entirety of the airport runway infrastructure is contained within the airport nucleus. The convex hull of the runway ends is not used because it could leave out the effect of a runway internally dominated by other runways. For the purposes of this research, the primary interest lies in the number of contour lobes and how these lobes are distributed about the runway.

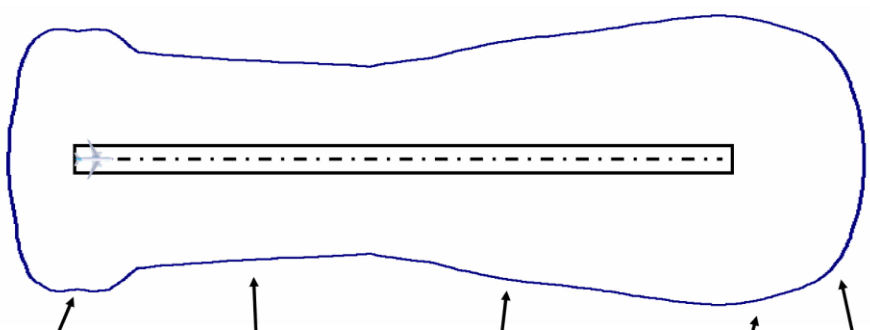


Figure 3.19: Aircraft-level departure contour taxonomy [123].

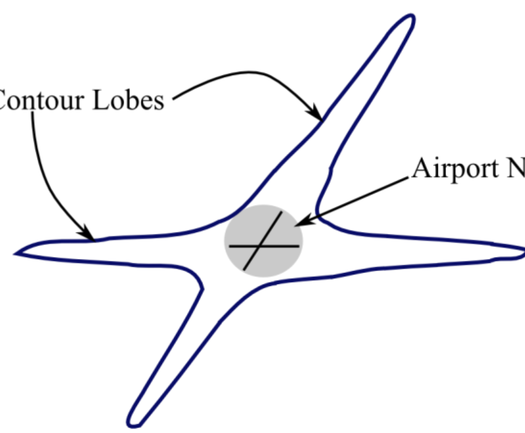


Figure 3.20: Airport noise contour taxonomy.

While metrics may or may not also be able to capture other nuances, such as the type of operations that make up a contour lobe, within the scope of this work these will not be considered necessary, since Generic Airports assume cross-flow operations on all runways. To discuss the number of contour lobes at an airport, an internally consistent method of qualitatively counting the contour lobes was developed to serve the purpose of this task going forward, and is discussed in detail in Appendix C.

3.3.2 Metric Requirements

Equally important to the successful selection of a shape metric is the examination of the requirements of a general metric. Juran and Kasser provide a list of such ideal characteristics:

- "*Provides an agreed basis for decision making*
- *Is understandable*
- *Applies Broadly*
- *Is susceptible of uniform interpretation*
- *Is economic to apply*
- *Is compatible with existing designs of sensors*" [124], [125]

Although some of these requirements may be more relevant than others, and some may even seem trivial, they coincide with the core reasons that a metric to measure contour shape is desired. Such a metric would provide a consensus standard for contour comparison, and ideally would be easy to compute, requiring little extra effort or computation time beyond that required to complete a noise study using the generic noise model developed above. The metric should, at its root, have some physical meaning, which is preserved through the analysis of the qualitative characteristics that are captured by the metric. These requirements also provide a sufficient starting point with which to generate more specific requirements:

1. The metric should correlate highly with the number of contour lobes at dissimilar operational volumes.

2. The metric should be sensitive to changes in contour shape caused by changes in runway orientation, thus capturing the distribution of contour lobes about the airport nucleus.
3. The metric should demonstrate discontinuity between drastically different airport configurations (ease of use).
4. The metric should be relatively insensitive or provide a predictable relationship to shape discrepancies between different operational volumes and aircraft distributions, maintaining a higher-level view of the noise contours.
5. The metric should be independent of airport-level translations and rotations.

Having defined the important measurable characteristics of shape and the requirements which a successful metric must meet, a hypothesis can be formalized:

I. *If a metric that scales with lobe number and lobe distribution about the airport nucleus can be identified, this metric will meet the necessary requirements for a contour shape metric as described above.*

Having identified the characteristics desired of a contour shape metric, a variety of metrics can be gathered that could potentially address all, or most, of these requirements for further examination.

3.3.3 Quantitative Shape Metric Search

Now that the object of measure is defined, a comprehensive search of metrics can be examined on a preliminary basis, to determine those that could meet the requirements presented above. There are a wide variety of possible sources to consider, including mathematical journals, basic geometric principles, and other fields interested in shape description [126] - [128]. Each of these sources can supply metrics that may be of use, but it is impossible to entirely uncover and test all the metrics available. A list of two of the most relevant metrics collected is presented below, while a comprehensive description of the metrics evaluated for this research are reserved for Appendix D.

3.3.3.1 Land-Use GIS Metrics

The land-use research field led to the two most useful metrics, the Spin Index, and the Detour Index. The Spin Index (SI) is defined as the "average of the square Euclidean distance between all interior points and the centroid." [127] An example can be seen in Figure 3.21.

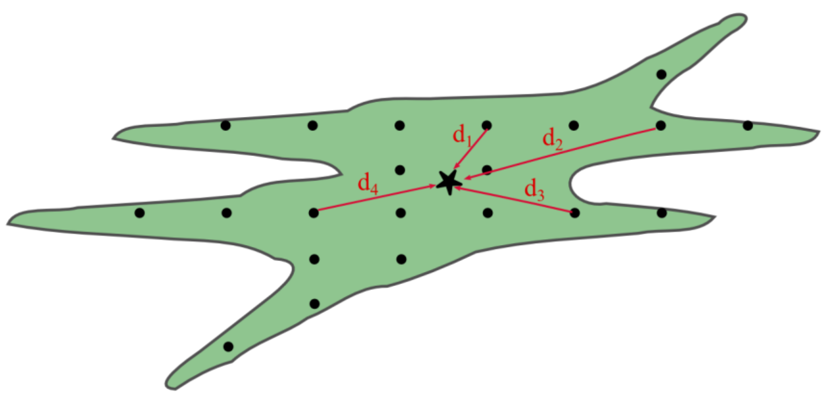


Figure 3.21: Spin Index (Adapted From [127]).

This metric emphasizes the distribution of the points further away from the central point of interest. This metric is calculated on the DNL 65 dB airport grid using Equation 3.5, and is normalized by the SI of the EAC (Equation 3.6) as shown in Equation 3.7 [127].

$$Spin = \frac{{d_1}^2 + {d_2}^2 + \cdots + {d_n}^2}{n} \quad (3.5)$$

$$Spin_{EAC} = 0.5 * radius_{EAC}^2 \quad (3.6)$$

$$Normalized\ Spin = \frac{Spin_{EAC}}{Spin_{Contour}} \quad (3.7)$$

The Detour Index (DetI) is defined as the perimeter of the convex hull of the shape as shown in Figure 3.22 [127].

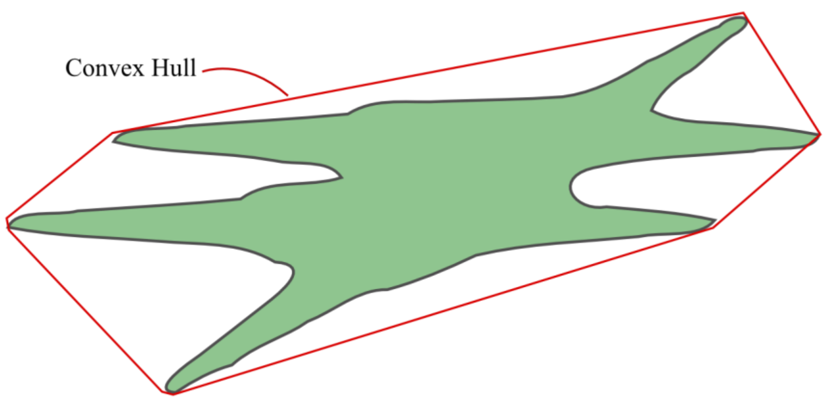


Figure 3.22: Detour Index (Adapted from [127]).

This metric, while conceptually less detailed than the Spin Index, may provide a sense of not only scaling with contour lobe quantity but also distribution, without requiring comparison to a central point. The DetI is calculated by implementing the

Graham Scan algorithm on the contour points [129]. It is normalized using the perimeter of the EAC as shown in Equation 3.8 [127].

$$Normalized\ Detour = \frac{Perimeter_{EAC}}{Perimeter_{Convex\ Hull}} \tag{3.8}$$

The summarized collection of metrics to be further analyzed with respect to the requirements posed is listed in Table 3.17.

Table 3.17: Collected shape metrics.

Metric	Source	Calculation Method
Area (*Control*)	*Control*	Contour Points
Perimeter Index	Classical Geometry/Land-Use	Contour Points
Vertices	Classical Geometry	Contour Points
Dispersion Index	Land-Use	Contour Points
Girth Index	Land-Use	Contour Points
Detour Index	Land-Use	Contour Points/
Proximity Index	Land-Use	Grid Points
Spin Index	Land-Use	Grid Points
Cohesion Index	Land-Use	Grid Points
Depth Index	Land-Use	Contour Points/Grid Points

3.3.4 Metric Assessment

In order to examine the metrics selected for further evaluation, they must be subjected to tests across different geometric configurations, at different operational settings, and assessed for sensitivity at various stages of the airport configuration space. Successfully completing this aspect of the project depends significantly on the development of Generic Airports, and the ability to leverage the developed generic noise model to run a variety of experiments in a short period of time. Although some metrics are expected to perform better than others, the relative speed and simplicity with which test cases can be run allow for a broad-spectrum evaluation of the shape metrics identified above. While a single metric that can achieve these goals may not exist, it is possible that a combination or collection of metrics would be appropriate.

In order to perform the experiments required to examine the ability of the collected metrics to scale with contour lobe quantity and distribution about the airport nucleus, some quantities must be fixed to ensure that each metric is evaluated only with respect to its intended use. Consequently, since geometric configuration exploration experiments were already proposed in the development of Generic Infrastructures in Section 3.2.4.5.2, the cases used for those experiments can be vertically integrated in the search for an ideal shape metric. For example, the tests presented earlier regarding Generic Infrastructures specifically vary airport geometries within the observed fundamental geometric classes, including augmentations that account for operational characteristics. These settings are precisely those desired in the search for an ideal shape metric.

Therefore, the approach required for these experiments will utilize a subset of the experimental settings presented in the geometric exploration described above. By calculating the selected metrics as described above for each of these cases, the results can be analyzed and utilized to observe trends within and between different geometric classes pertaining to the number of contour lobes and their consequent distribution about the airport nucleus.

To summarize, the geometric variables will be varied in a LHC DOE, and augmented by a truncated set of the operational settings. The operational settings will consist of three of the experimental blocks used for airport configuration exploration and the summarized experimental configuration for the generic noise model is provided in Table 3.18.

Table 3.18: Metric assessment experimental configuration.

Operations	**Fixed**
Aircraft	Representative Aircraft
Total Ops.	2-Level Discrete: 1250, 2250
Aircraft Distribution	2-Level Discrete: Light, Heavy
Stage Length	Uniform
Day/Night Ratio	1:0
Approach Operations	50%
Departure Operations	50%
Infrastructure	**Varying**
Number of Runways	1-3
Runway End Position	Range Dependent on Geometry
Runway Rotation	Range Dependent on Geometry
Runway Utilization	Uniform
Number of Runways	Cross-flow
Outputs	
Contour Areas	DNL 65 dB

Once the experiments are run through the generic noise model, the qualitative mapping between the contour outputs must be performed to ensure that the quantitative measures scale with the number of contour lobes and their distribution. This task must be achieved through an assessment of the number of contour lobes utilizing the pseudo-quantitative scale developed in Appendix C, and a categorical observation that lumps the resulting contours into the developed Generic Infrastructure categories. Since this is a qualitative process, there is a risk of imposing a certain bias. This bias will partially be offset by the total number of cases, which can be used as a distribution of multiple observations to examine the central tendencies and other statistical aspects of the data.

The data can then be assessed with respect to the ability to measure lobe quantity, lobe distribution, categorical segmentation, and insensitivity to operational variables in accordance with the requirements enumerated above. Recommendations can then be provided regarding the metrics that should be utilized for shape comparison. Using a statistical software package, the data can be analyzed with respect to trends and relationships of the geometric and operational input variables to provide a comprehensive examination of which metrics are best suited for contour comparison. It should be noted that the fifth requirement, specifying insensitivity to contour rotation or translation was used to screen the subset of metrics, and thus all are expected to meet this requirement.

3.3.4.1 Experiment I: Lobe Correlation

The first experiment (E-I) will consist of examining the correlation of the examined metrics with respect to the total number of observed contour lobes, in accordance with the first requirement for a contour shape metric. This analysis is done for each experimental block separately, to assess the differences caused by different operational volumes and aircraft distributions. Correlation information can be obtained using commercially available statistical analysis software. As a control, the correlation of total lobes to the contour area will be tracked to validate the assertion that contour area is a poor predictor of shape with respect to the number of contour lobes. Based on the lobe quantity correlations, an appropriate subset of the metrics for each experimental set will be selected for further examination.

3.3.4.2 Experiment II: Lobe Distribution

While the total number of lobes lends itself easily to a correlation assessment, the distribution of those lobes about the airport nucleus is a more complex matter. These will be inferred through the assessment of the metrics as they relate to the geometric variables used in the configuration exploration experiments. Since the generic noise model assumes straight ground tracks, the distribution of the contour lobes are entirely governed by the runway positions and orientations. By analyzing the relationship between the geometric variables and the resulting metrics, the ability to represent lobe distribution can be inferred and evaluated. Again, the metrics that continue to perform well with respect to the requirements will be carried through for further analysis.

3.3.4.3 Experiment III: Categorical Segmentation

After lobe correlation and distribution have been accounted for, it is necessary to check that the metrics collected can distinguish between different geometric types. For example, the metric should be able to discriminate between airports with one runway, two runways, three runways, or more. Similarly, the desired metric should be able to differentiate between geometric types with the same number of runways like a Parallel and Intersecting geometry. In order to test for this capability, the contours must first be qualitatively classified, according to the Generic Infrastructure categories identified in the development of Generic Airports. These classifications capture basic lobe-distribution characteristics that differentiate airports with the same number of runways. For example, an airport with two parallel runways shares certain similar characteristics when compared to an airport with two intersecting runways. Both have two effective runways, and both can have four contour lobes. They differ, however, in lobe distribution, as can be seen in Figure 3.23.

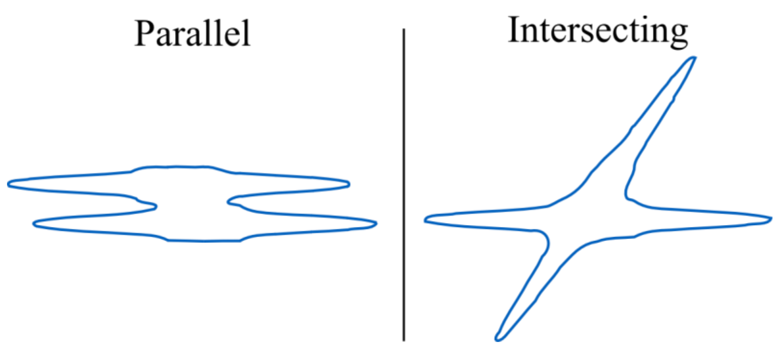


Figure 3.23: Juxtaposition of Parallel and Intersecting geometries.

These categorical segmentation tests can be performed on the experimental configuration data, which serves as a worst-case scenario, and on the MAGENTA 95 and Generic Infrastructure geometries.

3.3.4.3.1 Case 1: Categorical Segmentation of Configuration Exploration Cases

To assess the ability of the metrics to meet the third requirement of segmentation between Generic Infrastructure categories, the entirety of the experimental data can be analyzed for segmentation between the observed categories for each of the remaining metrics of interest. The mean values within each Generic Infrastructure category can be computed and plotted, along with appropriate measures of central tendencies of the data.

3.3.4.3.2 Case 2: Categorical Segmentation of MAGENTA 95 Airports and Generic Infrastructures

Once the top-performing metrics are verified to meet the specified requirements, further validations of the metrics can be pursued under more realistic conditions, such as a comparison to the MAGENTA 95 airport noise contours using the actual airport runway configurations under the same operational settings as the three experimental blocks. The experimental configuration differs slightly from the settings in Table 3.18. The configuration for this case (E-III.2) is summarized in Table 3.19. Whereas the comparison via the Generic Infrastructure configuration exploration experiments was designed to examine the possible extremes, this comparison provides a more conservative subset of the geometry-types that may be encountered. The metrics can thus be used to assess the success of the qualitative shape grouping, and to examine how well the Generic Infrastructures describe the mean shapes. If the metrics can discriminate the infrastructures with some similarity to the qualitative groupings, they can be used to distinguish between contours of differing types. This test case serves as an example of how the Generic Airports and contour shape metrics examined here can be used together in future developments.

Table 3.19: E-III.2 experimental configuration.

Operations	Fixed	
Aircraft	Representative Aircraft	
Total Ops.	2-Level Discrete: 1250, 2250	
Aircraft Distribution	2-Level Discrete: Light, Heavy	
Stage Length	Uniform	
Day/Night Ratio	1:0	
Approach Operations	50%	
Departure Operations	50%	
Infrastructure	**MAGENTA 95**	**Generic Infrastructure**
Number of Runways	INM Definition	Calibrated Generic Infrastructure
Runway End Position	INM Definition	Calibrated Generic Infrastructure
Runway Rotation	INM Definition	Calibrated Generic Infrastructure
Runway Utilization	Uniform	Uniform
Number of Runways	Cross-flow	Cross-flow
Outputs		
Contour Points (x,y)		
Contour Area	DNL 65 dB	
Airport DNL Grid		
Shape Metrics		

3.3.4.4 Experiment IV: Correlation to Operational Variables

The examination of multiple experimental sets with varying operational settings will provide the information necessary to examine the insensitivity to operational factors. While it is unlikely that the metrics will have no sensitivity to operational differences, the correlations are expected to be very minor, since almost all the metrics to be examined are normalized. For this experiment (E-IV), the experimental configuration in Table 3.18 will be used.

3.3.4.5 Experiment V: Metric Combinations and Trades

The results of the experiments described above may demonstrate that none of the collected shape metrics meet all of the requirements. Consequently, it may be possible to use a combination of metrics, either logically or mathematically joined to provide better lobe correlations and segmentation between categories. The benefits and drawbacks of such an approach can be analyzed by attempting combinations of the remaining metrics and analyzing any improvement or deterioration of lobe correlation and geometric segmentation.

3.3.5 Metric Recommendations and Experimental Summary

Finally, the ability of the top-performing metric(s) to meet the requirements can be summarized, mapping back the results of the assessments to the original desired requirements. The results of the metric assessment, including recommendations regarding which metric(s) should be applied will be provided.

A summary of the experiments used to evaluate the quality of the collected metrics in describing the total number of lobes and their distribution about airport nucleus is provided in Table 3.20.

Table 3.20: Summary of metric assessment experiments.

Exp.	Cases	Objective
E-I	1	Test ability of metrics to correlate with total number of contour lobes
E-II	1	Test ability of metrics to scale with lobe distribution
E-III	2	Test ability of metrics to discriminate between different qualitative shape categories
E-IV	1	Test insensitivity of metrics to operational factors
E-V	1	Test advantages of metric combinations if necessary

Having developed an approach to address each of the observed capability gaps, the rapid fleet-level modeling methodology, the categorization of airports to reduce the analytical space, and the development of contour shape metrics can be integrated into a generic fleet-level noise methodology, which can be implemented to evaluate the significance of different technological scenarios with respect to noise.

3.4 Use Cases: Technology Impact Assessment

Once the capability gaps identified above are addressed, the resulting generic fleet-level methodology can be leveraged to examine the system-wide impacts on noise due to a number of factors including technology scenarios. The methodology will thus be referred to as the System-Wide Assessment of Noise (SWAN) methodology. One of the primary and most valuable provisions enabled by the development of the rapid capabilities described above is the potential to perform various analyses in the context of technological infusions to the fleet over time.

In the future, technology infused aircraft will be implemented into the fleet, changing the environmental impacts at the fleet-level, including noise. Before this implementation occurs, these technologies must be identified, evaluated, and selected, as described by Kirby [73]. With respect to evaluation, the SWAN methodology can be used in a number of ways to provide early assessment of these potential technologies, to better inform decision-makers. On one hand, it can be used for exploratory forecasting, to assess what impacts a set of collected technologies can provide [73]. On the other hand, the SWAN methodology can be used for normative forecasting, examining, with a fixed set of technologies, what insertion of technology infused vehicles would be required to achieve specific goals [73]. In the event that these goals cannot be achieved, some information about the conditions required for success can be provided. Both of these forecasting methods will be demonstrated in this treatment, to provide answers to the research questions posed at the end of Chapter 2. The examples will be presented in the context of the resultant SWAN methodology, introducing the fulfilled capability gaps in Figure 3.24. These use cases will be used to demonstrate the application of the methodology by describing the steps of the problem setup and analysis. All three will follow the same basic application of the methodology, while differing in the execution of the fleet-level noise model.

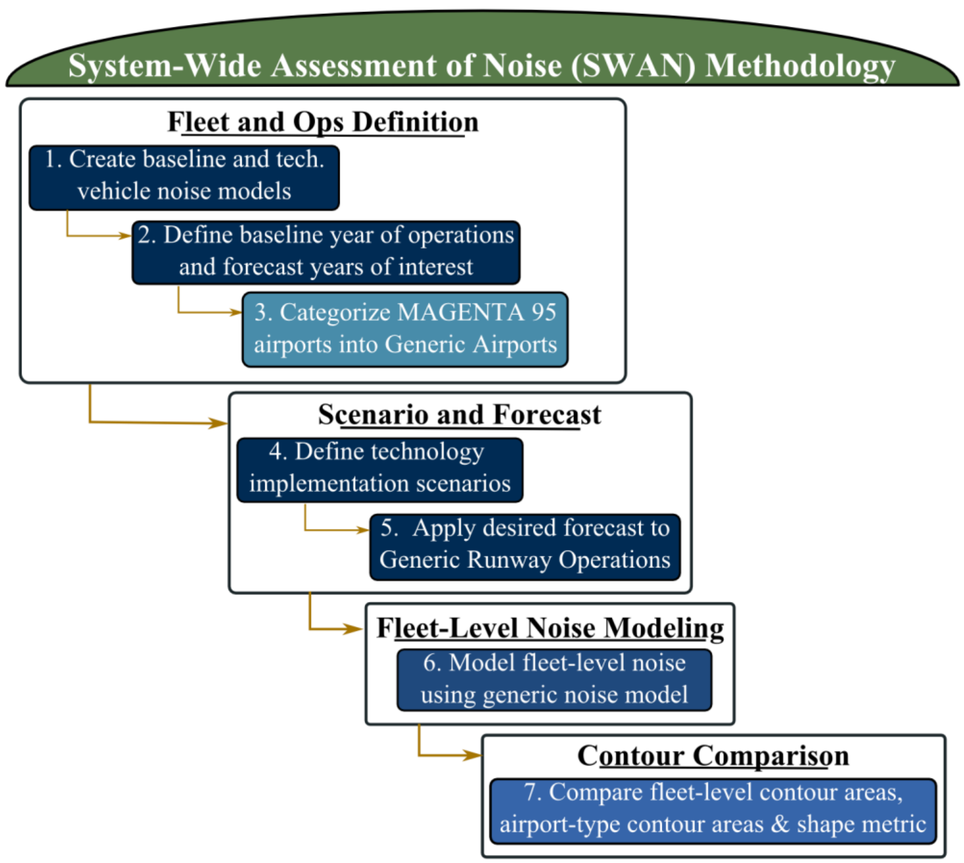


Figure 3.24: SWAN methodology.

Therefore, the process for all use cases will be described together, while differentiating between them at the appropriate steps.

3.4.1 Fleet and Operations Definition

The first block of the methodology requires defining the baseline information required to perform an analysis. These definitions include the current fleet, the baseline year, the technology infused vehicles, the forecast years of interest, and the definition of Generic Airports.

3.4.1.1 Step 1: Create Baseline and Technology Vehicle Models

The purpose of this step is to define the current and technology fleet of aircraft through vehicle-level detailed noise models. These include a grid for approach operations and for departure operations at all available stage lengths. Conforming to the assumptions posed in the development of the generic noise model, these grids must be computed at standard day sea-level conditions with straight ground tracks, at a notional single-runway airport as demonstrated in Figure 3.1. These grids must be computed for the representative vehicles that will model the current fleet of aircraft, as well as the technology infused vehicles that will be examined in the study. The technology infused vehicles will be modeled as a future generic fleet of aircraft, using a handful of technology equipped vehicle models to represent the potential future space.

NASA and the FAA are both examining potential technologies through a number of programs to enable the reduction of airport community noise even as operations increase. The technologies assessed for these use-cases consist of a notional set of possible technologies that could be available in the N+1 timeframe [82], [130], [131]. The technologies include a notional package for narrow-body (NB) and wide-body (WB) aircraft, and are summarized in Table 3.21 [82], [130], [131].

Table 3.21: Notional N+1 technology package [82], [130], [131].

Notional Techs.	NB	WB
60 Deg. Winglets	•	•
Adaptive Trailing Edge	•	•
Advanced Cooling Tech. 1	•	•
Advanced Cooling Tech. 2	•	•
CMC Nozzle	•	•
Highly Loaded Compressor	•	•
Highly Loaded Turbine	•	•
Landing Gear Fairings	•	•
Fixed Chevrons	•	•
Combustor Noise Liner	•	•
Variable Area Nozzle	•	
Stator Sweep and Lean	•	•
Acoustically Soft Vane	•	•
Noise Lip Liner	•	
Advanced Low-NO_x Combustor	•	•

The interested reader can consult the references provided for more specific details regarding each of the examined technologies, but this information is not germane to the process at hand. These technologies will be equipped across aircraft of varying seat class types and inserted into the forecasted flight schedule to assess their fleet-level impacts. Having defined the technology packages that will be modeled, the aircraft-level grids for each technology infused aircraft can be generated. The outcome of this step is a set of current and technology infused vehicle SEL noise grids for approach and departure operations. The inputs and outputs are summarized in Figure 3.25.

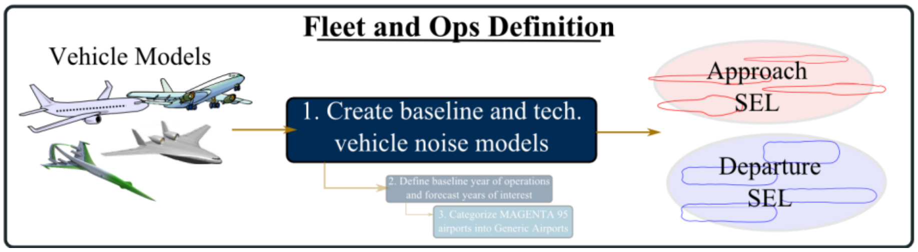


Figure 3.25: Step 1 of the SWAN methodology.

3.4.1.2 Step 2: Define Baseline Year of Operations and Forecast Years of Interest

The purpose of this step is to specify the baseline set of operations, as well as identifying the forecast years that will be evaluated. The baseline operations can be chosen from a number of available datasets as described above, but in support of the generic framework for fleet-level evaluation of environmental impacts, the 2006 datum year of operations built into the GREAT tool will be utilized. The NASA vision for noise reduction includes several goals at the aircraft-level for the N+1 (2015), N+2 (2020), and N+3 (2025) time frames [7]. Since the technologies examined will be N+1, these goals will be targeting the N+1 timeframe. The 2015 timeframe for N+1 technologies reflects developments up to TRL 4-6 [7]. The FAA has provided goals regarding population exposure reductions for the year 2018 [132]. This target forecast year will be the primary year of interest for the exploratory and normative example cases. A third normative example will be analyzed as well, utilizing 2025 as the analysis year to examine the notional impact of N+1 technologies on an N+2 timeframe. The main outputs of this step is a baseline set of operations required to generate Generic Airports and the target forecast years to analyze technology implementation, as summarized in Figure 3.26.

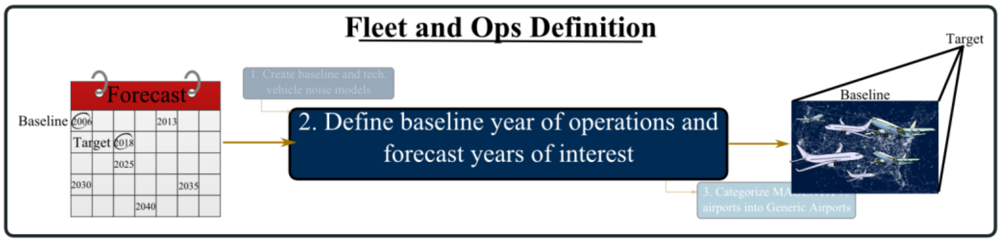


Figure 3.26: Step 2 of the SWAN methodology.

3.4.1.3 Step 3: Generate Generic Airports

The purpose of this step is to generate the set of Generic Airports from the datum operations and effective runway layouts of the study airports as described previously in this chapter. The process can be applied to any sample set of airports, but it is recommended that the MAGENTA 95 airports be used, since they account for the majority of the population exposed to significant noise. The first outcome of this step is a set of flight schedules encapsulating the operational aspects of the unique airports, with operations flown only by representative aircraft. The second is a set of infrastructure models that encapsulate the geometric aspects of the unique airports. The combination of the two yields a set of Generic Airports that can be analyzed through the generic noise model. A summary of Step 3 is provided in Figure 3.27.

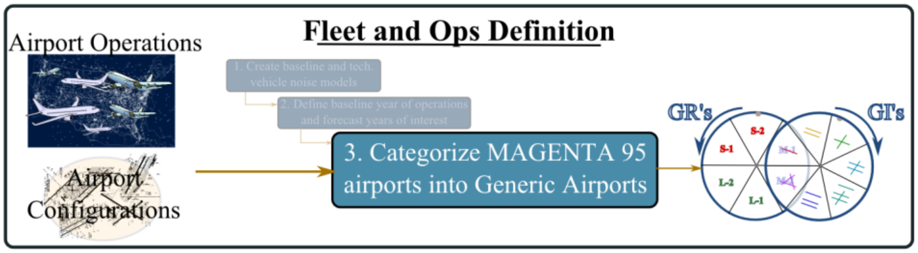


Figure 3.27: Step 3 of the SWAN methodology

3.4.2 Scenario and Forecast

The next block of the methodology consists of defining the number of future operations that will be accounted for the by the technology infused vehicles, as well as applying the forecasted change in operations to the Generic Runway models.

3.4.2.1 Step 4: Define Technology Implementation Scenarios

Generally, technology insertion will refer to the percentage of future flights flown by technology infused aircraft in the target forecast year. These insertions can be defined at different levels of granularity. For example, the specific insertion of SC4 vehicles can differ from that of SC9 vehicles. The process is summarized in Figure 3.28. For these notional examples, the technology insertion will be applied uniformly across all seat classes. There is some differentiation between the cases, as will be described below.

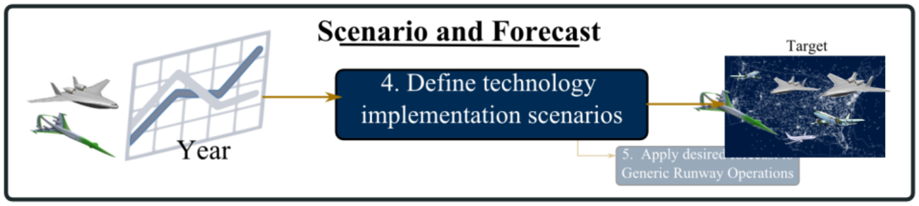


Figure 3.28: Step 4 of the SWAN methodology.

3.4.2.1.1 N+1 Exploratory Forecasting Scenario

This example demonstrates how the methodology can be used to evaluate a given set of technologies with respect to noise at the fleet-level without a specific goal in mind. A notional technology insertion of 50% will be assumed, meaning that 50% of the operations in 2018 will be performed by the technology infused vehicles. It is important to note that this is only a notional example, and must be considered under the caveat that it would be impossible for manufacturers to produce 50% of the U.S. fleet within a 5-year time frame, let alone provide enough time for the market to adopt the new aircraft. This example is purely notional, however, and is geared towards demonstrating the impacts of the notional technology packages with respect to contour area and shape.

3.4.2.1.2 N+1 Normative Forecasting Scenario

In the exploratory example, the N+ 1 technology infused aircraft were provided an assumed insertion at the 2018 target forecast year. This example aims to determine what minimum insertion of the technology infused vehicles would be required to meet goals for fleet-level reduction in contour area. Instead of varying the technological factors, the insertion of the vehicles will be adjusted to meet the constraint.

The specific FAA goals of noise mitigation are stated in population exposed [132]. FAA states that the goal is to reduce population exposure by 4% in 2018 based on 2007 population exposure [132]. This value is derived by compounding the average reduction in population exposed to significant noise based on historical data [132]. In order to determine the average reduction from 2006 population exposure, an economic analogy was employed. First the average annual rate of reduction from 2007 to 2018 was computed using Equation 3.9 [133].

$$(1 + i_{annual,avg})^{11} = 0.96 \tag{3.9}$$

The average annual reduction was then utilized to determine the compounded reduction in population exposed from a 2006 baseline instead, consistent with the FAA's initial assumptions, as shown in Equation 3.10 [132], [133].

$$(1 + 0.37\%)^{12} = 0.956 \tag{3.10}$$

This computation resulted in a compounded reduction of approximately 4.4% for 2018 based on a 2006 baseline. This reduction is applied directly to the reduction in contour area desired, assuming a linear relationship between population reduction and contour area reduction.

3.4.2.1.3 N+2 Normative Forecasting Scenario

Assuming that a feasible market penetration exists, the process can also be used to examine the effect of the N+ 1 technology infused aircraft for the N+2 forecast year of 2025. A continued compounding of the average annual reduction in population exposed will be assumed, which will be linearly related to the reduction in contour area. The compounded rate of reduction was found to be approximately 7% using Equation 3.11 [133].

$$(1 + 0.37\%)^{19} = 0.93 \quad (3.11)$$

While this situation is somewhat unrealistic, it demonstrates the types of investigative scenarios that can be evaluated with the methodology.

The outcome of this step for each case is to provide the information necessary to distribute the forecast-year operations in the Generic Runway models.

3.4.2.2 Step 5: Apply Forecast to Generic Runway Operations

The purpose of this step is to generate scaled Generic Runway models that follow the forecasted change in operations. This scaling can be achieved at a number of levels of granularity. For example, the average increase in operations at each airport volume group can be applied to the appropriate baseline Generic Runways, or the average increase of each Generic Runway group can be applied to the appropriate baseline Generic Runways. For simplicity, the average increase in operations by seat class at all 95 MAGENTA airports will be used to scale the baseline Generic Runways. These scaling factors are determined by evaluating the forecasted operations for the target year in GREAT, and computing the percentage increase from the baseline year by seat class. The forecast applied in GREAT will be the FAA Terminal Area Forecast (TAF) [83]. The resultant scaling vectors can then be applied to the baseline Generic Runway operational models, utilizing the assumed insertion of technology infused vehicles to distribute operations across the representative and future fleet. Commonly, a "status quo" (SQ) scenario is also modeled to compare the impact of the technology infusions to the consequences of implementing no new aircraft into the fleet. These operational models are also generated at this step using the forecast scaling vector, but assigning all flights to the representative aircraft. The output of this step is a set of operational models for the forecast year with and without technology infusions as shown in Figure 3.29.

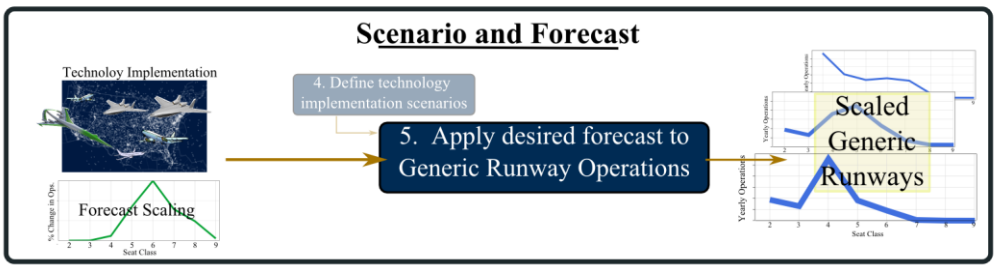


Figure 3.29: Step 5 of the SWAN methodology.

3.4.3 Fleet-Level Noise Modeling

Once the study has been setup properly, now the baseline, technology infused scenarios, and status quo forecast scenarios can be modeled to provide fleet-level assessments.

3.4.3.1 Step 6: Model Fleet-Level Noise Using Generic Noise Model

The purpose of this step is to execute the fleet-level noise model for the scenario. With the baseline Generic Runways, the technology infused forecasted Generic Runways, and the status quo forecasted Generic Runways, all the operational data required to compute fleet-level noise for a scenario is available to compute through the Generic Noise Model. Once this noise is computed, it can be distributed to the various Generic Infrastructures developed in the third step. Using the generic noise model developed previously in this chapter, the process can be done in a rapid automated fashion. The outcome of this step is the raw fleet-level assessment results for the baseline, technology infused, and status quo Generic Airports including contour areas for each Generic Airport and shape metric computation, as shown in Figure 3.30.

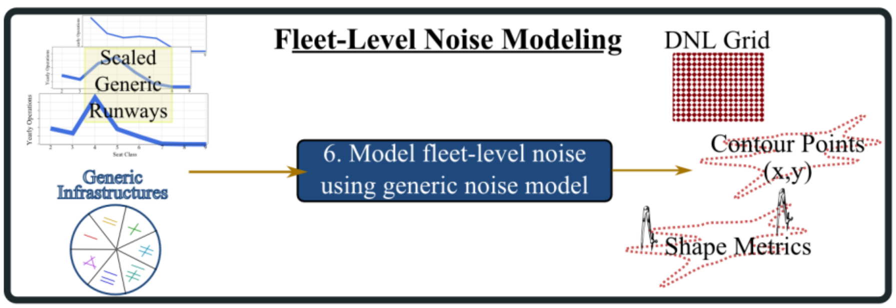


Figure 3.30: Step 6 of the SWAN methodology.

3.4.4 Contour Comparison

Once the scenarios are computed, the technology infused scenario can be compared to the baseline and status quo scenarios. Comparisons can be performed at the fleet-level for contour area, but using the Generic Airport types, comparisons of airport-level areas and shape impacts can be performed as well.

3.4.4.1 Step 7: Compare Fleet and Airport-Level Contour Areas and Shape

The comparison of fleet-level contour area is simply a matter of summing the Generic Airport contour areas for the baseline, technology infused, and status quo scenarios. Contour area comparison at the Generic Airport level can be done by measuring the change in area from the baseline case. Changes in shape, on the other hand, cannot be viewed simply as increases or decreases, since they do not measure the extent of the contour, but rather how the noise is distributed spatially around the airport. The general process is summarized in Figure 3.31. The process differs somewhat for each case and these will be described below.

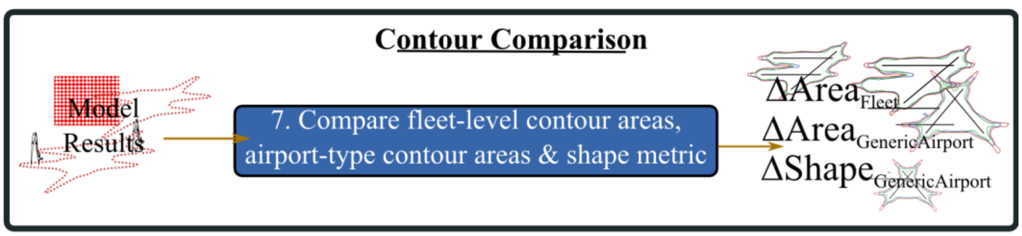


Figure 3.31: Step 7 of the SWAN methodology.

3.4.4.1.1 N+1 Exploratory Forecasting Scenario

For the exploratory case, only one comparison of the Generic Airports for the baseline, technology infused, and status quo scenarios are required, because the insertion of vehicles is pre-determined. The change in fleet-level and airport-level contour areas can be examined to determine the overall reductions in contour area. The shape metrics can be analyzed at the airport-level to examine deviations of the technology infused scenarios from the baseline and status quo computations. Airports that demonstrate significant shape changed based on the developed metric(s) can be further analyzed to determine the significance of the change. The outcome of this step is an objective measure of the contour area impacts due to the infusion of technologies at the fleet-level and at Generic Airport types, as well as a measured impact on the shape of the contours.

3.4.4.1.2 N+1 and N+2 Normative Forecasting Scenarios

In the normative cases, it is necessary to determine the minimum required insertion of the technology infused vehicles to meet the notional contour area reduction goals. By varying the market penetration in the direction of the constraint, the minimum penetration can be converged upon. This process requires application of the bisection optimization method, which is well suited to this optimization in one dimension [134]. The fleet-level contour area change must therefore be compared first, and checked against the fleet-level area reduction goal. If the result is not within the tolerance of the optimization, the process must return to Step 4 to define a new technology implementation scenario by varying the insertion of the technology infused vehicles into the schedule. The process then continues as described above until convergence is achieved, as shown in Figure 3.32. Once the process converges, the contour area reductions at specific airport types can be analyzed, along with the shape impacts of the technology infused scenario.

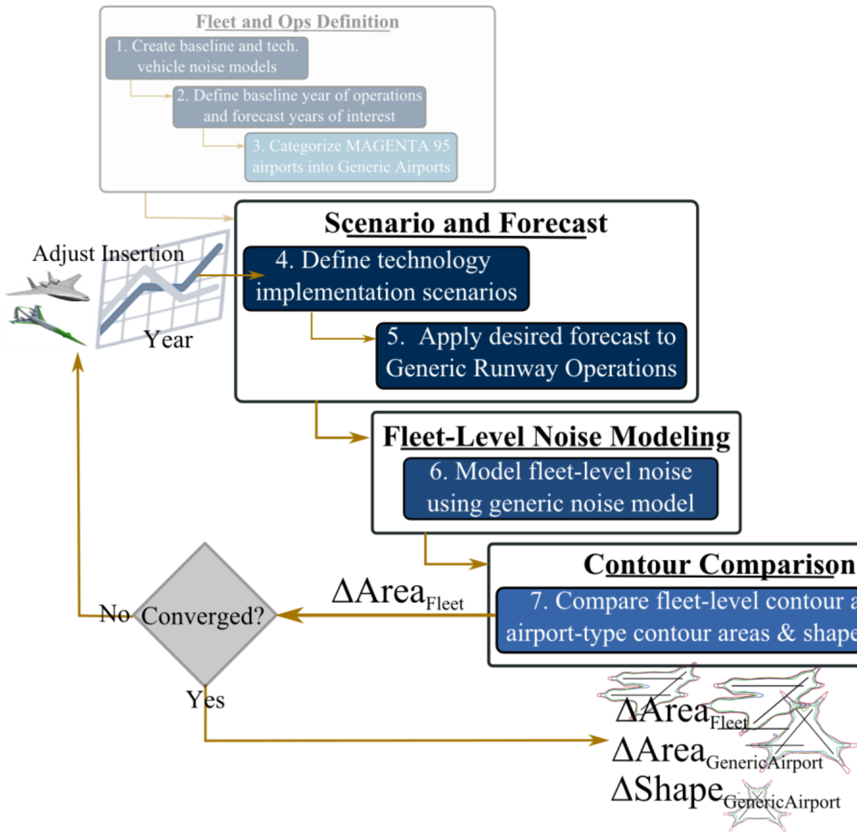


Figure 3.32: Iterative loop for normative assessments.

By addressing the capability gaps identified by laying out a structured roadmap consisting of research questions, hypotheses, and experiments, the approach described can be implemented. The use cases can then be executed to provide insight regarding the research questions posed at the end of Chapter 2. The following chapter will present the results of the experiments and use cases outlined in this chapter, and discuss the implications and significance of each.

CHAPTER 4

IMPLEMENTATION

This chapter will consist of the experimental results, relevant discussions, and subsequent recommendations that address the research questions posed in Chapter 3. The implementation will first address the development of the three capability gaps, followed by a demonstration of the use cases of the System-Wide Assessments of Noise (SWAN) methodology defined in Chapter 3.

4.1 Rapid Fleet-Level Noise Modeling

After pre-calculating the necessary aircraft-level grids to perform the experiments, the generic noise model was constructed and will be referred to as the Airport Noise Grid Integration Method (ANGIM). The experiments outlined in Section 3.1.3 were executed to verify and validate the model results.

4.1.1 Experiment I: Aircraft-Level to Runway-Level Integration

To verify the summation of aircraft-level noise responses logarithmically to yield runway-level responses, a simple flight schedule was constructed using five aircraft from the INM database. These aircraft were selected because they reasonably cover the spectrum of aircraft types that represent a typical fleet. The total operations consisted of 1000 flights. The runway geometry was a simple single-runway, with all traffic pursuing an eastern heading. This geometric setting allows for the summation of the aircraft-level grids to the runway-level to be evaluated in isolation of the interpolation required to integrate the runway-level to the airport-level.

The maximum absolute point-to-point error observed was DNL 0.1 dB on 100 % of the compared grid points. This error is attributed to significant figure rounding, introduced when converting from the logarithmic decibel scale to the linear scales and finally back to a decibel scale. The average point-to-point error was DNL 0.02 dB. This error is insignificant, and as could be expected, these results propagated favorably to the contour area, which was compared at contour levels between DNL 55-70 dB in Figure 4.1, along with the respective contour area tolerances. For all cases presented herein, the area was normalized by the reported INM area. The predicted area is well within the imposed tolerance bands of +/- 1.5dB. Similarly, as can be seen in Figure 4.2, the shape of the contours is accurately represented. To aid in visualization, only every fourth point of the predicted contour is depicted.

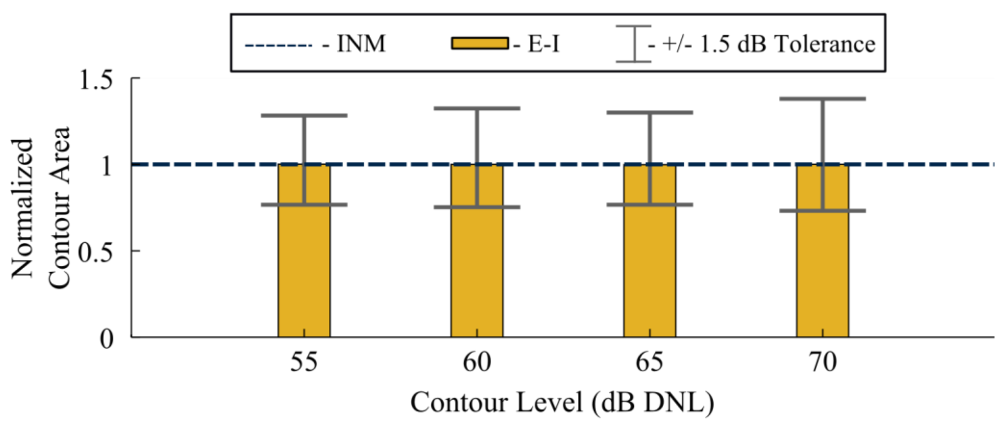


Figure 4.1: Contour area comparison for E-I.

