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# N+1 Systems Analysis Retrospective

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## 1.0 Introduction

"Systems analysis" refers to the study of operational components and the integrated interactions and impacts of the components within their environment. The use of systems analysis in general engineering studies has grown due to the broad applicability of the tools and methodologies to the design, evaluation, or optimization of conceptual systems (physical and otherwise). The increased use of systems analysis tools and methodologies has also led some to the merging of disciplines, as systems analysis and "systems engineering" are often used interchangeably (reference 1). Since both disciplines use terms with distinct meanings and defined relationships, these terms are not used interchangeably in this retrospective.

NASA uses systems analyses to help set strategic directions, establish goals, evaluate technology paths, and define technology portfolios within its aeronautical research programs. While the specific baselines, assumptions, and methodologies are dependent on the systems at issue, there remains the common practices of identifying and representing the components (e.g., top-down decomposition), modeling the operating environment and interactions, establishing baselines, developing alternatives, ranking alternatives, and defining the lifecycle of the system.

As with most continuous improvement organizations like NASA, periodic examination of internal processes like those using systems analyses, is conducted to capture lessons learned and to identify areas where processes can be improved or enhanced. The effort documented in this paper is part of NASA's continuous improvement practice of reflecting on past analyses to identify areas where the analyses could have provided improved or more broadly applicable results. Identifying problems or issues with the modeling and analysis tools is part of any retrospective; however, this effort focused on the study designs and assumptions.

Designs and assumptions differ for each particular use case (e.g., setting technology goals versus projecting impacts). This retrospective looked at a series of studies used to set single-aisle, commercial transport[1] performance goals for the 2015 timeframe, looking about 10-20 years into the future at the time they were set. Future technology levels are designated by "N+", where "N" or "N+0" refer to a current generation of aircraft flying at that time, "N+1" refers to the next generation, "N+2" to the generation after that, and so forth.

## 2.0 Background – Setting Goals

In the 2005 timeframe, NASA initiated a series of systems-analysis studies to assess the potential impacts of technological improvements on various classes of commercial aircraft (e.g., references 2 and 3). The studies were the basis for setting performance goals (Table 1) and selecting programmatic content, and technology portfolios. Technology paths comprising the technology portfolios were selected by identifying designs and enabling technologies which offered the best opportunities for meeting the timeframes and targeting the system-level metrics of interest. At the time of these studies, single-aisle transports were projected to comprise 65% of the transport aircraft produced over a 20-year period (reference 4) and the vehicle class targeted

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[1] "Single-Aisle Transport" is a common way to refer to a 737/A320 class airplane; although there are other types of single-aisle aircraft (e.g., regional jets).

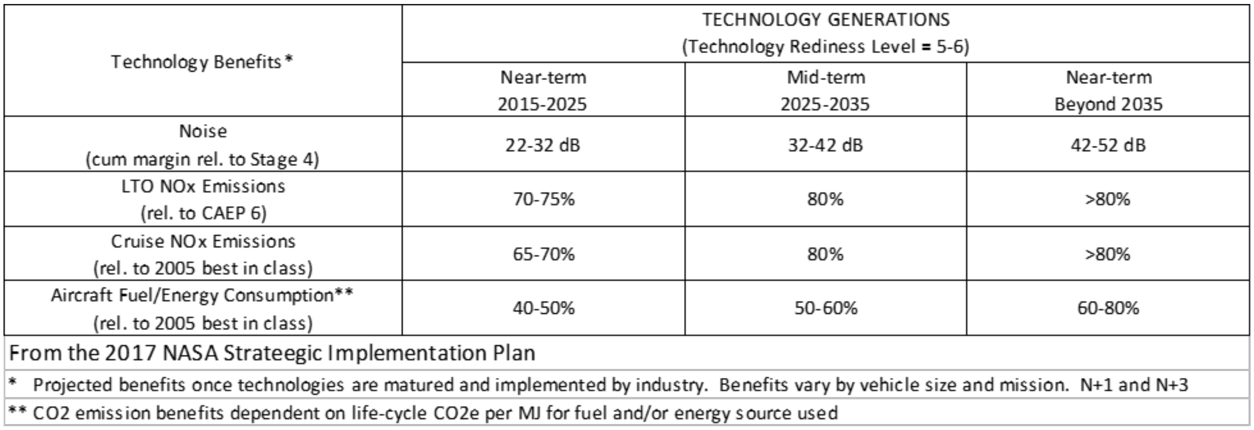
in the “N+1” studies. The goals were the product of assessing advanced technology paths on Boeing 737-800 with CFM[2] 56 engines, which represented the 2005 (N+0) best-in-fleet.