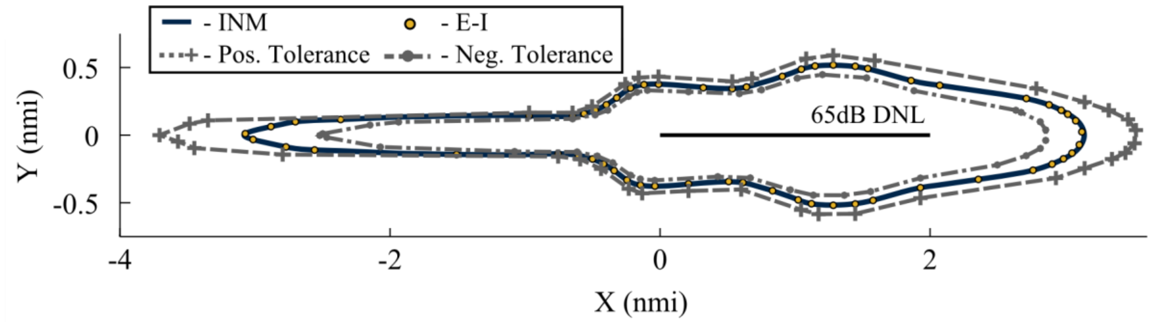


Figure 4.2: Qualitative shape comparison for E-I.

The results of this example were deemed sufficient to consider this aspect of the model verified. Since the operations were simply logarithmic additions of values computed using a detailed noise model, and no grid point interpolation was required, there were few potential sources for error.

4.1.2 Experiment II: Runway-Level to Airport-Level Integration

To test the assertion that runway-level grids can be interpolated and summed to airport-level grids, two test cases were devised that utilized INM-generated runway-level grids to interpolate and sum to the airport-level.

4.1.2.1 Case 1: Single Runway Configuration, Cross-Flow Traffic

The first case (E-II.1) uses the same flight schedule as the first experiment, but half the flights pursue a western heading in this scenario, while the other half pursues an eastern heading. This perturbation, while still resulting in a single-runway airport configuration, forces ANGIM to model these as two runways that occupy the same geographical space. This case exemplifies the simplest-case interpolation and summation of runway-level grids to the airport level. In this and all subsequent cases, only the intersection of the interpolated grids is compared with respect to INM, as the points outside the intersection cannot be used to predict noise responses. Any perimeter points of the intersection are also discarded because they are prone to large error due to extrapolation rather than interpolation. While these error points are well beyond the contour levels of interest, it is important to be rigorous for the purposes of reporting overall point-to-point accuracy.

The single-runway case yielded a maximum error of DNL 13.2 dB. While this maximum error is significant, the average absolute error across all compared points was only DNL 0.01 dB. Furthermore, 99.99% of the points were within the imposed tolerance band, with only four total points beyond this window. The contour area comparison depicted in Figure 4.3, demonstrates satisfactory accuracy with respect to the DNL 55-70 dB contour range. The contour shape comparison for the DNL 65 dB contour, which can be seen in Figure 4.4, demonstrates accurate shape prediction. Only every third test-case point is shown for clarity.

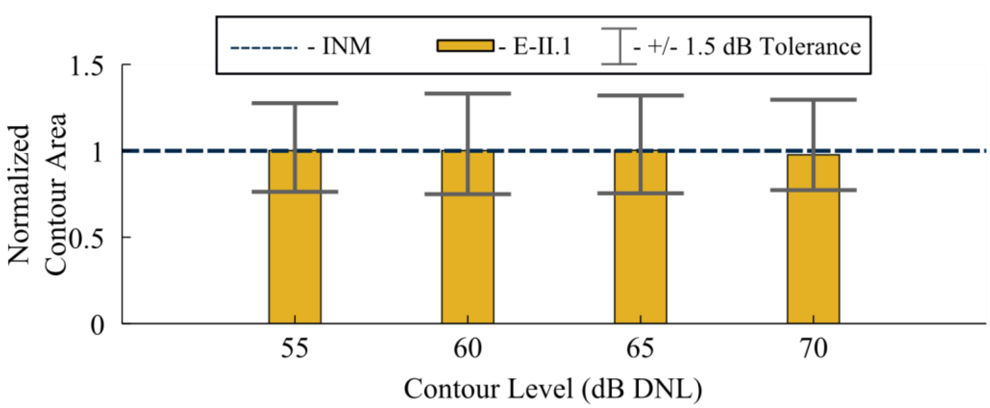


Figure 4.3: Contour area comparison for E-II.1.

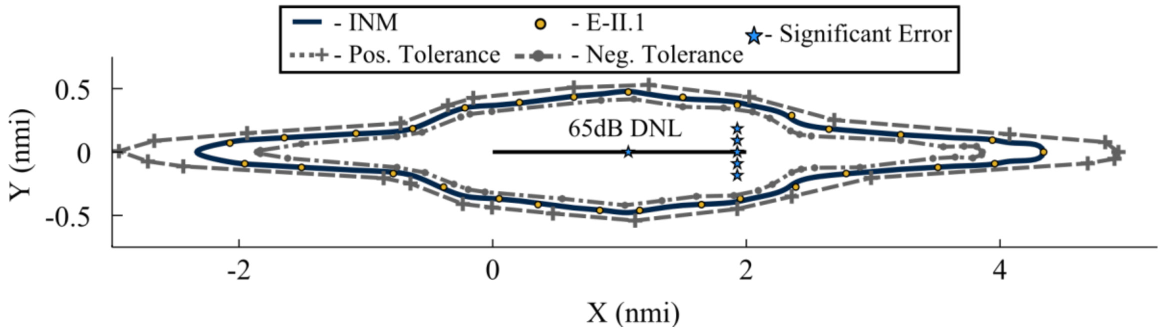


Figure 4.4: Qualitative shape comparison for E-II.1

Figure 4.4 also includes the points of significant error, which are clearly clustered around the eastern end of the runway. This type of significant error is common and will be discussed further after the second case of the experiment is presented.

4.1.2.2 Case 2: Cross-Runway Configuration, Departures Only

The second case (E-II.2) consists of a cross-runway airport with 2000 departure operations; 1000 on each runway. The headings are easterly and southerly and the respective aircraft used are a 737-800 and a 747-400. This case tests a difficult interpolation of a rotated runway. Moreover, by including only operations of the departure type, the roughness of the contours near the break-release caused by ground-based directivity can be used to further stress the interpolation of the runway-level grid to an airport-level grid [95].

The cross-runway case yielded a maximum absolute error of DNL 17.5 dB, which, again, is very significant. The average absolute error, however, was only DNL 0.02 dB, and 99.99% of the points were within the imposed tolerance bands. The contour area comparison, which can be seen in Figure 4.5, shows that contour areas are well within the imposed tolerance bands.

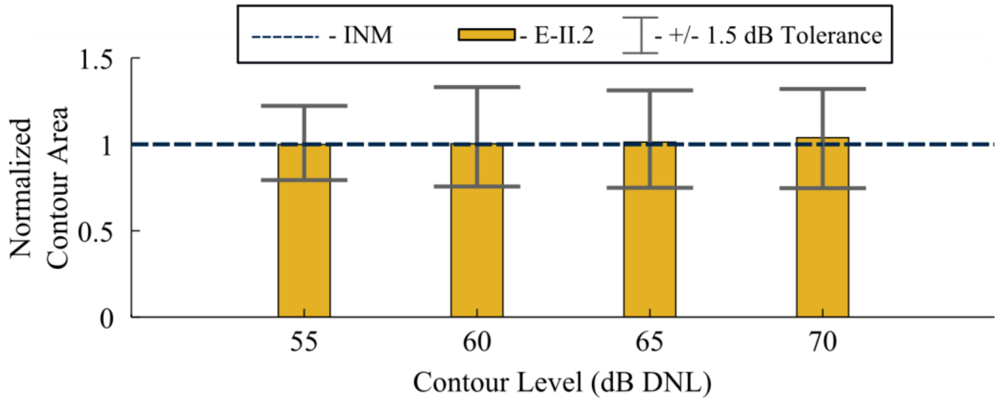


Figure 4.5: Contour area comparison for E-II.2.

The shape comparison for the DNL 65 dB contour with the significant error points depicted can be seen in and Figure 4.6. For clarity, only every third point is plotted for the test case. Again the significant error points are clustered at points near the rotated runway. Consequently, this was the runway-level grid that required interpolation. While the overall error is negligible, based on the first and second test cases, there are certain points clustered near the runway which seem to stress the interpolation of runway-level grids. Specifically regarding E-II.2, if the west-east runway grid is used as the reference grid, the error points occur near the north-south runway, which is the runway-level grid subjected to interpolation. The cause for this interpolation error can be attributed to the sharp change in noise-levels near the runway. Figure 4.7 demonstrates this effect along the axes of both runways. The large gradients in noise near the runway cause interpolation accuracy to suffer in these regions. These gradients are caused by the nature of noise propagation, and are further exacerbated in homogeneous operation-type scenarios such as the cross-runway case, which only considered departure operations.

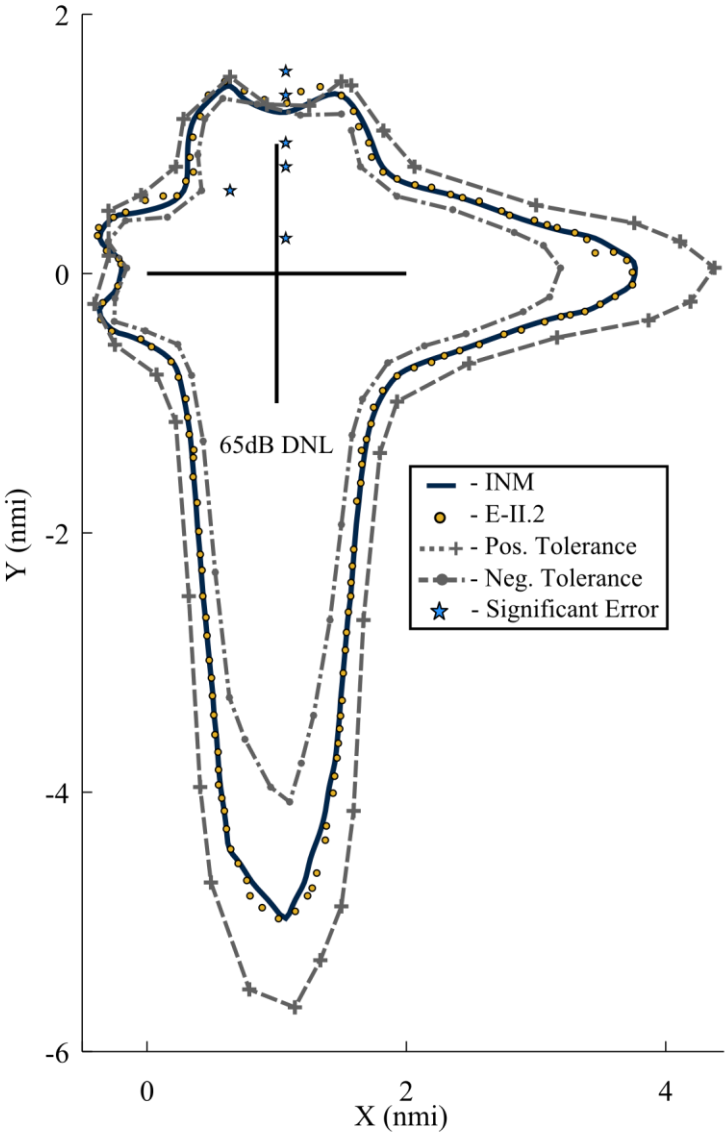


Figure 4.6: Qualitative shape comparison for E-II.2.

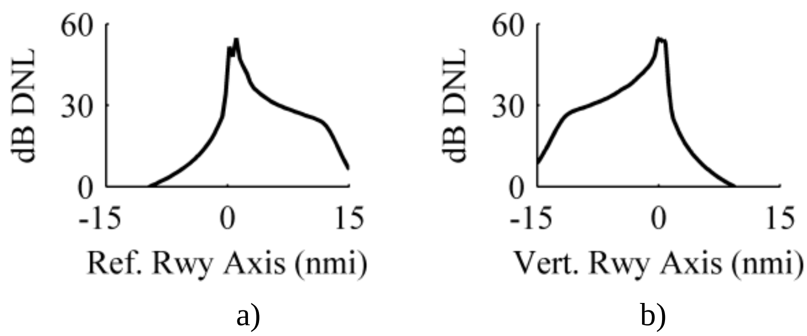


Figure 4.7: a) DNL along ref. runway axis. b) DNL along vertical runway axis.

Depending on the aircraft, a departure operation can also exhibit a dual-spike in noise due to increases in thrust at different portions of the maneuvers. Again, these spikes occur in a relatively short space near the runway, and thus tax the interpolation methods. This error however, can be mitigated simply by using grids of higher refinement. The speed of the generic method will be such that it is capable of accommodating a grid of much higher refinement than those used to enable comparison to INM. Modeling specific operation types in isolation, however, is not the intended purpose of the generic noise model. The details of break-release in a departure contour are unlikely to be relevant or noticeable at the airport-level.

Given the results of the previous validation exercises, it was determined that the results were sufficiently positive to continue with system-level validation. Having identified and characterized the error sources expected with the independent aspects of the model, it becomes easier to discuss system-level error attributed to interpolation and machine round-off sources.

4.1.3 Experiment III: System-Level Verifications

To verify the system-level functions of ANGIM, two test cases were devised in which comparison was performed with respect to INM studies where all assumptions were obeyed. These allow for the combined error of both major tenets of the modeling structure of ANGIM to be analyzed in conjunction.

4.1.3.1 Case 1: Single Rotated Runway Configuration, Cross-Flow

The first test case (E-III.1), presented for system-level validation with assumptions obeyed, consists of a single-runway airport, with cross-flow traffic, angled approximately 346 degrees from the horizontal axis. The INM study was provided by the FAA Office of Environment and Energy (AEE), consisting of 153 unique aircraft flying a total of approximately 530 operations split between approach and departure. Nighttime events accounted for 11% of the total operations. The traffic predominantly pursues a northwesterly heading but a minority percentage of the traffic pursues a southeasterly heading. It is important to note that these are representative scenarios of airport traffic, and are not necessarily designed to model a specific day.

This case yielded a maximum absolute error of DNL 12.5 dB with an average absolute error of DNL 0.14 dB. Meanwhile, 99.96% of the points were within the imposed tolerance band. The point-to-point error distribution, which can be seen in Figure 4.8, shows that all points constituting significant error, and some that do not (based on the tolerance band), are considered outliers to the overall distribution.

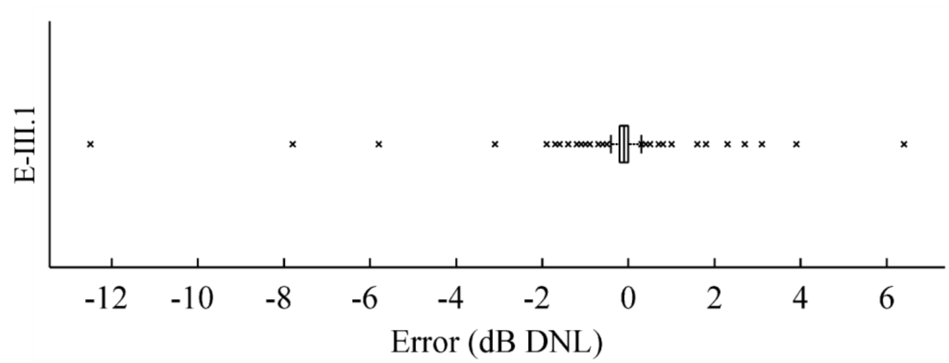


Figure 4.8: Point-to-point error distribution for E-III.1.

Similarly, the contour area comparison, shown in Figure 4.9, suggests that predicted contour area for the contour levels between DNL 55-70 dB is well estimated, although the DNL 70 dB contour shows a slight under-prediction.

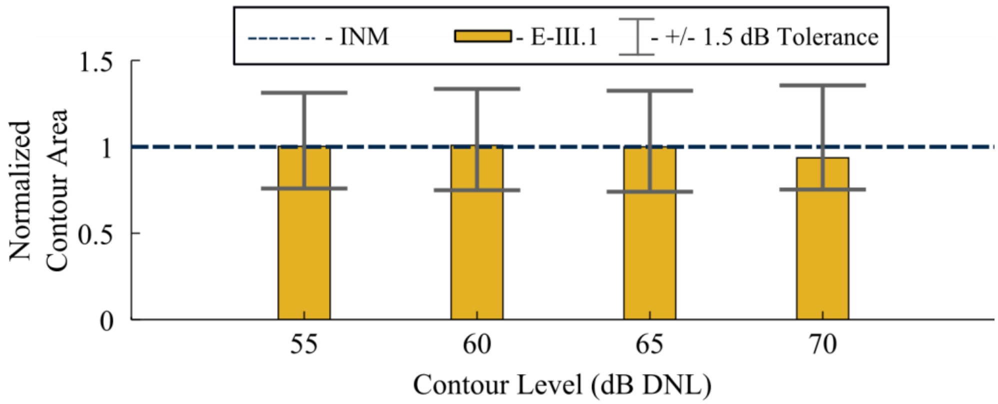


Figure 4.9: Contour area comparison for E-III.1.

Finally, the shape comparison along with the significant error points can be seen in Figure 4.10 for the DNL 65 dB contour. For clarity, only every fourth point of the test case contour is plotted. The results show that the significant error is again clustered near the runway, as expected, while the shape is still accurately portrayed. The increase in significant error points is demonstrative of the difficulty of interpolating rotated runways to an orthogonal grid. For this case, both runways had to be interpolated to match the reference grid used in INM, thus enabling point-to-point comparison. In a non-validation case, the first runway-level grid would be used as the target grid, reducing the interpolations required and the resulting error.

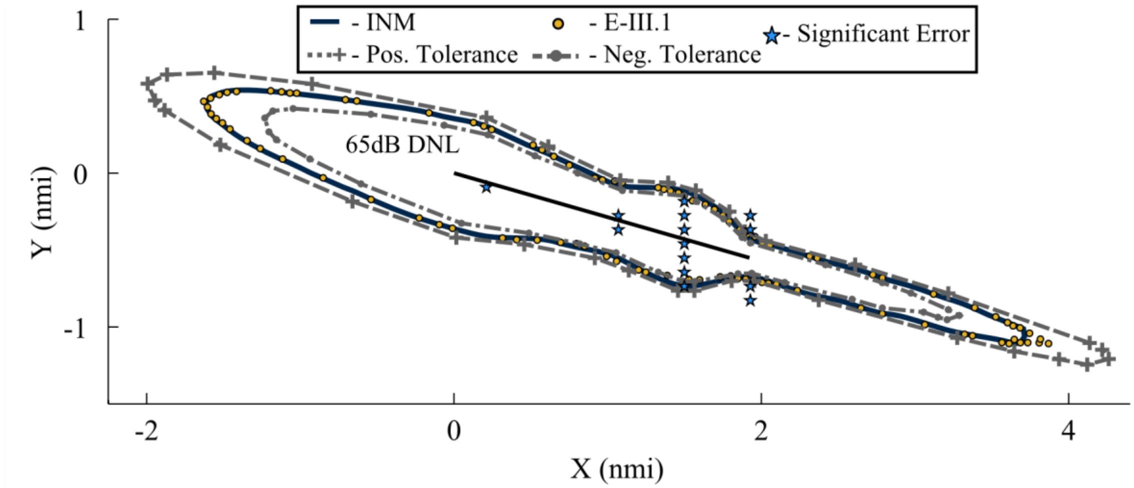


Figure 4.10: Qualitative shape comparisons for E-III.1.

4.1.3.2 Case 2: Four Parallel-Runway Configuration, Cross-Flow

The second test case (E-III.2) consists of a four parallel-runway airport, with cross flow traffic and consisted of 163 unique aircraft flying 2,652.85 operations split between approach and departure, 9.30% of which were nighttime events. Again, the INM model was set to conform to ANGIM assumptions. Due to the cross-flow configuration, this consisted of 8 runways: four in east-flow and four in west-flow occupying the same geographical space.

This case yielded a maximum absolute error of DNL 13.8 dB with an average absolute error of DNL 0.04 dB. The majority of the points (99.93%) were within the imposed tolerance band. The point-to-point error distribution is depicted in Figure 4.11, and similarly to the fourth test case shows that all points outside the tolerance band (and some points within) are considered outliers to the overall distribution.

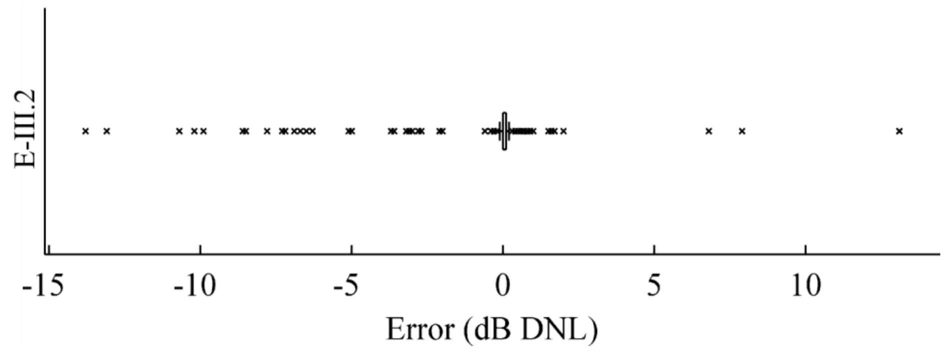


Figure 4.11: Point-to-point error distribution for E-III.2.

This result suggests that the error is very tightly contained well within the tolerance bands. The contour area comparison, shown in Figure 4.12, again shows satisfactory contour area prediction for the DNL 55-70 dB contours. Again the DNL 70 dB contour prediction struggles slightly more than the other contour levels. This inaccuracy is a result of the DNL 70 dB contour being much smaller than the others, and thus any inaccuracy in absolute terms will register a larger relative impact. Finally, the shape comparisons along with the significant error points for the DNL 65 dB contour can be seen in Figure 4.13. For clarity, only every eighth point is plotted.

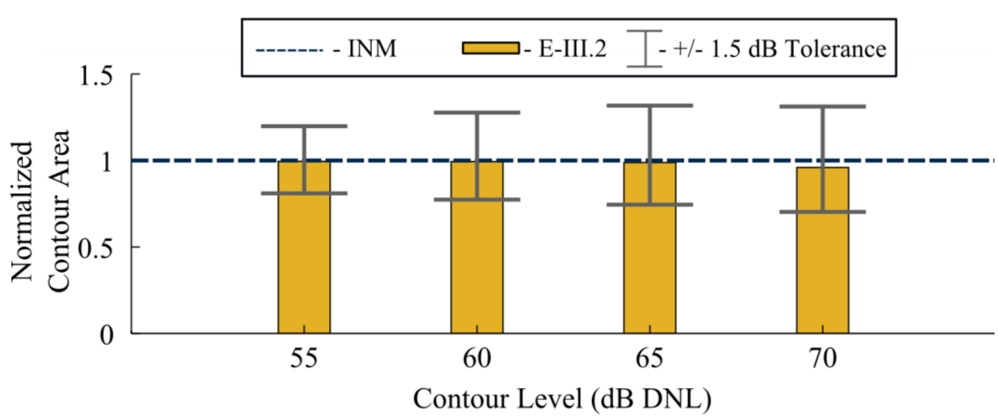


Figure 4.12: Contour area comparisons for E-III.2.

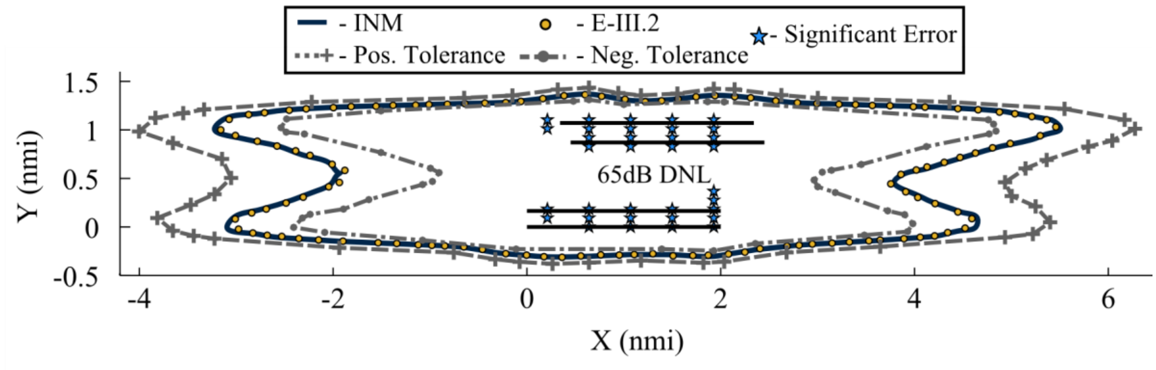


Figure 4.13: Qualitative shape comparison for E-III.2.

The significant error is, once again, clustered very close to the runways, thus having little effect on the ability of ANGIM to predict contour shape. This result suggests that the lack of runway-rotation benefits accuracy. The results of these system-level validations under obeyed assumptions demonstrate that the mathematical logic of the generic noise model is sound. The error due to interpolation is shown to scale with the number of grid interpolations that must be executed (i.e. the number of runways and their traffic flow). Furthermore, the rotation of the runways also stresses interpolation accuracy. These errors constitute only a small number of the total grid points and have little to no effect on the shape of the DNL 65 dB contour. These results further justify comparisons to cases in which assumptions are violated, which are useful for characterizing the effects of each assumption.

4.1.4 Experiment IV: Robustness to Assumption Violations

The final round of system-level validations consists of examples in which assumptions of ANGIM are generally violated by the INM study. The four-parallel runway case was utilized for these test cases. The cases in this experiment represent a significant break from the key assumptions of sea-level elevation and straight ground tracks, testing the effects of each assumption separately and in concert.

4.1.4.1 Case 1: Atmospheric Assumptions Violated

The first case (E-IV.1) consists of violating the sea-level assumption, while abiding by the straight ground tracks assumption, along with utilizing the nominal atmospheric and airport configuration settings included with the INM study. This case exhibited a maximum error of DNL 14.0 dB with an average point-to-point absolute error of DNL 0.43 dB. While point-to-point comparison becomes less meaningful as the assumptions are violated, still 99.62% of the points were within the imposed tolerance band. The point-to-point error distribution, shown in Figure 4.14, suggests that the significant error points are still considered outliers to the rest of the points, which lie within the imposed tolerance band.

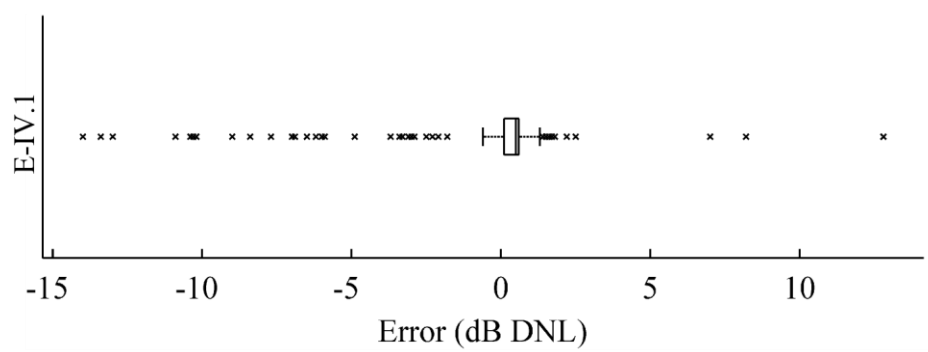


Figure 4.14: Significant error points for E-IV.1.

While most of the significant error is due to under-prediction, this behavior is somewhat predictable. The under-prediction is due to the effects of altitude, combined with other atmospheric effects, yielding greater noise due to the consequent performance effects on the aircraft trajectory, as well as atmospheric propagation characteristics. The contour area comparison in Figure 4.15 shows minor negative effect to the violated sea-level assumption, with predicted areas still well within the tolerance bands.

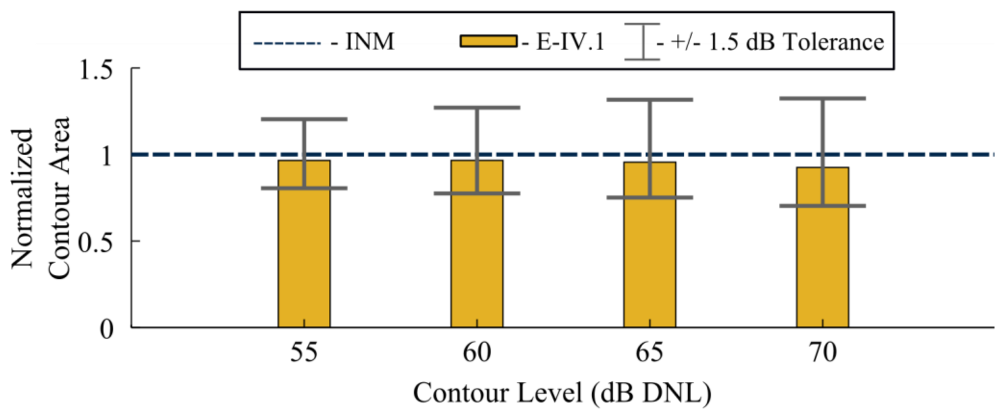


Figure 4.15: Contour area comparison for E-IV.1.

The qualitative shape comparison can be seen in Figure 4.16. For clarity, only every tenth point of the test case was plotted. The spatial distribution of the significant error was plotted separately for clarity in Figure 4.17. Observing Figure 4.17 shows there is still significant error clustered near the runway similar to that observed in E-III.2, but the main difference is the increase in error at the edges of the grid.

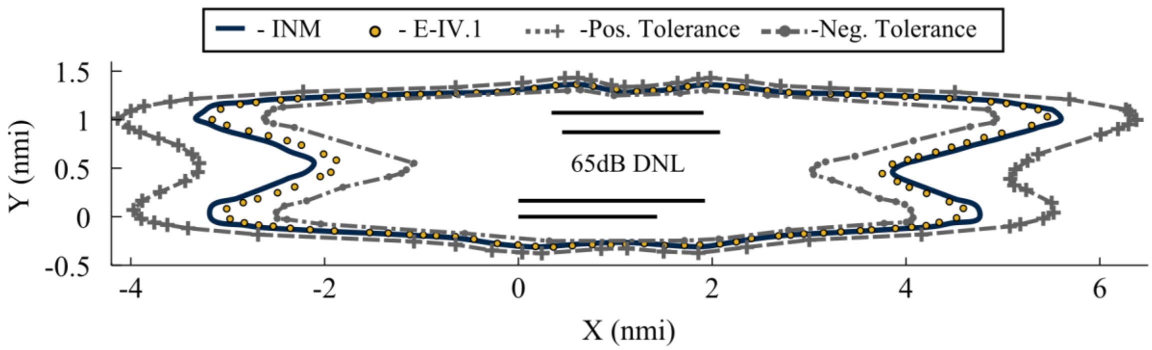


Figure 4.16: Qualitative shape comparison for E-IV.1.

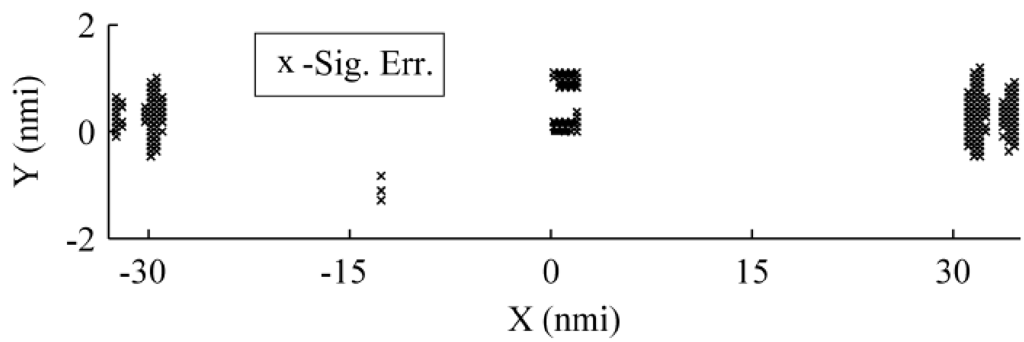


Figure 4.17: Spatial distribution of significant error for E-IV.1.

This error, however, is relatively minor with the average being DNL 1.64 dB and the maximum at DNL 1.7 dB. Fortunately, this error is relatively disconnected from the DNL 65 dB contour and thus has a minor effect on shape and area predictions. The quantitative shape error can be seen in Figure 4.18, where the radial axis is in nautical miles. Coupling this result with the qualitative contour shape comparison, it is apparent that shape fidelity is well maintained, staying within the imposed tolerance band in all regions. The most difficult area to model with respect to shape appears to be the closure points of the contour lobes.

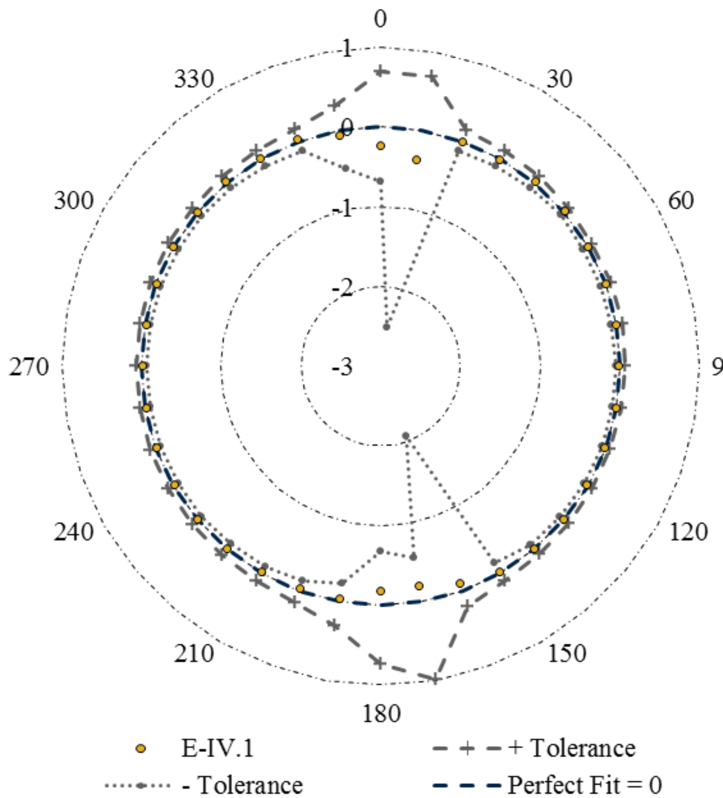


Figure 4.18: Radial contour point comparison for E-IV.1.

While several airports at significantly higher altitudes exist, an analysis of the airports in the INM database shows that approximately 80% of the airports are below 1,000 ft. of elevation [93]. From these results it can be concluded that the sea-level elevation assumption is a defensible one, and while error may increase with airport altitude, it does not corrupt the predictions to the point that they are unusable.

4.1.4.2 Case 2: Ground Track Assumptions Violated

The second case (E-IV.2) consisted of removing the straight ground track assumption in isolation of the sea-level assumption. This test case yielded an average error of DNL 4.49 dB with only 27.6% of the points inside the significant error band. As can be seen in Figure 4.19 the point-to-point error is much more broadly distributed, with the third quartile being outside of the imposed tolerance band. This result signifies the sensitivity of the point-to-point error, with respect to the ground track divergence. As can be seen in Figure 4.20, however, the contour area accuracy is not greatly affected and remains within the imposed tolerance bands. The ability to maintain contour area accuracy is due to the general capture of shape information provided by the proposed method. Figure 4.21 confirms that the basic qualitative shape characteristics are communicated. For clarity, only every tenth point of the ANGIM case is plotted.

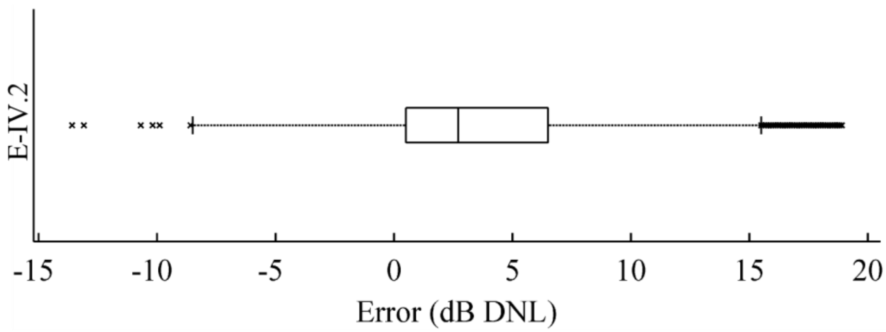


Figure 4.19: Point-to-point error distribution for E-IV.2.

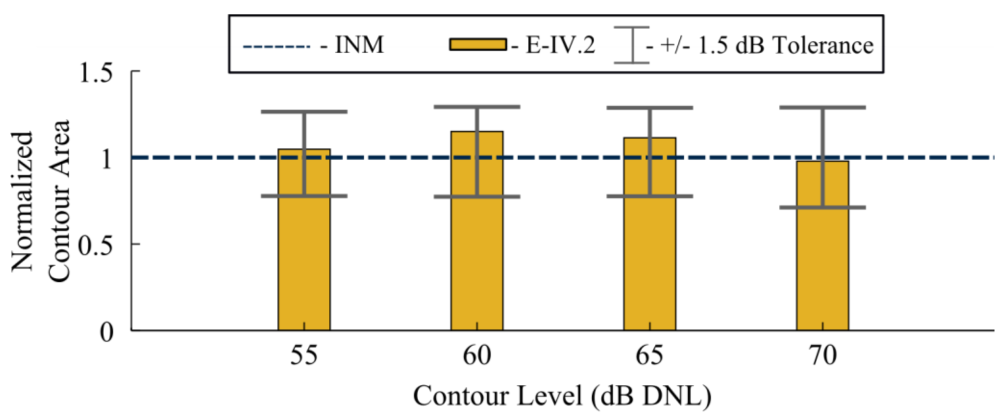


Figure 4.20: Contour area comparison for E-IV.2.

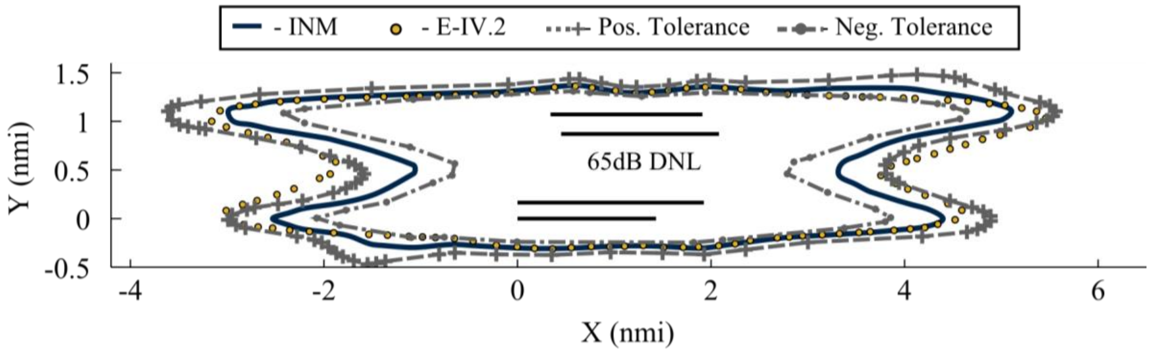


Figure 4.21: Qualitative shape comparison for E-IV.2.

Surprisingly, although the ground track deviation is significant and diverse, the overall objective shape error of the DNL 65 dB contour is within the tolerance band in many regions, as can be seen in Figure 4.22.

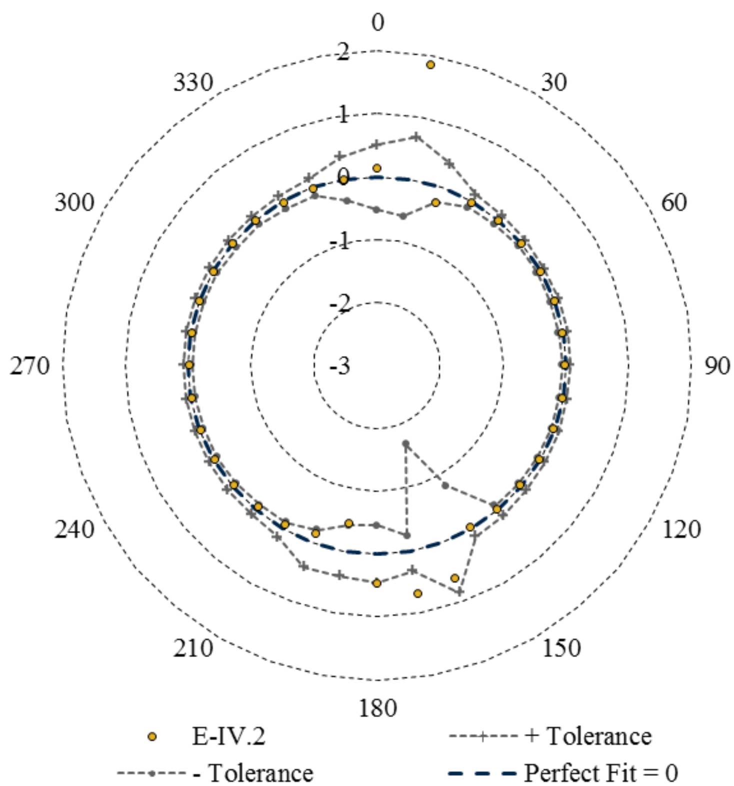


Figure 4.22: Radial contour point comparison for E-IV.2.

This ability to capture the contour shape and area is caused by the relative proximity of the DNL 65 dB contour to the runway nucleus, such that it is not significantly affected by the divergence of the ground tracks. In three-dimensional space, the divergence of the aircraft flight path is more pronounced as the aircraft gains altitude in departure, or at the beginning of the approach operation. Therefore, the divergence may occur at a sufficiently high altitude that the DNL 65 dB contour area and shape are only partially affected. The DNL 55 dB contour, by contrast, would exhibit significantly larger distortions in shape and area due to track divergence. Another potentially important factor, specifically for shape prediction, is that the ground tracks are divergent towards all sides of the airport, allowing the INM contour to retain a certain level of symmetry.

4.1.4.3 Case 3: Comparison to Full Detailed Model

The third case (E-IV.3) uses the entire nominal INM case for the four-parallel runway airport as would be consistent with a typical detailed noise study. Again, point-to-point error will be reported for completeness, although shape and area error are more instructive in these cases. The average absolute error observed was DNL 5.0 dB with 22.79% of the points within the significant error tolerance band. As the point-to-point error distribution confirms in Figure 4.23, the point-to-point error is quite large and again demonstrates the sensitivity of point-to-point error with respect to divergent ground tracks. Point-to-point accuracy, however, is inherently not a practical mode of comparison for this type of method, which ultimately relies on the ability to predict contour area and communicate basic shape information.

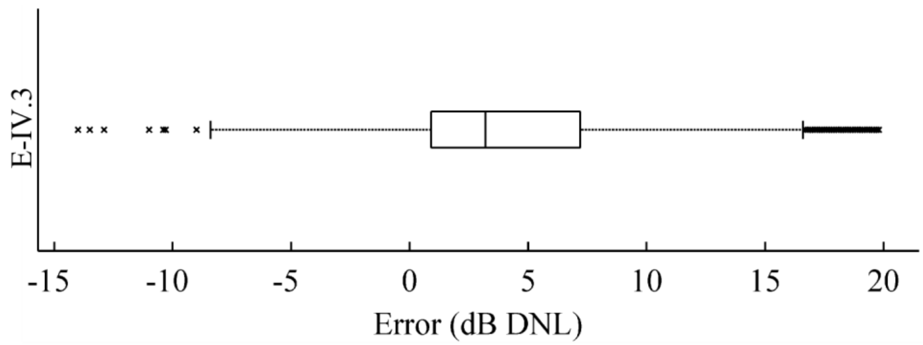


Figure 4.23: Point-to-point error distribution for E-IV.3.

As can be seen in Figure 4.24, the contour area comparison shows predicted areas that are still well within the imposed tolerance bands for the 55-70 dB DNL contour range.

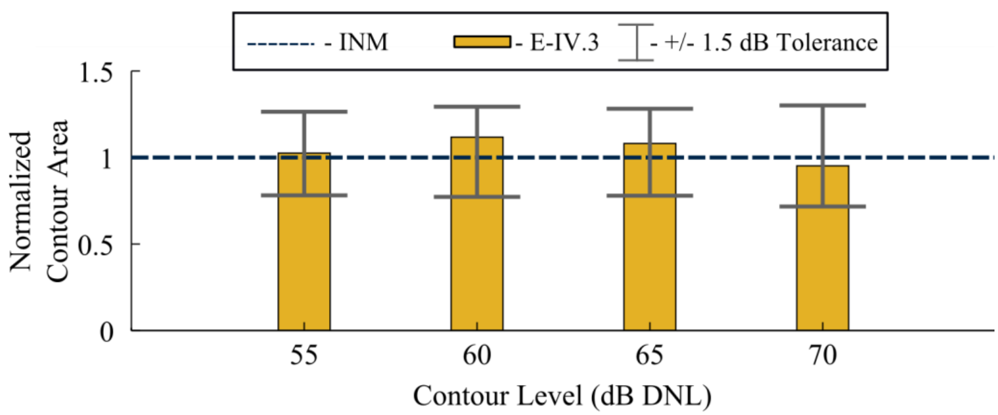


Figure 4.24: Contour area comparison for E-IV.3.

The contour area recovers some accuracy from the previous case due to the specific interplay of elevation and deviated ground tracks of this particular airport configuration. The qualitative shape comparison in Figure 4.25 shows that the basic essence of the shape is still communicated satisfactorily.

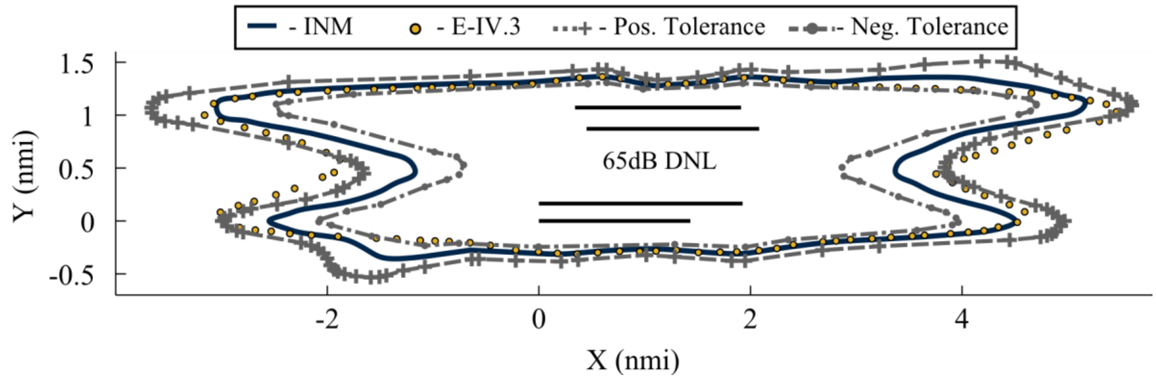


Figure 4.25: Qualitative shape comparison for E-IV.3.

These results confirm that ground track divergence is heavily driving the significant error over airport elevation. As with the previous case, the quantitative shape error for the DNL 65 dB contour shows that for many radial intervals, it is within the tolerance bands, while for others it is not, as can be seen in Figure 4.26. The accuracy comparisons, with respect to these cases, demonstrate that while ANGIM cannot necessarily provide excellent point-to-point accuracy under violated assumptions, with respect to sophisticated modeling methods, it can provide significantly more accurate information with respect to shape as compared to currently available simplified methods, while maintaining contour area fidelity as well. While the shape is not a perfectly accurate representation, considerably more shape information is provided over methods that assume single runway uni-directional flow. Simplifying assumptions, though they sacrifice some of the shape detail, allow for the basic characteristics of contour shapes to be communicated, while simultaneously improving the predicted area over what is possible with equivalency and regression methods.

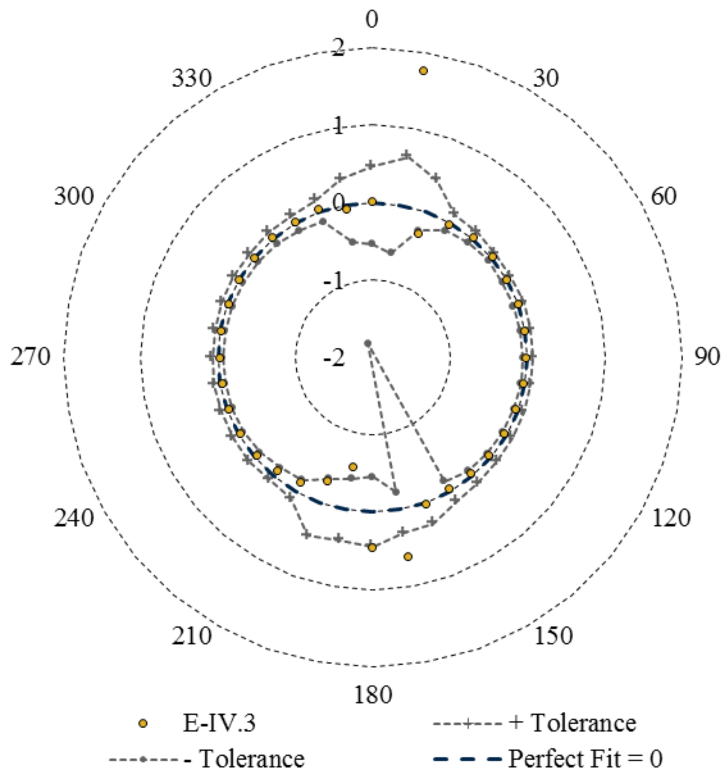


Figure 4.26: Radial contour point comparison for E-IV.3.

Accuracy is only a part of the comparison, however. If the runtime of ANGIM was comparable to a detailed analysis, then the question regarding the accuracy of the generic noise model would be moot.

4.1.5 Experiment V: Process Evaluation

In order to fully demonstrate effectiveness, the setup and runtime of ANGIM must be compared to INM. In some cases, only the runtime could be compared as the INM decks provided by AEE were already configured in detail. E-II.2 could not be compared because there is no way to distinguish when INM is working at the runway-level or the airport-level, and thus any comparison would be meaningless. A summary of the process evaluations is listed in Table 4.1. INM's runtime for the final two cases can range anywhere between approximately two days and 2 weeks, depending on the output options designated for the calculation of detailed grids as specified in the INM User's Guide [107]. It is important to note that these are the times required for INM to produce the results required to perform comparisons to ANGIM. The advantage of the generic noise mode quickly becomes apparent, providing significantly more shape information than other generic methods while allowing for a large number of cases to be run in a short period of time.

Table 4.1: Process criteria summary.

Case	Assumptions Obeyed?	INM (minutes)		ANGIM (minutes)	
		Setup	Runtime	Setup	Runtime
I-1	Yes	26	3.50	2	0.05
II-1	Yes	12	3.75	2	0.13
III-1	Yes	N/A	15.62	1	1.2
III-2	Yes	N/A	56.6	1	5.92
IV-1	No, elevation	N/A	56.12	1	5.92
IV-2	No, ground tracks	N/A	2 days - 2 weeks	1	5.92
IV-3	No	N/A	2 days - 2 weeks	1	5.92

Enabling a large number of cases to be executed allows for the rapid-fleet-level estimation of noise. While some accuracy and detailed modeling capability is sacrificed, as was demonstrated above, a significant amount of time is saved. Thus, more exploratory cases can be evaluated at the screening level before investment in detailed modeling resources is required. Although detailed methods are still preferred for focused analysis, ANGIM enables the evaluation of a large number of technology package implementation scenarios earlier in the decision-making process in support of the generic framework for fleet-level environmental assessments. Perhaps of equal significance, is the ability to run ANGIM in an automated fashion, allowing a large number of cases to compute without requiring any user in-the-loop interaction. This capability is seriously limited in detailed methods, but the simplification of inputs required for ANGIM enables the rapid setup and execution of batch runs at a large scale.

4.1.6 Discussion

This work constitutes a summary of the verification and validation exercises performed to benchmark the developed rapid generic fleet-level noise model; ANGIM. ANGIM was evaluated via unit-level tests and system-level tests in which the "gold standard" (INM) both obeyed and violated assumptions. Comparisons were made with respect to the point-to-point accuracy, the contour areas, the shape, and the process characteristics of the ANGIM and INM cases. The results were used to characterize the expected error under various scenarios of varying conditions. The results of the validation of accuracy, especially in the context of setup and runtime, provide sufficient justification that ANGIM can be used for screening-level analyses of noise contours at the airport and fleet-level. By capturing the airport-level between the aircraft and fleet-levels, the shape characteristics of noise contours are leveraged to improve the estimation of affected area. Because the approach is not limited to using INM as the aircraft-level grid generation tool, it is flexible enough to incorporate aircraft with different technology packages implemented, or to handle evolutions in aircraft noise modeling. Providing shape information improves the fidelity of communicated results, because area by itself only provides a measure of contour scale. It is important to note that ANGIM is not intended as a replacement for detailed noise models such as INM or AEDT, but rather as a preliminary screening step to better direct and focus the intense efforts required to perform detailed analyses of fleet-level noise. Allowing the user to perform multiple varied runs in a short period of time enables more exhaustive trade studies in the technology selection space.

Based on the results, ANGIM can be used in any situation where the assumptions are reasonably obeyed, as shown by the comparisons to INM results. Unlike the equivalency and regression methods surveyed in Chapter 2, there is no need to also assume pre-determined airport geometries. In the case of AEM, only single-runway uni-directional flow is allowed, and thus the method is only considered sufficiently accurate to provide binary decision-making requiring further detailed study. Regression methods on the other hand, gather INM data from airports with limited geometric variability, and suffer in prediction accuracy when assessments are made for airports outside of the sample set used to create the regressions. While even the predicted areas can sometimes be acceptable, the lack of shape information makes any future endeavors to predict the affected population significantly less accurate. ANGIM can be used to provide significant resource reductions to evaluate a large number of cases, as long as the user properly accounts for the assumptions made. Therefore, it is most valuable in exploring cases that do not examine modifications to variables that are simplified or defaulted, as described by the assumptions, but are instead interested in fleet-level trends of changes to technological and operational settings. While a breakdown in assumptions naturally results in loss of fidelity with respect to all metrics compared, the contour area and shape predictions still fared relatively well and demonstrate that the assumptions are defensible. The effect of divergent ground tracks is most significant to the accuracy of the prediction, and therefore airports with multiple exceptionally extreme diversions may lead to increased error. Caution should be used when analyzing a given airport, comparing the ground tracks and the actual Part 150 contours to a straight ground track version in ANGIM, especially with respect to shape. Consideration should also be given to the symmetry of the ground track deviations, as a symmetric fluctuation aids ANGIM in retaining the basic contour shape characteristics, while an asymmetric ground track deviation may result in larger shape error.

Although assumptions have been made to simplify the process, it is important to note that all ANGIM comparisons were done without performing any calibrations. In future developments it is possible to apply calibrating factors to further tune ANGIM responses to better match a detailed INM study for a given airport. For example, the relationship between altitude and noise response is relatively well understood, and can probably be accounted for after the airport-level grid is calculated, improving accuracy. The other major assumption, straight tracks, may also have opportunities for calibration that can be examined via spatial surrogate modeling. Future work, which will be discussed in more detail in Chapter 6, could also characterize and examine the effect of each particular ground track divergence to the overall error.

ANGIM, along with the entire generic fleet-level noise modeling framework developed for this research, must eventually be incorporated within a comprehensive environmental forecast analysis to create a multi-objective environmental trade space for evaluating proposed environmental emissions mitigation strategies across multiple metrics at the fleet-level. In fact, the true value of ANGIM is in its application to a generic framework for modeling fleet-level environmental effects, including the development of Generic Vehicles that appropriately capture noise characteristics for various classes of aircraft [9], [135]. The runtime of the model is most sensitive to the number of aircraft in the flight schedule and the number of runways in the airport geometry. By incorporating generic vehicles, the computational efficiency of the method can be maximized. Similarly, the definition of each specific airport is another example of incongruent levels of fidelity being utilized early in the decision process. If representative airports could be developed specifically for fleet-level noise evaluation, the speed and efficiency of the approach can be further cultivated. Essentially, what is desired is a set of Generic Airports that represent the large majority of airports, in the same way that Generic Vehicles represent the large majority of vehicles in the fleet. Using these capabilities in concert would allow the user to infer behaviors of many airports by simply analyzing a representative subset with operations consisting of the generic vehicles. The development of Generic Airports is enabled by a capability such as ANGIM, and the results of this activity are the subject of the next section.

4.2 Airport Categorization

The activities defined in the approach were carried out under the assumptions stated, utilizing the techniques outlined in detail to create generic classes of airports from the MAGENTA 95 sample set of airports. The overall goal is to create a set of Generic Airports that can be used to infer trends about the specific airports in a fleet-level study, without having to run an airport-level noise model for each airport.

4.2.1 Operational Characteristics

The operational characteristics considered for grouping were the average daily operations, or operational volume, and the distribution of those flights across different seat classes of aircraft, ranging from 2-9. These categorizations were used to create Generic Runways, which encapsulate the operational essence of the airports they represent. Generic Runways were then verified and validated to ensure that they produce reasonable representations of the MAGENTA 95 sample airports.

4.2.1.1 Total Operations Volume Grouping

K-Means statistical clustering was utilized for the operational volume groupings. The clustering provides the user with the option of selecting the total number of groups. Based on several trial runs, a total of three volume categories, Small, Medium, and Large, were chosen, and are summarized in Figure 4.27. While the total number of categories was chosen, the bounds were determined by the statistical clustering algorithm. It could have been possible to further articulate the Medium airport category into two separate clusters and the Large category into two as well, or place the Large airport with the lowest average daily operations into the Medium category. Ultimately, the categories provided by the clustering were left intact to preserve the mathematical process in this development phase. After Generic Airports have been shown to demonstrate accuracy based on the logic used to create them, future versions can explore specific trades in the process to maximize the utility of the end result. The volume categories chosen sufficiently articulate the operations volume space to ensure that aircraft distribution groupings are within the same general order of magnitude.

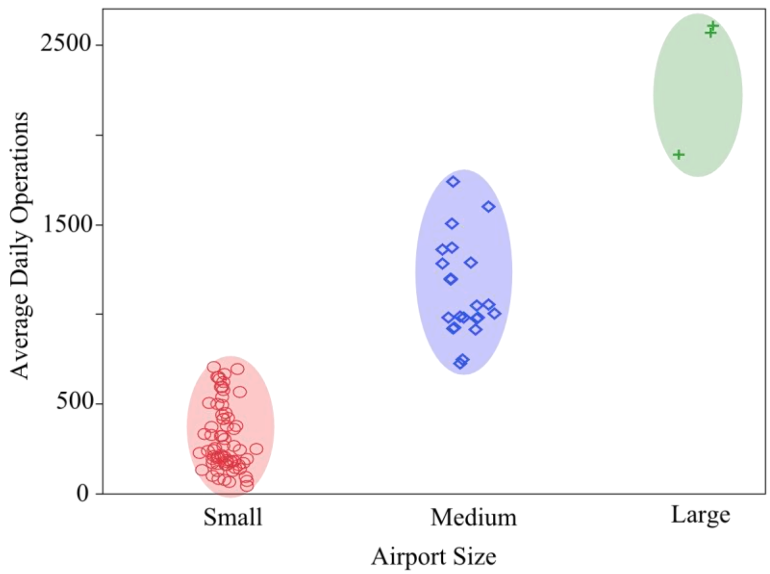


Figure 4.27: Clustering by average daily operations.

4.2.1.2 Seat Class Distribution Grouping

Once the operational volume groups were created, the distribution of flights by seat class was analyzed within each volume group. Again, based on trial analysis, it was projected that six Generic Runways would likely provide a total number of Generic Airports between the desired ¼ - ⅓ of the 95 total airports. This kind of reduction of the airport space would be significant for rapid fleet-level modeling purposes. These projections were possible due to the parallel development of Generic Runways and Generic Infrastructures, which will be presented below. Again, it is possible that slightly more or less runways would be desired under different conditions, especially if the number of volume clusters is modified, but these trades will be left for future work, as they are not immediately relevant to the successful development of the process.

The six generic runway configurations defined consist of two Small (S1 and S2), two Medium (M1 and M2), and two Large (L1 and L2). K-means clustering was again implemented to generate these clusters, and the resulting clustered seat class distributions can be seen in the parallel plots in Figure 4.28. As can be seen in the figure, airports with similar seat class distributions are grouped together, which can then be used to define the Generic Runways. Of particular interest is the comparison between S2, M2, and L2 clusterings which display rather similar trends in seat class distribution. If the airports had not been previously clustered by operational volume, these airports may have been clustered together, which would have confounded the average Generic Runway operations because of the varied range in total operations.

The Generic Runways were created by averaging the total number of operations of the airports represented by each grouping, averaging the seat class distributions and assigning those average operations to the representative aircraft for each seat class. In future work, the Generic Vehicles, originally developed by Becker and that are currently being modified, will be utilized in lieu of the representative aircraft [9], [135]. The representative aircraft were chosen by analyzing the distribution of flights by each seat class type in the MAGENTA 95 baseline operations, and by the contour size as well. The aircraft selected provide the best possible average representation of each seat class, but it is expected that Generic Vehicles will be able to attain a greater level of precision in this regard. The chosen representative aircraft are listed in Table 4.2.

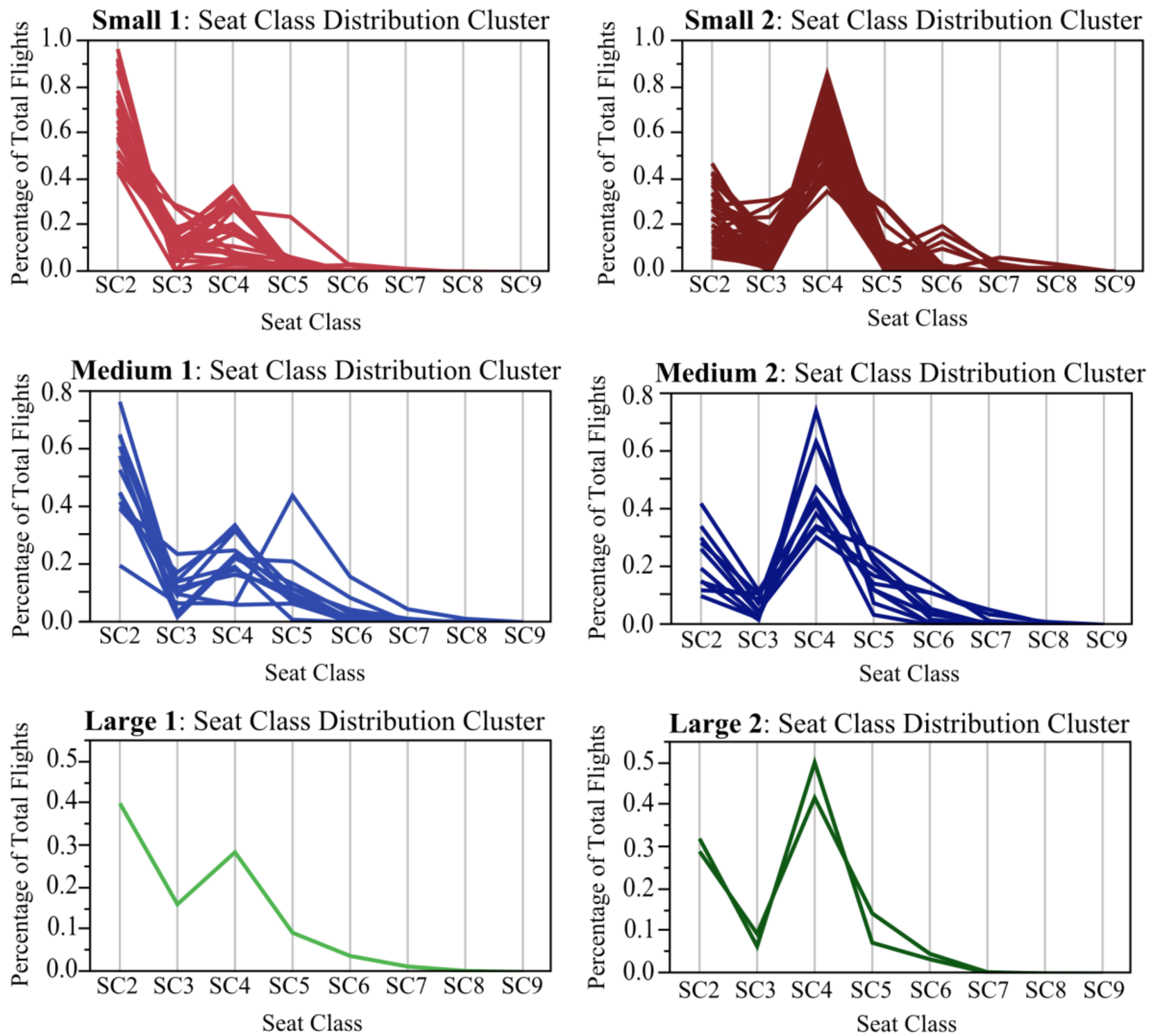


Figure 4.28: Seat class distributions Generic Runways.

Table 4.2: Representative ACCODE/ENGCODE combos by seat class.

Seat Class	ACCODE	ENGCODE
2	CRJ1	1GE035
3	A320-2	1CM008
4	B737-6	3CM031
5	B737-8	8CM051
6	B767-4	2GE045
7	B777-2	2PW061
8	B747-8	2GE045
9	B747-8	2GE045

Besides distributing total operations amongst the various seat classes, the Generic Runways also required stage length information to constitute a complete operational input to ANGIM. The stage length distributions of flights were also averaged from the actual schedules of the airports within each Generic Runway group. A summary of the Generic Runway distributions are listed in Table 4.3.

Table 4.3: Summary of Generic Runway characteristics.

GR	# of Apts.	Ops/Day	%SC2	%SC3	%SC4	%SC5	%SC6	%SC7	%SC8	%SC9
S1	29	250.29	66.67	11.52	18.28	3.11	0.34	0.07	0.02	0.00
S2	41	345.44	23.49	9.29	57.58	7.14	2.01	0.35	0.14	0.01
M1	12	1162.81	50.91	10.64	21.55	12.62	3.37	0.66	0.23	0.03
M2	10	1091.78	23.41	6.60	47.22	15.88	5.34	1.29	0.24	0.03
L1	1	2571.33	40.28	16.19	28.59	9.40	3.88	1.34	0.30	0.04
L2	2	2253.03	30.65	8.00	46.10	10.87	4.08	0.26	0.04	0.00

Fractional operations are a function of the mathematical averaging. While some Generic Runways have relatively sparse membership, it is important to recall that these Generic Runways must be able to account for changes to the operational landscape, as well as potentially account for airports outside the baseline sample set utilized to create the groups.

4.2.1.3 Generic Runway Verification and Validation

Once Generic Runways were constructed and defined for input into the ANGIM model, the experimental plan to confirm their utility could be carried out. This plan included a baseline verification, identification of bias error due to aircraft variability with respect to the representative aircraft, and robustness to possible future flight schedules.

4.2.1.3.1 Experiment I: Baseline Verification

The first experiment consisted of comparing the Generic Runways to the unique MAGENTA 95 airport operations using only the representative aircraft in both the actual and Generic Runway flight schedules. The operations were all flown on single-runway cross-flow airport configurations, to remove any bias due to geometric effects. The purpose of this experiment is to isolate the observed error as much as possible to yield only the precision error caused by averaging the airport operational characteristics in each statistical grouping described above, and the error due to not utilizing seat class distribution as a grouping variable. The experiment acts as a verification that the statistical methods used to generate the Generic Runways are behaving as intended and have been implemented properly. The results for each Generic Runway and in total are listed in Table 4.4.

Table 4.4: Baseline verification of Generic Runways.

GR	GR Area (nmi^2)	# of Airports	Pred.Area (nmi^2)	Actual Area (nmi^2)	Error (nmi^2)	% Error
S1	0.49	29	14.21	12.89	1.32	10.24
S2	0.86	41	35.26	35.21	0.05	0.14
M1	1.85	12	22.20	22.17	0.03	0.14
M2	2.35	10	23.50	23.56	-0.06	-0.25
L1	3.95	1	3.95	3.95	0.00	0.00
L2	3.97	2	7.94	7.93	0.01	0.13
Totals		**95**	**107.06**	**105.71**	**1.35**	**1.28**

As can be observed from the results, the error is negligible in all Generic Runway groups except for S1. In fact, the error in S1 is responsible for the large majority of the fleet-level error, which is above 1%. While the error by percentage for S1 is 10.24%, the total error is only 1.32 nmi^2, which accounts for 1.25% of the actual computed fleet-level area. Overall, the airports represented by S1 only account for 12% of the fleet-level area, spread out over 29 airports. S1 is also the Generic Runway with the smallest DNL 65 dB contour as this group contains airports with very low average daily operations. Consequently, such low operations at times barely produce contiguous definable DNL 65 dB contours. As a result, the S1 is over-predicting the overall contour area for these airports. The cause for this over-prediction is that all operations were modeled as daytime operations, due to a lack of distinction in the datum year operations. If nighttime flights were included the overall fleet-level area would increase, and the over-prediction of S1 would be expected to subside. Based on the behavior of the other Generic Runways, the variables used for grouping are clearly sufficient in articulating the uniqueness within the operational landscape of the MAGENTA 95 airports.

4.2.1.3.2 Experiment II: Robustness to Aircraft Variability

The Generic Runways were next compared to the MAGENTA 95 operations, utilizing the appropriate unique aircraft designated in the original flight schedules. Generic Runways, of course, continue to utilize the representative aircraft. The purpose of this experiment was to introduce diversity within the aircraft fleet, forcing the Generic Runways to predict behavior in the face of fleet variability. While this activity is expected to be better served by the upcoming set of Generic Vehicles, providing this test with the representative aircraft demonstrates the ability of the Generic Runways to retain their accuracy in a sub-optimal setting, while quantifying the resulting error. At such a point, calibrations can be applied to obtain a more accurate set of Generic Runways, including adjustments to account for contours that barely produce a DNL 65 dB contour. The results of the validation to aircraft variability are listed in Table 4.5. The variability improves the ability of S1 to predict its constituent group. Most Generic Runways are not severely affected, although errors increase across the board. The largest absolute and percent error is for the L2 Generic Runway, which represents only two airports.

Table 4.5: Generic Runway robustness to aircraft variability.

GR	GR Area (nmi^2)	# of Airports	Pred.Area (nmi^2)	Actual Area (nmi^2)	Error (nmi^2)	% Error
S1	0.49	29	14.21	13.94	0.27	1.94
S2	0.86	41	35.26	36.98	-1.72	-4.65
M1	1.85	12	22.20	23.06	-0.86	-3.73
M2	2.35	10	23.50	22.97	0.53	2.31
L1	3.95	1	3.95	4.34	-0.39	-8.99
L2	3.97	2	7.94	10.96	-3.02	-27.56
Totals		**95**	**107.06**	**112.25**	**-5.19**	**-4.62**

L2 presents such large error because, although both airports are categorized as Large, one has operations very close to the upper range of the Medium operational cluster while the other is at the top of the Large operational cluster. As a result, the averaging of the daily operations for the Generic Runway occurs over a large range, leading to increased error. Again, the overall contribution of L2 error to the fleet-level contour error is only approximately 2.7%. The purpose of the Generic Runways is to capture the diversity in the operational landscape of airports. While larger errors may be present in some groups, these are relatively small contributions in absolute terms to the overall fleet-level predicted area.

Nonetheless, some of this variability can be accounted for by applying calibrations through perturbation of the average daily operations to better approximate the airports within each group. The amount of adjustment was determined by calculating the necessary change at the Generic Runway level, and then using the ratio of the areas and the known operations volume of the Generic Runways to solve for the desired new total operations, as shown in Equation 4.1.

$$\frac{Area_{GR-orig}}{Area_{GR-Desired}} = \frac{Ops_{GR-orig}}{Ops_{GR-Desired}} \tag{4.1}$$

This is an approximate linear relationship, but it is applicable in this case, and frequently one iteration of the process is sufficient to converge on a calibrated operationa volume. For Generic Runways requiring substantial adjustment, sometimes two iterations are required, because the linearity of the equation is best preserved in smaller ranges. The calibrated average daily operations and validation results are listed in Table 4.6. As can be inferred from the calibrated data, the operations for the Large Generic Runways required a significant increase to the original average operations, specifically for L2. This increase is partially a result of the large range of operational volume that L2 must cover, but also demonstrates that at higher operational volumes, the aircraft variability can become more of an issue.

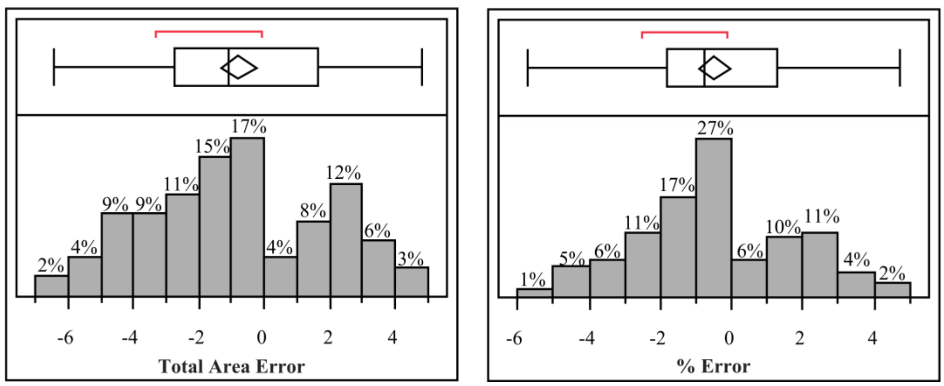
Table 4.6: Generic Runways calibrated for aircraft variability.

GR	Avg. Daily Ops.	GR Area (nmi^2)	# of Airports	Pred.Area (nmi^2)	Actual Area (nmi^2)	Error (nmi^2)	% Error
S1	237	0.48	29	13.92	13.94	-0.02	-0.14
S2	370	0.90	41	36.90	36.98	-0.08	-0.22
M1	1215	1.92	12	23.04	23.06	-0.02	-0.09
M2	1050	2.29	10	22.90	22.97	-0.07	-0.30
L1	2857	4.34	1	4.34	4.34	0.00	0.00
L2	3260	5.48	2	10.96	10.96	0.00	0.00
	Totals		**95**	**112.06**	**112.25**	**-0.19**	**-0.17**

This result is only logical, as more operations implies more opportunities for unique aircraft that differ from the representative set to fly in the schedule. Therefore, it is important that Generic Vehicles appropriately balance the mix of aircraft for a given category, not only in their noise but also their prevalence in the fleet, so that accuracy can be maintained at higher operational volumes as aviation demand increases as purported by recent forecasts.

4.2.1.3.3 Experiment III: Robustness to Forecast Variability

The final experiment to evaluate Generic Runways tests their ability to scale with the operational landscape in a large number of potential situations. For this purpose, the actual MAGENTA 95 airport operations were varied using composite beta distributions, applied through a scaling factor on the total number of flights by seat class. Each case represents a different potential change to the operational landscape. The Generic Runways were then scaled parametrically by seat class using the same scaling factors, and the ability of Generic Runways to retain their accuracy can thus be examined. The success of the experiment is measured by examining the actual versus predicted responses of the Generic Runways and the MAGENTA 95 at the fleet-level and also within each Generic Runway group. The correlation of total error to change in operations by seat class can be used to analyze the specific shortcomings of the representative aircraft, and used to quantify what error can be attributed to these aircraft. The distributions of the fleet-level absolute and relative error are shown in Figure 4.29, and relevant statistics are listed in Table 4.7.



a) b)

Figure 4.29: a) Distribution of absolute error. b) Distribution of relative error.

Table 4.7: Generic Runway error statistics.

Error Type	Range	Mean	Median	Std. Dev.
Absolute (nmi^2)	-6.42 – 4.83	-0.82	-1.08	2.73
Relative (%)	-5.75 – 4.72	-0.51	-0.74	2.20

The overall error results show about 11% range on error, but 33% of the cases are within +/- 1% and 60% are within +/- 2% error. 81% of the cases are within +/- 3% relative error, which is acceptable when dealing with fleet-level estimates. The relevant statistics for each Generic Runway are listed for absolute and relative error respectively in Table 4.8 and Table 4.9.

Table 4.8: Absolute error statistics by Generic Runway.

GR	Range (nmi^2)	Mean (nmi^2)	Median (nmi^2)	Std. Dev. (nmi^2)
S1	-4.20 – -0.26	-2.31	-2.36	0.97
S2	-1.92 – 1.66	0.33	0.475	0.76
M1	-0.84 – 2.75	1.26	2.01	0.92
M2	-0.99 – 1.63	0.45	0.50	0.67
L1	-0.59 – 0.36	-0.17	-0.14	0.22
L2	-1.54 – 0.93	-0.38	-0.42	0.60

Table 4.9: Relative error statistics by Generic Runway.

GR	Range (%)	Mean (%)	Median (%)	Std. Dev. (%)
S1	-25.20 – -2.45	-15.71	-16.49	5.26
S2	-5.88 – 5.20	0.60	1.02	1.93
M1	-3.26 – 10.74	4.37	4.79	3.39
M2	-4.91 – 5.78	1.42	1.60	2.40
L1	-9.74 – 8.09	-2.62	-3.16	3.64
L2	-9.21 – 8.88	-2.03	-2.94	4.12

These Generic Runway statistics paint a clearer picture as to where the total error is originating. Again the smallest runway, S1, is responsible for the largest mean error in both relative and absolute terms. This under-prediction is most likely a result of the scaling up of MAGENTA 95 operations that previously had little or no DNL 65 dB contour area into regions that cause the DNL 65 dB contour area to be much larger. Recall that S1 was calibrated to *reduce* the predicted area, suggesting that some of this calibration may have been overzealous. These issues can be removed by including nighttime flight percentages in the Generic Runway models. Future work can focus on gathering and incorporating this data. The L1 and L2 Generic Runways do relatively well under fluctuations to the flight schedule, maintaining very low mean relative and absolute errors. M1 also presented high error, which could not necessarily be accounted for from the analysis provided thus far. Some of the error present overall, however, is due to failures of the representative aircraft in properly depicting the aircraft within each seat class, which will be discussed momentarily.

To visualize the ability of the Generic Runways to retain trends at different future forecasts, the actual by predicted fleet-level areas can be compared. The comparison for S1 can be seen in Figure 4.30.

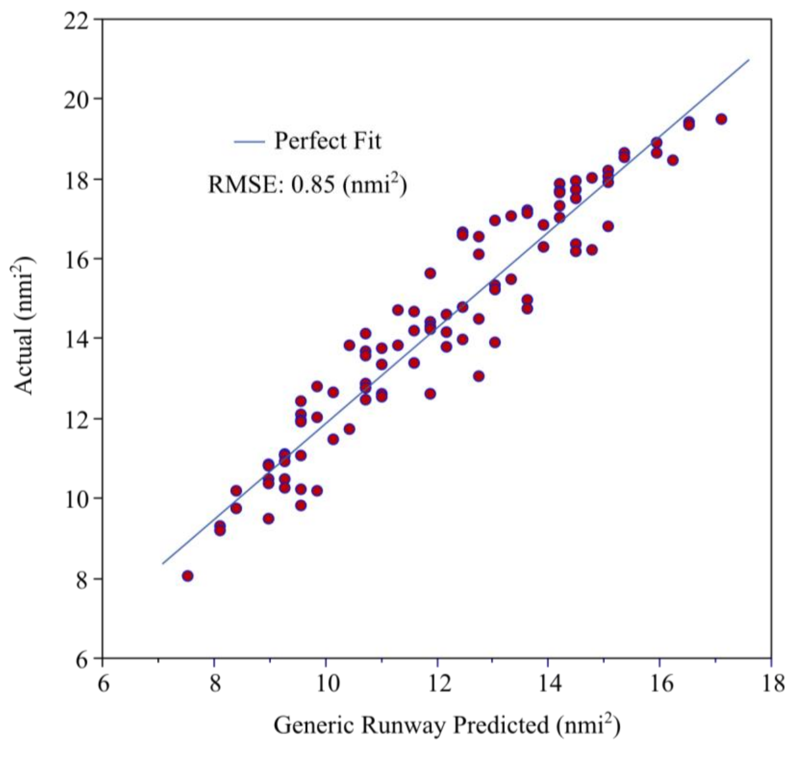


Figure 4.30: Actual by predicted results for S1.

Each dot represents a potential future forecast case, which can result in a net scaling up or down of DNL 65 dB contour area for each Generic Runway and the fleet-level. These results confirm the error observed by analyzing the individual statistics for S1. Because S1 is such a small runway relative to the others, the root mean square error (RMSE) is still only 0.85 nmi^2. This Generic Runway was probably over-calibrated, and the large band of error is due to MAGENTA 95 contours not producing a definable DNL 65 dB contour area when flights are overall reduced. Again, the introduction of nighttime flights should provide a better trend and lower RMSE. Analyzing the actual by predicted response of S2 shows more accurate prediction in Figure 4.31. S2 shows a lower root mean square error than S1 and maintains a much better predictive trend.

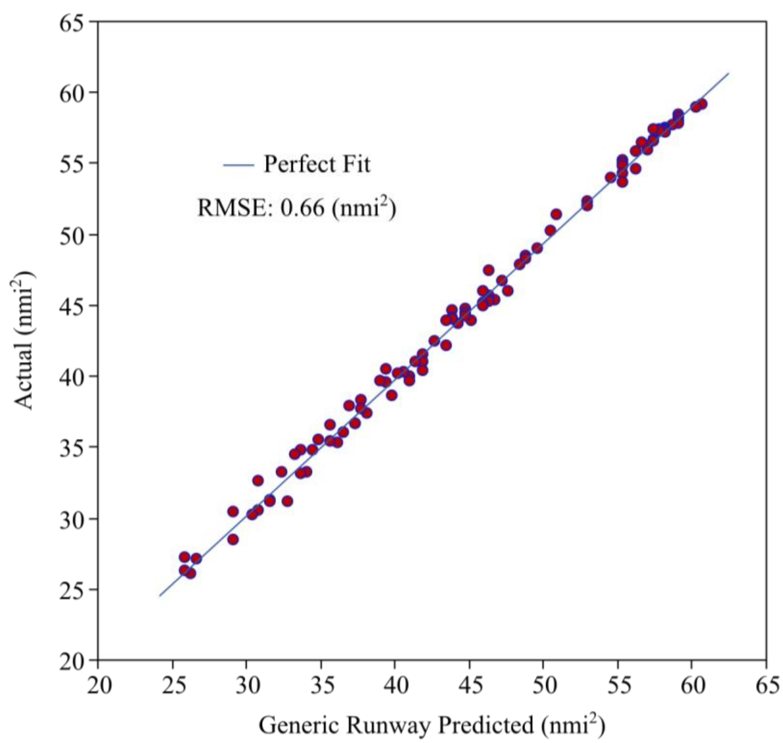


Figure 4.31: Actual by predicted results for S2.

The remainder of the Generic Runway actual by predicted plots are reserved for Appendix E. Thus far, the Generic Runways have demonstrated certain inaccuracy when flights are scaled down, but in general have demonstrated that they can scale with the actual flight schedule trends. Most of this error is accounted for by the exclusion of nighttime flights, which explains why the Generic Runways retain accuracy better at higher contour areas. The overall fleet-level actual by predicted results can be seen in Figure 4.32. As can be seen from the data, the error decreases as the fleet-level predictions increase, and the Root Mean Squared Error is 2.70 nmi^2, which is very low at the fleet-level.

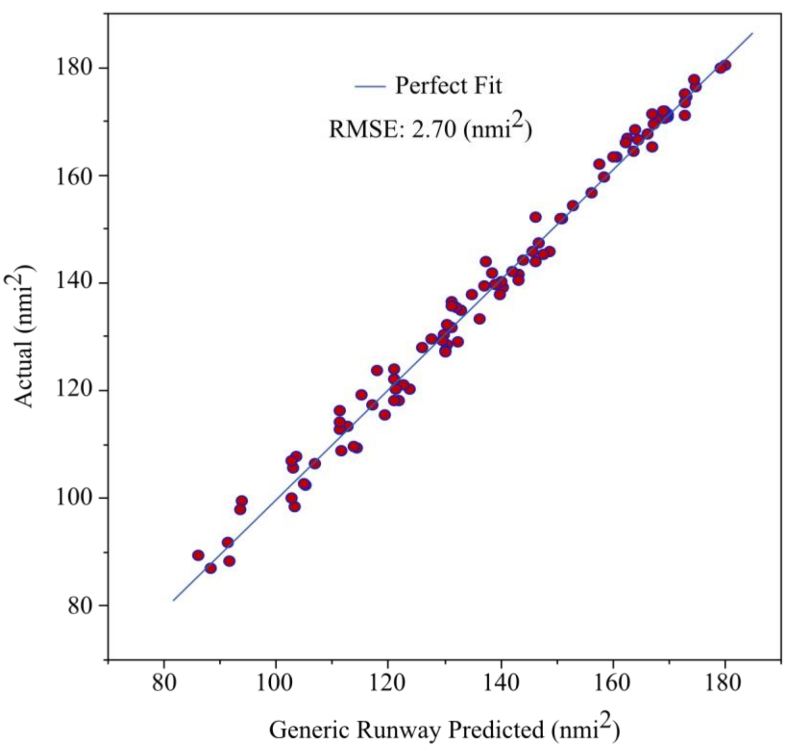


Figure 4.32: Fleet-level Generic Runway actual vs. predicted.

These results suggest that Generic Runways are successfully preserving the operational trends observed in the actual cases, and that they can be used to scale operations to predict future forecasted flights properly. The increase in error at lower total fleet-level values is probably caused by the operational scalings resulting in several MAGENTA 95 contours presenting null DNL 65 dB areas,which is a confounding result that may be removed by including nighttime flights in future iterations.

Looking into the specific correlations by change in seat class operations can provide a clearer picture with respect to the amount of error caused by the specific representative aircraft chosen for each seat class. The correlation values for each seat class change with respect to relative total error and M1 absolute error are listed in Table 4.10. The results show significant correlations to seat classes 5 and 6, and less significantly for seat classes 3 and 4.

Table 4.10: Correlations with respect to change in relative error.

Correlation	SC2	SC3	SC4	SC5	SC6	SC7	SC8	SC9
% Total Error	-0.05	-0.42	-0.37	0.62	0.63	-0.04	-0.14	-0.04
M1 Error (nmi^2)	-0.16	-0.32	-0.02	0.83	0.41	-0.35	-0.34	-0.11

The high correlations for certain seat classes suggest that as operations of that particular class are increased, the error is also generally increased. This increase in error is caused by the magnification of any bias error due to the representative aircraft chosen for a given seat class. The correlations observed demonstrate that specific seat classes have representative aircraft that are not quite appropriate proxies for the diversity within those seat classes, and this error is magnified as operations of that seat class are increased. It is expected that if these biases are removed that the error could be reduced significantly. Generic Runways could be re-developed utilizing better representative aircraft, but these exercises are ultimately moot until proper Generic Vehicle baselines are developed as described by Becker but with noise characteristics included [9], [135]. Some of the inaccuracies caused by calibration, and the cost-benefit of modifying the total number of volume and seat class distribution clusters should all be included in future re-assessments.

The main sources of error for the Generic Runways in predicting forecasted trends are the confounding effects caused by null DNL 65 dB MAGENTA 95 contours in low-demand scenarios, and the relative inability of the representative aircraft to serve as proxies for the diversity within each seat class. As demand increases, the Generic Runway accuracy increases, despite the shortcomings of the representative aircraft, suggesting that the error caused by lack of nighttime flight modeling is dominant over the error caused by the representative aircraft. In general, the Generic Runways capture the operational trends observed in the MAGENTA 95 as flight schedule is allowed to fluctuate, demonstrating their applicability in forecasting scenarios.

Having executed the development of Generic Runways to classify and encapsulate the operational characteristics of the MAGENTA 95, attention can turn to the development of Generic Infrastructures that will attempt to classify the airports with respect to their common geometric attributes, to ultimately yield Generic Airports.

4.2.2 Geometric Characteristics

In order to create Generic Infrastructures, first the runway layout and the representative contour were utilized to infer information regarding the total number of effective runways, reducing the geometric space to a more manageable set of geometries. Once classification was completed, several experiments could be carried out to assess the success of the groupings.

4.2.2.1 Observation and Classification

After reducing the MAGENTA 95 airport geometries to effective runway layouts as defined in Section 3.2.4.3, the resulting infrastructures were observed for patterns in their arrangement. After careful repeated observation, seven basic geometric categories were identified that provided a satisfactory baseline qualitative classification of the airport space. These are the Single, Parallel, Intersecting, Parallel-Intersecting, Parallel-Single, Parallel-Intersecting-Single, and Triple Intersecting. They are qualitatively characterized by the examples shown in Figure 4.33. The baseline settings for each Generic Infrastructure were determined through qualitative observation and utilizing any relevant federal guidelines, when available [122]. The Generic Infrastructures can be further categorized into fundamental geometries, comprised of the Single, Parallel, Intersecting, Parallel-Intersecting, Triple Intersecting geometries, and the compound geometries, which contain the remaining two. The fundamental geometries are categorized as such because each contains a meaningful runway interaction that cannot be observed in a different fundamental geometry.

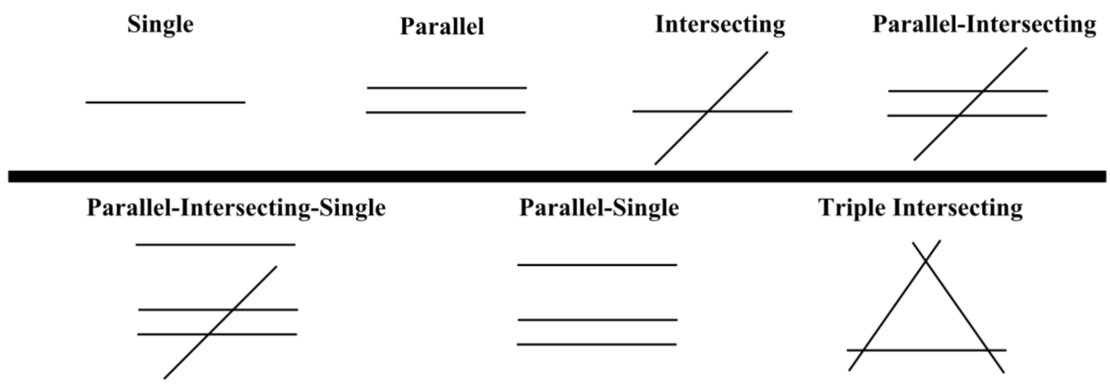


Figure 4.33: Baseline observed Generic Infrastructures.

For example, the Parallel geometry introduces the relationship between two parallel runways, whereas the Intersecting geometry introduces the relationship between two intersecting runways. The Parallel-Intersecting is also a fundamental geometry because it introduces both interactions in tandem, whereas the Parallel-Single and Parallel-Intersecting-Single do not introduce any further runway intersections or novel interactions. While the Single is considered a fundamental geometry, it is a trivial case. With the baseline infrastructures defined, the experimental plan to finalize the Generic Infrastructures can be executed.

4.2.2.2 Generic Infrastructure Verification and Validation

Generic Infrastructures were verified and validated through a set of experiments, each providing certain information that can be utilized to calibrate the final infrastructures to yield a satisfactory result.

4.2.2.2.1 Experiment IV: Baseline Verification

The first experiment (E-IV) to test the baseline Generic Infrastructures consist of comparing the generic classes to the actual unique configurations of the MAGENTA 95 through ANGIM. A fixed flight schedule of operations was utilized for this exercise, comprised of the M2 generic runway. The operations selected are somewhat arbitrary, and the only strict requirement is consistency across all geometries to evaluate the baseline set. A sufficiently large number of total operations were selected, however, to ensure that definable contours resulted for each airport. The baseline comparison results are listed in Table 4.11.

Table 4.11: Baseline Generic Infrastructure assessment.

Infrastructure	Apts.	True Area (nmi^2)	Pred. Area (nmi^2)	Error (nmi^2)	% Error
Single	16	26.30	25.28	-1.02	-3.88
Parallel	9	18.30	17.28	-1.02	-5.57
Intersecting	34	63.55	61.25	-2.3	-3.62
Parallel-Intersecting	28	63.35	60.9	-2.45	-3.87
Parallel-Intersecting-Single	2	2.44	2.33	-0.11	-4.51
Parallel-Single	1	2.19	2.15	-0.04	-1.83
Triple Intersecting	5	11.30	11.76	0.46	4.07
Sum	**95**	**188.23**	**180.95**	**-7.28**	**-3.87**

The results demonstrate that the overall area estimate is relatively accurate, considering these are the baseline geometries. One could suggest that these results are equally indicative that geometry, or shape, is not as important to achieving area accuracy. This assertion would be incorrect, however, since one need only multiply the Single infrastructure area by the total number of airports to arrive at the fleet-level estimate assuming only single-runway airport geometries. This assumption would result in approximately 38 nmi^2 of total error, therefore demonstrating that shape *is* important to area accuracy, the geospatial significance of contour shape notwithstanding. Nonetheless, the error within the geometries and at the fleet-level still suggests certain room for improvement. It should also be noted that two airports were predicted using super-positions of the Generic Infrastructures, due to the uniqueness of the geometries. These were Dallas Forth-Worth (DFW), and Chicago O'Hare (ORD), and examples of these geometries can be seen in Figure 4.34. DFW was predicted using a Parallel-Intersecting superimposed with an Intersecting, while ORD was predicted by superimposing two Triple Intersecting geometries. It may be necessary to ultimately provide these major and important airports with unique infrastructures, which will be discussed at the appropriate time. The overall prediction error for each Generic Infrastructure group can be visualized in Figure 4.35.