Table 1. NASA subsonic transport system-level metrics and goals.

| Technology Benefits* | TECHNOLOGY GENERATIONS (Technology Rediness Level = 4-6) | | |
|---|---|---|---|
| | N+1 (2015) | N+2 (2020) | N+3 (2025) |
| Noise (cum margin rel. to Stage 4) | -32 dB | -42 dB | -52 dB |
| LTO NOx Emissions (rel. to CAEP 6) | -60% | -75% | -80% |
| Cruise NOx Emissions (rel. to 2005 best in class) | -55% | -70% | -80% |
| Aircraft Fuel/Energy Consumption** (rel. to 2005 best in class) | -33% | -50% | -60% |
| * Projected benefits once technologies are matured and implemented by industry. Benefits vary by vehicle size and mission. N+1 and N+3 values are referenced to a 737-800 with CFM56-7B engines, N+2 values are referenced to a 777-200 with GE90 engines | | | |
| ** CO2 emission benefits dependent on life-cycle CO2e per MJ for fuel and/or energy source used | | | |

Although not a direct result of the N+ systems studies, the metrics table was updated for presentation in the 2015 NASA Strategic Implementation Plan (SIP – Table 2). Of note for the retrospective were the changes of some goals to ranges as well as the changing target timeframes to ranges (reference 6).

Table 2. N+1 subsonic, single-aisle transport metrics and performance projections.



| Technology Benefits* | TECHNOLOGY GENERATIONS (Technology Rediness Level = 5-6) | | |
|---|---|---|---|
| | Near-term 2015-2025 | Mid-term 2025-2035 | Near-term Beyond 2035 |
| Noise (cum margin rel. to Stage 4) | 22-32 dB | 32-42 dB | 42-52 dB |
| LTO NOx Emissions (rel. to CAEP 6) | 70-75% | 80% | >80% |
| Cruise NOx Emissions (rel. to 2005 best in class) | 65-70% | 80% | >80% |
| Aircraft Fuel/Energy Consumption** (rel. to 2005 best in class) | 40-50% | 50-60% | 60-80% |
| From the 2017 NASA Strateegic Implementation Plan | | | |
| * Projected benefits once technologies are matured and implemented by industry. Benefits vary by vehicle size and mission. N+1 and N+3 | | | |
| ** CO2 emission benefits dependent on life-cycle CO2e per MJ for fuel and/or energy source used | | | |

The N+1 systems analysis studies started with models of the 737-800 and CFM56 engines (2005 baseline models) and added advanced technologies to the airframe and engines. An iterative “spiral” approach to the modeling allowed for revisiting the results and making improvements with each complete spiral. Only suites of compatible advanced technologies were used in each of the spirals.

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[2] CFM is a joint partnership between GE (U.S.A.) and Safran Aircraft Engines (France)

### 2.1 Propulsion System

The engines analyzed in references 2 and 3 for setting the N+1 goals were modifications to the CFM56 models: two-spool, separate-flow turbofans designed with the same Aerodynamic Design Points (ADP) and same Overall Pressure Ratios (OPR) at the ADPs as the CFM56. The engine trades looked at two different compressor types: “high work” and “low work.” The rationale for the two variations was to replicate the disparate design philosophies between the two major U.S. engine manufacturers. The engines were designed for equal thrust at rolling takeoff conditions (standard sea level (SSL), Mach 0.25). Because variable pitch fan blades present additional technological challenges, they were deemed too aggressive for the N+1 timeframe. However, including the high bypass ratio, low fan pressure ratio systems required some type of variable geometry to ensure operability. Therefore, the use of a variable area nozzle was included in the studies when needed for achieving the desired 20% fan-surge margin throughout the operating envelope.