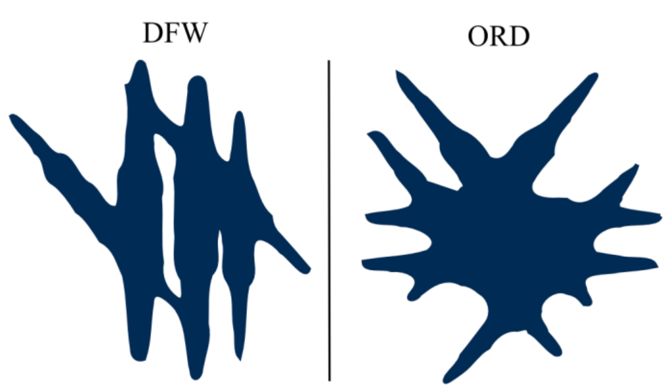


Figure 4.34: Extremely unique airport geometries.

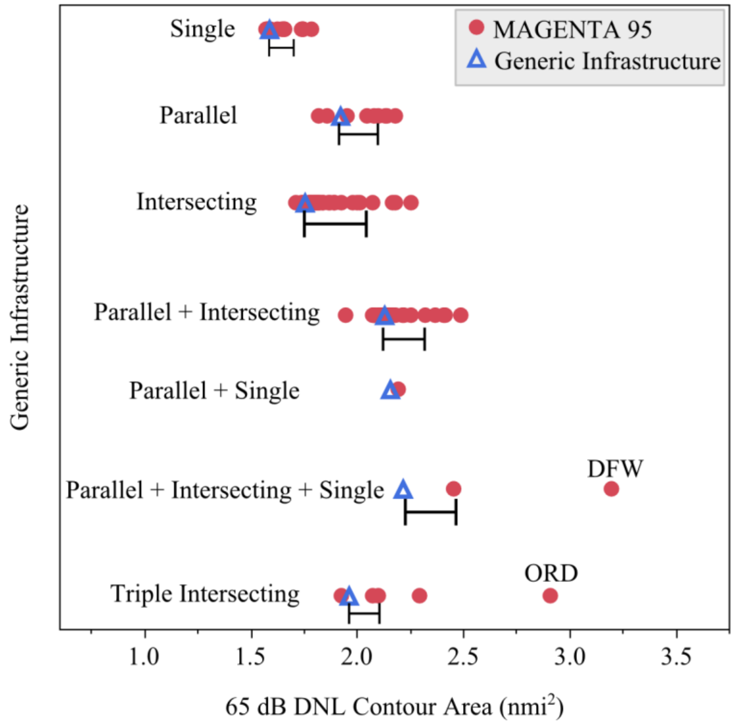


Figure 4.35: Distance from mean of baseline Generic Infrastructures.

Each infrastructure shows every unique airport classified within each geometric category, while also depicting where the baseline Generic Infrastructure falls within these categorizations. The distance between the Generic Infrastructure and the mean value of the unique geometries is the baseline error for that geometric category. The information from this experiment serves as the direction and magnitude in which calibration must occur. The mode of applying such a calibration, however, still remains unknown, and is the subject of the next experiment.

4.2.2.2.2 Experiment V: Robustness to Airport Geometry Variability

The next assessment (E-V) consists of an examination to improve the robustness of the Generic Infrastructures to properly represent various airport geometries. The purpose of the experiment is to uncover the relationship between the geometric variables of the fundamental geometries, and to determine if any relevant sub-categories exist with respect to DNL 65 dB contour area, thereby serving as a quantitative validation of the qualitative classifications performed. The experiment was performed through four infrastructures, corresponding to the fundamental geometries excluding the Single geometry. The variables examined for each fundamental geometry were the cartesian position of the left runway-end and the rotation about that end, if applicable. The primary runway maintained a fixed reference position. The ranges used for the DOE are listed in Table 4.12. Only the Parallel and Intersecting experimental results will be discussed, leaving the Parallel-Intersecing and Triple Intersecting results for Appendix F. Operational settings for total operations and aircraft distribution were varied as well, as defined in Section 3.2.4.5.2.2, to ensure variability in operations did not conceal any important effects. Each case was run through ANGIM assuming even runway utilization and cross-flow operations on each runway.

Table 4.12: Geometric variable ranges.

GI	X_2 (nmi)	Y_2 (nmi)	θ_2 (deg)	X_3 (nmi)	Y_3 (nmi)	θ_3 (deg)
Parallel	-1.25 – 1.25	0 – 1.6	N/A	N/A	N/A	N/A
Intersecting	0.3 – 5.3	-1.5 – 1.5	0 – 180	N/A	N/A	N/A
Parallel-Intersecting	-1.25 – 1.25	0 – 1.6	N/A	0.3 – 5.3	-1.5 – 1.5	0 – 180
Triple Intersecting	-1.5 – 1	-1.5 – 1.5	15 – 75	1 – 3.5	-1.5 – 1.5	105 – 165

4.2.2.2.2.1 Case 1: Parallel Configuration

The Parallel configuration robustness assessment allows for the observation of a contour progressing from a single-runway configuration to a parallel-type contour geometry. Each dot represents a configuration of parallel runways, repeated at multiple operational settings.

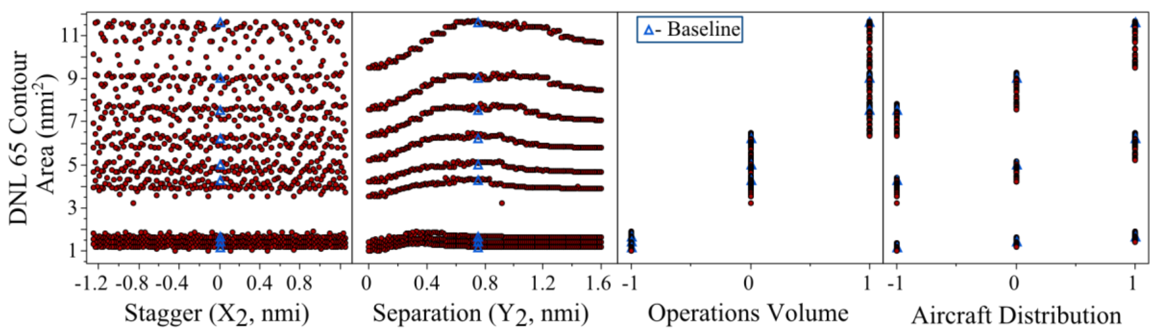


Figure 4.36: Parallel configuration exploration results.

The first conclusion that can be drawn from the results is that stagger has very little influence on the overall contour area. The second immediate conclusion is that operational settings have the effect of exaggerating any existing trends. For example, at low operations volume and low aircraft distribution, the relationship with respect to runway separation is noticeable but muted, and the variability in the resultant DNL 65 dB contour area of the cases is very small. As the operational settings increase, the relationship to runway separation differentiates the resulting contours more significantly, and the peak region shifts to greater and wider range of runway separation. Since the general trend is not affected by operational settings, the experimental block with the highest settings will be used for analysis, serving a similar function as a microscope magnification, as shown in Figure 4.37.

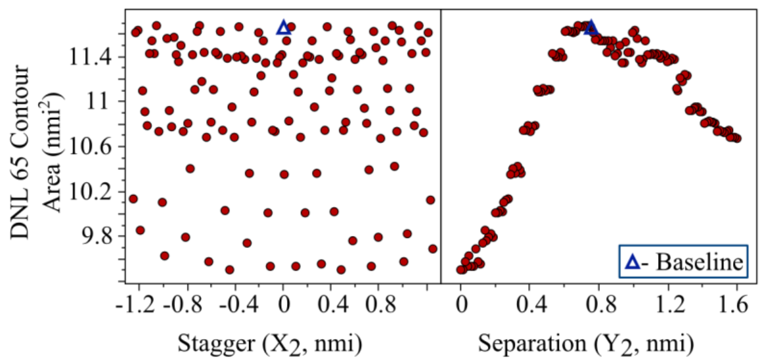


Figure 4.37: Parallel configuration exploration at highest operational settings.

The results demonstrate, again, a very minimal relationship to runway stagger, while the separation exhibits a parabolic relationship to contour area. This behavior follows the progression of an airport geometry from a Single configuration to a Parallel configuration with contiguous DNL 65 dB contour, and finally to a Parallel configuration in which the contours for each runway are separate contiguous entities as shown in Figure 4.38.

Figure 4.38: Transition of contours as runway separation increases.

The contour area therefore increases as two major contour structures emerge but remain contiguous, and finally begins to decrease as they separate and behave more as two separate Single contour geometries. It is also interesting to note that the cases are somewhat discretely clustered, with respect to contour area, as runway separation increases, suggesting that increases in contour area are discontinuous at certain key runway separation values. The main conclusion that can be drawn, with respect to the Parallel configuration, is that a secondary configuration may exist in which contours are not contiguous, which may affect overall contour area prediction. Nonetheless, the behavior of this subcategory is not sufficiently disparate to require a new geometry as the multimodal behavior is minor and most relevant only at very high operational settings. Perhaps more importantly, the mode of calibration for a Parallel geometry is discovered to strictly depend on the runway separation, with runway stagger only used as a secondary calibrating mode to converge on a desired average.

4.2.2.2.2.2 Case 2: Intersecting Configuration

The Intersecting configuration robustness assessment allows for the observation of progression from a Single or Parallel, to an Intersecting geometry, depending on the separation and rotation of the intersecting runway. Operational settings were again found to only serve to magnify the results of the analysis, and therefore only the highest operational setting will be discussed. The results can be seen in Figure 4.39. Each dot represents an Intersecting airport configuration at various geometric variable settings. Naturally the rotation of the intersecting runway is of paramount importance, but, interestingly, the stagger seems to have some linear relationship as well.

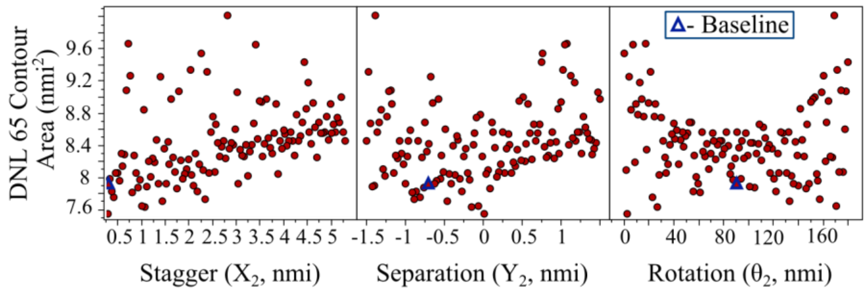


Figure 4.39: Intersecting configuration exploration.

In order to simplify the analysis, however, the rotation of the intersecting runway can be reduced to range from $0 < \theta < 90$. The reason this symmetry could not be leveraged prior to performing the experiments is that the relationship between stagger, separation, and rotation was not entirely understood with respect to contour area. For example, based on the stagger of the representative runway, a rotation of 45 degrees could result in an open-V configuration or a closed-V. Based on the results, however, while the shapes may differ, it appears that the relationship to area with respect to stagger is linear, except at rotations close to parallel as shown in Figure 4.40. The highlighted dots represent the cases with $\theta > 30$.

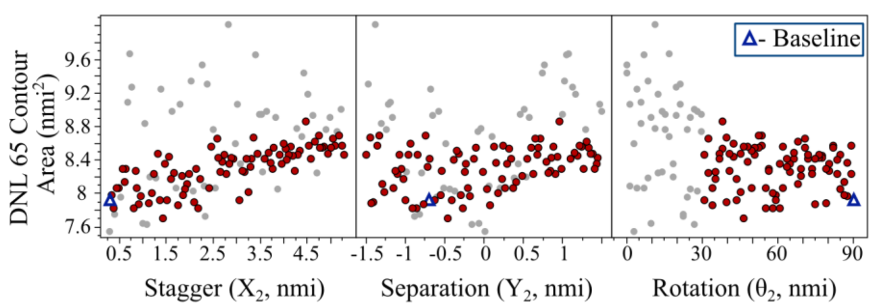


Figure 4.40: Intersecting configuration exploration with reduced runway rotation.

At this level of rotation, the stagger has a decidedly linear relationship to contour area. Below thirty degrees, the stagger ceases to have a specific trend, devolving to the trends observed in the Parallel configuration exploration. These results suggest that from a contour area standpoint, a rotation lower than thirty degrees yields behavior similar to Parallel geometries. Separation on the other hand has secondary impact when rotation of the intersecting runway is above thirty degrees. Below thirty degrees it again recovers the Parallel behavior in which separation increasing away from zero increases the contour area. Again, no significant sub-categories have emerged, but it is interesting to note that stagger and rotation provide the primary modes for calibration. Furthermore, these results suggest a region of intersecting runway rotation where the geometry may be considered Parallel, at least with respect to DNL 65 dB contour area.

4.2.2.2.3 Experiment VI: Generic Infrastructure Calibration and Final Validation

Having completed the baseline analysis, and examined the effect of the various geometric varibles, the information from both can be utilized to perform calibration. The baseline analysis, as mentioned previously, provides the direction and magnitude of calibration, while the robustness assesments provides the mode of calibration. The baseline analysis shows that the Single, Intersecting, Parallel-Intersecting, and Parallel-Intersecting-Single have the most significant opportunities for calibration, because the Generic Infrastructure is furthest from the mean geometry of the MAGENTA 95 from the baseline verification experiment. These infrastructures can be tuned by perturbing the geometric variables examined for the robustness assessment, using the observed trends to converge on an appropriate geometry. A particularly useful calibration is the Single geometry, which was originally defined as one runway. Some of the constituent unique airport geometries have parallel runways with non-zero, but minimal separation. This situation suggests that a sub-geometry *does* exist between the Single and Parallel geometries. Instead of introducing a new infrastructure, however, the Single geometry can be viewed as a subcategory of the Parallel class and adjusted to an 'effective' single, modeled by a closely separated parallel runway set. The calibrations were applied through observation of the geometric behaviors, but were not applied through mathematical optimization. A mathematical optimization of the Generic Infrastructures could have been possible if surrogate models were generated to represent the relationships between contour area and runway positioning. Then, a Monte Carlo assessment of the surrogate models could be utilized to find a mean geometric design [136]. This aspect of the Generic Infrastructure calibration was left outside the scope of this work because shape description missing from the current analysis. The actual calibration of the Generic Infrastructures must take into account shape as well as area, and that dimension is not currently available, and an exact calibration to area could provide negative results with respect to shape. Once the third capability gap is addressed for the purposes of this research, future work can absorb those capabilities to expand the evaluation of airport geometries to include objective characterizations of shape. The resultant geometric settings for the calibrated infrastructures can be seen in Table 4.13, assuming that the reference runway is always situated at the origin. Once calibrations were completed, the tuned Generic Infrastructures were compared to the actual unique MAGENTA 95 airport geometries, using the same operational settings as were used in the baseline verification. The results are listed in Table 4.14.

Table 4.13: Calibrated Generic Infrastructure settings.

GI	X_2 (nmi)	Y_2 (nmi)	θ_2 (deg)	X_3 (nmi)	Y_3 (nmi)	θ_3 (deg)	X_4 (nmi)	Y_4 (nmi)	θ_4 (deg)
Single	0	0.1	0	N/A	N/A	N/A	N/A	N/A	N/A
Parallel	-0.2	0.55	0	N/A	N/A	N/A	N/A	N/A	N/A
Intersecting	-0.75	-0.5	40	N/A	N/A	N/A	N/A	N/A	N/A
Parallel-Intersecting	0.4	0.55	0	1	-0.5	40	N/A	N/A	N/A
Parallel-Intersecting-Single	0.5	0.75	0	0.29	-0.71	40	0	2	0
Parallel-Single	0	0.75	0	0	2	0	N/A	N/A	N/A
Triple Intersecting	0	-0.3	50	.71	1.23	310	N/A	N/A	N/A

Table 4.14: Calibrated Generic Infrastructure validation.

Infrastructure	Apts.	True Area (nmi^2)	Pred. Area (nmi^2)	Error (nmi^2)	% Error
Single	16	26.30	26.20	0.10	0.39
Parallel	9	18.30	19.30	-1.00	-5.44
Intersecting	34	63.55	64.80	-1.25	-1.97
Parallel-Intersecting	28	63.35	61.57	1.78	2.81
Parallel-Intersecting-Single	2	2.44	2.36	0.08	3.16
Parallel-Single	1	2.19	2.15	0.04	2.05
Triple Intersecting	5	11.30	12.36	-1.06	-9.34
Sum	**95**	**188.23**	**188.73**	**0.50**	**0.27**

The experiment results clearly show the benefit of examining the behavior of the geometric variables to contour area as the error has been reduced to well below 1%. The largest errors still exist within the Parallel-Intersecting and Intersecting geometries, although the relative errors are not the highest. While there are still relatively high errors within certain groups, the combined Triple Intersecting and Parallel group errors only account for 1% of the fleet-level contour area.

Again, any further calibrations must be cautioned against for the time being, because no objective shape information is currently available. The calibrations performed here were done manually so that the resulting geometries ensured a qualitatively satisfactory representation of the general shape characteristics of the observed contours. When shape characteristics for contours mature via this research, the calibrations can be revisited to remove qualitative oversight.

4.2.3 Generic Airports

Once the Generic Runways and Generic Infrastructures have been developed, the two sets can be combined as needed to generate the total set of Generic Airports. The combination led to a total of 21 generic airports, less than a quarter of the original sample set. If specific infrastructures are used for DFW and ORD the total number will remain unchanged, as they are also fairly unique from an operational perspective. Future trades can examine the cost-benefit of adding operational or geometric articulation to the generic space. Having generated the combinations of Generic Runways and Generic Infrastrucures necessary to describe all MAGENTA 95 airports, the Generic Airports can be validated against the actual operational and geometric data.

4.2.3.1 Experiment VII: Generic Airports Validation

The final evaluation (E-VII) consists of validating the ability for Generic Airports to predict the in-group and total fleet-level DNL 65 dB contour area of the 95 MAGENTA airports using the actual operations, unique aircraft, and actual infrastructure geometries. The purpose of this test is to examine the validity of the enabling assumption that operational and geometric characteristics could be decoupled along the lines of contour magnitude and shape respectively. The test also assumes that Generic Airports will inherit the robustness from the operational and geometric developments. All necessary ANGIM assumptions were observed, runway utilizations were assumed even, and cross-flow operations were assumed for all runways. The summary of the total fleet-level estimate results are listed in Table 4.15 and the distribution of the absolute errors for all generic airport groups can be seen in Figure 4.41.

Table 4.15: Summary of prediction error for Generic Airports.

Pred.Area (nmi^2)	Actual Area (nmi^2)	Error (nmi^2)	% Error
144.25	148.21	-3.96	-2.67

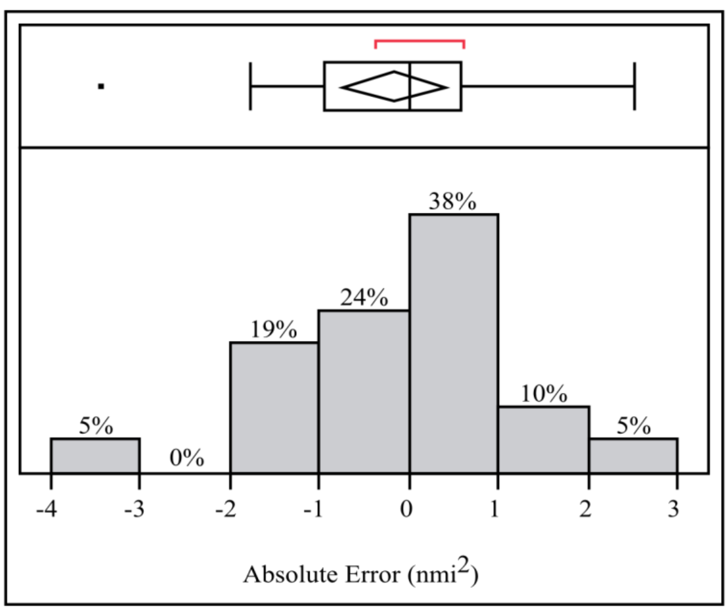


Figure 4.41: Absolute error distribution for Generic Airport groups.

As can be seen, the total area is well predicted, with overall relative error below 3% with this error evenly distributed about zero. Relevant statistics about the in-group error can be seen in Table 4.16, and a visualization of how well Generic Airports predict actual airport noise can be seen in Figure 4.42.

Table 4.16: Statistics for Generic Airport error distribution.

Error Range (nmi^2)	Mean (nmi^2)	Median (nmi^2)	Std. Dev. (nmi^2)
-3.45 – 2.53	-0.19	0	1.25

The plot of the Generic Airports overlaid with the actual MAGENTA 95 airport areas demonstrates how well the independent and decoupled development and calibration of Generic Runways and Generic Infrastructures has performed in delivering mean representations of the actual airports within each group. As can be seen from the results, the Generic Airports are mostly situated in the mean region for each category. There are a few categories, however, where the Generic Airports struggle, including the Parallel-Single-M1 and the Triple Intersecting-M2. The groups in which error is more prevalent typically have a very low number of airports to represent, which naturally reduces the possible accuracy to be gained by averaging geometric and operational characteristics. Calibration of these specific combinations is possible, but it is important to recall that calibration should be done at the Generic Runway or Generic Infrastructure level, as the relatively low amount of variability within these types will provide significantly increased computation speed.

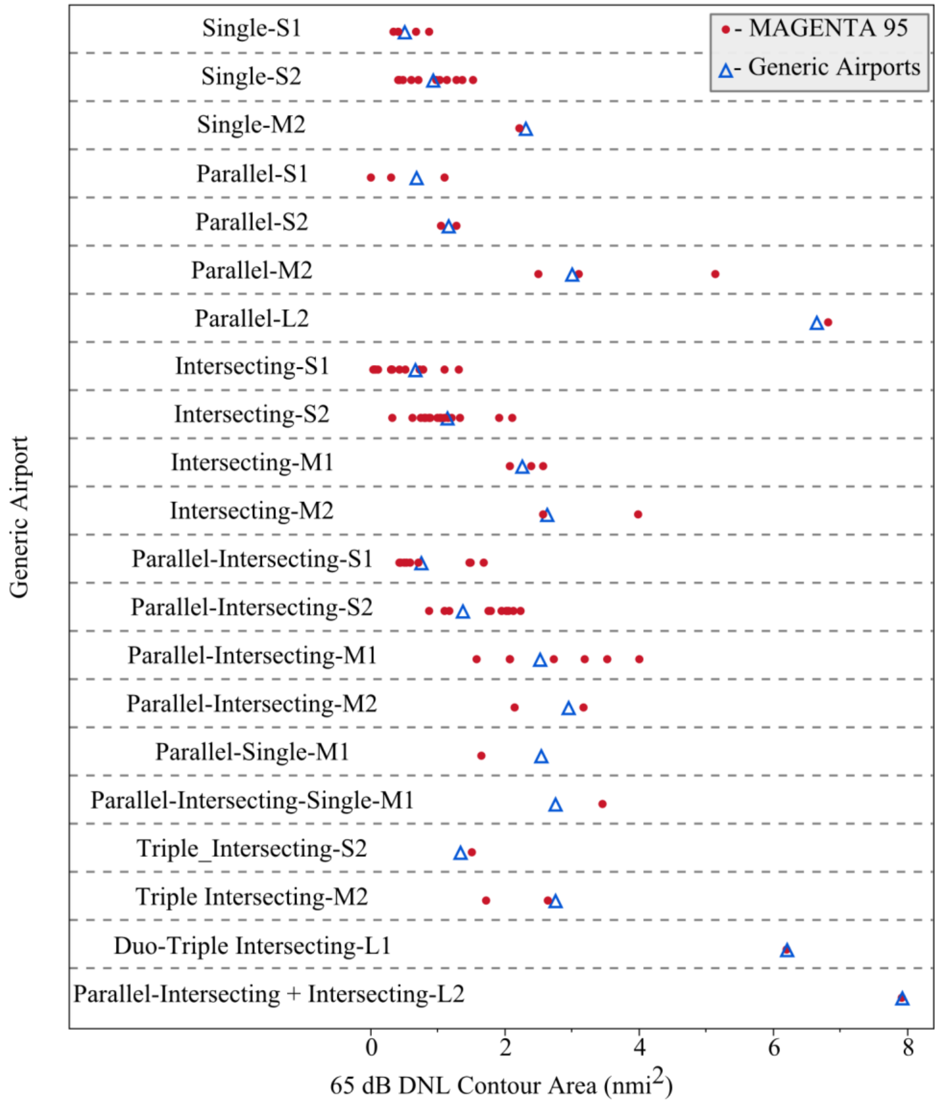


Figure 4.42: Distance from mean of Generic Airport categories.

On the other hand, if calibration is done at the Generic Airport level, the simplicity in combining a handful of types will be somewhat compromised because instead of having six operational categories and nine geometric categories, there will be 21 entirely unique versions of each. While this would still result in a significant savings, it would not fully exploit the potential gains because the current Generic Airports allow the user to generate only 6 operational scenarios, significantly reducing the runtime required through ANGIM. These operational scenarios are then applied to the nine geometric categories as necessary. The operational savings ratio in actual model executions is 6:95, while the geometric savings (typified by the interpolation of runway-level grids to the airport level) is 21:95. Therefore, the true savings of the Generic Airports is lower than the apparent 21:95 Generic Airport to actual airport ratio. The process criteria for Generic Airports versus running the actual MAGENTA 95 through ANGIM are listed in Table 4.17.

Table 4.17: Process criteria evaluation of Generic Airports.

ANGIM Function	Runtime (minutes)		Time Savings
	MAGENTA 95	Generic Airports	
Operational	33	2	94%
Geometric	130	18	86%
System-Level	163	20	88%

4.2.4 Discussion

The experimental results regarding development of Generic Airports presented above demonstrates the implementation required to create a set of Generic Airports in support of a generic framework for fleet-level environmental analysis. These Generic Airports can be used to infer noise-specific trends about airports, by simply analyzing the generic version, while saving runtime in early fleet-level airport noise analyses. Generic Airports were constructed by decoupling the operational and geometric characteristics into Generic Runways and Generic Infrastructures respectively. Generic Runways were created using operational data to group airports by total operations, and seat class distribution of flights. Generic Runways were then verified to ensure that the mathematical model behaved as expected, and were validated, with respect to fleet diversity and variation in operational scenarios. The Generic Runways demonstrated that they can predict the baseline fleet-level DNL 65 dB contour area of the MAGENTA 95 sample airports, as well as preserving trends and accuracy in the face of a changing operational landscape. Generic Infrastructures, on the other hand, were created by gathering geometric data, such as actual runway layout, and resulting contour geometries to create reduced effective runway layouts. These effective geometries were then observed and qualitatively categorized to yield seven Generic Infrastructures. Baseline Generic Infrastructures were used to examine the direction required for calibration, while a configuration exploration was utilized to define the mode of calibration for each generic classification. Calibration was then performed utilizing this information and the final validation was executed to demonstrate the ability of Generic Infrastructures to predict the fleet-level DNL 65 dB contour of the MAGENTA 95 airports successfully. Twenty-one Generic Airports were then constructed by joining the two components, and similarly shown to provide accurate in-group and total predictions of the DNL 65 dB contours for the 95 sample airports.

Reducing the preparation, runtime, and analysis requirements by approximately 88% is a significant improvement that affords a higher volume of fleet-level analyses, leading to more informed decisions. By examining the generic classes presented here, a significant amount of insight can be gained without requiring the analysis of specific airports. Utilizing these generic classes allows computational and time resources to be allocated with greater confidence and efficiency.

While a successful preliminary set of Generic Airports was presented here, there are still opportunities for further research in this area. While these will be summarized below, each will be discussed in more detail in Chapter 6. For example, the variables utilized for grouping were relatively limited in number, and the cost-benefit of including more detailed variables could be examined, with respect to the total number of final Generic Airports (resulting in a loss of computational efficiency), as compared to the increased precision and robustness of the final set. Furthermore, different classifications could be experimented with, especially with respect to the operational characteristics, to find an ideal number with respect to accuracy and reduced modeling time.

Ultimately, Generic Vehicles must be implemented into the process, instead of the representative vehicles used as a proxy for this research. Including Generic Vehicles will require re-assessment and specific calibrations different than those presented above. An automation of the Generic Runway creation process in particular should be explored, which would allow a user to create different sets under separate conditions for comparison or testing, and to generally improve the implementation of the process. With respect to Generic Infrastructures, quantitative methods should be employed to provide a less subjective approach to the categorization of airport geometries. An objective categorization of the grouping variables may yield a more robust and internally consistent result. Consequently, the contour shape metrics that would enable such an improvement will be the subject of the next section of this research.

4.3 Metrics of Evaluation

The final capability gap identified is in the lack of shape metrics that can be used to compare and contrast contours of different varieties. While contour area is a critical measure, some understanding of how that area is distributed about the airport is critical to getting a complete picture of airport community noise, which is inherently a spatial problem. Current methods have ignored the importance of shape because of the difficulty in assessing its value on a large scale of fleet-level evaluations. The real issue is not the complexity of shape, but the lack of objective measures that define the seemingly abstract notion.

In order to address this gap, it was hypothesized that an appropriate metric should measure the number of total contour lobes, and their distribution about the airport nucleus. A metric that could perform these functions would also be able to distinguish between drastically different geometric categories but should also remain insensitive to changes in total operations. An experimental plan was developed and executed to test the shape metrics, the results of which will be presented below. The experimental set consisted of the Parallel, Intersecting, Parallel-Intersecting, and Triple Intersecting configuration exploration experiments presented in the development of Generic Infrastructures. For some experiments, the MAGENTA 95 actual infrastructures and Generic Infrastructures were also applied. Each version of these tests was run at three different operational settings, consisting of the operational settings for blocks one, two, and five from the configuration exploration experiments. For simplicity, all results presented will pertain to all operational variants of the experimental sets, unless otherwise specifically stated.

4.3.1 Experiment I: Lobe Correlation

The first requirement, against which the collected shape metrics were evaluated, was meant to ensure the resulting metrics would correlate with the total number of contour lobes. The contour lobes for each experimental block were counted manually, using the qualitative lobe-counting method defined in Appendix C. While everything possible was done for these values to remain internally consistent, it is important to recall that they are inherently subjective observations. The metrics were assessed for linear correlation to the total number of lobes for the Parallel, Intersecting, Parallel-Intersecting, and Triple Intersecting configuration exploration experiments. Linear correlation is desired because a strictly increasing or decreasing trend of the metric with respect to total lobes is necessary to avoid confusion on lobe quantity. The correlation of area to the total number of lobes was also analyzed, to serve as a control, and to provide further justification that contour area is not a sufficient descriptor of shape. The results of each operational setting are listed in Table 4.18. The first important result of this experiment is that the control variable; contour area, has very little correlation to the total number of lobes for all operational settings.

Table 4.18: Correlation to total number of contour lobes.

Block	Area (nmi^2)	Perimeter Index	Vertices	Dispersion Index	Girth Index	Detour Index	Proximity Index	Spin Index	Cohesion Index	Depth Index
1	0.0259	-0.4954	0.3811	0.5962	-0.3882	0.6996	.4919	0.6024	0.5459	-0.2535
2	0.1275	-0.7375	0.5491	0.7795	-0.3940	0.7965	0.7873	0.8488	0.8114	-0.2825
5	0.0619	-0.6045	0.4358	0.6892	-0.3793	0.7499	0.6169	0.7140	0.6746	-0.1067

Block 2, which consists of 2250 average daily operations and a heavy aircraft distribution, has the highest correlation of contour area to the total number of counted lobes. Block 5, on the other hand, has 2250 average daily operations and a light aircraft distribution, while having the second highest correlation of contour area to the total number of counted lobes. Block 1 has 1250 daily operations with a heavy aircraft distribution, and the lowest correlation of contour area to the total number of counted lobes. This ordering suggests an increase in correlation of lobe number to contour area as operational settings increase. Of the shape metrics tested any that displayed correlations across all operational settings above 0.5 were retained, including the Dispersion Index, Detour Index, Spin index, and Cohesion Index. Each of these metrics originates primarily from land-use related research, and it is not surprising that these metrics would already have been previously developed to practically describe shape characteristics. Other more fundamental metrics, such as the vertices, did not correlate sufficiently well, but may require fine-tuning beyond application of the basic mathematical theory. Correlations seem to vary significantly in different operational settings, but it is important to recall that the requirement is not that the lobe counts be insensitive to operational setting, but rather that the metrics themselves be insensitive. Lobe counts are expected to change significantly as operational settings vary, and these issues will be addressed further below.

4.3.2 Experiment II: Lobe Distribution

Once a subset of metrics was identified for further analysis, each was tested for their ability to assess the distribution of the lobes. This assessment can be achieved by examining each metric with respect to the geometric variables to identify the underlying relationship. In order to examine the geometric categories most efficiently, the analysis will be done with respect to the base experimental categories. For example, all experimental cases within the Parallel configuration exploration will be analyzed together, regardless of whether a case resulted as a Single or a Parallel geometry. This assessment is not specifically concerned with distinguishing between different geometries, but instead seeks to define how the geometric variables affect shape characteristics. The results for the Parallel and Intersecting experimental cases will be examined in detail, while the Parallel-Intersecting and Triple Intersecting results will be reserved for Appendix G.

4.3.2.1 Parallel Configuration Exploration Cases

The Parallel configuration exploration cases varied the stagger and separation of the parallel runway to a fixed reference runway, and can be used to observe the relationship between these variables and the remaining metrics. The results of this analysis can be seen in Figure 4.43. Each dot represents a unique geometric configuration of a Parallel airport. The resulting trends to each geometric variable provide insight into the ability of the metric to scale with lobe distribution. Analyzing these results, it is apparent that the main variable of importance is the runway separation. This relationship is important, because it will capture the transition from a Single geometry to a Parallel. The stagger of the parallel runway seems to have little effect, although it does exhibit a secondary parabolic trend with respect to each metric except the Dispersion Index.

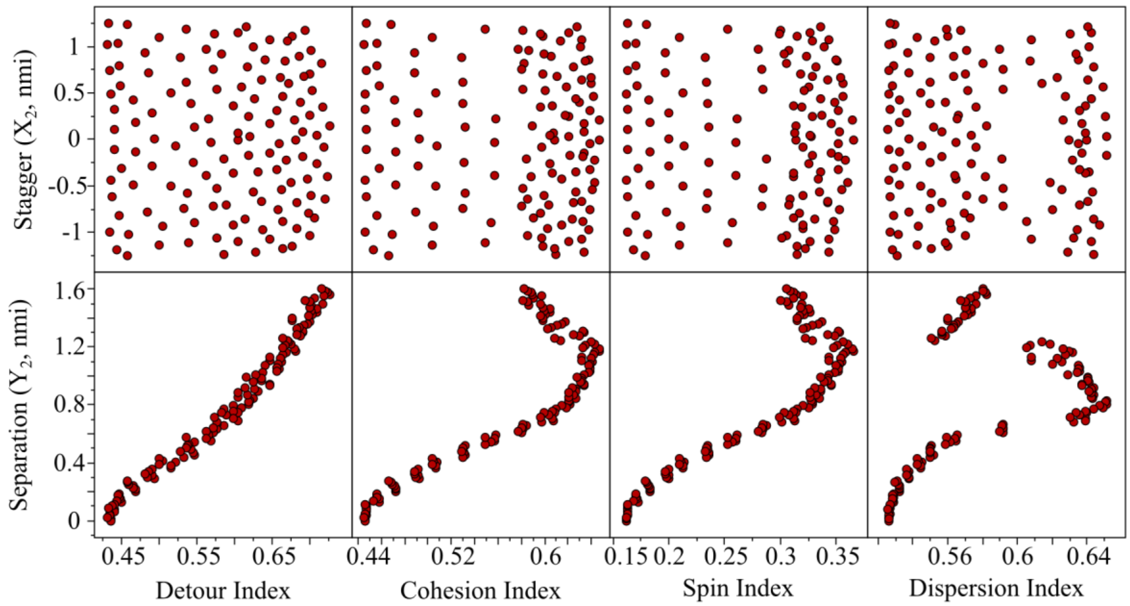


Figure 4.43: Parallel configuration geometric variable relationships.

The relationship to runway separation for the Detour Index is linear, while for Spin and Cohesion Indices it exhibits a parabolic relationship. Dispersion Index demonstrates a more complex third-order relationship. These relationships are not trivial, and their characteristics are critical in identifying which metric is most suitable. A parabolic relationship to runway separation is problematic because it assigns the same value to contours that have significantly different distributions of contour lobes. A contour with very high runway separation cannot be reflected or otherwise transformed isometrically in any way that results in a contour with low runway separation. On the other hand, a runway with highly negative stagger can simply be reflected to recover a runway with highly positive stagger. Examples of each are shown in Figure 4.44. As a result, the minor parabolic relationship of each metric to stagger is not problematic as it can be resolved by symmetry, whereas the runway separation cannot.

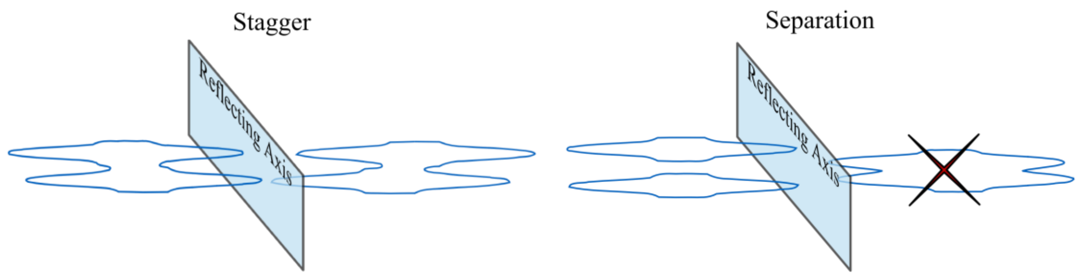


Figure 4.44: Stagger resolved by symmetry; separation is not.

The ideal metric for this category is the Detour Index, as it exhibits a linear relationship to the separation of the runways. The other metrics may still retain a secondary value because they still track other important aspects of the shapes that cannot be inferred via only the Detour Index.

4.3.2.2 Intersecting Configuration Exploration Cases

The Intersecting configuration exploration cases varied the stagger, separation, and rotation of an intersecting runway relative to a fixed reference runway, and can be used to observe the relationship between these variables and the selected metrics. The results of this analysis can be seen in Figure 4.45. Each dot represents a unique Intersecting airport geometry. With respect to the specific trends, the Detour and Dispersion indices show a parabolic trend with respect to rotation of the intersecting runway, with the relationship for Detour being more pronounced. The Dispersion and Detour indices also shows a minor relationship to stagger, but the Cohesion and Spin indices exhibit a stronger linear relationship to stagger. The relationship to runway rotation is much more important, as it defines the distribution of the contour lobes most appropriately, and consequently creates the necessary separation between Parallel and Intersecting geometries.

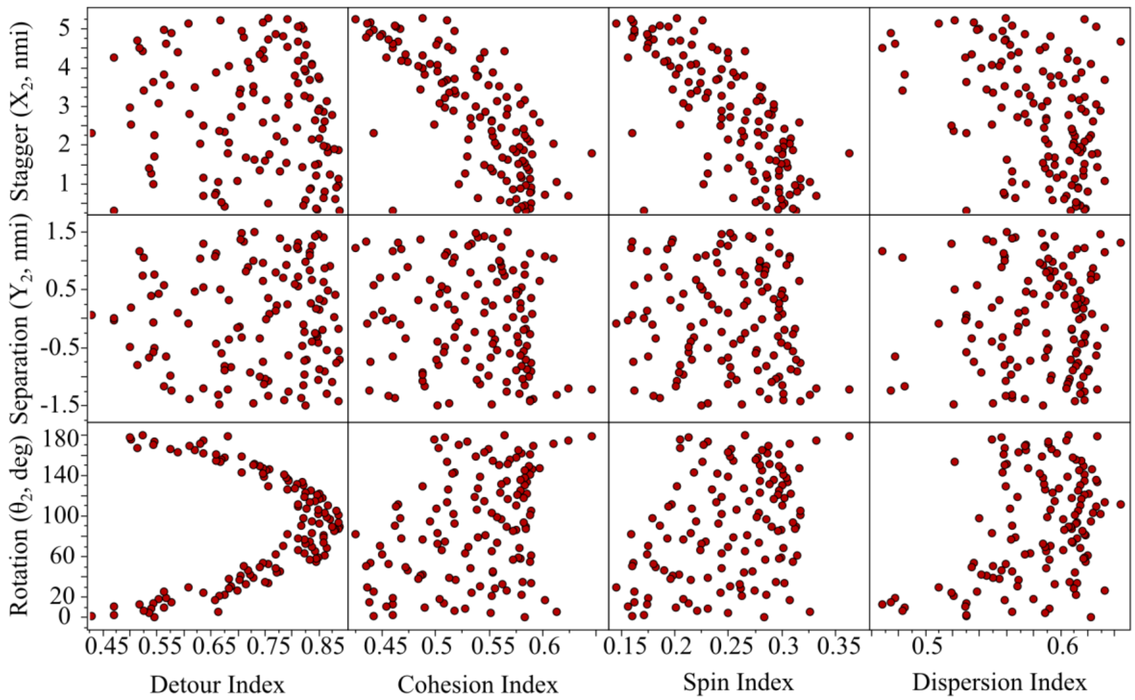


Figure 4.45: Intersecting configuration geometric variable relationships.

Furthermore, although the behavior is parabolic, with respect to rotation, this behavior can also be resolved by symmetry as shown in Figure 4.46. Stagger of the intersecting runway can also significantly affect the distribution of the contour lobes from a qualitative standpoint. The Detour Index exhibits a linear behavior with respect to stagger in the mid-range of runway rotations. In fact, the metric exhibits very high sensitivity with high and low rotations, while demonstrating more stability in mid-range rotations.

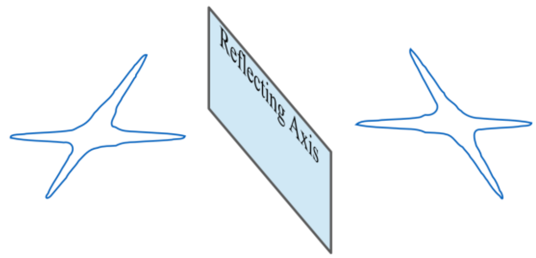


Figure 4.46: Rotation can be resolved by symmetry.

For example, near a Parallel configuration, changes in the rotation that steer the geometry away from Parallel cause *large* changes in the resultant Detour Index. Closer, to a cross-runway configuration, the Detour Index demonstrates a heavier dependence on the stagger of the intersecting runway and less sharp dependence on the rotation as shown in Figure 4.47.

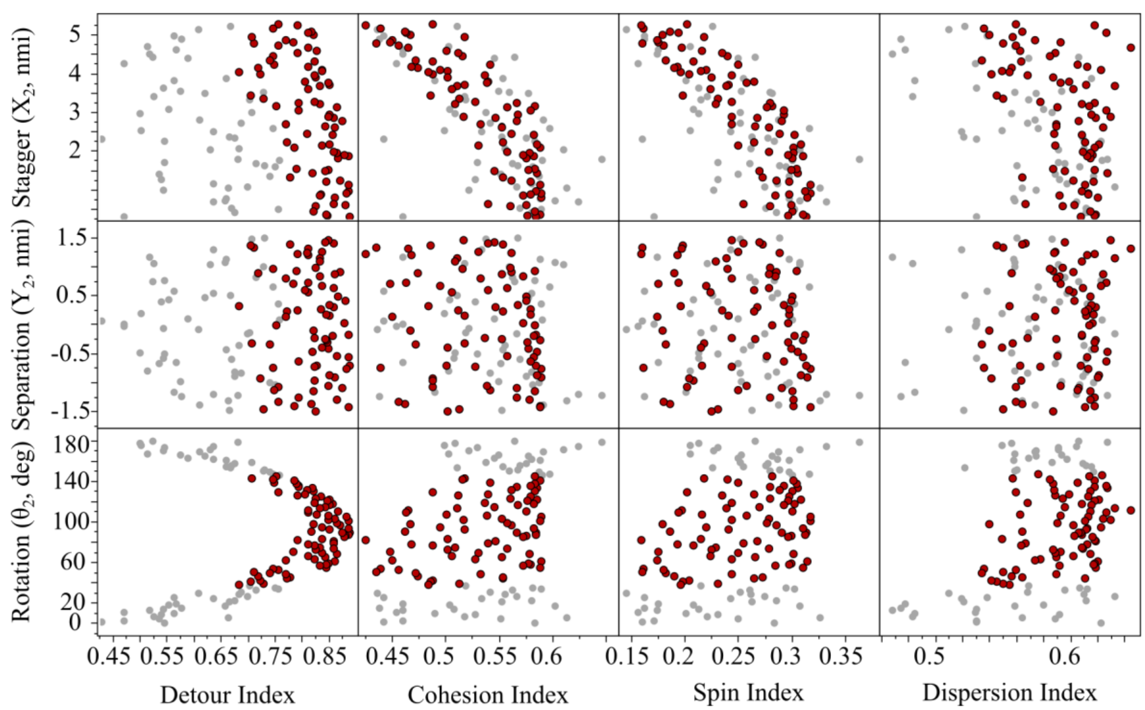


Figure 4.47: Intersecting configurations cases with θ>60 degrees selected.

Therefore, the Detour Index is also the best performing metric for this geometric category, since the high sensitivity to runway rotation should provide better segmentation of the Parallel and Intersecting geometries. Again the Spin and Cohesion indices both retain a certain value due to the stronger relationship they exhibit to stagger.

4.3.2.3 Summary of Lobe Distribution Assessment

Based on the analyses of the lobe distribution experimental results, the Detour Index provides a nearly comprehensive set of relationships, including sensitivity to parallel runway separation, and intersecting runway rotation. The Cohesion and Spin indices, however, also provide a useful sensitivity to stagger of an intersecting runway, which can impact the resulting geometry and therefore may still retain some utility going forward. The Dispersion Index was observed to have weak but non-negligible relationships to the geometric variables. When compared to the strong relationships observed in the other metrics, it was clearly the least satisfactory of the group. It is important to recall, however, that these configuration exploration experiments were designed to assess a wide variety of geometric scenarios. Therefore, no metrics will be discarded, for the time being.

4.3.3 Experiment III: Categorical Segmentation

The third experiment consists of examining the ability of the collected metrics to segment the different qualitatively observed categories along their respective spectra. Again, these classifications were qualitative, and may be prone to certain inconsistencies. These inconsistencies, however, should occur in borderline regions between geometric categories, and the metrics will be evaluated in their capacity to distinguish such geometries. The categorical segmentation was examined with respect to the configuration exploration cases, the MAGENTA 95 geometries, and the Generic Infrastructures. For the purposes of these discussions, the Single, Intersecting, and Parallel geometries will be referred to as 'Simple' geometries, while the remainder will be referred to as 'Complex' geometries.

4.3.3.1 Case 1: Configuration Exploration Cases

The overview the categorical segmentation between different geometric categories for the configuration exploration cases can be seen in Figure 4.48. Each marker represents a unique geometry examined in the configuration exploration cases. The mean and standard deviation of each is marked by the line series and the error bars respectively. It is important to recall that these serve as a worst-case scenario evaluator for the metrics, because extreme airport configurations were included to ensure that the entire space was characterized. Based on these results, a number of preliminary conclusions can be drawn. None of the metrics show a strict segmentation or discontinuity between all of the observed geometric types, although there are marked differences in the mean values of some of the metrics. The Detour Index performs the most useful segmentation of the geometric categories, distinguishing between Simple geometries with relative effectiveness. Although the mean values differ for Complex geometries observed, the differences are not nearly as substantial. The Spin Index, or Cohesion Index, provides a slightly better separation of Complex geometries from the Simple geometries.

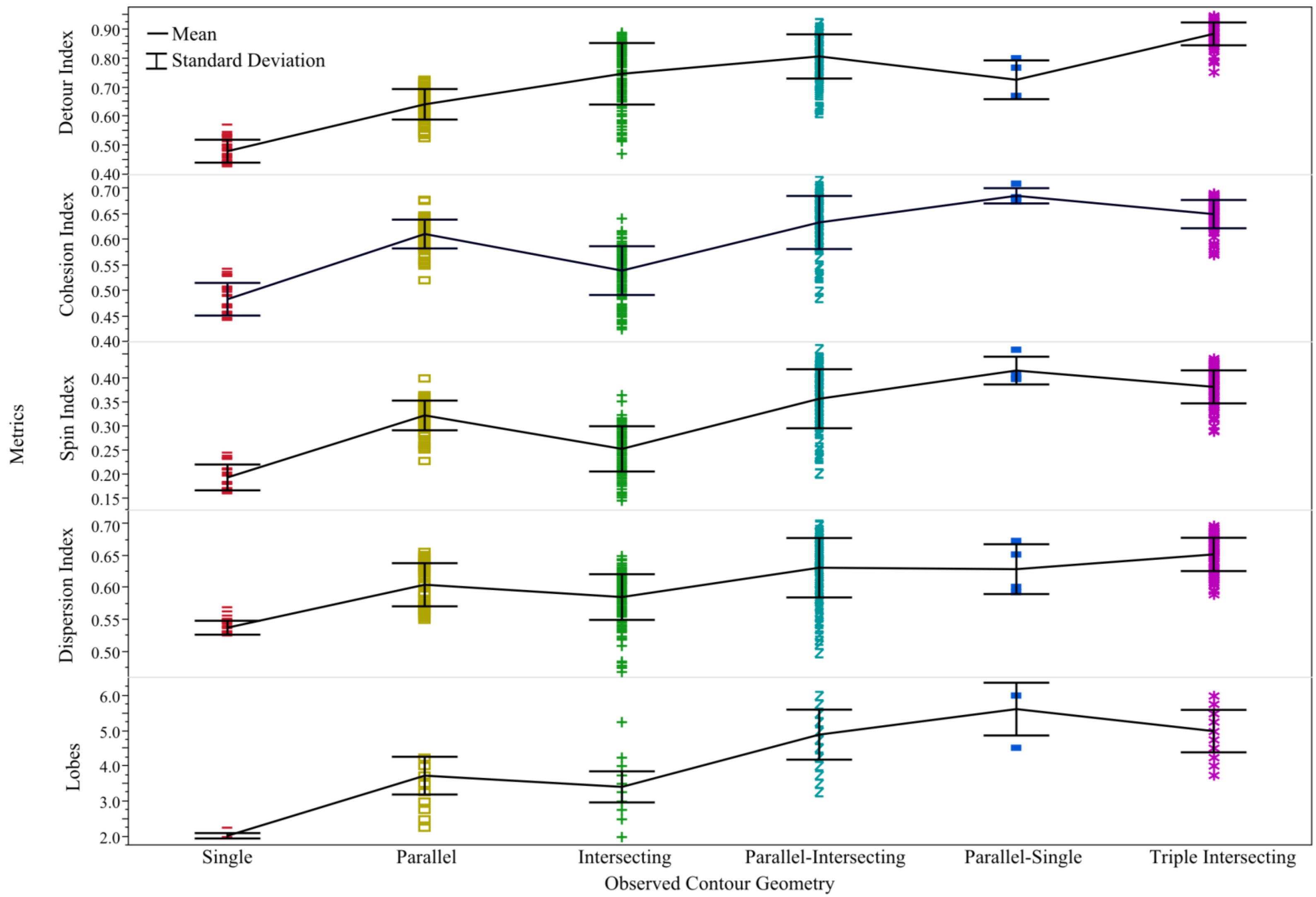


Figure 4.48: Categorical segmentation of configuration exploration cases.

These metrics still struggle to distinguish specifically between Triple Intersecting, Parallel-Single, and Parallel-Intersecting. Dispersion Index, on the other hand, manages mostly to separate all geometries from the Single category, but provides no other segmentation. The most useful differentiator between Simple and Complex geometries is the number of contour lobes, hence the importance of linear correlation of the metrics to the total number of contour lobes. The ability to predict contour lobes linearly based on these shape parameters may become a useful metric in its own right, useful for separating certain general types of geometries from others.

Again, it is important to note that the cases presented thus far were intended to explore the extremes of the configuration space, and thus serve as a worst-case scenario for the metrics examined. For this reason, no metrics have been discarded during this portion.

4.3.3.2 Case 2: MAGENTA 95 Airports and Generic Infrastructures

To provide a more realistic set of airport geometries through which a useful shape metric must provide segmentation, the MAGENTA 95 unique airport infrastructures and the Generic Infrastructures were used to calculate shape metrics, under the same operational settings as those used for the configuration exploration experiments. The categorical segmentation results can be seen in Figure 4.49. The results demonstrate that the configuration exploration experiments were in fact an extreme view of the categorical segmentation capabilities of the collected metrics. With the MAGENTA 95, it is obvious that the Detour Index can still distinguish between the different Simple geometries.

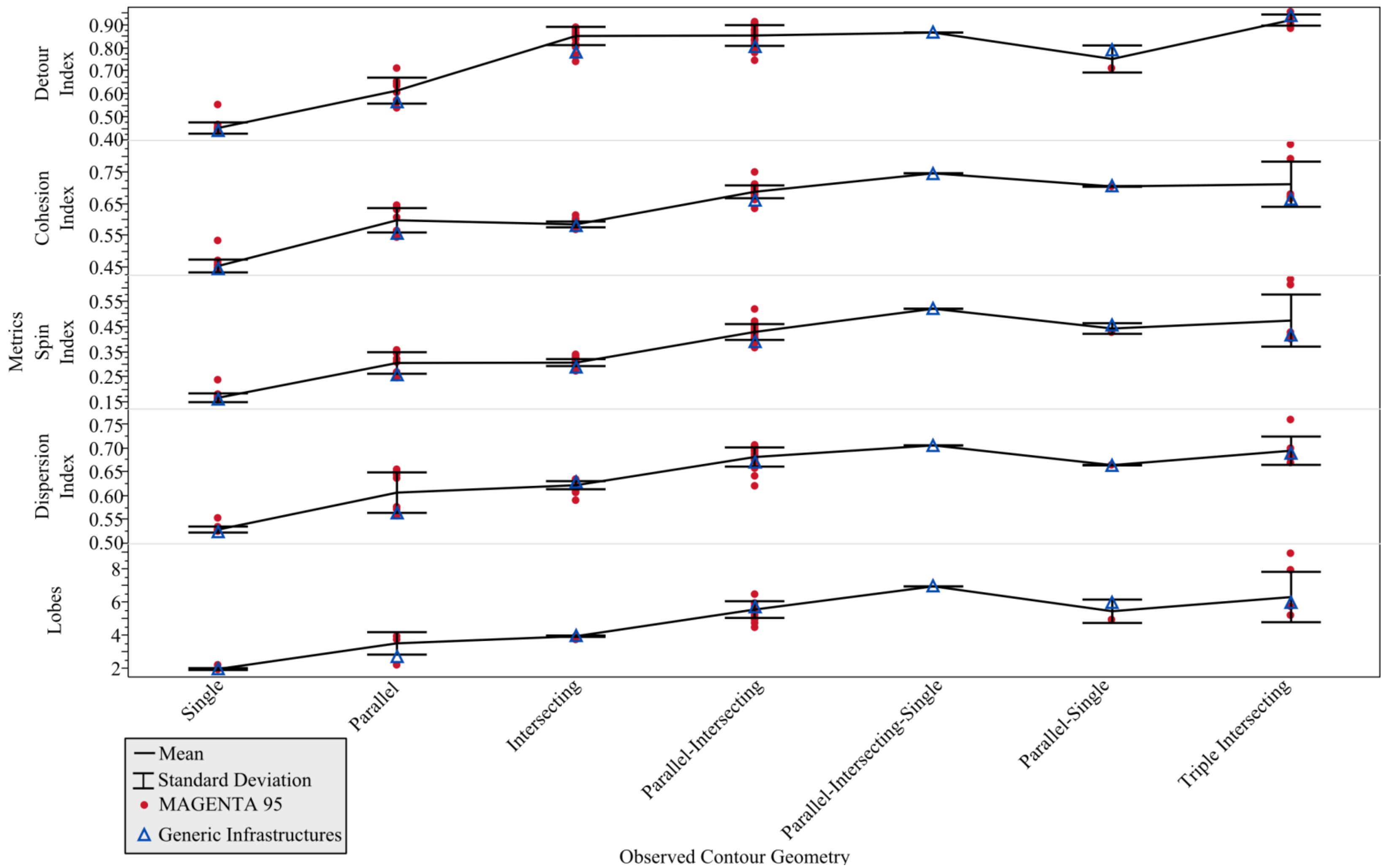


Figure 4.49: Categorical segmentation of MAGENTA 95 and Generic Infrastructures.

The Cohesion, Spin, and Dispersion indices assign similar values to the Parallel and Intersecting geometries. The Detour Index is still not sufficient in distinguishing between the Complex geometries and the Intersecting geometries. The Detour Index is affected by any runway rotation, regardless of the number of runways in the geometry, because the most extreme rotation in the geometry will drive the perimeter of the convex hull of the contour. With the MAGENTA 95, however, the Cohesion, Spin, and Dispersion can now distinguish easily between Simple and Complex geometries. The Spin and Cohesion indices can also differentiate between the Parallel-Intersecting, Parallel-Single, and Parallel-Intersecting-Single geometries to some extent. The lack of drastic segmentation is not surprising because these geometries can become very similar as they increase in complexity. Both the Spin and Cohesion indices remain ambivalent with respect to Triple Intersecting geometries, but the Detour Index clearly separates these from the remainder of the Complex geometries. Based on these results it can be concluded that a logical combination of the Detour and Spin or Cohesion indices can properly segment the space. While both the Spin and Cohesion indices are valuable here, the Spin Index is the natural choice because it is significantly less expensive to calculate as opposed to the Cohesion Index. The Spin Index relates each grid point to a central point. The Cohesion Index relates each grid point to every other point in the grid.

A logical combination of the metrics would entail simultaneous evaluation of the Detour and Spin indices. Therefore, if the Spin Index were between approximately 0.45 and 0.65, then the Detour Index could be used to define whether the geometry is a Single, Parallel, or Intersecting. Above a value of 0.65, the Spin Index could be used to distinguish between the Complex geometries unless the Detour Index is above approximately a value of 0.85, in which case it is a Triple Intersecting airport. Applying this process logically is complicated and impractical, but mathematical combinations of these will be explored to mimic the logical combination of the metrics.

Also of note is the distribution of the Generic Infrastructures overlaid with the MAGENTA 95 geometries. With respect to certain metrics and for certain geometries, they provide an acceptable mean representation, but in other cases, they are well below the mean. This result exemplifies the effect of lacking a quantitative shape evaluator during Generic Infrastructure generation. For example, the Intersecting Generic Infrastructure is well behaved for all indices except the Detour Index, where it scores below one standard deviation of the MAGENTA 95. Based on the analysis with respect to the geometric variables, a valid hypothesis would be that the rotation of the intersecting runway is too high or too low. Since the infrastructure could only be optimized with respect to area, however, this aspect of the geometry was not captured. The ability to incorporate the shape metrics identified here during Generic Infrastructure generation and calibration will be a critical enabler in future versions to yield more representative Generic Airports.

4.3.4 Experiment IV: Correlation to Operational Settings

Once lobe correlation, distribution, and categorical segmentation have been assessed, it is still necessary to ensure that the metrics are not overly dependent on the operational settings. In order to achieve this test, all experimental blocks were analyzed together to determine the linear correlation, if any, to the operational settings. The correlations of each of the remaining metrics with respect to operational volume and aircraft distribution are listed in Table 4.19.

Table 4.19: Metric correlations to operational factors.

Operational Variable	Detour Index	Cohesion Index	Spin Index	Dispersion Index
Operations Volume	-0.02	0.01	-0.01	-0.02
Aircraft Distribution	-0.02	-0.05	-0.05	-0.02

These correlations are clearly negligible for each metric suggesting that within these ranges, the shape metrics are not affected by changes in operations volume or aircraft distribution. Nonetheless, only three operational blocks were utilized for these assessments, and further investigation may be warranted as the operational settings do affect the contour shapes. Beyond analyzing the correlation, the distribution of the ranges for each observed category were analyzed for signs of shifting as operational settings varied. As listed in Table 4.20 for the Parallel configuration exploration geometries, the range of metric scores is almost unchanged as operational settings vary.

Table 4.20: Metric ranges for Parallel geometries.

Experimental Block	Detour Index	Cohesion Index	Spin Index	Dispersion Index
Block 1	0.53 – 0.79	0.55 – 0.70	0.26 – 0.43	0.55 – 0.69
Block 2	0.52 – 0.73	0.55 – 0.65	0.25 – 0.37	0.55 – 0.65
Block 5	0.55 – 0.77	0.55 – 0.68	0.26 – 0.41	0.56 – 0.66

This result is significant because it suggests that a configuration of a given type will always score within a certain range, at least within the operational settings analyzed. While the ranges of the distributions remain very similar, the actual distributions can shift as certain geometries change their appearance. For example, the location at which a Parallel configuration becomes two separate contours occurs at approximately the same Detour Index value for all experimental blocks. Based on the operational settings, however, more or less of the cases may exhibit discontinuous contours, which highlights the dichotomy of the effect of operational variables. While the metrics are insensitive to the operational variables in the ranges analyzed, the contour shapes are not, and can depend heavily on these operational factors at fixed geometric settings.

4.3.5 Experiment V: Metric Combinations and Trades

Based on the analysis provided thus far, several metrics have been found to be useful in correlating with the total number of lobes, the distribution of the lobes, and the categorical segmentation of different geometric categories while maintaining generality with respect to the operational ranges analyzed. Of these, the two that perform best in tandem are the Detour and Spin indices. Thus far, neither of these metrics has single-handedly provided a comprehensive treatment of all the desired requirements. While this result is not unexpected, it may be possible to mathematically combine these metrics to yield a single measure that provides the desired characteristics. The three basic options considered were linear summation, multiplication, and a combination of both yielding a non-linear summation. Multiplication is less desirable because all the indices are already bounded between zero and unity, and so any multiplication must also inhabit this region, further compressing the range of metric values. The Spin and the Detour indices have scored the geometries in different areas of this spectrum, and a multiplicative connection, while improving the lobe correlation, will not impact the categorical segmentation because the metric will still be bounded between zero and unity. A linear summation is more desirable because it superimposes the characteristics of the two metrics. The metric physically represents a measure of the number of contour lobes and how they are consequently distributed. The summation can be tuned by varying the coefficient of summation for each metric as shown in Equation 4.2, and simplified in Equation 4.3 as the Detour-Spin Index Ratio (DSR).

$$X * Detour\ Index + Y * Spin\ Index = Detour - Spin\ Index \qquad (4.2)$$

$$\frac{X}{Y} * Detour\ Index + Spin\ Index = DSR * Detour\ Index + Spin\ Index \qquad (4.3)$$

The DSR serves to trade between the characteristics of each metric. With respect to Spin and Detour indices, the Spin Index can distinguish between Parallel-Single and Parallel-Intersecting geometries to some extent, while unable to distinguish between Parallel and Intersecting geometries. Detour Index on the other hand exhibits the opposite behavior. Through trial and error it was found that a DSR somewhere between ½ - ⅓ may be appropriate, although a specific recommendation will not be made due to the lack of sufficient data thus far. None of the completed experiments was designed for the purposes of tuning this ratio, so this aspect will be left for future work. For this research, the DSR will be set to unity for simplicity. The lobe and operational setting correlations of each configuration exploration experimental block with respect to the Detour-Spin Index are shown in Table 4.21. The overall correlation to the lobes for all operational settings combined is 0.83. As can be seen from the results, the correlations, with respect to total lobes, are much higher, while the correlation to operational settings remains negligible. The lobe distribution characteristics are summarized in Figure 4.50 and Figure 4.51.

Table 4.21: Detour-Spin Index correlations.

Correlating Factor	Detour-Spin Index		
	Block 1	Block 2	Block 5
Lobes	0.75	0.89	0.83
Operations Volume		0.00	
Aircraft Distribution		-0.03	

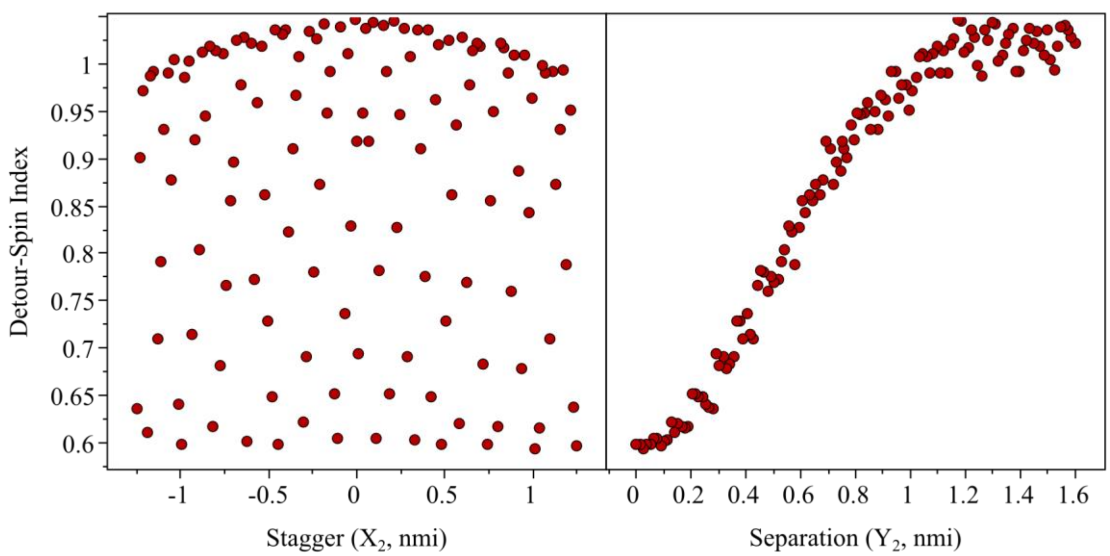


Figure 4.50: Parallel configuration exploration relationship to DSI.

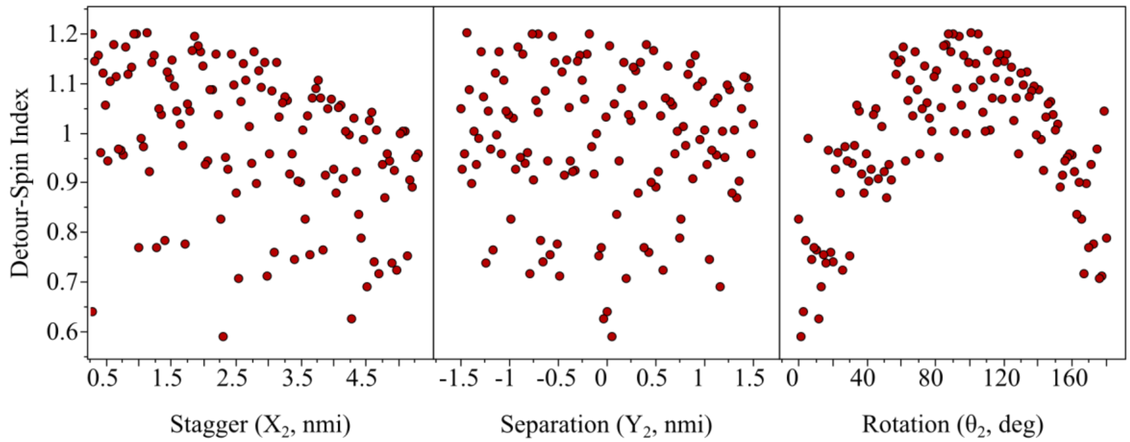


Figure 4.51: Intersecting configuration exploration relationship to DSI.

The lobe distribution results for Parallel-Intersecting and Triple Intersecting geometries are reserved for Appendix G. For each geometric category except Triple Intersecting, the Detour-Spin Index provides a combination of the attributes exhibited by the Detour and Spin indices, including the ability to scale with the separation of a parallel runway in the presence of an intersecting runway. In the Triple Intersecting cases, no extra information is provided, but the relationships to intersecting runway rotation and stagger remain present. The relationships were similar for all operational settings analyzed.

The categorical segmentation of the Detour-Spin Index can be seen in Figure 4.52. As can be seen from the categorical segmentation, the combined metric provides a more unified metric segmentation of the MAGENTA 95 geometries and especially of the Generic Infrastructures, with which the metric is intended to be used.

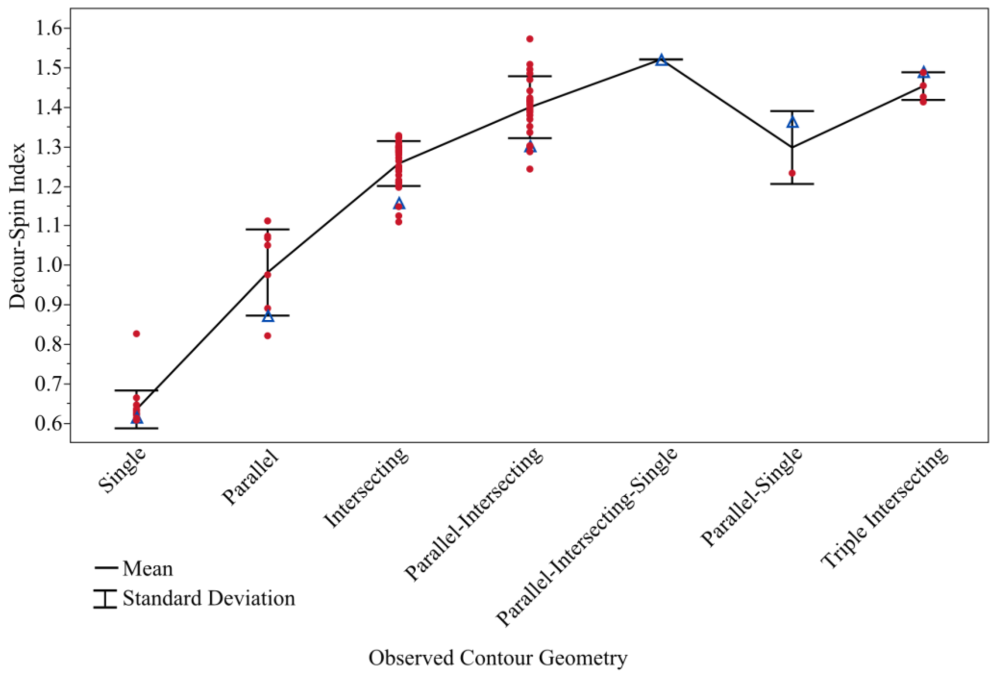


Figure 4.52: Detour-Spin Index categorical segmentation.

The metric still struggles in differentiating Parallel-Intersecting, Parallel-Single, and Triple Intersecting configurations from each other, but the situation is not improved by adding other current metrics to the summation. These results suggest that as configurations get more complex, all airport configurations with three runways are viewed very similarly by the collected and linearly summed shape metrics. Direct inspection was necessary to determine if some of the overlap between geometries was due to reasonable misclassifications during the qualitative categorization of the contour shapes or if they are rooted in a deficiency of the metric. For example, the overlap between the Single and Parallel categories can easily be explained by examining the contours for each airport in Figure 4.53. One is classified as a Parallel, while the other is a Single, but they are both obviously in the transition region between the two geometries.

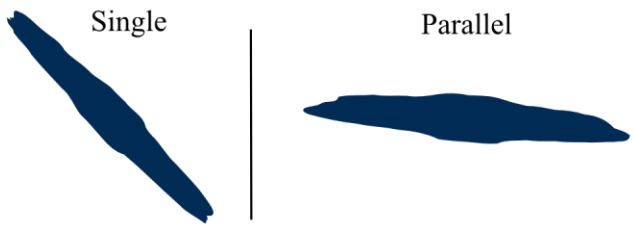


Figure 4.53: Overlapping Parallel and Single cases.

Similarly, the overlap between the Parallel and Intersecting geometries is caused by Intersecting geometries with more extreme rotations, which can begin to appear like a Parallel contour, as shown in Figure 4.54. The Parallel geometry consists of a separated set of parallel contours. These geometries should occupy this transitory region and therefore are not considered deficiencies of the metric. On the other hand, the Generic Infrastructure is also in this transitory region, further highlighting that calibration to contour area ignored the critical shape characteristics.

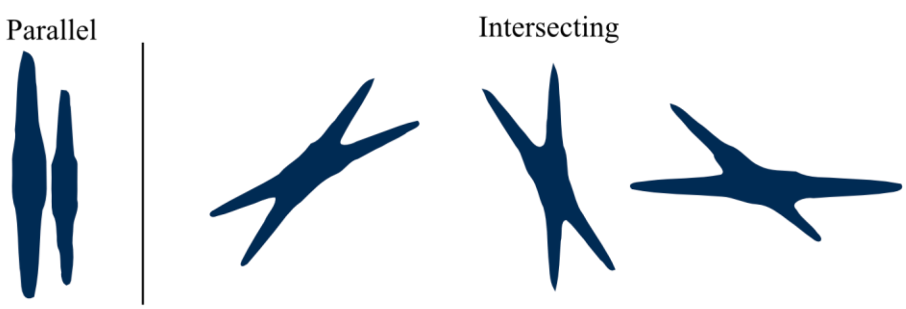


Figure 4.54: Overlapping Parallel and Intersecting cases.

There are also two cases, one classified as a Parallel-Intersecting, and the other as a Parallel-Single, that are well within the range for the Intersecting categories.

Examining these in Figure 4.55 shows that both are in a transition region from Intersecting to Parallel-Intersecting and Parallel-Single. At the other end of the Parallel-Intersecting spectrum is the case shown in Figure 4.56, which demonstrates that while the majority of the airports could be reasonably classified under the Generic Infrastructures, there will always remain certain unique outliers. The most unique of these were provided with special infrastructures, but this particular geometry was deemed sufficiently similar to the Parallel-Intersecting geometry in Generic Infrastructure development.

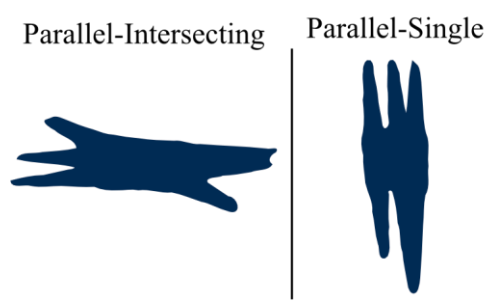


Figure 4.55: Overlapping Parallel-Intersecting and Parallel-Single cases.

Figure 4.56: Outlier Parallel-Intersecting case.

Examining the Triple Intersecting geometries that overlap with the Parallel-Intersecting regions in Figure 4.57 demonstrates the sensitivity to relatively low runway rotation. Confusion of these types of geometries is normal for a continuous metric, because a qualitative observer could argue for different classifications. By using the Generic Infrastructures, however, these issues are less prevalent because these contours occupy a more segmented space with respect to the Detour-Spin Index. While not pictured, the results for the other operational settings are similar, but the best results are obtained with higher operational settings, which suggest that the DSR may be a function of operational volume. Further examinations may benefit from broader metric searches to try and supplement the Detour-Spin Index. The metrics collected and examined for this work only constitute a relatively focused approach, and certainly do not include the breadth of potential shape metrics that could be of use.

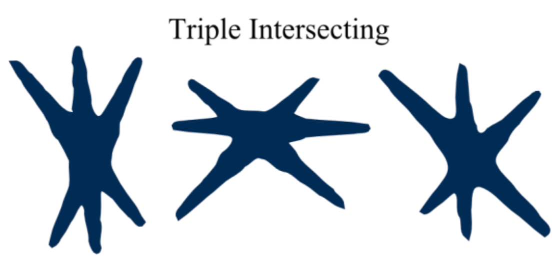


Figure 4.57: Triple Intersecting cases overlapping the Parallel-Intersecting region.

4.3.6 Metric Recommendations

The metrics presented were evaluated based on the correlation to the total number of contour lobes, the ability to describe the distribution of the contour lobes about the airport nucleus, and the ability to distinguish between the Generic Infrastructure geometric categories defined in the development of Generic Airports. All metrics were also assessed to ensure that they were insensitive to operational settings. The area was tested as a control for lobe correlation, demonstrating that it is not a sufficient descriptor of airport contour shape. From these tests, the Detour Index was determined to be the most useful metric, although supplementation with the Spin Index was highly beneficial. The Cohesion Index provided similar supplementation, but the relative expense required in calculating this metric with no extra benefit compared to the Spin Index led to it being discarded. The Dispersion Index, which also showed good correlation with respect to the number of contour lobes, did not provide sufficiently useful relationships to the lobe distributions nor categorical segmentations.

After examining the metrics in isolation, a linear summation of the Detour Index and the Spin Index was attempted, and shown to provide increased correlation to contour lobes while maintain low correlation with respect to the operational factors. The Detour-Spin Index also provided an improved description of the lobe distribution, and yielded significant improvements to the categorical segmentation. The Detour-Spin Index still showed some overlap between actual MAGENTA 95 infrastructures, but was mostly due to infrastructures that were difficult to classify qualitatively. In conjunction with the Generic Infrastructures, the Detour-Spin Index yields a useful segmentation that can be easily applied, especially if shape characteristics are utilized to tune the Generic Infrastructures. Further study is still required to gain better understanding of a broader operational range and how these factors may affect the ranges for each metric. For the purposes of the SWAN methodology, however, the metric can be applied to compare Generic Airport geometries between scenarios. The operational factor relationships will need further definition before concrete ranges for the Detour-Spin Index can be set for each geometric category.

While the Detour-Spin Index provides the most utility, the computations of the Detour and Spin indices should also be carried through separately, to distinguish the physical meaning of each metric with respect to a specific shape. Utilizing a linear summation alone would remove the useful physical interpretations that these values provide. These effects are important because both metrics may not always change at the same rate, or in the same direction between scenarios.

Having addressed the three capability gaps of a rapid generic fleet-level noise-modeling capability, airport categorizations to reduce the required modeling load, and definition of a useful shape metric, the three aspects of this research can be combined to demonstrate the value of the SWAN methodology in practice.

4.4 Use Cases: Technology Impact Assessment

Once the assessed capability gaps required to enable a generic fleet-level noise methodology are in place, the methodology was applied to evaluate technological infusions to the fleet in future forecast years to evaluate their ability to meet national fleet-level noise reduction goals. The resulting SWAN methodology enables the rapid assessment of technological impacts at the fleet-level with respect to contour area and shape, providing better quality information earlier in the decision-making process. The methodology can be implemented to provide answers to the overarching research questions proposed at the conclusion of Chapter 2. The SWAN methodology was implemented as defined in Chapter 3, repeated in Figure 4.58 for reference. The use cases will be implemented following these steps describe the results exploratory and normative forecasting scenarios.

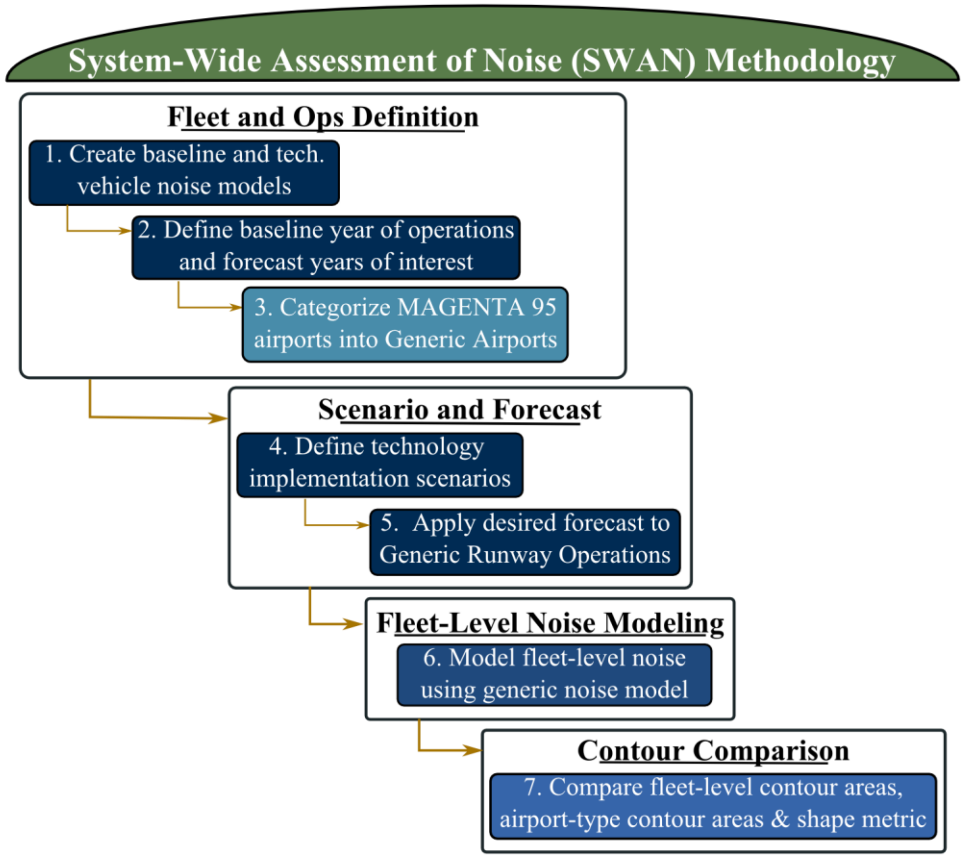


Figure 4.58: SWAN methodology.

4.4.1 N+1 Exploratory Forecasting Scenarios

The first example consists of an exploratory forecasting scenario to examine the fleet-level noise effect notional technologies in the N+1 timeframe. Each aspect of the implementation will be described culminating in the analysis of the results.

4.4.1.1 Fleet and Operations Definition

The first block of the methodology consists of setting the baseline information required to model fleet-level noise, as well as the technology space to be analyzed, and the creating of Generic Airports.

4.4.1.1.1 Step 1: Create Baseline and Technology Vehicle Models

As described earlier, vehicle-level noise can be acquired a number of ways including AEDT, INM, or the Aircraft Noise Prediction Program (ANOPP) developed by NASA, in conjunction with EDS. AEDT already has the necessary information to model the current fleet of aircraft. Nominally, the Generic Vehicles would be utilized in the SWAN methodology, but in the meantime, the current fleet will be treated by a set of representative aircraft that best approximate the average aircraft with respect to noise for each seat class. The AEDT tester, a program developed to rapidly assess single-event noise for one aircraft with AEDT algorithms, can be used to generate the SEL noise grids for the representative aircraft [137].

In order to define technology impacts at the vehicle-level however, ANOPP is most appropriate as it can model noise from specific components, whereas AEDT and INM utilize experimental data in the form of Noise Power Distance (NPD) curves [95]. ANOPP can be linked with EDS to model technology impacts at the aircraft level, and then exported as an AEDT model to ensure that noise computations are performed under the same standards and assumptions [137]. By creating general technology infused vehicles, the future fleet can be represented by a smaller number of aircraft models. The outcome of this step is a set of aircraft-level SEL grids for the representative aircraft fleet and technology vehicles incorporating the technologies summarized in Table 3.21. Only technology vehicle models for seat classes 3-9 were available at the time of this writing, and all results will reflect a status quo response with respect to seat class 2.

4.4.1.1.2 Step 2: Define Baseline Year of Operations and Forecast Years of Interest

The baseline year of operations is 2006, utilizing the datum year of operations available in the GREAT tool. The forecast year of interest is 2018. This information will be necessary to generate baseline and scaled Generic Airports scaled.

4.4.1.1.3 Step 3: Generate Generic Airports

Generic Airports are generated using the datum year of operations and the infrastructure models defined in INM for each airport. The grouping process follows the execution demonstrated in Section 4.2. The result is a baseline set of Generic Runways and Generic Infrastructures, which serve as the operational and infrastructure inputs respectively to the generic noise model ANGIM.

4.4.1.2 Scenario and Forecast

Once the fleet of aircraft and the baseline operations are set, the technology implementation scenarios must be defined, and the forecast must be applied to the baseline Generic Runway models.

4.4.1.2.1 Step 4: Define Technology Implementation Scenarios

This notional example will assume 50% of the 2018 operations will be performed by the notional technology infused vehicles. It is important to recall that these scenarios are purely notional, and do not take into account the required time to manufacture and distribute new aircraft in such a timeframe.

4.4.1.2.2 Step 5: Apply Desired Forecast to Generic Runway Operations

The TAF forecast, applied to the 2006 datum year operations in GREAT is utilized to provide projected operations in the target year of 2018. These values are used to determine the fleet-wide change in operations by seat class, and these scaling vectors are then applied to the Generic Runway models as shown in Figure 4.59.

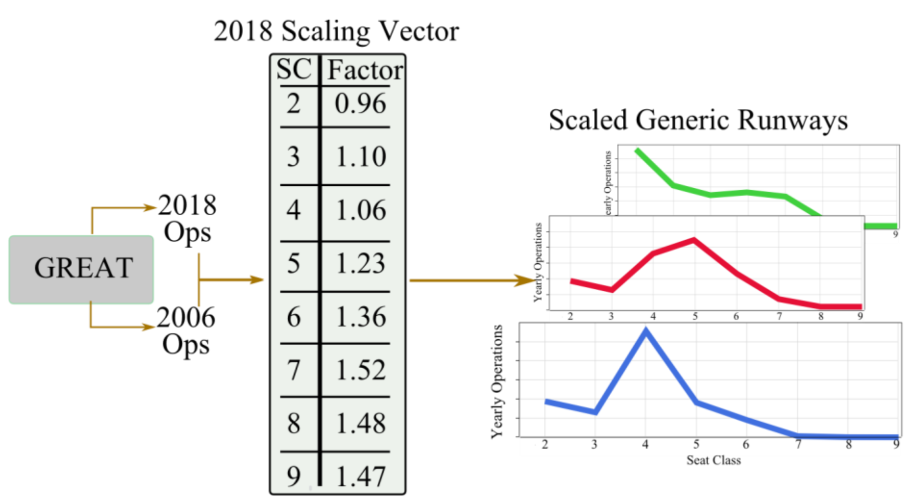


Figure 4.59: Application of forecast scaling by seat class to Generic Runways.

A status quo (SQ) scenario is computed by assigning all forecasted Generic Runway operations to the baseline representative aircraft, representing a scenario in which no technology infusions occur. The technology infused forecasted Generic Runways are then created by assigning 50% of the forecasted flights to the technology infused vehicles.

4.4.1.3 Fleet-Level Noise Modeling

Once the models required for executing fleet-level analyses through ANGIM for the baseline, status quo, and technology infused Generic Airports are created, the modeling process can be carried out.

4.4.1.3.1 Step 6: Model Fleet-Level Noise using Generic Noise Model

The baseline, status quo, and technology infused Generic Airports were modeled through ANGIM, requiring approximately twelve minutes of computation time for each set of Generic Airports. ANGIM was linked to the computer codes created to evaluate the shape metrics such that contour areas, contour points, and DSI values were output for each airport type.

4.4.1.4 Contour Comparison

Once the execution of the fleet-level noise model is complete, the data can be analyzed to yield specific insights with respect to the technology impacts at the fleet-level and at specific airport types.

4.4.1.4.1 Step 7: Compare Fleet and Airport-Level Contour Areas and Shape

The fleet-level contour area demonstrated a decrease of approximately 2.5 nmi^2 at the fleet-level, amounting to a 1.8% decrease in DNL 65 dB contour area compared to the 2006 baseline scenario. Interestingly, not all Generic Airport categories experienced a decrease in contour area. A summary of the results with respect to the 2006 baseline are listed in Table 4.22. It is important to note, when utilizing shape metrics, they must be viewed as measures of shape change, as opposed to measures of increasing or decreasing noise.

Table 4.22: 2018 exploratory forecasting results relative to 2006.

Generic Airport	Δ Area (nmi^2)	%Δ DSI	%Δ DI	%Δ SI
Single-S1	0.02	5.59	1.76	16.90
Single-S2	-0.05	10.61	7.10	18.57
Single-M1	-0.22	-1.97	-1.61	-2.70
Parallel-S1	0.05	1.16	-0.65	7.77
Parallel-S2	0.05	7.13	0.98	21.29
Parallel-M2	-0.21	-0.14	0.58	-1.15
Parallel-L2	-1.08	1.56	0.92	2.67
Intersecting-S1	0.06	1.63	0.06	9.41
Intersecting-S2	0.04	2.80	-0.71	13.67
Intersecting-M1	-0.15	0.77	-0.65	4.06
Intersecting-M2	-0.18	-1.53	-0.56	-3.60
Parallel-Intersecting-S1	0.13	4.74	-0.16	22.87
Parallel-Intersecting-S2	0.09	7.16	-0.56	25.48
Parallel-Intersecting-M1	-0.13	2.90	0.05	7.25
Parallel-Intersecting-M2	-0.24	1.66	0.84	2.84
Parallel-Intersecting-Single-M1	-0.07	-0.20	-0.27	-0.01
DFW	-0.85	-1.21	-0.01	-3.29
Parallel-Single-M1	-0.06	1.67	0.48	5.03
Triple Intersecting S2	-0.09	10.82	-0.49	38.25
Triple Intersecting-M2	-0.15	1.49	0.07	3.69
ORD	-0.29	-0.67	-0.24	-1.32

The positive or negative nature of a change in shape is dependent on the basic shape itself, and the DSI metric must be decomposed into its parts to examine physical shape changes. The results in Figure 4.60 show the DSI value for each Generic Airport for the baseline case, the 2018 technology response scenario, and a 2018 status quo scenario. The increase in operations in most cases has relatively little effect on the metric, but the introduction of technology infused aircraft affects the DSI of several geometries. The DSI can be used to highlight airport types that exhibit a change in shape beyond that observed by the increase in operations alone.

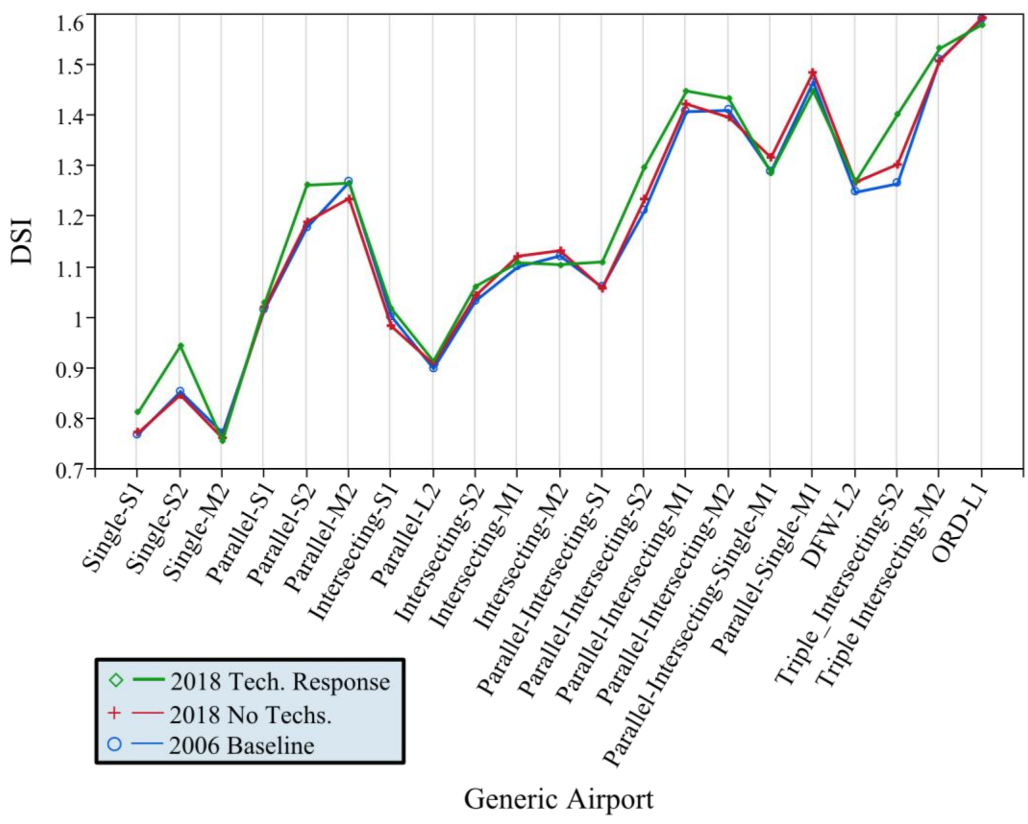


Figure 4.60: Detour-Spin Index by Generic Airport.

The Single-S2 and the Parallel-S2 geometries will be assessed explicitly as an example. The Detour and Spin indices can be used separately to discern the basic change in shape that has caused a deviation from the baseline DSI. Applying the metrics in this manner, the shape effects of the technology infused aircraft can be analyzed quickly at all airports to determine which are impacted the most with respect to shape.

4.4.1.4.1.1 Single-S2

The first example reviewed is the Single-S2 airport, shown in Figure 4.61, which exhibits a significant impact due to the technology infused aircraft.

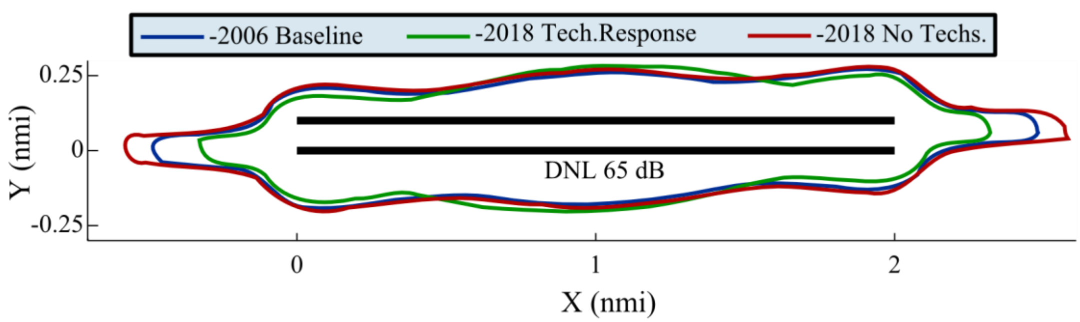


Figure 4.61: Single-S2 contour responses.

It is important to recall the Single geometry is modeled by two closely separated runways. This decision was made as a calibration to better match the actual MAGENTA 95 geometries. The results show an increase in both the Detour and Spin index. Since the Single geometry is relatively thin in one principal direction, the metrics are very sensitive to changes in the length of the contour lobes. Both metrics are normalized using the Equal Area Circle, and increase the closer a shape approximates a circular spatial distribution. In the context of fixed operations, the Spin Index directly implies the compactness of the shape, while the Detour Index implies how much of an obstacle a shape represents relative to its area [127]. In the context of comparing cases at different operational and technological conditions, the Spin Index implies a change in compactness relative to a change in contour area. The Detour Index implies a change in how spatially dispersed the contour boundary is relative to a change in contour area. The increase in Spin Index for the Single-S2 due to technological infusion suggests that the effect of the technologies is to make the resulting contour more compact relative to its area. The increase in Detour Index, on the other hand, suggests that the contour is now more evenly distributed in all directions relative to its area. Both of these conclusions are supported by the shortening of the contour lobes and the increase in the vertical axis due to the infusion of the technological aircraft. Note that the effects of maintaining the status quo did not generally affect the shape of many of the Generic Airports. The ability to propagate detailed models of technology infused aircraft, however, allows the effects of these technologies to be modeled beyond photographic scaling of contour area. Current methodologies would treat these technological infusions by relating the effect to a change in operations, missing the effect on contour shape.

4.4.1.4.1.2 Parallel-S2

The second Generic Airport explicitly examined is the Parallel-S2 configuration, shown in Figure 4.62, which exhibited a large change in DSI due to technology insertion, and also an increase of 0.05 nmi^2 in contour area. This geometry exhibited a much more significance increase in Spin Index than Detour Index. This result suggests that the overall distribution of the shape relative to the change in area is minor. On the other hand, the apparent increase in compactness is significant, despite the relative lack of change in the length of the contour lobes. In this case, the DNL 65 dB contour is comprised of two discontinuous contours.

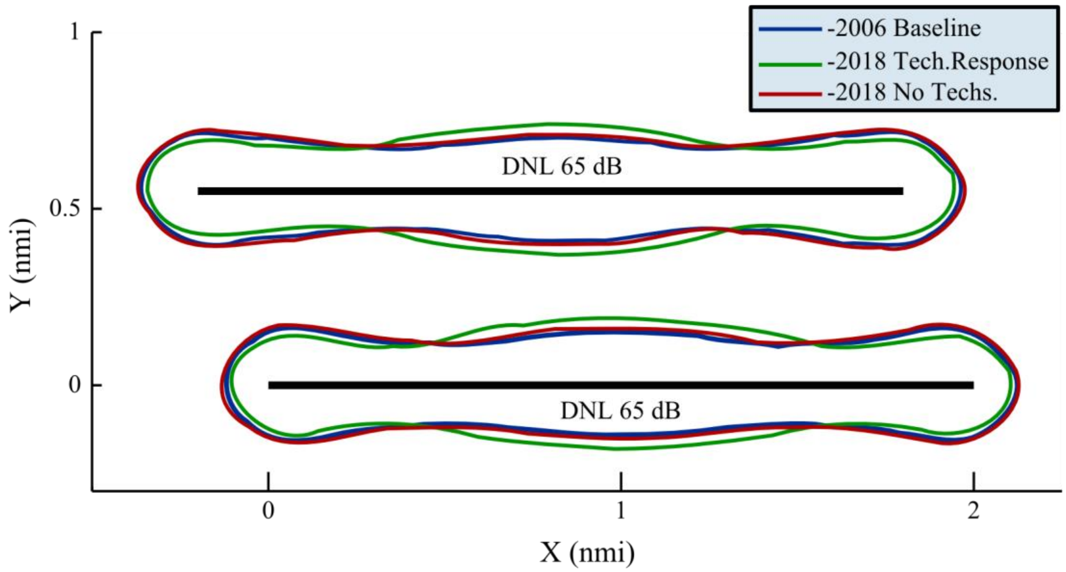


Figure 4.62: Parallel-S2 contour responses.

While this is obvious from qualitative observation, it can also be deduced by observing the high DSI value presented for all parallel Generic Airports except Parallel-L2. The high values result from sufficiently low operations causing the DNL 65 dB contour to be discontinuous. Since the infrastructure category is known ahead of time in this case, this conclusion can be drawn.

This difference is not trivial, however, because it signifies large portions of the DNL 65 dB boundary are dominated by the airport nucleus, and any improvements in this region will not provide any reduction in population exposed. The increase in Spin Index is still caused by an increase in compactness of the shape relative to its change in area, but this increase in compactness is driven by the increase in width of both discontinuous contours in the center of each runway. These changes in shape have no benefit or disadvantage inside the airport nucleus, but constitute a disadvantage along the exterior contour boundaries. While the increase has been minor, there has been some tradeoff between the length of the contour lobes and their widths. Since half of these width increases are directed towards the airport nucleus, however, the positive area reduction is probably larger than the contour area can suggest alone.

4.4.2 N+1 Normative Forecasting Scenario

The second use case is a normative forecasting example, because the problem is inverted to provide the required insertion of the notional technology package to achieve the desired compounded fleet-level noise reduction from the baseline 2006 year, based on averaged historical data. The problem uses the exact same approach outline above, except with an iterative loop between the Contour Comparison and the Scenario and Forecast blocks, as shown in Figure 4.63. As can be seen in the figure, the contour comparison in Step 7 is first used to examine the fleet-level reduction to contour area, providing the information back to the definition of technology implementation scenarios (Step 4). Based on whether the fleet-level reduction is above or below the constraint, a new insertion of technology infused vehicles is defined in Step 4 using the bisection method [134]. This new insertion is then used to create a new technology infused set of forecasted Generic Runway models in Step 5, and evaluated using ANGIM in Step 6.

Throughout the process, the baseline and status quo cases do not vary. This process was utilized to converge upon a fleet-level DNL 65 dB contour area reduction of 4.4% in 2018, relative to the 2006 baseline.

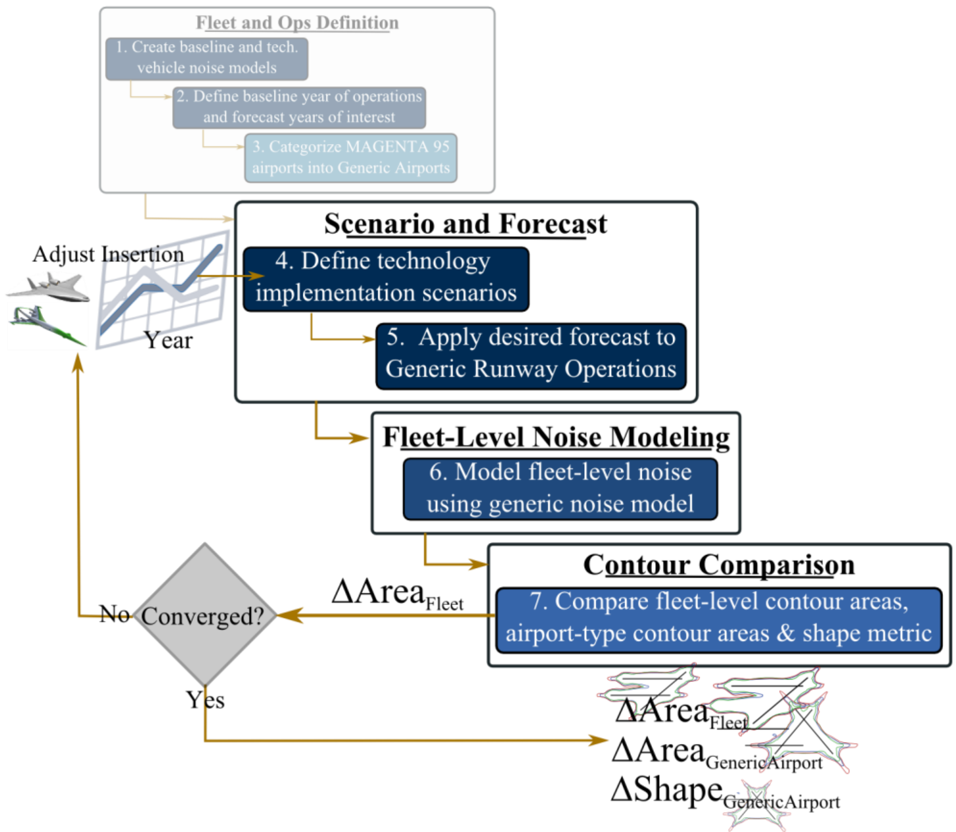


Figure 4.63: Iterative loop for normative analyses.

4.4.2.1 Step 7: Compare Fleet and Airport-Level Contour Areas and Shape

Convergence within a tolerance of +/- 0.5 nmi^2 at the fleet-level was achieved after three iterations, resulting in a required technology aircraft insertion of 62.5%. The result implies that using these technologies, 62.5% of the flights in 2018 would have to be performed by new aircraft to meet the contour area reduction goal of 4.4% relative to the 2006 baseline year. The contour area and shape results are listed in Table 4.23, which shows that some configurations still observe a net increase in contour area.

Table 4.23: 2018 normative forecast results relative to 2006.

Generic Airport	Δ Area (nmi^2)	%Δ DSI	%Δ DI	%Δ SI
Single-S1	0.02	7.43	2.22	22.78
Single-S2	-0.08	15.41	11.01	25.36
Single-M1	-0.34	-1.59	-1.79	-1.17
Parallel-S1	0.06	1.91	0.05	8.70
Parallel-S2	0.03	6.45	1.02	18.96
Parallel-M2	-0.36	0.04	1.20	-1.60
Parallel-L2	-1.51	2.48	1.45	4.27
Intersecting-S1	0.06	1.81	0.18	9.90
Intersecting-S2	0.03	2.23	-1.01	12.28
Intersecting-M1	-0.24	0.44	-0.78	3.23
Intersecting-M2	-0.31	-0.96	-0.49	-1.97
Parallel-Intersecting-S1	0.13	4.43	-0.46	22.50
Parallel-Intersecting-S2	0.07	8.07	-0.78	29.04
Parallel-Intersecting-M1	-0.22	3.72	0.43	8.72
Parallel-Intersecting-M2	-0.37	2.64	1.26	4.65
Parallel-Intersecting-Single-M1	-0.16	0.52	0.08	1.67
DFW	-1.26	-2.39	-0.01	-6.49
Parallel-Single-M1	-0.15	1.48	0.39	4.57
Triple Intersecting S2	-0.11	11.83	-0.73	42.28
Triple Intersecting-M2	-0.26	2.75	-0.38	7.62
ORD	-0.43	-1.53	0.14	-4.05

The shape results are qualitatively similar to the exploratory example in terms of change in DSI, so these results will continue to refer to Figure 4.60 . To demonstrate the physical significance of the shape metrics further, the Parallel-Intersecting-S2 and the Parallel-Intersecting-M1 airports will be analyzed explicitly.

4.4.2.1.1 Parallel-Intersecting-S2

The contour responses for the Parallel-Intersecting-S2 airport can be seen in Figure 4.64, which demonstrate an area increase of 0.07 nmi^2. The shape metrics demonstrate a decrease in Detour Index, however, which suggests that the difference between the perimeter of the convex hull and the perimeter of the Equal Area Circle is less for the technology response case.

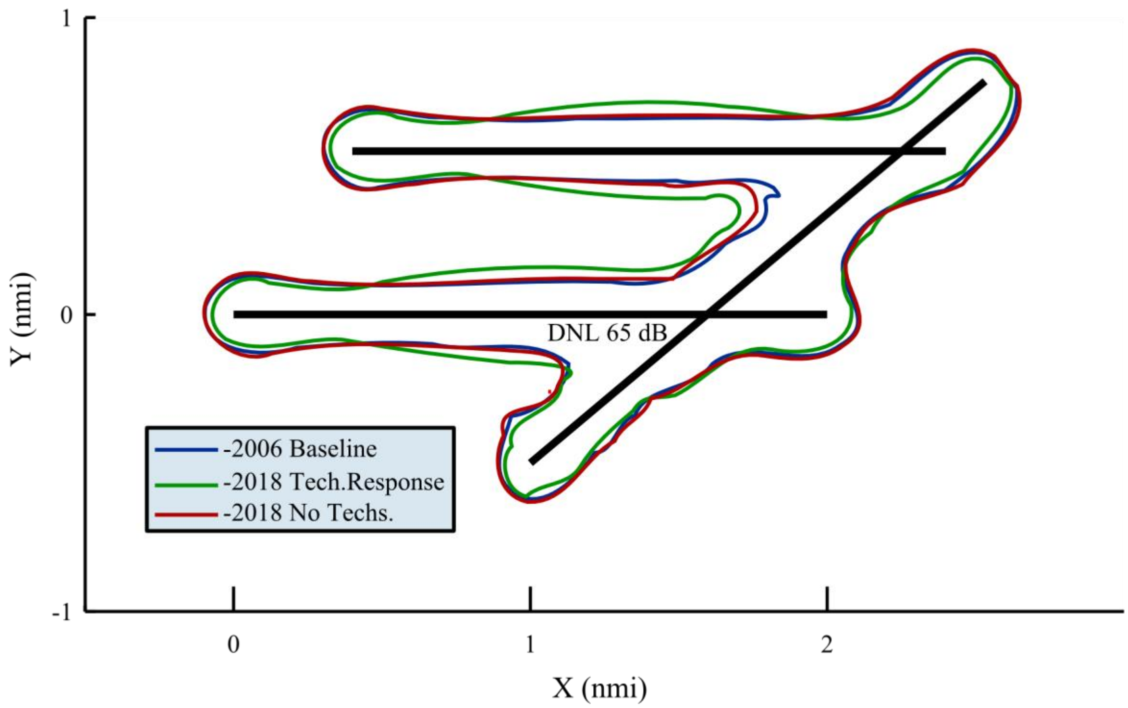


Figure 4.64: Parallel-Intersecting-S2 contour responses.

This result is largely caused by the shortening of the parallel contour lobes, while their increased girth has little impact on the convex hull of the shape. Again, these increases in contour width are partially dominated by the airport nucleus and provide no detriment to a surrounding community. The Spin Index has undergone a relatively large increase, suggesting increased compactness relative to the decrease in area. This result is also due to the increase in width of the parallel contours. As the area between these is filled, the shape will become significantly more compact, although ultimately, the increase in area will limit the potential increase in Spin Index. While the overall area of the contour has increased, a majority of the exterior airport boundaries are recessed, suggesting that area may be under-reporting the benefit of the technologies.

4.4.2.1.2 Parallel-Intersecting-M1

The second airport explicitly analyzed was the Parallel-Intersecting-M1 configuration. This airport has significantly higher operations volume than Parallel-Intersecting-S2, but demonstrates a decrease in contour area relative to the baseline case. The contour responses can be seen in Figure 4.65. Both the Detour and Spin indices have increased accompanied by a general reduction in the technology response contour boundary in almost all regions of the airport boundary. Again, the boundaries that have not receded are located in the region dominated by the airport nucleus, and do not increase population exposure. The increase in Detour Index relative to the 2006 baseline is due to the general recession of the contour boundary, reducing the perimeter of the convex hull, while the increase in Spin Index is due to the general increase in compactness due to contour recession and increased width of the parallel contour lobes.

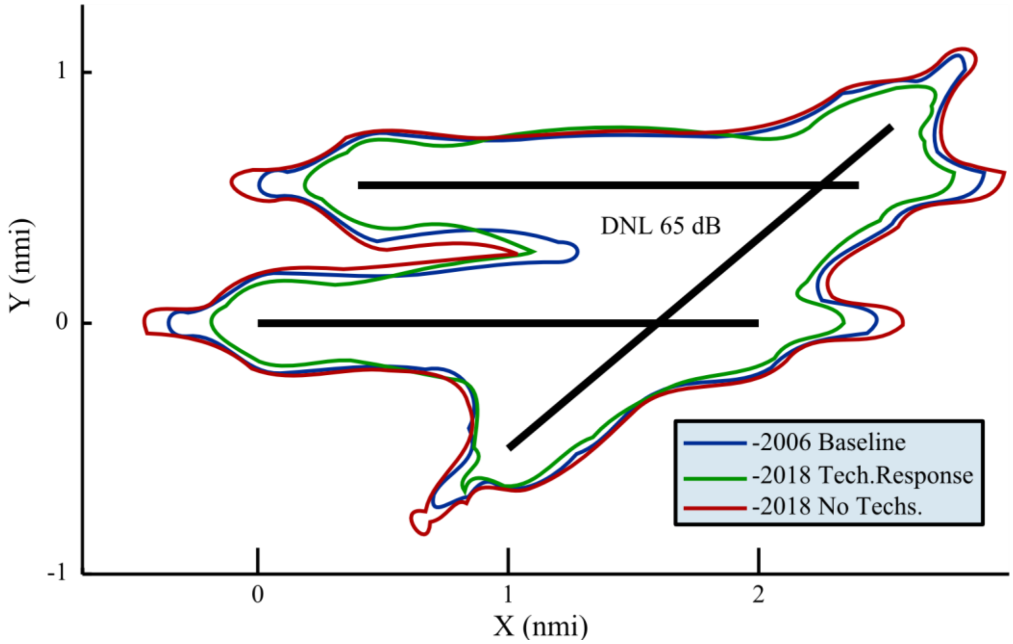


Figure 4.65: Parallel-Intersecting-M1 contour responses.

4.4.2.1.3 Case 1 Summary

While the fleet-level noise reduction goals imposed by this example are feasible by 2018, they would require a 62.5% insertion of the notional technology infused vehicles by that time. Considering N+1 technologies will not become available to enter the market until 2015 at the earliest, it is unlikely that over half the fleet would turnover by 2018, not to mention the inability of manufacturers to produce aircraft at the required rate. Interestingly, however, there appears to have been a "tipping point" between the insertion assumed for the N+1 exploratory forecasting example and the N+1 normative forecasting example. While a 50% insertion yielded only a reduction of 1.8% in contour area, only another 12.5% insertion of technology infused vehicles was required to meet the area reduction goals. The introduction of shape metrics underlines the importance of examining the effects of technology infusion on different airport types. While contour area can increase in certain cases, these may still result in a net reduction in population exposed, and may lead to better predictions about technology impacts. The results of the examples for 2018 thus far suggest that contour area may not fully explain the benefits of technology infused vehicles with respect to population exposed, especially for airports with parallel runway sets. Because capacity-related airport expansions generally dictate the construction of parallel runways, this result could prove significant if observed throughout various cases [122].

Consequently, the assumption of relating contour area reduction directly to population reduction is challenged by these results. A population prediction will ultimately be necessary, but is beyond the scope of this work. Nonetheless, the ability to examine contour shape effects of technological infusions may lead to more accurate estimates of technology benefits with respect to population exposure.

4.4.3 N+2 Normative Forecasting Scenario

The second normative example follows the same process as the N+1 scenario, except for a few minor adjustments. In Step 2, the target forecast year is 2025, to examine the required insertion to meet fleet-level noise reduction goals using only N+1 technologies in an N+2 timeframe. In Step 4, a baseline insertion of 75% used to seed the bisection optimization. In Step 5, the 2025 forecast vectors are applied to the Generic Runway models as shown in Figure 4.66. This configuration is qualitatively similar to the N+1 normative forecasting example, except the target forecast year and the required contour area reduction are different.

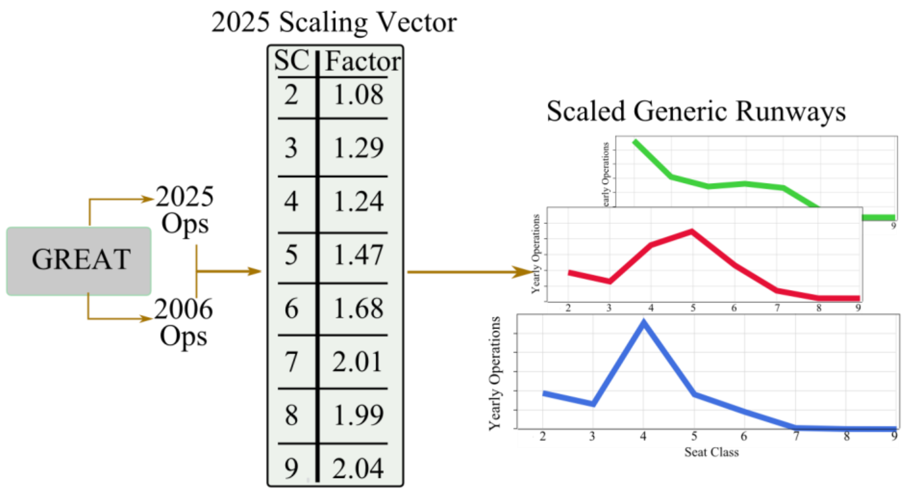


Figure 4.66: Application of forecast scaling by seat class to Generic Runways.

4.4.3.1 Step 7: Compare Fleet and Airport-Level Contour Areas and Shape

The iteration between Step 7 and Step 4 was performed until a reduction in fleet-level contour area of 7% is achieved relative to the 2006 baseline. The bisection method converged after five iterations yielding a required 98.4% insertion of technology infused vehicles to reduce fleet-level contour area by 7% from the 2006 baseline. The contour area and shape metric results are listed in Table 4.24. Again, while the constraint is met, not every Generic Airport exhibits a net reduction in contour area. While most of the increases are minor, the Parallel-Intersecting-S1 exhibits a significant increase in contour area, along with other geometries that incorporate S1 and S2 operations. This result is most likely caused by the lack of a seat class two technology infused aircraft. As operations increase and these aircraft types are not reduced in noise, the operational configurations that operate seat class 2 aircraft in large quantities relative to other aircraft types will begin to see increases in contour area.

Table 4.24: 2025 normative forecasting results relative to 2006.

Generic Airport	Δ Area (nmi^2)	%Δ DSI	%Δ DI	%Δ SI
Single-S1	0.04	16.19	5.15	48.74
Single-S2	-0.11	26.13	16.68	47.55
Single-M1	-0.47	-3.47	-1.69	-7.11
Parallel-S1	0.08	6.84	0.68	29.32
Parallel-S2	0.05	15.91	2.07	47.78
Parallel-M2	-0.60	-2.87	0.67	-7.88
Parallel-L2	-2.15	1.00	2.50	-1.58
Intersecting-S1	0.08	4.29	-0.15	26.39
Intersecting-S2	0.05	5.17	-1.31	25.24
Intersecting-M1	-0.31	-0.20	-1.31	2.36
Intersecting-M2	-0.43	-2.32	-0.88	-5.38
Parallel-Intersecting-S1	0.19	6.06	-0.45	30.17
Parallel-Intersecting-S2	0.10	10.10	-1.14	36.75
Parallel-Intersecting-M1	-0.32	5.28	0.50	12.57
Parallel-Intersecting-M2	-0.53	3.63	1.25	7.11
Parallel-Intersecting-Single-M1	-0.22	0.02	0.18	-0.40
DFW	-1.70	-3.47	-0.08	-9.30
Parallel-Single-M1	-0.21	1.93	0.73	5.36
Triple Intersecting S2	-0.16	14.93	-1.01	53.58
Triple Intersecting-M2	-0.41	3.51	-1.18	10.81
ORD	-0.62	-3.02	0.02	-7.60

The Detour-Spin Index values for each Generic Airport for the baseline, technology response, and status quo cases are shown in Figure 4.67. The effect of much larger operations at all airports has caused the status quo examples to deviate more significantly from the 2006 baseline with respect to DSI, although in many cases the technology infusions still result in a more significant change. These changes allow one to pinpoint airport configurations that have been impacted with respect to shape as a result of the technology infusions. Of these cases, the Triple Intersecting-S2, and Triple Intersecting-M2 configurations will be examined explicitly.

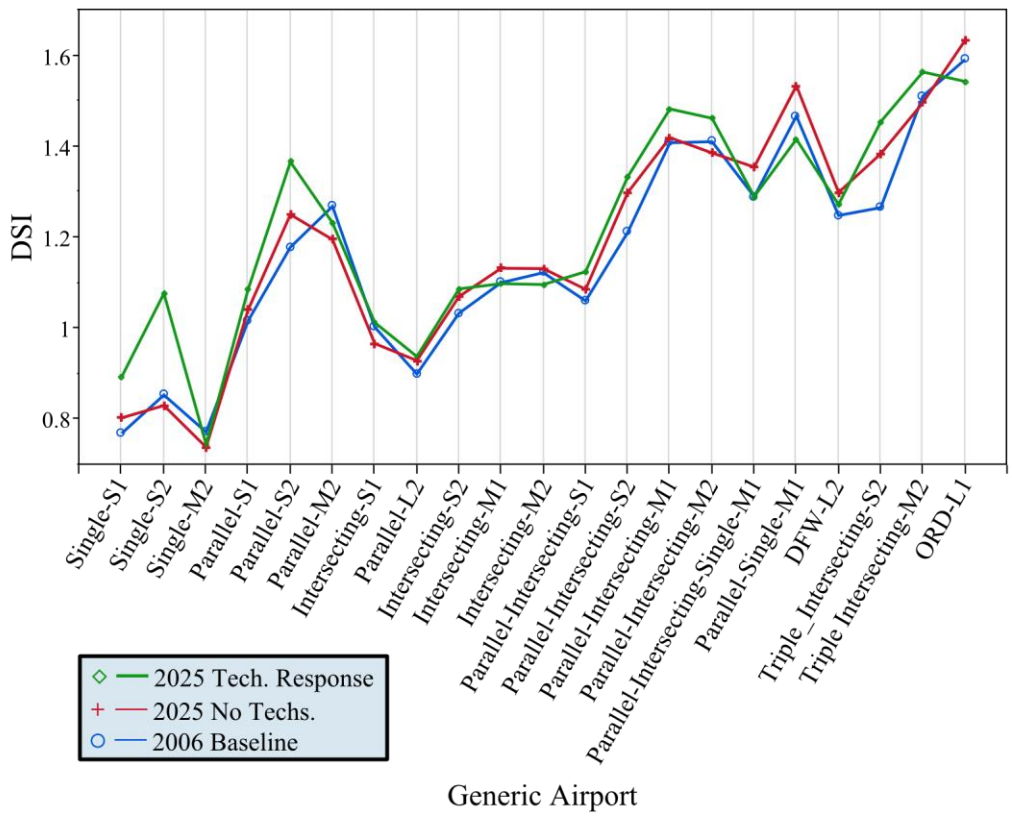


Figure 4.67: Detour-Spin Index by Generic Airport.

4.4.3.1.1 Triple Intersecting-S2

The first airport analyzed was the Triple Intersecting-S2 configuration, which exhibited a reduction in contour area. The contour responses can be seen in Figure 4.68. Interestingly, the increase in operations from 2006 to 2025 has little effect on the overall size of this contour. The main effect is to reduce the size of the central area of the airport that has less than DNL 65 dB noise, which is responsible for the increase in DSI caused solely by the increase in operations. The technology infused aircraft result in a relatively large reduction in Detour Index and Spin Index. The reduction in Detour Index is obviously due to the decrease in contour lobe length for each runway.

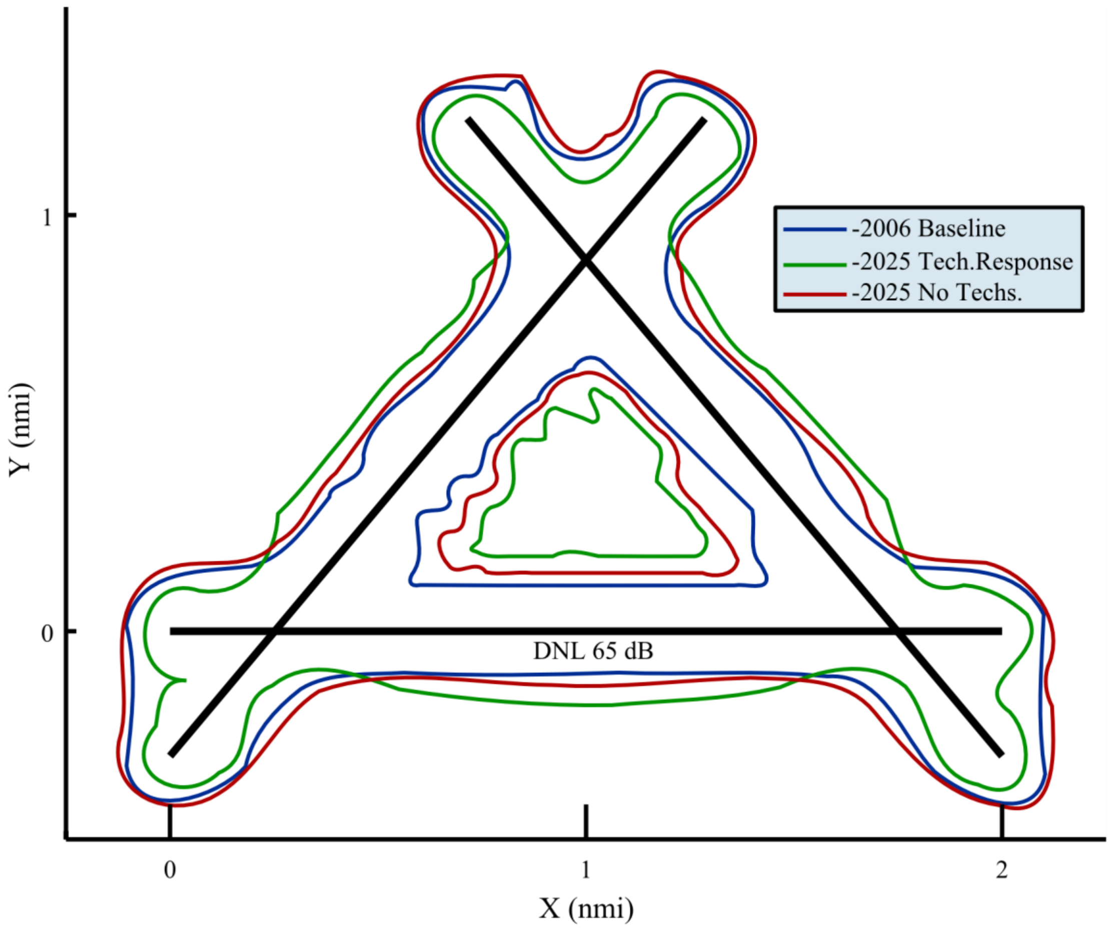


Figure 4.68: Triple Intersecting-S2 contour responses.

For Triple Intersecting geometries, the location of these lobes drives the value of the Detour Index, as the central regions of each runway lobe do not protrude sufficiently to be part of the convex hull. The increase in Spin Index is also a result of the reduction of the contour lobe lengths, but is more pronounced because of the reduction of the central area of the airport that has less than DNL 65 dB noise exposure. The technology infused vehicles have the effect of compressing the noise closer towards the runways, impacting the size of this region. Again, this effect probably causes an underestimate in the benefits of the technologies because closing this central contour gap increases contour area while not risking further exposure to the population. Similar to other contours, there is some increase in area towards the outer boundary of the airport at the mid-regions of each runway, which would increase the population impacted by significant noise at these locations of the contour boundary.

4.4.3.1.2 Triple Intersecting-M2

The second airport analyzed was the Triple Intersecting-M2 configuration, shown in Figure 4.69.

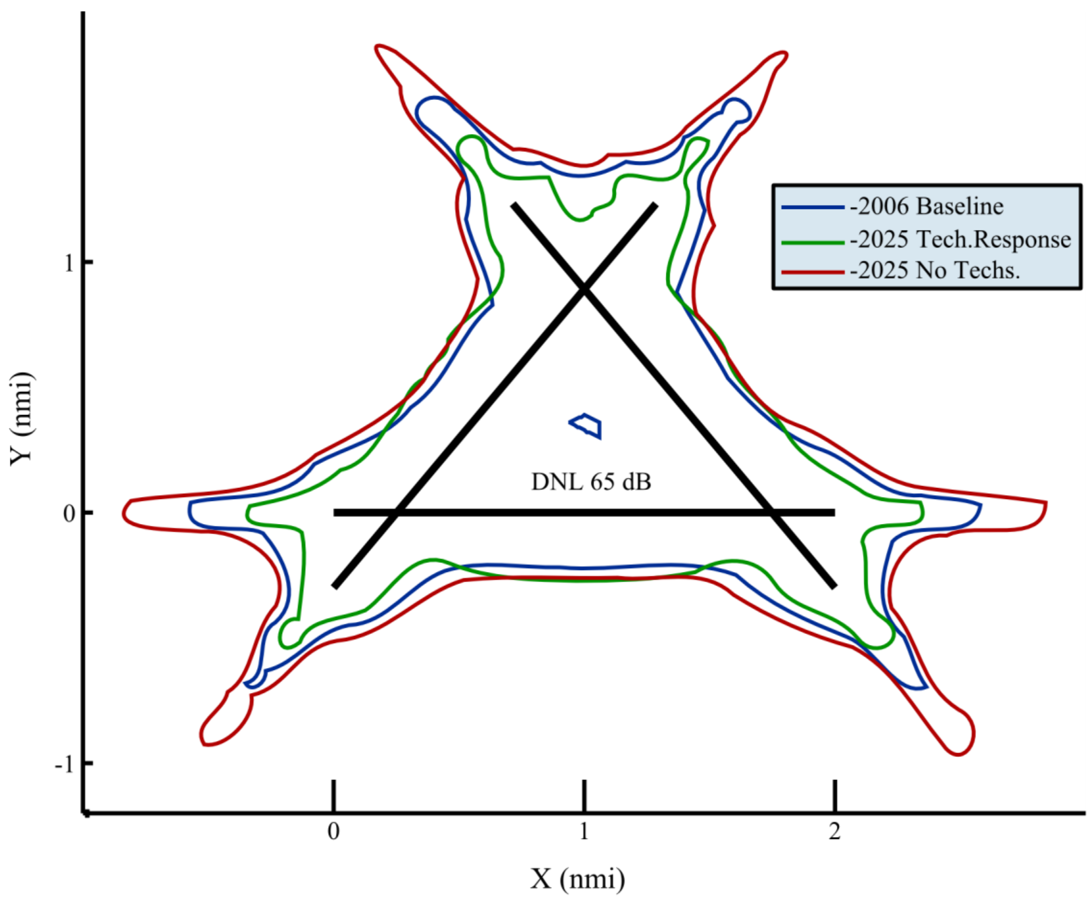


Figure 4.69: Triple Intersecting-M2 contour responses.

This airport exhibited a reduction of 0.41 nmi^2 in contour area. Also of note, the 2025 status quo case results in a much larger contour than the 2006 baseline, unlike the results shown for the Triple Intersecting-S2 configuration. Again, this demonstrates the importance of capturing different operational scenarios as well as geometric scenarios to perform fleet-level noise evaluations. Similar to the Triple Intersecting-S2 example, the Detour Index is decreased due to the reduction in the length of the contour lobes of each runway. These have a significant impact on the convex hull of the contour. Furthermore, the Spin Index exhibits an increase, again due to the increased compactness of the shape caused by the reduction of contour lobe lengths and the elimination of the low-noise region at the center of the airport nucleus.

4.4.3.1.3 Case 2 Summary

This scenario was performed to further highlight how the methodology presented here can be utilized to analyze various technology goals. While meeting this particular goal is technically feasible within the parameters of the notional example presented here, it is important to note that the required market penetration of N+1 technologies is nearly 100%. To put this value in a different perspective, the required aviation market would have an almost *entirely* new fleet compared to the aircraft currently in operation today. This turnover in an aircraft fleet is *highly* unlikely in the span of approximately twelve years. It is important to note that both normative examples were notional, and only examined one technological scenario under various operational conditions. Nonetheless, the required insertion to meet fleet-level noise reduction goals by 2025 would strongly suggest the need to continue N+2 and N+3 technology development programs moving forward.

The SWAN methodology provides decision makers with more accurate information about the fleet-level effects of technology infused aircraft with respect to noise. This information is provided via contour areas *and* contour shape characteristics, which sometimes demonstrate that contour area is not fully describing the benefits or disadvantages of a technological scenario at a given airport type.

CHAPTER 5

CONCLUSIONS

The research presented in this document was intended to assess the capability gaps obstructing the development of a generic fleet-level noise methodology, address these deficiencies through a structured research plan, and implement the resulting System-Wide Assessment of Noise (SWAN) methodology through use cases designed to answer the overarching research questions. The capability gaps included developing a rapid fleet-level noise modeling capability, categorizing airports to reduce the modeling load at the fleet-level, and the search and assessment of existing shape descriptor metrics that improve the communication of shape characteristics beyond qualitative visualization. Each of these capability gaps was addressed via research questions, literature search, logical reasoning, hypotheses, and experiments. Concluding remarks for each are presented below, followed by a revisiting of the research objective and overarching research questions in the context of the use cases of the methodology.

5.1 Generic Fleet-Level Noise Modeling

The rapid generic fleet-level modeling capability developed was the Airport Noise Grid Integration Method (ANGIM). The original research questions posed were:

I. *What are the important variables to consider for a generic fleet-level modeling tool?*

II. *How can detailed tools be leveraged to provide noise information for a simplified fleet-level modeling capability?*
   a. *What simplifying assumptions can be made to speed up the process?*
   b. *How can contour shape information be retained?*

III. *What are the sources of error in such a model?*

The first question was answered via examination of the variables included in detailed modeling methods, leading to the decision to capture airport geometric variables and fleet-level operational variables such as fleet mix, total operations, trip length distributions, day/night operations, runway utilization, and traffic flow. These operational variables capture the various degrees of freedom from a fleet-level perspective. To leverage detailed aircraft acoustical modeling capabilities, pre-calculated aircraft-level noise grids were generated using detailed models. By making simplifying assumptions of mainly straight ground tracks and sea-level standard atmosphere, these grids can be summed logarithmically to yield runway-level grids. To capture contour shape information, each runway-level grid can then be interpolated and summed to yield an airport-level grid. To answer the final research question, two hypotheses were proposed:

I. *If aircraft-level grids can be pre-calculated, leveraging detailed noise modeling methods, then the logarithmic addition of these grids can approximate a runway-level grid with acceptable accuracy with respect to a detailed model.*

II. *If runway-level grids can be calculated using pre-calculated aircraft-level grids, the runway-level grids can be translated, rotated, interpolated, and summed to approximate an airport-level grid within acceptable accuracy and significant time savings with respect to a detailed model.*

These aspects of the model were compared in isolation and at the system-level to detailed models, demonstrating the accuracy of the model under ideal conditions (assumptions obeyed). Runway-level summation was confirmed to be nearly precise, exhibiting error due to significant figure resolution when converting from logarithmic to linear scales and vice versa. Runway-level grid interpolation and summation to yield an airport-level grid was also confirmed as valid, although interpolation of the grids introduces some significant error. These errors are present at points near the runway, and increase as the number of runway-level interpolations increases. Due to the proximity to the runway, the error points have no effect on the DNL 65 dB contour area.

Having confirmed the hypotheses, ANGIM was then compared to detailed models in which major assumptions regarding ground tracks and atmosphere were systematically violated to demonstrate the potential error caused by these assumptions. Under ideal conditions, with all assumptions obeyed, the model is very accurate, only suffering significant error points very close to the runway due to sharp gradients in predicted noise stressing the interpolation methods. At altitudes of approximately 1,000 feet, the model still retains basic shape and contour area precision. The increased significant error occurs at grid points far away from the runway, and also far removed from the DNL 65 dB contour. Further tests may be required to capture the total effect, but the lack of impact due to atmospheric variation suggests that a simple calibration correction may be easily developed and applied. Under significant ground track divergence, ANGIM provided contour area predictions well within the tolerance bands, while the contour shape was more severely affected, sometimes stretching beyond the tolerance band. Nonetheless, the basic shape of the contour was retained, although the geographical preciseness was significantly affected by the divergent ground tracks. From these results, it is preferred that airport ground tracks exhibit symmetric divergence when using ANGIM, although for screening-level assessments, ANGIM is applicable to capture fleet-level trends due to operational and technological scenarios.

The model was able to demonstrate significant time savings, especially over full detailed models in which all ANGIM assumptions are violated. Considering the contour area is well within the tolerance band, ANGIM provides a significantly faster method of predicting fleet-level noise within a certain tolerance. Beyond the runtime of the model, which can be reduced in detailed methods to a certain extent by making similar assumptions, ANGIM has the advantage that it is simple to setup, and accessible to any windows machine.

ANGIM is a major enabling capability because it can be run in batch format, which allows for the computation of thousands of cases if necessary, without requiring a user-in-the-loop. Since ANGIM has simple inputs, these batch runs can be linked to Design of Experiments cases, or to large fleet-level analyses. This capability enables large-scale investigations of fleet-level noise including variables such as aircraft mix, stage length distribution, runway utilization, traffic flow, approach/departure ratios, day/night operations ratios, and runway configuration, which take on the order of days instead of weeks or months. Without such a capability, the development of Generic Airports, and a contour shape descriptor would have been severely hampered.

5.2 Airport Categorization

Once a generic noise modeling capability was successfully developed and validated, ANGIM could be flexed as a virtual test-bed in which the assessments required to generate airport categorizations could be executed. The categorization of airports was identified as a large capability gap because of the inefficiency of calculating a large number of unique airports when performing a fleet-level study. Because noise is a spatial problem at its core, the airport-level cannot be bypassed when generating fleet-level estimates without risking significant inaccuracy. By creating a set of Generic Airports, only a handful of airport-level noise scenarios have be executed to reasonably approximate the fleet-level impacts. The research questions developed to address this issue were:

III. *What subset of airports should be considered for grouping?*
   a. *What variables should be considered for grouping?*
   b. *What grouping strategy and techniques should be employed?*

IV. *How can the groupings be verified and validated?*
   a. *What is the increase in accuracy versus assuming single-runway airports?*
   b. *How can groupings be made appropriately robust?*

The MAGENTA 95 were selected as a logical sample set, as these include the United States airports that account for 90% of the population exposed to 65 dB DNL noise [89], [90]. The airport groupings were performed in two parallel stages in accordance with the hypotheses:

I. *If variable types are decoupled, groupings for each are facilitated, and the super-position of both groups can be used to predict fleet-level noise.*

II. *If the operational airport space can be segmented and clustered, yielding average Generic Runways, and representative aircraft used for the Generic Runways are reasonably average representations of the true fleet, then Generic Runways will be able to accurately predict the fleet-level area due to operational effects only, and will be able to maintain similar accuracy as the flight schedule varies over time.*

III. *If runway layouts can be reduced to effective runway layouts using resultant contour information, the qualitative categorization of these layouts will yield an accurate representative average of the geometric diversity present of the MAGENTA 95.*

Generic Runways were constructed using statistical clustering methods, and using average representations of the clusters to generate single-runway single-flow flight schedules with representative aircraft for ANGIM that encapsulated the operational aspects of the actual represented airports. This grouping strategy was chosen due to its flexibility and statistical objectivity. These Generic Runways were verified, and validated in the face of aircraft and forecast variability, and were shown to maintain satisfactory accuracy and trends. Most of the error observed was determined to be caused by null DNL 65 dB contour areas caused by a net scaling down of operations, and the inability of the representative aircraft to serve as a proxy for a true Generic Fleet. The latter was expected, and confirmed due to the correlation of total error and changes in operations by certain seat class representative aircraft.

Generic Infrastructures, on the other hand, were classified qualitatively, as an objective measure of the noise contour shapes was not available at the time. In order to improve the grouping, the actual runway layouts were reduced using the resultant DNL 65 dB noise contour to yield a set of effective runway layouts. Effective runway layouts define runways only where necessary to yield a similar contour to the one observed during classification. This simplification of the space increased the confidence with which unique infrastructures could be classified qualitatively. To test the hypothesis that the groupings could provide accurate fleet-level contour area predictions by capturing the basic shape characteristics, the baselines were created and verified. At this point, the fleet-level prediction was accurate with certain expected precision error. One could propose the antithesis that the results equally suggest shape is not important, but this notion is easily discounted by demonstrating the error due to assuming only single-runway airports. For the specific experimental settings used, this error accounted for 38 nmi^2, compared to approximately 8 nmi^2 of error using baseline Generic Infrastructures. To improve the predictive ability, and as a checks and balance on the qualitative groupings, robustness assessments were used to explore the configuration space for the fundamental geometric categories. Having found no significant sub-categories of note, this information was then leveraged to calibrate the Generic Infrastructures with respect to contour area, demonstrating excellent accuracy when compared to the unique MAGENTA 95 infrastructures.

To test the hypothesis that operational and geometric characteristics could be grouped separately and combined to yield accurate fleet-level estimates, the combination of Generic Runways and Generic Infrastructures were used to construct Generic Airports. These were compared to the fleet-level estimates of the unique MAGENTA 95 operations and geometries, and showed reasonable and well-distributed error between the airport groups, with a total error of approximately 3%. This error is expected to decrease by including day/night operation splits, and introduction of a new Generic Fleet. The total set of Generic Airports consisted of 21 unique operational-geometric combinations, resulting in less than a quarter of the beginning sample set. The time savings are not sufficiently represented by this ratio, since the de-coupling of the operational and geometric characteristics yielded an 88% time savings over calculating the MAGENTA 95 with actual operations and infrastructure through ANGIM. With the information provided through this research, a path has been forged through which Generic Airports can be improved. While a singular set was the purpose of this exercise, it was noted that multiple decision points exist that affect the overall granularity of the final airport set, such that gradations of Generic Airports can be generated based on the desired fidelity required in a given study. The lack of objective shape evaluators was also noted as a major shortcoming in the process proposed. Although precautions were taken to ensure oversight of the qualitative groupings performed, a quantitative grouping based on shape characteristics could compound the effectiveness of the Generic Infrastructure development process. While these could not be utilized for this incarnation of Generic Airports, the search for a metric that communicates basic qualitative characteristics of airport noise contours objectively was executed as a separate task, and it is recommended that the metrics analyzed be applied to Generic Infrastructure development henceforth.

5.3 Contour Shape Comparison Metrics

In order to identify a metric that could effectively describe airport noise contour shape, a set of research questions outlining the problem were posed:

I. *What characterizes an airport noise contour shape, as opposed to an aircraft contour shape?*
    a. *What are the general requirements for metrics?*
    b. *What requirements are specific to this type of metric?*

The first task required was to define, objectively, what the object of measure entailed. The airport-level noise contour was thus decomposed into an airport nucleus, or a central region bounded by the runway configuration, and a set of contour lobes distributed about this region. From a fleet-level perspective, these are the characteristics that differentiate airport noise contours. Requirements analysis was performed to determine that the metric should provide categorical segmentation of different geometries as classified in the development of Generic Infrastructures, be insensitive to operational settings, and be able to recognize differences between similar contour shapes along a continuous scale. Based on the measurable qualities and the desired requirements, a hypothesis was formulated:

I. *If a metric that scales with lobe number and lobe distribution about the airport nucleus can be identified, this metric will meet the necessary requirements for a contour shape metric as described above.*

Several metrics were gathered, including from fundamental geometric backgrounds, and the land-use planning field. These were then examined through a set of experiments. The first test measured the ability to correlate with the number of contour lobes. The four highest performing metrics were then examined for response to lobe distribution, by examining the ability to scale with airport geometric variables. Finally, categorical segmentation was evaluated with respect to the different geometries including extreme geometries, and the more realistic MAGENTA 95 and Generic Infrastructures. Each was also shown to be insensitive to the number of operations and aircraft distribution. None of the collected metrics presented a complete satisfaction of all the desired requirements, and thus a linear combination of the two best-performing metrics was attempted, yielding improvements in all requirements. While categorical segmentation in a continuous scale will always be difficult, the resulting Detour-Spin Index was easily capable of separating the representative Generic Infrastructures, such that the metric can be used to infer the geometry without requiring visual inspection of the contour. As part of the SWAN methodology, a metric such as this can be used to identify impacts to the contour shape due to technology infused aircraft. More shape metrics are likely available in the literature, or could be in development, and the search for these should not be discontinued. While the Detour-Spin Index is very valuable to the current state-of-the-art in generic fleet-level noise evaluation, the most important contribution of this task is the definition of the desired characteristics of the metric, and the development of an experimental plan to identify the fitness of a metric to provide these qualities.

5.4 Use Cases: Technology Impact Assessments

Once these three capability gaps were addressed, they could be combined to demonstrate the implementation of the SWAN methodology through three separate use cases. These scenarios included an exploratory case, evaluating a notional set of technologies in the N+1 timeframe to meet fleet-level goals, and two normative cases evaluating the required technology vehicle fleet insertion to achieve fleet-level noise reduction goals. The overarching research question and hypothesis, which these use cases were designed to address were:

> *R.Q. - How do technology infused aircraft impact the contour area and shapes of airports in the context of total forecasted operations, and fleet mix?*

> *H - If technology infused aircraft are applied to a fleet of operations via a forecast, their impact will not be uniform across all airport types, and will not be restricted to reductions in contour area only, but also to impacts to the airport noise contour shapes, which may impact the ultimate measured benefit of a given set of technologies. These impacts at the screening level will be more appreciable in a generic framework as opposed to the cumbersome and time consuming detailed approaches currently available.*

The methodology was implemented in an exploratory forecasting scenario in the N+1 timeframe, and in two normative forecasting scenarios in the N+1 and N+2 timeframes respectively. In each scenario, the methodology was implemented to examine the fleet-level impacts of technology infused vehicles to contour area. Moreover, the effects on contour area at different Generic Airport types were assessed, as well as the impact on shape due to technology infusions. In all scenarios, it was noted that the impact on contour area was very airport specific, and in all scenarios there were airports that did not result in an overall reduction in contour area, due to the counteracting increase in forecasted operations.

With respect to shape impacts, the DSI metric developed to analyze contour shape was able to highlight Generic Airport types that were impacted with respect to shape. Compared to the impacts caused by increased operations, the technology infusions caused significant deviations in many Generic Airports. In general, it was observed that airports with parallel runway sets could increase the potential benefit of the technologies examined due to an increase in area between the runways (within the airport boundary), and a simultaneous decrease across other boundaries. The technologies were observed to not only reduce noise, but also to concentrate it closer to the runway, and the impacts of this behavior was noted by the DSI metric capturing the increase in contour width at certain airports. The SWAN methodology demonstrated that for the notional set of N+1 technologies examined, the impact on airport noise contours is not simply a photographic scaling of the contour, but that nuances with respect to shape are present and can have important consequences with respect to the potential population exposed.

In comparison to the status quo methodology, the SWAN methodology provides the appropriate fidelity for the problem, while retaining accuracy and trends exhibit by the detailed modeling methods. The status quo methodology requires cumbersome detailed noise models evaluated at the highest level of fidelity for each airport in the study, and ultimately only provides a fleet-level contour area increase or decrease, A detailed fleet-level analysis under ideal conditions could possibly take on the order of days or weeks, based on comparisons provided for this research. The SWAN methodology can accomplish a fleet-level noise evaluation in approximately twelve minutes, enabling the analysis of broad technology space. This capability can provide decision-makers with analytical information on which to base technology investment decisions. By screening out the best technologies with the SWAN methodology, decisions can be made based on physics based modeling information, while reserving the detailed fleet-level models for the most promising technology options. As a result, the overarching hypothesis cannot be rejected based on the data observed for this research. Other technology infusion scenarios should be analyzed in future use cases, to further evaluate the capability of the SWAN methodology to answer the relevant research questions regarding fleet-level noise.

5.5 Key Contributions

The research presented here was ultimately motivated by a research objective regarding the development of a generic fleet-level noise methodology. Specifically, the research objective was:

> *Research Objective: To develop a generic fleet-level noise methodology that supports the generic framework for fleet-level environmental analyses and enables rapid evaluation of technology response scenarios with respect to contour area and shape impacts.*

The capabilities developed for this research result in a System-Wide Assessment of Noise (SWAN) methodology that can be utilized to examine the impacts of technology infusions in the context of forecasted operations during early technology identification, evaluation, and selection phases. This methodology constitutes a significant advancement in the state-of-the-art of generic fleet-level noise modeling. Significant reductions in required modeling time were achieved with respect to fleet-level noise modeling through the development of ANGIM and Generic Airports, while improved ability to describe contours beyond simply contour area was provided by the Detour-Spin Index. Beyond the procedural improvements of the methodology, these capabilities have provided unprecedented access to examine a number of factors with respect to airport and fleet-level noise that were previously unavailable. Prior to this research, generic fleet-level noise utilized simplistic models designed to predict the DNL 65 dB contour area, completely ignoring the importance of contour shape in predicting an exposed population. The entirety of this research can be viewed as an attempt to update these methods to re-introduce the importance of airport configurations and resulting contour shapes, and to demonstrate that while shape is a complex, sometimes abstract, quantity, it can be defined objectively and leveraged within large-scale analyses. This goal is accomplished by a rapid generic fleet-level noise modeling tool that can retain contour shape characteristics, Generic Airports that capture operational and shape characteristics of the most important airports with respect to fleet-level noise, and a metric that enables quantitative comparison of contour shapes.

Aircraft environmental technology programs are extremely costly, due to the high price tag required to bring technologies to the maturity where the market can safely absorb them. As a result, a mistake in investment direction could yield a sub-par technology, or worse, a negligible impact. Aircraft design development can be a decade-long process or more, and there is no opportunity to recover from such an enormous mistake. Therefore, it is important equip decision-makers with the best tools available. With the SWAN methodology, the rapid screening-level assessment capability, GREAT, which previously only included fuel burn, NO_x, and CO_2 emissions, can now examine the full environmental metric space, making the optimal decisions required to meet all future environmental goals. By relieving the pressure placed on aviation of potential damage to the environment, the industry can grow to its capacity-limit. Only the need to reform and better manage aircraft operations will stand in the way of a prosperous future for aviation. The result will be a substantial benefit to aircraft manufactures, aircraft operators, passengers, and the people who live around the airports.

CHAPTER 6

FUTURE WORK

While the research presented here depicts the successful development of the SWAN methodology, which can be implemented to improve knowledge about the fleet-level technology space, there are significant improvements and further analyses that would be of great contribution to the research objective. While these tasks were outside the scope of this project, a summary of the potential improvements, adjustments, and innovations that should be pursued will be provided here. These will be stratified with respect to the specific capability gaps, and miscellaneous suggested areas of continue research.

6.1 Airport Noise Grid Integration Method

The Airport Noise Grid Integration Method (ANGIM) presented for this research consisted of an un-calibrated logarithmic summation and interpolation of detailed aircraft-level noise grids. As a result, there were expected errors when compared to detailed models in which the basic simplifying assumptions were not observed. The most impactful of these assumptions are the standard day sea-level atmosphere, and the straight ground tracks. The former primarily affects the magnitude of the noise at each observer point, while the latter affects the overall shape. A calibration factor for each that does not significantly impact the overall runtime would be a significant enabler in providing a further level of analysis between the screening-level provided by ANGIM and a full detailed model. While a calibration factor can be suggested, a plan for its achievement must still be defined.

The most relevant developments should occur in spatial regressions that can be verified at the aircraft level, and attempted at the airport-level. With respect to atmospheric calibrations, the relationships between these characteristics and the resultant noise level is well understood in the literature, and some preliminary research has already been conducted to produce calibrations for these values [138], [139]. This work included spatial regressions of DNL values using neural network models. Some investigation was done into similar spatial fitting of deviated ground tracks, but the treatment was minor. Ground tracks are much more complex, because like airports, they are unique and infinite in the number of potential ways they can exist at a given airport. It may be beneficial to take a similar approach to Generic Airports, in which ground tracks are first classified, before a spatial regression plan is developed and tested.

ANGIM can also undergo a number of procedural improvements, such as cleaning up the computational process unifying the environment into a single computing language. These are not of academic interest of course, but the value would be in better integrating ANGIM into the GREAT tool to provide a unified fleet-level environmental trade space that includes fuel burn, NO_x, and noise.

6.2 Generic Airports

Generic Airports provide a number of opportunities for improvement beyond the completed set presented above. With respect to Generic Runways, a number of cost-benefit tradeoffs can be made to improve the total number of Generic Airports while better articulating the airport operational space with respect to total operations and seat class distribution. Beyond the framework presented above, a variety of different avenues could be investigated, such as the potential benefits of introducing further operational variables for grouping, or utilizing different clustering methods. The analysis of distribution by seat class could also be challenged, and Generic Runways could be developed along different lines such as the original Generic Vehicle classes or by identifying the most relevant aircraft with respect to noise, to produce groupings that focus on these aircraft primarily [9]. Each of these approaches can be done separately in a disjointed fashion, but a structured approach that identifies the best possible combination for the overall problem would be a more valuable and significant contribution. Generic Runways should also be re-calibrated to include the newer Generic Vehicles, which will include noise characteristics, and will require updating as baseline forecast year progresses and Generic Vehicles continue to evolve. The versions presented for this research are not the ultimate result, as the purpose of the research was to demonstrate the process for Generic Airport development. Within each step there may be opportunities for innovation and improvement.

Generic Infrastructures are also full with potential for further research. The main deficiency in the categorizations, for example, was the lack of an objective geometric shape descriptor, which was ultimately developed as part of this research. Not only was a single useful descriptor defined, but a large number of metrics that each describes different characteristics of a contour shape were identified and made operational. These metrics must be re-absorbed in the Generic Infrastructure development process to lend some objectivity to the geometric classifications. These metrics may also impact the ability to introduce more complex variables, such as runway utilization and traffic-flow used at various airports. Not only can the contour shape metrics be used to provide objective infrastructure categorization, but they can also be used to improve the quality of Generic Infrastructure calibrations. Currently, the calibrations were done for contour area, and they were not automated because it was understood that the problem neglected numerous dimensions of shape. The contour shape metrics now provide the ability to represent some of these dimensions, and Generic Infrastructures can thus be tuned along the Pareto-surface of area *and* shape. By including these metrics in Generic Infrastructure development, a more exact approach can be taken in which response surface equations are used to describe the relationships of the geometric variables to area and shape characteristics. Once sufficient fits are achieved, Monte Carlo exploration of the space can be performed, which can then be used to find an optimal solution that best meets the characteristic shape and area criteria [136].

6.3 Contour Shape Metrics

The contour shape metric that resulted in the best performance overall was the Detour-Spin Index, a linear summation of the Detour and Spin indices. While the metric was found to provide the best satisfaction of the requirements under the parameters of the experiments imposed upon it, the list of metrics examined is not an inclusive list of the possible measures of shape. There are countless shape metrics in various fields, and these could be examined for their value as a single metric, or in conjunction with those examined here. For example, in image processing and data analysis fields, statistical moments are utilized to describe shape, building on the work conducted by Tukey et. al.

in describing multivariate datasets [140]. Other potentially similar approaches include one-dimensional Fourier transformations [141]. These are an extension of the contour radial points utilized to compare shape accuracy in the validation of ANGIM. A one-dimensional Fourier transformation can be applied to determine the Fourier coefficients, which are independent of scale, translation, and rotation. More complex Polar Fourier transformations can be utilized to evaluate images in the spectral domain, which can further lead to useful discrimination of different airport noise contour shapes [141]. These metrics could be evaluated and applied to provide measures of airport noise contour shape, but the complexities may require some tradeoff between computation time and the power of the metric results. The metrics analyzed for this research were relatively simple to implement with raw outputs from ANGIM, whereas more sophisticated imaging techniques may require some interfacing to allow for proper execution. Nonetheless, there are a number of shape-related problems with respect to airport noise that could very well benefit from the effort to apply such shape measures, and these should be investigated in future works.

While not all the metrics were found to meet the requirements for contour shape comparison, they all provide certain characterizations of the shape, and can be useful for a number of applications, such as the development of Generic Infrastructures mentioned above. Shape metrics can also be applied at the aircraft-level although different requirements will dictate the success or failure of a metric. The shape metrics can be used to distinguish between the operational mixes that make up an airport-level noise contour. Any evaluation of new metrics or the metrics presented here for a different application should repeat the metrics requirement analysis process to determine the characteristics against which the metrics should be evaluated.

Further research can be conducted with the current set of metrics as well, examining a wider range of operational settings including more intermediate cases. The relationships of the variables to the optimal Detour-Spin Ratio (DSR) can also be examined to define a quantitative relationship that is more broadly applicable. DSR may prove to be a function of other variables, such as the operational settings, and its optimal value may be a floating point between certain ranges dependent on these settings. These studies can also help to define specific ranges for certain geometric types within a certain confidence interval. It may also be beneficial to attempt to characterize changes in shape to identify increases in contour area that could affect the population, versus increases in contour area that could not affect the population exposed to significant noise. By including a categorization of the area increases in this fashion, better projections of the impacts to population could be provided.

While the DSI and the Detour and Spin indices were found to best characterize the noise contours, it may be desirable to continue to implement the other metrics in applied examples, examining their contributions to the overall description of contour shape changes. They may still retain certain value, which was not necessarily completely examined in this work.

6.4 Future Use Cases

The SWAN methodology can also be used in a number of ways to examine a variety of different aspects of the airport noise issue through various use cases of the methodology.

6.4.1 Evaluation of Development Program Technologies

The SWAN methodology can be implemented to assess the fleet-level impacts of CLEEN, ERA, and FW technologies that are currently being investigated. The process can be carried out similarly to the use cases presented here, with the appropriate desired technology vehicle models, operations forecasting methods, and market behavior information. In such a scenario, the technology infused vehicles can be implemented over time, with specific infusion rates for each vehicle class. The SWAN methodology can then be used to evaluate the noise at multiple forecast years of interest to provide assessments in multiple timeframes.

6.4.1.1 Multi-Year Assessments

The SWAN methodology developed here is very quick at computing fleet-level noise. It is therefore possible to compute noise responses for any year in the forecast for a given scenario without expending too much computation and modeling resources. By providing analyses at multiple years of the forecast, a discrete time history of fleet-level noise can be provided, demonstrating the impact that yearly changes in the forecast and technology infusions throughout can have at the system level.

6.4.1.2 Multi-Objective Environmental Tradeoffs

The integration of the SWAN methodology into GREAT would allow for dynamic trades to be performed between fuel burn, NO_X and, noise impacts under varying forecast and policy scenarios. The integration with GREAT only modifies the methodology to make it more general to include the fuel burn and NO_x prediction capabilities already contained within GREAT, as shown in Figure 6.1.

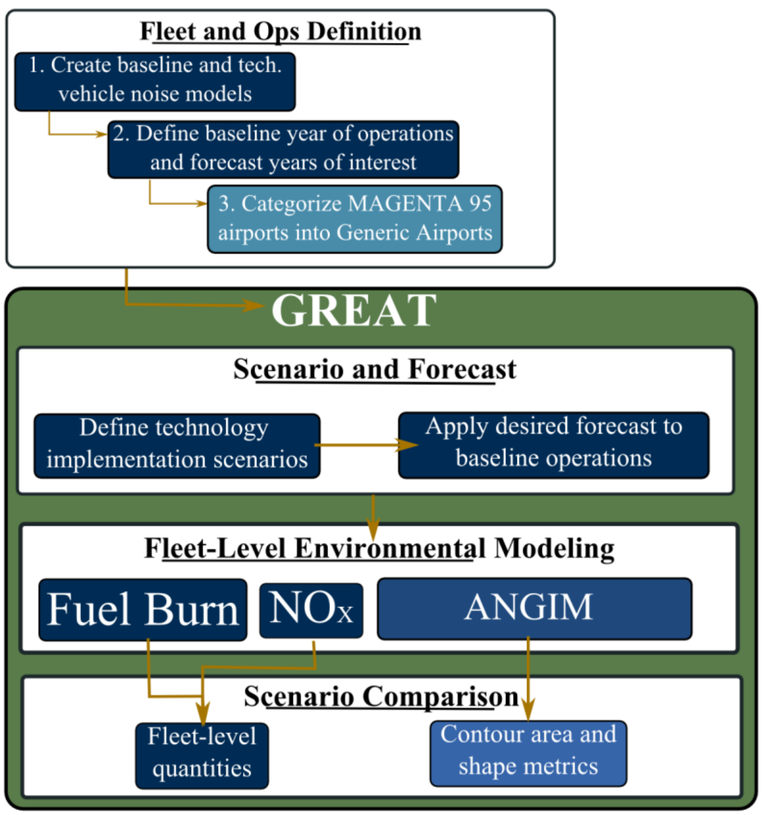


Figure 6.1: Integration of the SWAN methodology into GREAT.

Technology development programs are not solely concerned with fleet-level noise, and their interest in examining the trade space between the major environmental metrics makes for very valuable use cases to demonstrate the greater impact of the methodology to the generic framework for fleet-level environmental modeling.

6.4.2 Fleet-Level Noise Sensitivity Studies

The SWAN methodology is not limited to only evaluation of technological scenarios. In order to better understand the major drivers of fleet-level noise, large-scale Design of Experiments (DOE's) can be evaluated through the SWAN methodology. The results can be used to determine the significant factors affecting contour area and shape at differing airport types. Ultimately, the data could be used to develop surrogate models for contour area and shape based on a Generic Airport type, further simplifying the analysis process.

6.4.3 DNL Discrete-Event Simulation Analysis

Using the SWAN methodology, a discrete event simulation study can be performed that examines how DNL is impacted at a given airport type by each specific flight in schedule in the context of the previous flights that have occurred throughout the course of the day. This type of analysis requires tens of thousands of cases, and would not have been possible without a generic fleet-level noise modeling capability developed for this research. This analysis could lend insight into which aircraft under which situations impact the DNL the most, and if there are potential situations in which the metric does not capture the impact of a particular aircraft.

6.4.4 Population Models

The noise exposure problem, while treated from the perspective of airport and fleet-level noise, also has a population component that is equally difficult to treat. While the noise produced by the system is a function of the aircraft operations, the populations around airports also vary and can shift in size and location over time. Similar to the increase in noise around airports, the population surrounding these transportation hubs can also grow closer to the airport boundary, leading to increases in population exposed. Applying the SWAN methodology to existing detailed population models would be a mistake in the application of the methodology. The fidelity level provided by the SWAN methodology does not match the fidelity of detailed population data or population forecasts. A methodology that enables the linkage of population data to the generic framework is required to similarly reduce the uniqueness observed between populations near different airports. The conceptual Generic Populations must be able to categorize and articulate the current baseline populations, and provide methodologies to model the growth and behavior of populations near airports. Achieving such a task will require a categorization of populations around varying airport types, an understanding of the factors that drive population growth and shift, and a management of the coupled aspects of aviation growth and the surrounding population.

6.5 The Next Frontier

The aspects capability gaps developed to enable a generic-fleet-level noise methodology can also be turned inward, to produce higher-level improvements to the

SWAN methodology. The pieces have been only superficially connected, but more substantial linkages between them can result in further improvements. The SWAN methodology presented here is only one solution to an extremely complex problem. In an ideal grand concept, only a surrogate model would be required to provide a noise contour given airport geometric, atmospheric, and operational characteristics. This capability is still only conceptual, but the methodology presented here holds the key to unlocking the capabilities required to achieve such a surrogate model.

If a quantitative understanding of the operational space can be gained via large-scale design of experiments through ANGIM, and if spatial regressions can be developed successfully for noise grids, then the contour shape descriptors could be used as inputs to generate spatial regressions for contour shapes. By combining the knowledge of the operational characteristics that can be gained through ANGIM at the different Generic Airports, and the geometric variety that can be observed and described via multiple shape metrics, it may be possible to generate a specific airport noise contour without running a detailed model or even ANGIM beyond the cases used to generate and validate the surrogate model. Therefore, the SWAN methodology presented here not only provides the ability to examine a previously unobtainable aspect of the problem, but it also provides the necessary foundation to build the tools and capabilities that will ultimately lead to its replacement.

Achieving this goal would require the sum total of the future work described in this chapter. Each improvement to the methodology can be viewed as a piece of the puzzle required to achieve a more general model. For example, operational variable design explorations can assess the importance of each variable and examine the potential for fitting a model for the magnitude of noise. ANGIM spatial calibrations would provide the necessary foundation in spatial regressions to link contour shape metrics to the creation of contours without the need for an airport-level grid of observer points.

If these capabilities can be developed in parallel and combined, the grand concept should be achievable. The result could lead to a significant improvement in generic fleet-level noise modeling beyond what was presented for this research. The opportunities for investment and growth in this area of research are vast and plentiful, and should be explored to the greatest depths possible to provide even faster and more accurate models of fleet-level noise, which can be used in conjunction with other rapidly computable environmental metrics to improve the quality and quantity of information provided to decision-makers. These decision-makers can then select investment options with greater confidence that the end result will lead to a more efficient and environmentally sustainable future for the aviation industry.

APPENDIX A

DESCRIPTION OF ACOUSTIC SCALES

This appendix describes the development of various environmental acoustic measures related to aircraft noise, including frequency weighting development and application.

A.1 Measurements of Sound

Sound is nominally measured as fluctuating pressure waves. These waveforms are a function of spatial position as well as a time. The temporal and position aspect of sound pressure waves suggests that the sound can vary depending on the time and place of the measurement. Sound is commonly discussed in the decibel scale, commonly through Sound Pressure Levels (SPL). SPL provides a logarithmic measure of the effective sound pressure of a sound relative to a reference value (typically defined for the medium in which the sound is traveling). These scales are used because of the large variation in orders of magnitude between pressure fluctuations encountered in the acoustic environment [138]. SPL is computed using equation A.1 [138].

$$SPL = 10\log_{10}\left(\frac{P_{rms}^2}{P_{ref}^2}\right) \qquad A.1$$

I – intensity of sound

T – duration of the sound

p – pressure wave as a function of space and time

u – velocity wave as a function of space and time

The temporal aspect of sound can also be used to transform the response into a spectrum of SPL levels occurring at various frequencies.

A.2 Measurement of Environmental Noise

With respect to environmental noise, the information provided by the direct measurement of sound introduces several complications. The first is related to the temporal characteristics of sound. Because the sound level can fluctuate throughout the duration of the event, it is difficult to directly use an analog pressure wave response to determine exposure. Secondly, the different frequencies of an aural signature can have different SPL values, depending on the tonal components of the sound. It is generally agreed upon that these frequency spectra provide too much information upon which to base different noise rating scales. Finally, the effect of noise on human psychology and physiology can vary significantly depending on the frequency [138].

It is important to recall that noise is defined as unwanted sound, and therefore introduces a subjective property. The human ear can react differently to different frequencies at different levels, and these reactions can vary from one person to another [138]. In order to treat this inherent subjectivity, relationships between frequency and loudness were developed, demonstrated in Figure A.1 [138], [142]. By exposing observers to sound at various frequencies, a set of equal loudness contours (measured in phons) can be constructed across the spectrum of frequencies. This information can then be used to create frequency weightings for various purposes.

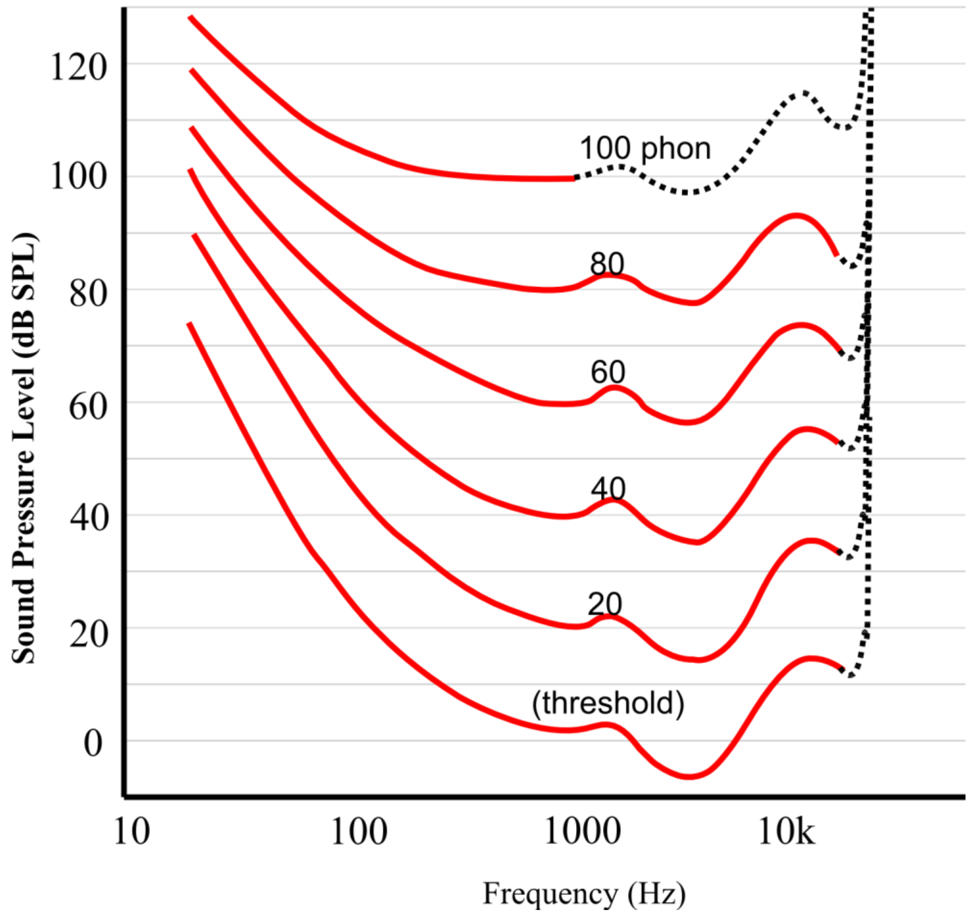


Figure A.1: Equal loudness contours [138], [142].

Frequency weightings are designed to modify the spectral signature of a sound, such that the resulting SPL values for each frequency more closely represent what the human ear perceives. These weightings are created by attempting to match a reference equal loudness contour [138]. There are multiple frequency weightings that are applied to various metrics but the most popular and widely applied is the A-weighting, which emphasizes mid-range frequencies while de-emphasizing frequencies in the low and high regions that typically affect the human ear differently [138]. The A-weighting curve can be seen in Figure A.2 [138].

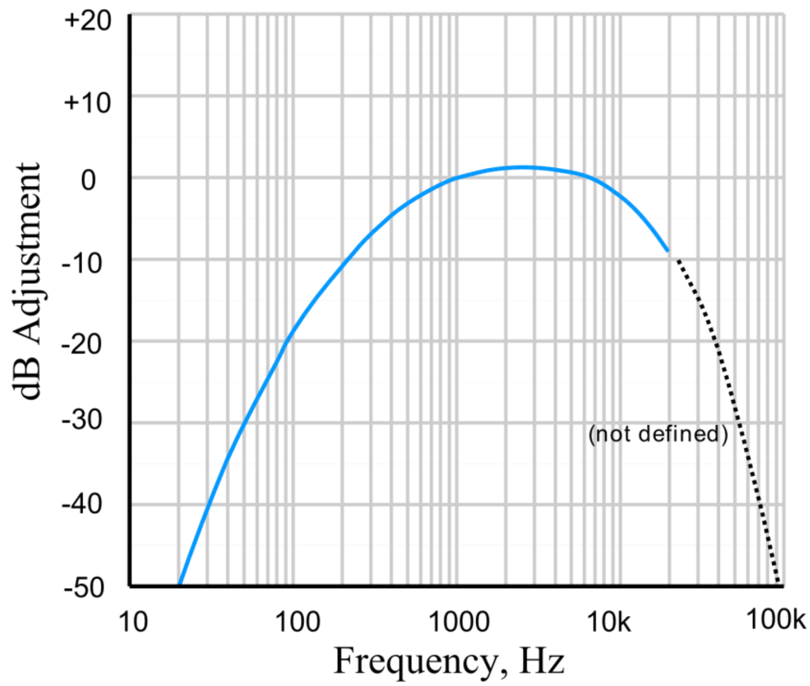


Figure A.2: A-weighted frequency spectrum [138].

The A-weighting is designed to adjust the spectrum of sound to mirror the 40 phon equal loudness curve, and serves to map the subjective perception of sound in the human environment to an objective correction of the SPL at different frequencies [138]. The A-weighted values at each frequency band in the spectrum can then be re-combined to yield the overall A-weighted SPL as a function of time.

In order to communicate community noise, however, the A-weighted SPL as a function of time is still not sufficient for use as a noise rating. To manage this issue, a number of cumulative metrics exist that collapse the SPL over the duration of the event and average it over a reference time. These metrics include the SEL and the DNL. The only difference between the various A-weighted metrics is in the time through which each value is averaged. For example, SEL averages the sound response to reference duration of one second. The computation of SEL from A-weighted SPL can be done using a discrete summation as shown in Equation A.2 [48].

$$SEL = 10\log_{10}\left[\frac{1}{t_0}\sum_{t_1}^{t_2}\left(10^{0.1L_A(i)}\Delta t\right)\right] \qquad A.2$$

SEL – Sound Exposure Level

t_o – reference time of 1 second

t_1 – time at which sound commences

t_2 – time at which sound ceases

$L_A(i)$ – A-weighted SPL at time i

$\Delta t - t_2 - t_1$

The SEL can also be directly integrated from the A-weighted pressure wave equation, as discussed in Chapter 1. The SEL levels can then be utilized to generate cumulative metrics averaged over different timeframes, such as the DNL.

The interested reader is referred to Kinsler et. al. for more information regarding fundamental measurements and visualizations of sound pressure waves, and the application of frequency weightings for different environmental noise ratings [138].

APPENDIX B

ANGIM DETAILED PROCESS DESCRIPTION

This appendix contains the specific steps required to execute the Airport Noise Grid Integration Method (ANGIM).

B.1 Pre-Calculate General Single-Event Aircraft Grids

The first step is to calculate the single-event aircraft noise grids at a generic single-runway airport using a detailed noise model. A separate grid must be calculated for approach and departure at each available stage length. Again, only one half of the aircraft-level noise grid needs to be calculated, with the runway acting as the axis of symmetry. If the grid size is chosen intelligently, such that it captures sufficient noise information for all aircraft at an acceptable granularity, this step should only have to be executed once for each aircraft in the fleet. By storing these generic operations, they can be recombined later, saving actual modeling time.

B.2 Define Flight Schedule and Airport Geometry

The second step is to define the airport flight schedule and geometry. The airport geometry defines the runways in Cartesian coordinates including any necessary rotations. Each runway is defined by a runway-end and an angular component that defines the runway traffic heading. So if cross-flow is desired, for example, both runway-ends must be defined separately with headings that are 180 degrees apart. The method treats this situation as two runways that occupy the same geographical space, but with opposite headings. Therefore, the runway configuration input treats the total number of runways, the configuration of the runways, and the traffic flow on each runway. The flight schedule assigns specific aircraft at a given stage length (a surrogate for aircraft weight) to each runway, providing the number of day and night operations for approach and departure. Thus, the flight schedule input treats the total number of flights, the aircraft performing these flights, the stage length of the flights, the nighttime operations, the operation types, and the runway utilization.

B.3 Convert Single-Event Noise to Sound Exposure Ratio

The third step converts the single-event noise grids for each aircraft operating on a given runway to a sound exposure ratio by solving for the argument of the logarithm function, the Exposure Ratio (E), as shown in Equations B.1 and B.2 [48].

$$SEL_{AC} = 10\log_{10}\left\{\frac{\left[\int_{t_1}^{t_2} p_A^2(t)dt\right]}{p_0^2 t_0}\right\} = 10\log_{10}(E_{AC}) \qquad (B.1)$$

$$\Rightarrow E_{AC} = 10^{(SEL_{AC}/10)} \qquad (B.2)$$

The exposure ratio is a linear term and therefore can be scaled based on the number of operations. The exposure ratio can also be summed across multiple flight and operation types at common grid points.

B.4 Scale Exposure Ratio by Number of Operations

The fourth step consists of scaling the noise exposure ratios based on the number of operations designated to an aircraft for a given runway in the flight schedule as shown in Equation B.3 and B.4.

$$E_{AC,dep,rwy,day} = DepOps_{AC,rwy,day} * E_{AC,Stg} \qquad (B.3)$$

$$E_{AC,app,rwy,day} = AppOps_{AC,rwy,day} * E_{AC} \qquad (B.4)$$

For departure, the stage length of the operation is considered, while for approach no stage consideration is necessary. Although only the equations for the daytime operations are shown, exposure ratios for nighttime operations are also calculated in the same fashion. At this point, the day and night operations are kept separate, so that the DNL 10 dB penalties for nighttime flights can be applied when converting to DNL.

B.5 Summation of Exposure Ratios Across Operation Types

The fifth step combines all approach and departure operations separately across all aircraft at a given runway, while still maintaining the separation between night and day operations as shown in Equations B.5 and B.6.

$$E_{dep,rwy,day} = \sum_{AC} E_{AC,dep,rwy,day} \qquad (B.5)$$

$$E_{app,rwy,day} = \sum_{AC} E_{AC,app,rwy,day} \qquad (B.6)$$

Again, although the equations only specifically pertain to daytime operations, nighttime exposure ratios of the runway are calculated in the same fashion.

B.6 Sum Total Approach and Departure Sound Exposures

The sixth step combines all approach and departure operations on the runway to yield the day and night exposure ratios for the runway, as exemplified in Equation B.7.

$$E_{rwy,day} = E_{dep,rwy,day} + E_{app,rwy,day} \qquad (B.7)$$

The summation process followed thus far is theoretically equivalent to when INM sums the contributions of different flight segments to create a flight-level sound exposure grid, which is then summed over all flights to yield an airport-level exposure ratio using Equations B.8 – B.10 [95].

$$E_{wt,seg} = \left[(W * N)_{day} + (W * N)_{eve} + (W * N)_{ngt}\right] * E_{seg} \qquad (B.8)$$

$$E_{wt,flt} = \sum_{i=1}^{n_{seg}} E_{wt,seg(i)} \qquad (B.9)$$

$$E_{wt,arpt} = \sum_{k=1}^{n_{flt}} E_{wt,flt(k)} \qquad (B.10)$$

B.7 Convert Total Sound Exposure Ratio to DNL

After being combined, the seventh step takes the runway-level output and converts it to DNL, which is the standard metric for evaluating airport noise responses, via Equation B.11.

$$DNL = 10\log_{10}\left[E_{rwy,day} + 10 * E_{rwy,nght}\right] - 49.4 \qquad (B.11)$$

B.8 Mirror Grid About Horizontal Axis

The runway grid is then mirrored about the horizontal axis to provide a full runway-level noise response. The mirroring is achieved simply by switching the sign on all non-zero y-coordinates of the runway-level grid, and appending them to the existing grid. This aspect of the process allows for the pre-calculation of aircraft-level grids to be more simplified, require less storage space, and speed up the integration from aircraft-level grids to the runway level.

B.9 Apply Runway Translation and Rotation

The runway-level DNL grid is then rotated and translated based on the geometric definition of the airport. The grid is first rotated, to preserve the left-end of the runway as the axis of rotation. The translations are then applied to all grid points once rotation has been completed.

B.10 Combine Runway-Level Grids

Once steps three through nine have been completed for all runways defined in the airport geometry, these runway grids are interpolated to a common grid and their noise values are logarithmically summed. To interpolate noise grids, one is first selected as the reference grid, and other grids are superimposed, using the nearest neighbor approach and logarithmic interpolation to determine the noise value at the reference grid. All noise values at the same grid point can then be summed via Equation B.12.

$$DNL_{Aprt} = 10\log_{10}\left(\sum_{rwy=1}^{tot\ rwys}\left[10^{(DNL_{rwy}/10)}\right]\right) \qquad (B.12)$$

B.11 Calculate Contour Areas

The final step is to plot the airport-level noise contours and calculate any desired metrics such as contour area. Area calculation can be done using a number of methods, the simplest of which involves implementing Gauss's Area Formula, shown in Equation B.13 [143].

$$Area = \frac{1}{2}\left|\sum_{i=1}^{n-1} x_i y_{i+1} + x_n y_1 - \sum_{i=1}^{n-1} x_{i+1} y_i + x_1 y_n\right| \qquad (B.13)$$

APPENDIX C

CONFIGURATION EXPLORATION SETTINGS

This appendix summarizes the specific settings of the configuration exploration experiments utilized in Generic Infrastructure development. The configuration explorations are designed to examine the extremes of the fundamental geometric categories to uncover the relationships between these variables and contour area. The experiments also serve as a validation of the qualitative grouping, ensuring that no significant subcategories exist in the geometric space.

C.1 Intersecting Configuration

The intersecting configuration will introduce one new variable over the parallel configuration: the angle of rotation of the second runway, as shown in Figure C.1. Again, assuming the first runway is spatially fixed, the point of intersection on the second runway is defined by varying the position of the left runway end. Hence the DOE will include three geometric design variables. Ranges must be relatively exhaustive, to sufficiently explore the potential configuration space. The ranges for the stagger, separation, and rotation will be 0.3 to 5.3 nautical miles, -1.5 to 1.5 nautical miles, and zero to 180 degrees respectively. The rotation can be analyzed up to 180 degrees by invoking the law of symmetry. While further symmetric assumptions could be made, conservative assumptions are made due to the lack of understanding of the relationship between the geometric variables and contour area. These ranges are also selected conservatively to ensure that obtuse, acute, cross, and non-intersecting runway configurations within this category are observed and are listed in Table C.1.

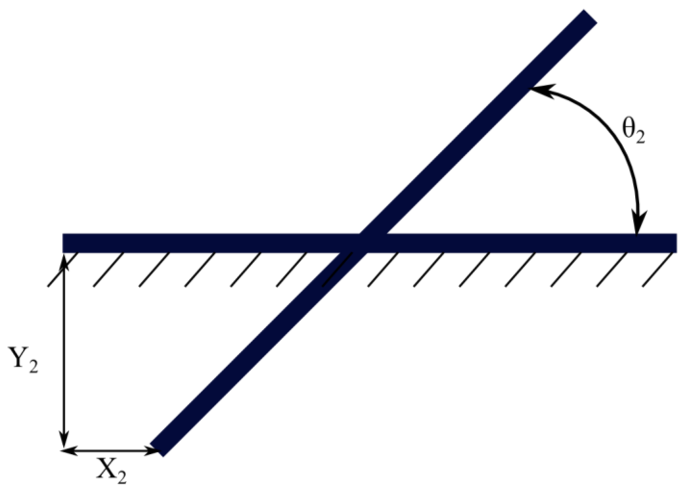


Figure C.1: Intersecting geometry.

Table C.1: Variable ranges for Intersecting configuration exploration.

	X_2	Y_2	θ_2
Range	0.3 – 5.3	-1.5 – 1.5	0 – 180
Baseline	0.3	-.71	90

C.2 Parallel – Intersecting Configuration

The Parallel – Intersecting configuration is merely a superposition of the previous two cases. It cannot be trivialized, like other configurations however, as this combination can result in further intersections of the runway axes. This interaction cannot be directly inferred via superposition. The variable list is similarly a summation of the number of variables. The first runway remains spatially fixed, the second parallel runway is varied by the left-end position, and the intersecting runway is varied by translating the left-end position and the angle with respect to the reference runway, as shown in Figure C.2. The DOE will consist of five geometric design variables, with ranges also prescribed by the ranges utilized for the parallel and intersecting configuration-explorations. These are listed, along with the baseline configuration setting in Table C.2.

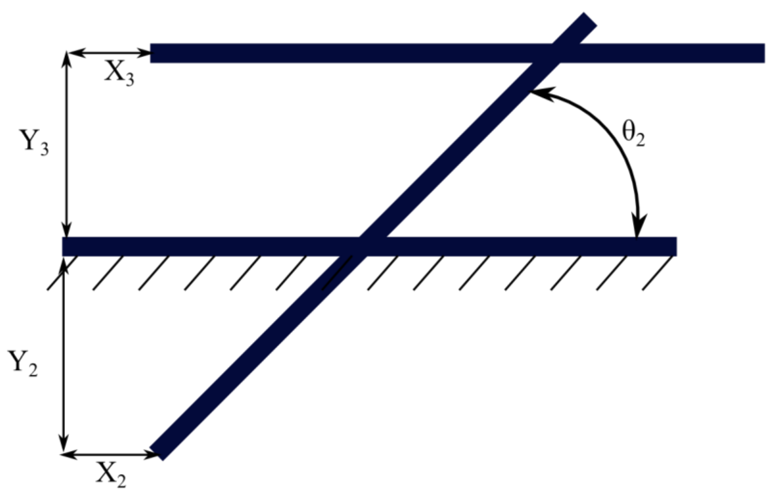


Figure C.2: Parallel – Intersecting geometry.

Table C.2: Variable ranges for Parallel – Intersecting configuration exploration.

	X_2	Y_2	X_3	Y_3	θ_3
Range	-1.25 – 1.25	0 – 1.6	0.3 – 5.3	-1.5 – 1.5	0 – 180
Baseline	0	0.8	0.3	-0.71	90

C.3 Triple Intersecting

The Triple Intersecting configuration may seem to be inherently more complicated, but it is very similar to the Parallel – Intersecting configuration except that the angle of both the second and third runway is allowed to vary. This experiment simply introduces another angular variable to determine the rotation of the third runway, as shown in Figure C.3. The addition of this variable yields a total of six geometric variables for the DOE. The ranges will be somewhat more constricted, to ensure that the essence of the triple intersection of runway axes is maintained. The ranges and the baseline values are listed in Table C.3.

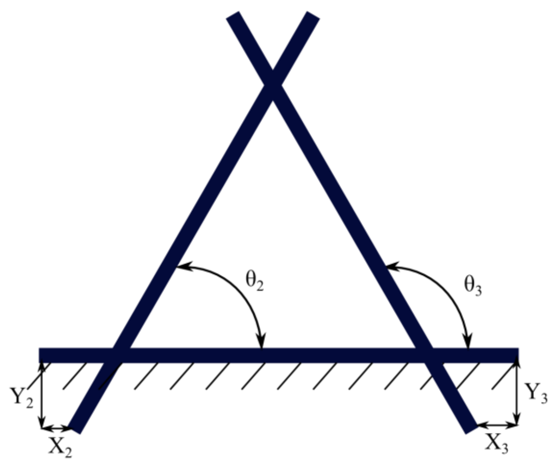


Figure C.3: Triple Intersecting geometry.

Table C.3: Variable ranges for Triple Intersecting configuration exploration.

	X_2	Y_2	θ_2	X_3	Y_3	θ_3
Range	-1.5 – 1	-1.5 – 1.5	15 – 75	1 – 3.5	-1.5 – 1.5	105 – 165
Baseline	0.2	-0.47	45	1.8	-0.47	135

APPENDIX D

CONTOUR LOBE COUNTING SCALE

This appendix summarizes the pseudo-quantitative scale employed to count the number of contour lobes of an airport noise contour for the metric assessments. Lobe counting must be a subjective process, since a metric that would provide lobe counts would preclude the need to address this capability gap in the first place. This aspect of the problem uncovers a classical "chicken and egg" paradox, since one cannot evaluate metrics for lobe counting without first counting the lobes subjectively. This process must be made as strict as possible through the development of a pseudo-quantitative scale that reasonably removes random subjectivity. While the scale could be adjusted and updated in the future, utilizing a consistent and well-defined scale ensures that the forthcoming results follow appropriate trends, even if the values are somewhat randomly distributed.

The scale devised consists of first classifying contour lobes into macro or micro-lobe categories. A macro-lobe is one that originates nominally from the runway nucleus and is primarily related to an "effective runway" of the airport. For a detailed description of effective runways, refer back to Section 3.2.4.3. Under the assumption of straight ground tracks, one effective runway can have up to two macro-lobes, one on either side of the airport nucleus. A macro-lobe counts a full lobe toward the total lobe count of an airport contour. Two examples of macro-lobes can be seen in Figure D.1. A micro-lobe, on the other hand, can exist as part of a macro-lobe, or as a micro-lobe protruding from the airport nucleus. A micro-lobe is typically caused by the incomplete fusion of two lobes from two separate effective runways.

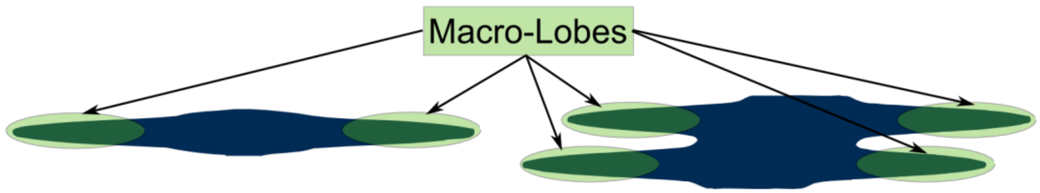


Figure D.1: Macro-lobe structures.

The lobes are not sufficiently separate to behave as two macro-lobes, but instead result in a macro-lobe structure with micro-lobes present. A micro-lobe can count as a quarter-lobe, half-lobe, or three-quarters-lobe, which provides the pseudo-quantitative scale required to count total lobes with reasonable resolution. They are additive and are counted on-top of the macro-lobe count. Two examples of macro and micro-lobe structures together can be seen in Figure D.2.

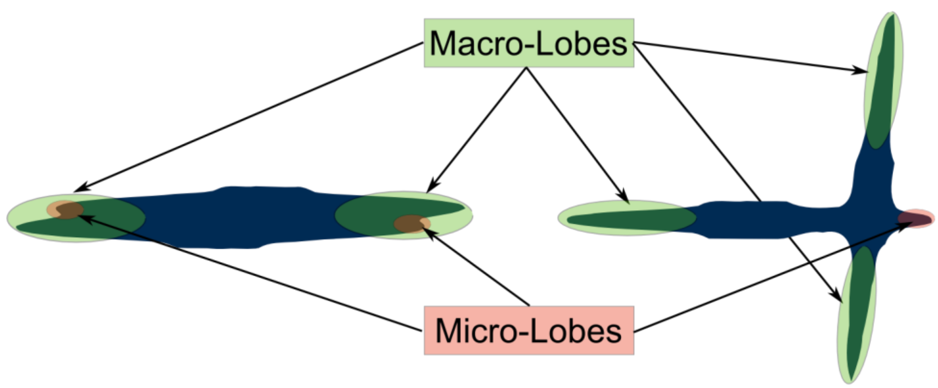


Figure D.2: Macro and micro-lobe structures.

APPENDIX E

COLLECTED SHAPE METRICS

This appendix summarizes the various metrics collected and implemented on airport noise contours. A brief description of each is given, including the source, and the manner in which it can be computed.

E.1 Classical Differential Geometry

The logical place to begin a search for shape metrics is the classical differential geometry field. Mining this field for metrics that may be useful, the arc-length, or perimeter, was identified as a possible measure of lobe quantity and distribution. This metric is capable of capturing information about the number of contour lobes. For example, if two airport configurations have the same operations, the difference in the arc-lengths should be a result of the difference in the number of contour lobes. This metric does not, however, provide information with respect to the distribution of contour lobes about the airport nucleus, and will likely not be independent of total operations, as it is a measure of scale. The latter shortcoming only highlights the necessity for normalized metrics, of which many exist in other fields. These include normalized versions of the arc-length, and will be discussed at the appropriate time.

Another potential metric was encountered by practical application of the fundamental geometric concept of vertices on a shape, defined as locations along the curve where the curvature is at a local minimum or maximum. Another way to consider a vertex is the location where the velocity of the tangent vector is at a local minimum or maximum, as shown in Figure E.1 [126].

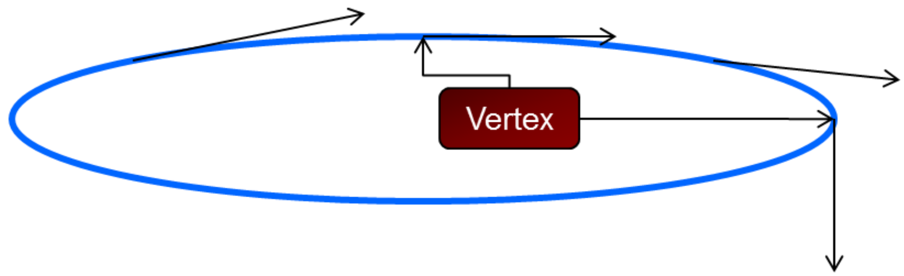


Figure E.1: Vertices occur at null velocity of tangent vector.

These are likely to occur more often the less convex a shape is, so there is a potential for the number of vertices to scale with the number of contour lobes, although there is probably no information retained regarding the distribution of the lobes.

E.2 Land-Use GIS Metrics

While the arc-length and number of vertices may provide a measure of the quantity of contour lobes, the lack of ability to measure their distribution lead to a search for metrics that specifically achieve this function. Such metrics are often applied in other disciplines such as land-use and other Geographical Information System (GIS)-dependent focuses. This particular set was developed by Parent and Civco, to describe different geographical boundaries such as counties [127]. One of the main challenges in applying these metrics lies in the practical application of the measurement, as modifications can and should be made to tailor them specifically to the problem of describing noise contours. Furthermore, noise contours do not always result in a single contiguous shape.

Therefore, the existence of multiple sets of contiguous contours could possibly affect the applicability of normalized measures such as those presented below. These metrics are subdivided into four separate categories: metrics that describe the distribution of the shape about a central point, metrics that describe the distribution of points within a shape, metrics that characterize the interior and perimeter of the shape, and measures that treat the shape as an object to traverse or circumvent [127]. Some of these can be identified as more appropriate than others on a preliminary basis, but they will all be presented below.

E.2.1 Distribution of Shape About a Central Point

Of the metrics discovered in the land-use field of research, those that capture the distribution of a shape around a central point are the most relevant [127]. They not only may scale with the number of contour lobes, but also may provide scaling based on the location of those lobes. In practice, the central point can be defined arbitrarily, as a reference point that is cohesive amongst different airport configurations. For the purposes of this problem, however, the central point of interest is the airport nucleus, or, more precisely, the centroid of the airport nucleus. This point will be substituted for the centroid of the shape in the metrics presented below when applicable.

The first metric of interest is termed the Proximity Index (PI), which is defined as the "average Euclidean distance from all points to the centroid." [127] An example can be seen in Figure E.2. PI is calculated using the DNL 65 dB airport grids, rather than the DNL 65 dB contour points, using Equation E.1, and is normalized using the Proximity Index of the Equal Area Circle (EAC), shown in Equation E.2, thus yielding the normalized PI in Equation E.3 [127]. The Proximity Index is very similar to the Spin Index except that the distances between all points and the centroid are not squared.

$$Proximity = \frac{d_1 + d_2 + \cdots + d_n}{n} \qquad (E.1)$$

$$Proximity_{EAC} = \frac{2}{3} * radius_{EAC} \qquad (E.2)$$

$$Normalized\ Proximity = \frac{Proximity_{EAC}}{Proximity_{Contour}} \qquad (E.3)$$

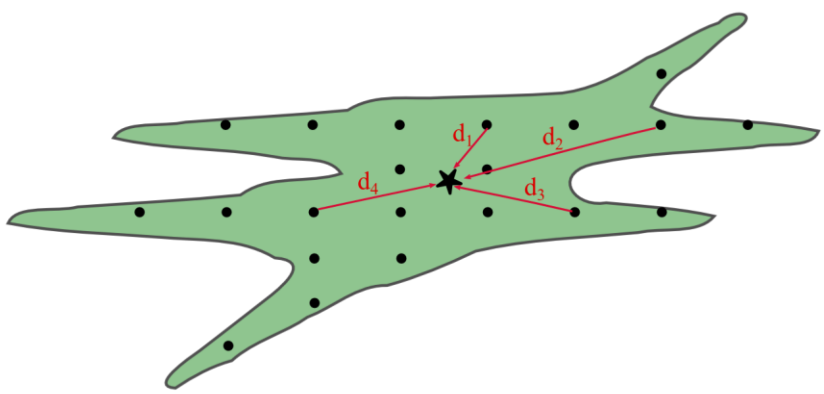


Figure E.2: Proximity Index (Adapted From [127]).

The third metric that describes the distribution of a shape about a central point is the Dispersion Index (DI). DI is defined as the "average distance from the centroid of all points on the shape perimeter", as shown in Figure E.3 [127].

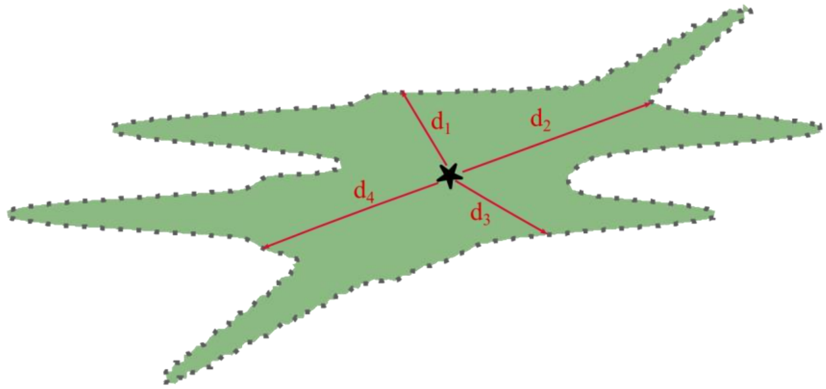


Figure E.3: Dispersion Index (Adapted from [127]).

As such, it is calculated on the DNL 65 dB contour points as opposed to the detailed noise grid. The DI is calculated using Equation E.4 [127].

$$Dispersion = \frac{d_1 + d_2 + \cdots + d_n}{n} \qquad (E.4)$$

At first glance the equation suggests the same calculation process as the PI, but the difference is that these distances are calculated along the edge of the shape, using the contour points, as opposed to using the grid points. The metric is normalized by the deviation, or a measure of the distance between the contour points and a circle of equal dispersion, as shown in Figure E.4 [127]. The dispersion of the circle is simply the radius by reduction of Equation E.4. Therefore, the deviation is calculated using Equation E.5, and the DI is normalized using Equation E.6 [127].

$$Deviation = \frac{d_1 + d_2 + \cdots + d_n}{n} \qquad (E.5)$$

$$Normalized\ Dispersion = \frac{Dispersion - Deviation}{Dispersion} \qquad (E.6)$$

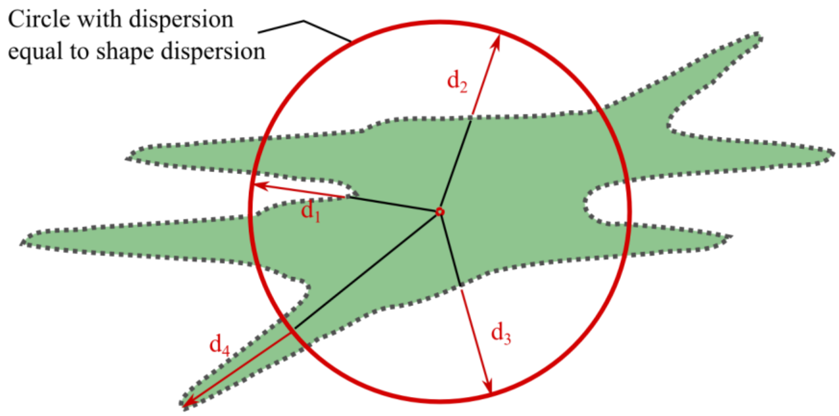


Figure E.4: Deviation (Adapted from [127]).

E.2.2 Distribution of Points Within Shape

Another group of metrics from the land-use research field capture the distribution of the points within the shape [127]. These metrics operate on the noise grid with noise above DNL 65 dB as opposed to the DNL 65 dB noise contour. Although point spacing would typically be a fixed distance between points in an airport-level noise contour grid, the distribution of points near lobes may affect the way in which these metrics scale. They may not, however, provide much information as to how that shape is distributed about the airport nucleus, as there is no relation to a central point.

The only metric considered useful for further examination from this category is the Cohesion Index (CI). This metric is defined as the "average distance between all pairs of interior points", as shown in Figure E.5 [127].

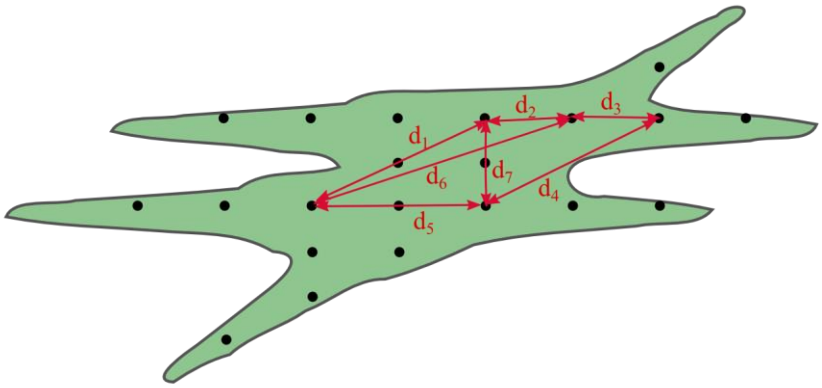


Figure E.5: Cohesion Index (Adapted from [127]).

The CI is calculated via Equation E.7 [127].

$$Cohesion = \frac{d_1 + d_2 + \cdots + d_n}{\binom{n}{2}} \qquad (E.7)$$

The normalization is performed via the CI of the EAC, as shown in Equation E.8 and Equation E.9 [127].

$$Cohesion_{EAC} = 0.9054 * radius_{EAC} \qquad (E.8)$$

$$Normalized\ Cohesion = \frac{Cohesion_{EAC}}{Cohesion_{Contour}} \qquad (E.9)$$

The CI is expected to correlate well with the number of contour lobes although the lack of information regarding the distribution of the contour lobes may prove to be a major deficiency.

E.2.3 Characterizing the Shape Interior and Perimeter

Yet another group of metrics developed by Parent and Civco characterize the shape interior and perimeter [127]. These metrics again will likely scale with the number of contour lobes but their ability to scale with lobe distribution about the airport nucleus is indeterminate at this preliminary stage of evaluation. Of the metrics in this group, three were identified for further analysis. One of these is a normalized version of the arc-length, or perimeter, described above. This metric has multiple methods for normalization, and thus a modified version of the index will be demonstrated below [127], [128].

The first such metric is the Depth Index (DeI) defined as the "average distance from the shape's interior points to the nearest point on the perimeter", as shown in the example in Figure E.6 [127]. This particular metric is unique in that both the contour points and the grid points are required for calculation. It is calculated using Equation E.10 and normalized by the DeI of the EAC, as shown in Equation E.11 and Equation E.12 [127].

$$Depth = \frac{(d_1 - Edge_{nearest}) + (d_2 - Edge_{nearest}) + \cdots + (d_n - Edge_{nearest})}{n} \qquad (E.10)$$

$$Depth_{EAC} = \frac{1}{3} * radius_{EAC} \qquad (E.11)$$

$$Normalized\ Depth = \frac{Depth_{Contour}}{Depth_{EAC}} \qquad (E.12)$$

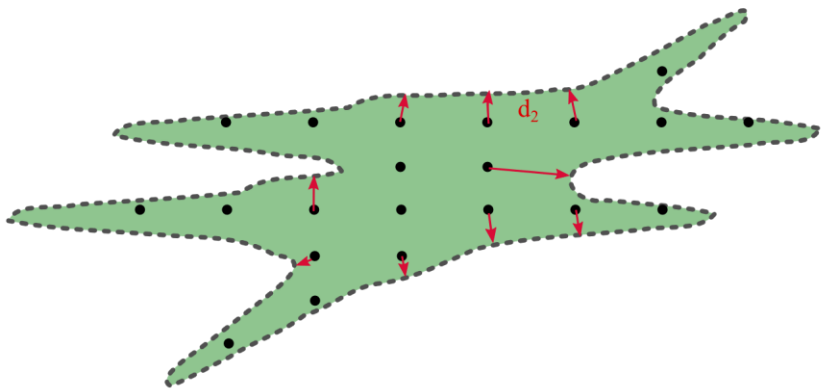


Figure E.6: Depth Index (Adapted from [127]).

The second metric recommended for analysis is the Girth Index (GiI), defined as the "largest circle that can be inscribed in the shape", as shown in Figure E.7 [127].

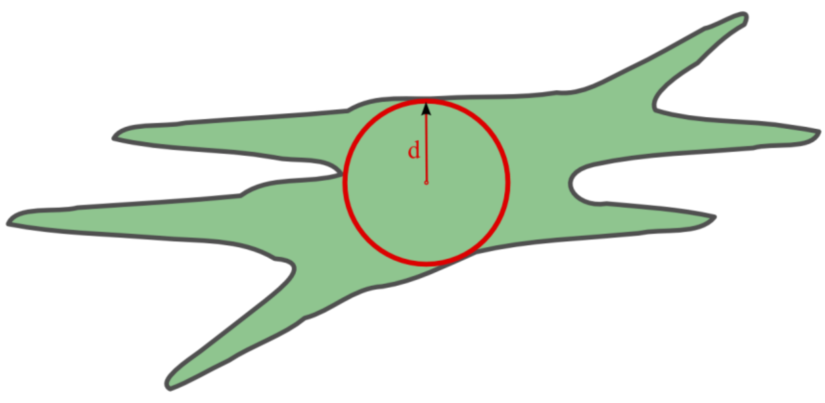


Figure E.7: Girth Index (Adapted from [127]).

Again, the occasional presence of multiple contiguous contours comprising an airport-level noise contour is a major challenge for this metric. To simplify this metric, it was redefined for the purposes of this research as the largest circle that could be inscribed inside the contour from the center of the reference runway. This metric must assume that a reference runway exists. While in practice this may not always be a correct assumption, it is certainly true for the generic infrastructures developed above. This assumption is sufficient for evaluating the value of the metric, and the challenge of removing the assumption can be dealt with if and when it is necessary pending the assessment. The GiI is normalized by the radius of EAC as shown in Equation E.13 [127].

$$Normalized\ Girth = \frac{Girth_{Contour}}{Radius_{EAC}} \qquad (E.13)$$

The Perimeter Index is defined as the perimeter of the EAC divided by the perimeter of the shape [127]. While the perimeter itself was already considered for analysis, the normalized version is more valuable to test, and thus will be used to modify the arc-length metric presented above. Further research into a Perimeter Index, however, led back to the field of mathematics, in which a different normalization by the perimeter of the convex hull of the shape was applied [128]. This normalization strategy provides a more explicit measure of convexity, as it measures deviation from the closest convex shape that would enclose all exterior points of the shape [128]. Therefore, normalizing by the convex hull perimeter was selected and will be termed the Modified Perimeter Index (MPI). The convex hull will be found using an implementation of the Graham

Scan Algorithm [129]. The perimeter or arc-length of the contour is calculated using the DNL 65 dB contour points, which form many ordered line segments. The length of these line segments can easily be computed.

E.2.4 Measure of an Object to Traverse or Circumvent

The final group of metrics characterizes the shape as an object to traverse or circumvent [127]. These metrics employ simplifying geometries, such as the convex hull of the contour shape for example. These metrics, while conceptually less detailed than the other metric types, may provide a sense of not only scaling with contour lobe quantity but also distribution, without requiring comparison to a central point. Of these metrics, only the Detour Index (DetI), was considered sufficient for further analysis, and was discussed in Section 3.3.3.1.

APPENDIX F

GR ROBUSTNESS TO FORECAST - RESULTS

This appendix summarizes the actual by predicted results of the Generic Runway robustness to forecast variability assessments. Each Generic Runway is presented along with the root mean square error in nmi^2. The actual by predicted for M1 can be seen in Figure F.1.

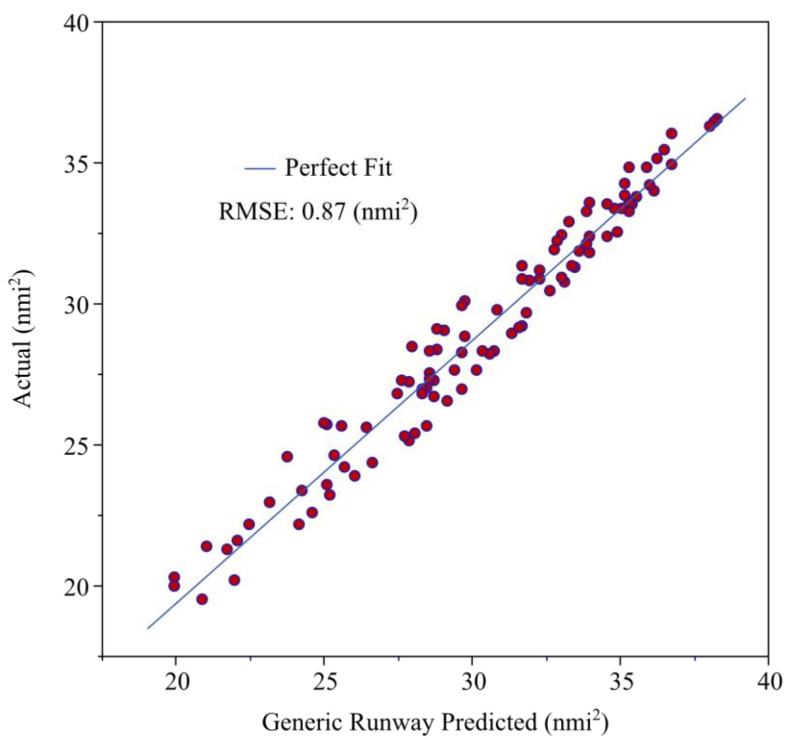


Figure F.1: Actual by predicted results for M1.

The results again confirm the error previously identified for M1. Althought the root mean square error is low, the spread of the predictions is relatively high. The predictions are closer to the line of perfect fit as the total contour area for M1 increases, suggesting that part of the problem could again be caused by disappearing DNL 65 dB contours confounding the results. Nonetheless, the error above the baseline M1 DNL 65 dB contour area is also relatively high, and may be caused by inappropriate vehicles representing seat classes 4 and 5, which heavily feature in the M1 runway distribution. The actual by predicted results for M2 can be seen in Figure F.2. M2 demonstrates relatively low root mean square error, although again the error for cases that have been scaled down is higher, consistent with the other Generic Runways. As flight predictions result in increases to total contour area, the prediction improves.

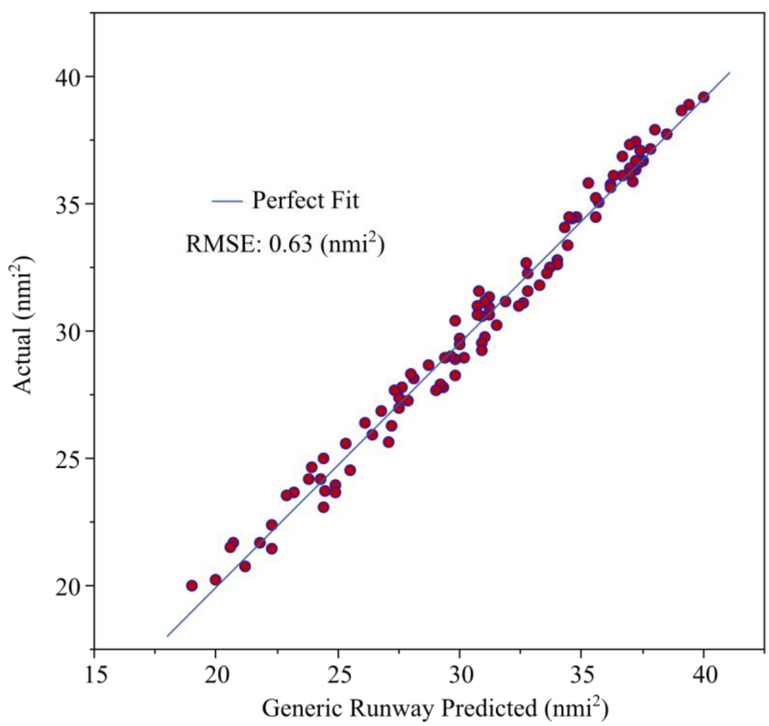


Figure E.2: Actual by predicted results for M2.

The actual by predicted for L1 can be seen in Figure F.3. The root mean square error for L1 is very low, but so is the magnitude of the fleet-level contour area contribution predicted. Similar to S1 and M1, the prediction shows an inability to predict with as much accuracy when the flight scenarios result in a decrease in demand, while increases only seem to positively affect the predicted response.

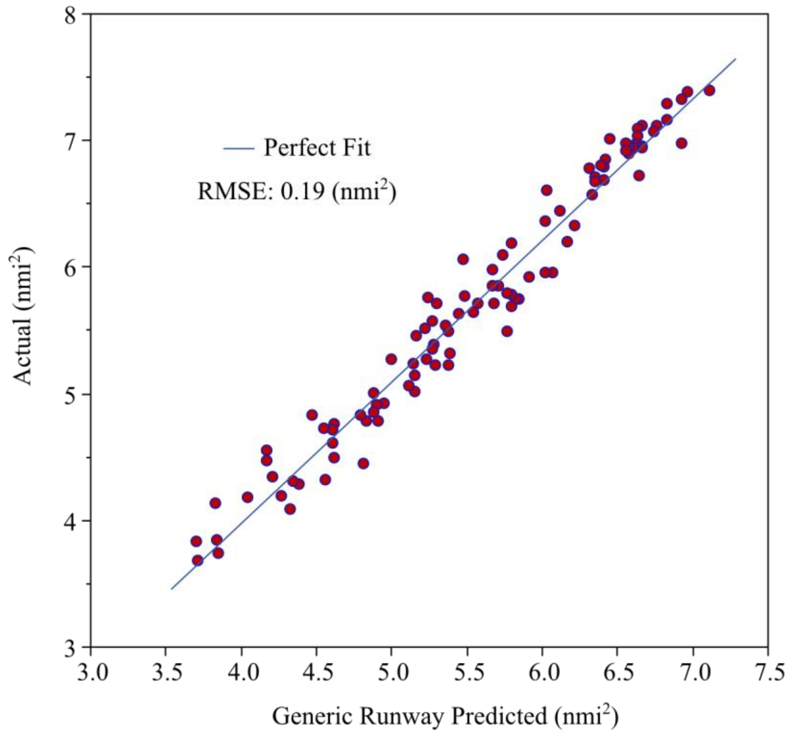


Figure F.3: Actual by predicted results for L1.

The actual by predicted for L2 can be seen in Figure F.4. L2 shows a slightly better overall prediction compared to L1, although the root mean square error is technically of a higher magnitude. Again the scaled down cases suffer more inaccuracy than those that scale up.

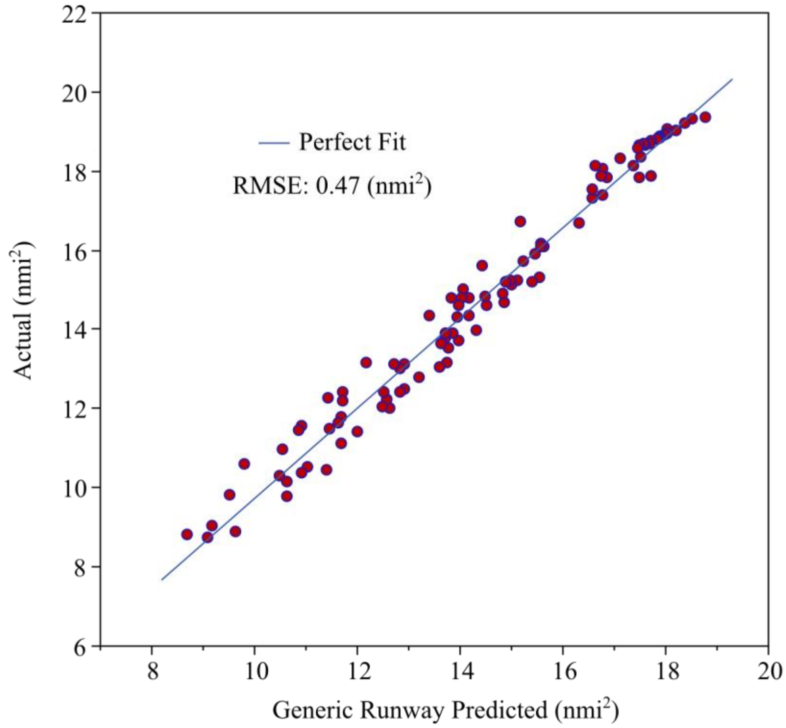


Figure F.4: Actual by predicted results for L2.

APPENDIX G

CONFIGURATION EXPLORATION RESULTS

This appendix summarizes the configuration exploration results for the Parallel-Intersecting and Triple Intersecting geometries, which were omitted from the main text for brevity.

G.1 Case 3: Parallel-Intersecting Configuration

The Parallel-Intersecting configuration robustness assessment allows for the observation of progression from Intersecting or Parallel geometry, to a Parallel-Intersecting geometry depending on the separation of the parallel runway, and separation and rotation of the intersecting runway. This experiment case introduces an airport configuration of three runways with a maximum of two total runway intersections. Operational settings were again found to only serve to magnify the results of the analysis, and therefore only the highest operational setting will be discussed, as shown in Figure G.1. Each dot represents a separate geometric variation of Parallel-Intersecting airport geometry. The results demonstrate the effect of combining the Parallel and Intersecting configurations. The resulting behavior with respect to contour area is much more difficult to discern, however. It is immediately noticeable that the stagger of the parallel runway has very little effect, but the separation of the parallel runway now has less of an impact than the trends observed in the Parallel configuration. The rotation appears to have almost no effect except at very high and very low values. These rotational values correspond to the intersecting runway approaching a parallel placement, resulting in a

Parallel-Single geometry. Based on these results, no significant subcategories with respect to contour area can be defined, but the mode of calibration can be seen to behave similarly to superimposing the modes for Parallel and Intersecting. Therefore, a combination of those geometries is likely to yield a sufficient starting point from which perturbations can be performed.

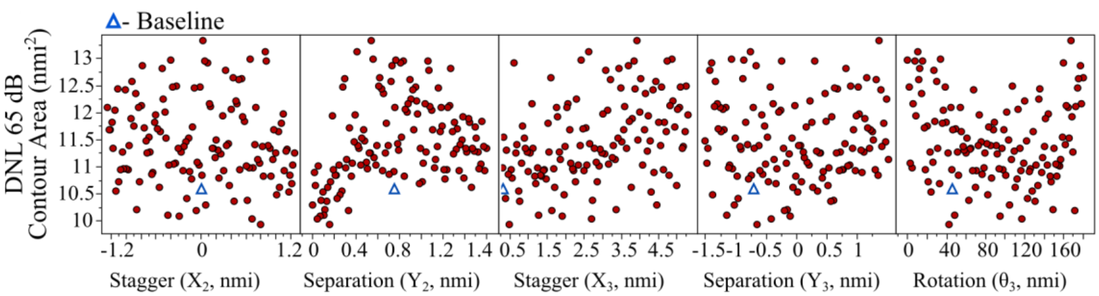


Figure G.1: Parallel-Intersecting configuration exploration.

G.2 Case 4: Triple Intersecting Configuration

The Triple Intersecting configuration robustness assessment allows for the observation of progression from Parallel-Intersecting to Triple Intersecting geometry depending on the rotations of the intersecting runways. This experiment case introduces an airport configuration of three runways with three possible total runway intersections. Operational settings were, again, found to only serve to magnify the results of the analysis, and therefore only the highest operational setting will be discussed, as shown in Figure G.2. Each dot represents a unique Triple Intersecting airport geometry case.

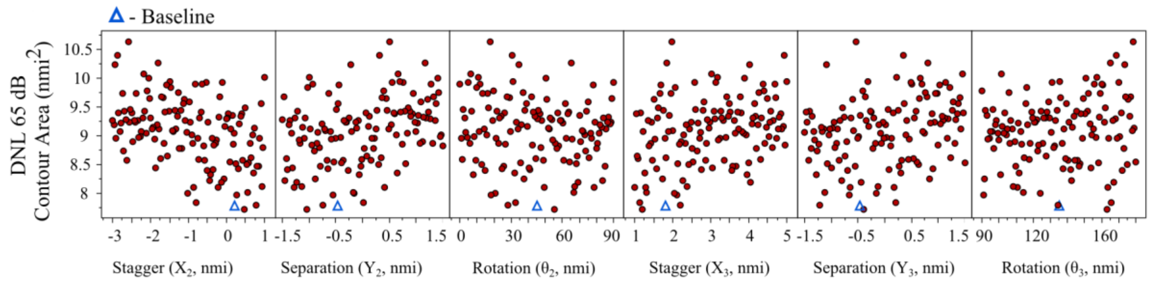


Figure G.2: Triple Intersecting configuration exploration.

The results clearly show that the stagger of the first intersecting runway has a negative correlation to the DNL 65 dB contour area. The second intersecting runway stagger exhibits a positive correlation. Since the ranges for each are complementary, this suggests that the further any intersecting runway gets from the center of the reference runway, the higher the contour area. The rotation of both intersecting runways also suggests a similar behavior in which the highest contour areas occur when the intersecting runways are nearly parallel to the reference runway. The separation behaves similarly for both runways, in which an increase in separation generally leads to an increase in DNL 65 dB contour area. This behavior can be utilized to calibrate the Generic Infrastructure to better represent the contour area of various infrastructures. The Triple Intersecting category was difficult to constrain properly due to the higher number of interacting geometric variables, and many of the resulting geometries were very unique and unlikely to occur in realistic situations. Nonetheless, no secondary geometries were identified or considered necessary to appropriately model the geometric class.

APPENDIX H

LOBE DISTRIBUTION EXPERIMENT RESULTS

This appendix summarizes the lobe distribution experiments for the Parallel-Intersecting and Triple Intersecting geometries. These experiments were conducted to assess the ability of the collected shape metrics to scale with the geometric variables of an airport. Due to the straight ground track assumption, the positioning of these runways directly dictates the distribution of contour lobes about the airport nucleus. This appendix also contains the results of the lobe distributions for these geometries with respect to the combined Detour-Spin Index metric.

H.1 Parallel-Intersecting Configuration Exploration Cases

The Parallel-Intersecting configuration exploration cases varied the stagger and separation of a parallel runway, and the stagger, separation, and rotation of an intersecting runway relative to a fixed reference runway, and can be used to observe the relationship between these variables and the remaining metrics. The results of this analysis can be seen in Figure H.1. Each dot represents a unique Parallel-Intersecting airport geometry. While a Parallel-Intersecting configuration is a conjoined Parallel and Intersecting airport configuration, the behavior of the metrics, with respect to the geometric variables, shows that interactions of the intersecting runway are much more dominant than those of the parallel runway, and thus dictates more about the contour with respect to the collected shape metrics.

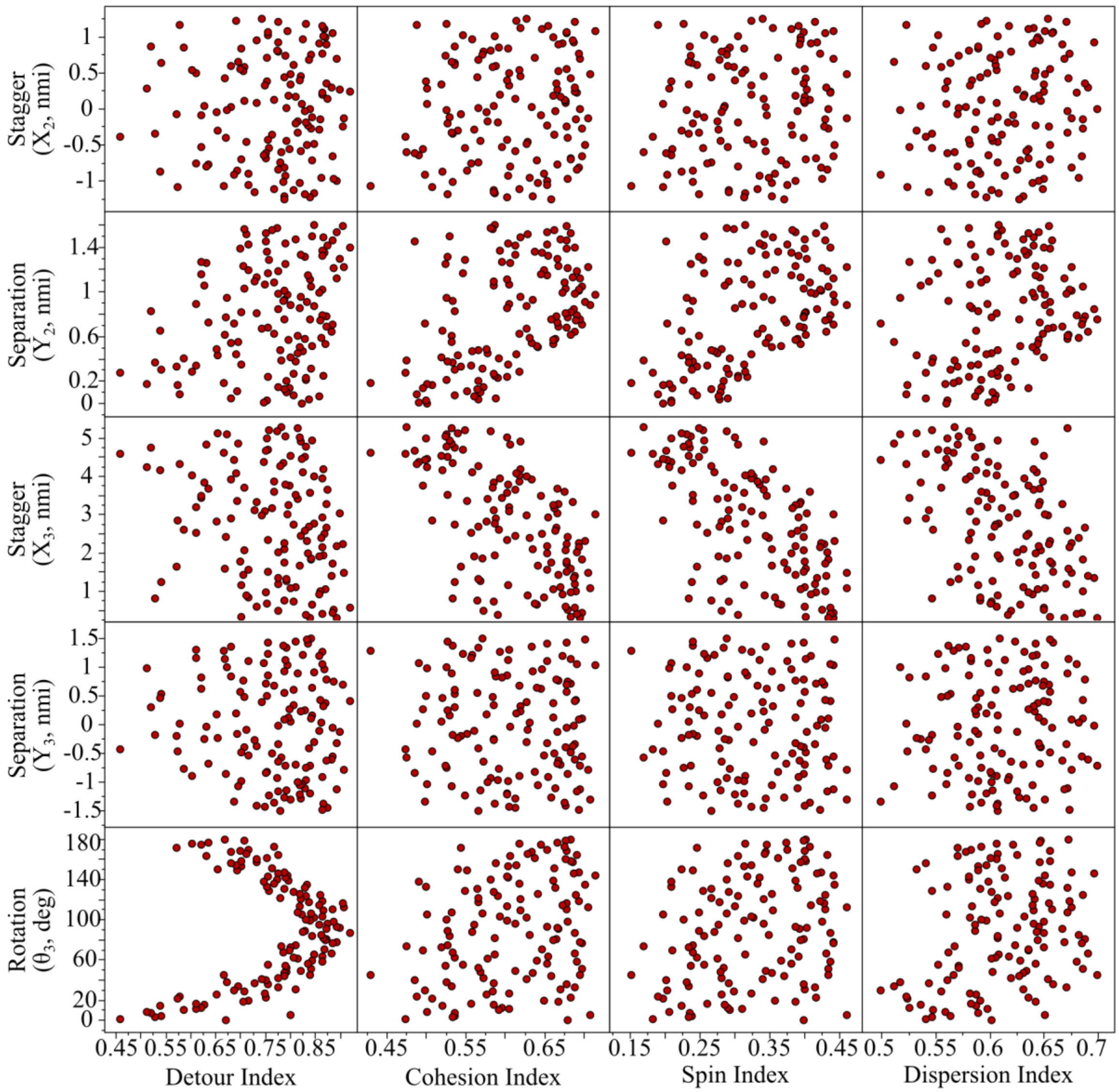


Figure H.1: Parallel-Intersecting configuration exploration geometric variable relationships.

Again the rotation is of primary importance with a secondary influence provided by the stagger of the intersecting runway, in much the same way the Intersecting configuration exploration results behaved. When the rotation of the Intersecting runway becomes very high or very low (close to parallel), the separation of the parallel runway recovers some of the behavior observed in the Parallel runway configuration exploration results with respect to Detour Index. At this extreme rotation, the Intersecting runway continues to influence the contour shape through its stagger. Again, since the rotation of the Intersecting runway is so critical to the distribution of the contour lobes, the Detour Index is the most appropriate metric for the Parallel-Intersecting experimental group. Again the Spin and Cohesion indices contribute certain value which the Detour Index cannot provide with respect to the relationships to stagger of the intersecting runway and separation of the parallel runway.

H.2 Triple Intersecting Configuration Exploration Cases

The Triple Intersecting configuration exploration cases varied the stagger, separation, and rotation of two intersecting runways relative to a fixed reference runway, and can be used to observe the relationship between these variables and the remaining metrics. The results of this analysis can be seen in Figure H.2. Each dot represents a unique Triple Intersecting airport geometry. Examining the results, it is clear that only the Detour Index responds to the rotation of both intersecting runways with noticeable significance, although the Spin and Cohesion indices again exhibit a relationship to the stagger of the intersecting runways. The results from this particular geometric category make it difficult to conclude if a certain metric is more appropriate than the others, although the Dispersion Index can be comparatively judged to have little value. Similar to the Intersecting and Parallel-Intersecting cases, the closer the intersecting runway rotations are to a mid-range, the more pronounced is the relationship of the Detour Index and the intersecting runway stagger values.

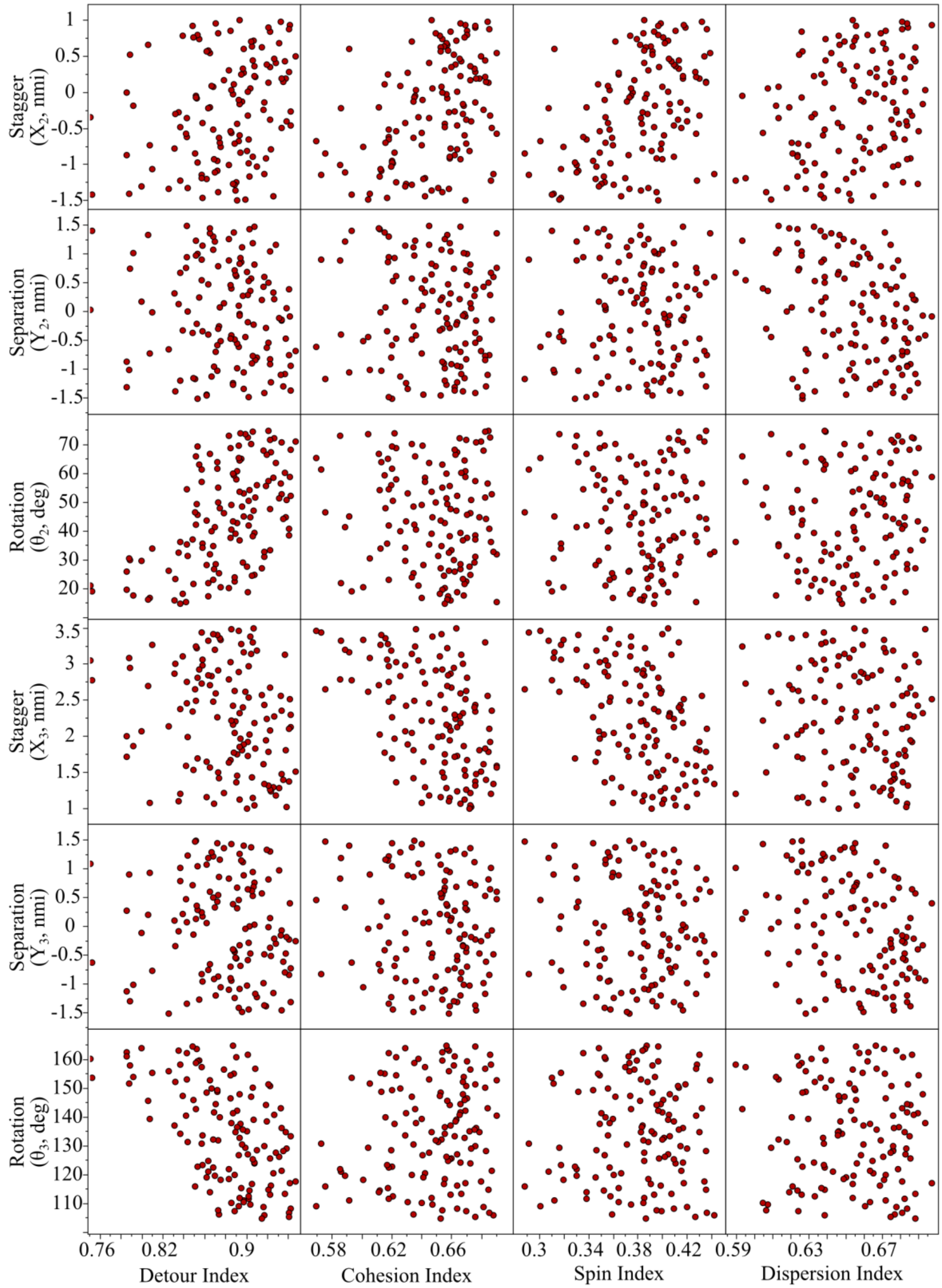


Figure H.2: Triple Intersecting configuration exploration geometric variable relationships.

While it is difficult to conclude a specific recommendation for this geometric set, in context of the success of the Detour Index from the previous geometries, it must be selected as the primary metric. Spin or Cohesion indices do provide valuable and more significant relationships to other important variables such as the stagger of the intersecting runways, which is a common theme throughout all of the geometric categories analyzed.

H.3 Detour-Spin Index Results

The results presented here summarize the lobe distribution results of the Parallel-Intersecting geometry and the Triple Intersecting geometry with respect to the Detour-Spin Index. Figure H.3 contains the results for the Parallel-Intersecting geometry.

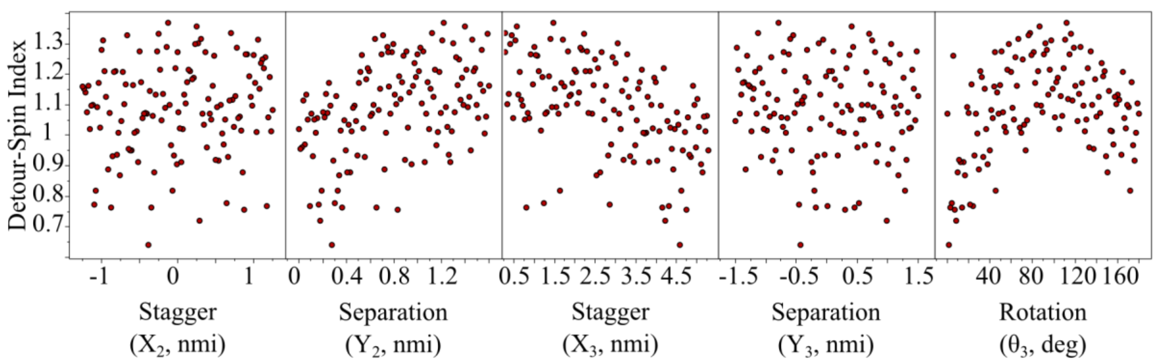


Figure H.3: Parallel-Intersecting configuration exploration relationship to DSI.

Note the improved capture of separation for the parallel runway, stagger for the intersecting runway, and rotation for the intersecting runway. The rotation effect is somewhat less pronounced than for the Detour Index alone, but the overall result is to provide a good combined scaling with the important geometric factors.

Figure H.4 demonstrates the results of the Triple Intersecting lobe distribution examination with respect to Detour-Spin Index. As can be seen from the results, the DSI captures the stagger, separation, and rotation of both intersecting runways satisfactorily. While a strict trend is somewhat difficult to observed, this is due to the interplay between the different variables.

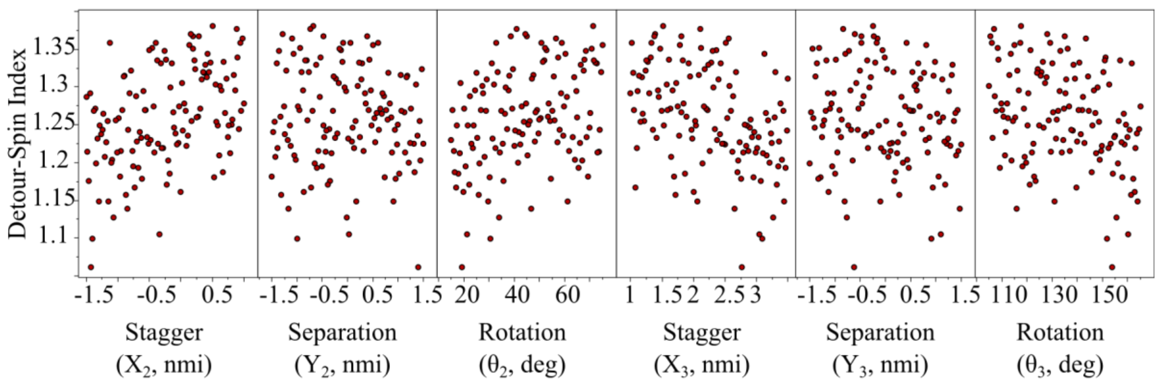


Figure H.4: Triple Intersecting configuration exploration relationship to DSI.

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VITA

José Enrique Bernardo was born in Lima, Perú, and moved to the United States with his family at the age of five. José grew up in Pittsburgh, Pennsylvania, and as a child he wanted to be an astronaut. By the time he was in middle school, he knew he wanted to be an engineer.

José attended the University of Pittsburgh, where he received his Bachelor of Science in Mechanical Engineering in 2008. As an exciting cap to his undergraduate education, José and a team of his classmates proposed, designed, built, and flew a microgravity experiment aboard NASA's reduced gravity research aircraft.

José continued his education at the Aerospace Systems Design Laboratory (ASDL) at the Georgia Institute of Technology, working under the direction of Dr. Dimitri Mavris. José received his Masters in Aerospace Engineering in 2009. His independent research project seeded the research that would become his doctoral research. Although José still dreams of going to space, he has realized his true passion lies in creative problem-solving.

José is happily married to his high school-sweetheart, Laura, and enjoys spending weekends with her and their beagles, Patas and Della. After graduation, José will perform postdoctoral work, before pursuing a career in academia.