The low-pressure turbine (LPT) cooling philosophy was another area in which advanced technology assumptions were made to the CFM56 model. The initial assumption of an uncooled LPT was removed and a cooling analysis was implemented for each engine to determine the amount of cooling air necessary to maintain acceptable high-pressure turbine (HPT) and LPT temperatures. For the N+1 systems analysis, LPT efficiency was varied as a function of cooling level. A significant change to the engine design was the assumption of a two stage HPT rather than the single stage HPT of the CFM56. The two-stage design was believed to be more representative of likely industry designs (reference 7).

Cycle analysis was performed for the engines with the Numerical Propulsion System Simulation (NPSS) code (reference 8). Analysis of the aeromechanical characteristics and estimates of the engine weight were performed with the Weight Analysis of Turbine Engines (WATE) code (reference 9). Estimates for engine NOx emission indices were obtained from correlations developed by NASA combustor technologists during the latter stages of NASA’s Ultra-Efficient Technology Program (reference 10). (For more details of the complex trade-space for the engine modeling and analysis, please refer to references 2 and 3).

### 2.2 Aircraft

The N+1 studies assumed that the advancement of airframe technology would be primarily through the extensive use of composite materials for the airframe structures and natural laminar flow control. Predictions at the time of the N+ studies were that composite materials would comprise up to 50% of the primary structures of new aircraft designs (reference 11). Composite materials were assumed for wings, fuselages, and tails, resulting in assumed benefits of 15% structural weight savings. Natural laminar flow was assumed for wings, tails, and nacelles. Other technology improvements included an increase in hydraulic system pressure (5,000 psi) and a drag reduction. Cruise Mach was increased slightly to 0.8. The design range (with 32,400 lb. payload) was increased from 3,060 nm to 3,250 nm. Basic 737-800 geometry was maintained in the new design with a slight increase in wing sweep to accommodate the higher cruise Mach number.

The airframe model was a derivative of a 737-800 baseline model intended to be representative of a potential advanced technology replacement aircraft. The aircraft sizing and performance computer code, Flight Optimization System (FLOPS – reference 12), was used as the primary aircraft sizing and analysis tool. Spreadsheet analyses were used to determine landing gear length, engine-out drag, and vertical tail size.

### 2.3 Noise Reduction

For the N+1 noise-reduction goal, chevrons were modeled for all core nozzles and for all fixed-area bypass nozzles. Conventional inlet, inter-stage and aft fan duct liners were applied to reduce fan inlet and discharge noise. In addition to conventional liners, two advanced technologies were applied for fan noise reduction: soft vane stators and over-the-rotor foam metal treatment (references 13 and 14). Other assumptions regarding noise-reduction technologies included innovative slat cove fillers, flap porous tips, continuous mold-line links, trailing edge noise suppression treatments, and landing gear spoilers and fairings.

The primary tools used for the noise analysis included: NPSS for the engine cycle analysis, WATE for the engine aeromechanical and flow-path analysis, FLOPS for the aircraft trajectory simulation, and Aircraft Noise Prediction Program (ANOPP – reference 15) for the source noise prediction and propagation. The Effective Perceived Noise Level (EPNL) was calculated at the noise certification points defined in Federal Aviation Regulation (FAR) Part 36.

## 3.0 N+1 Systems Analysis

The advanced propulsion assumptions resulted in 0.5 to 1 pt. improvement in all turbomachinery efficiencies. There was also a -25% total turbine cooling via high temperature materials. These advanced materials enable +50-degree T3 and +100-degree T41.

Advanced materials and structures produced -15% total fuselage, wing and empennage weight (via composite materials). Aerodynamic improvements produced -1% total aircraft drag from the variable camber and other excrescence drag cleanup assumptions. There was a 7% total aircraft drag reduction resulting from the natural laminar flow control assumptions (see Figure 1). By increasing the hydraulic pressure capability to 5000 psi, results showed a 15% hydraulic system weight reduction.

The results showed a 33% fuel consumption reduction from the advanced engine and airframe technologies. The Landing and Take Off (LTO) $NO_X$ goal (60% below CAEP[3]6) was exceeded with the combination of advanced engine cycle and low $NO_X$ combustor technology.

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[3] Committee on Aviation Environmental Protection

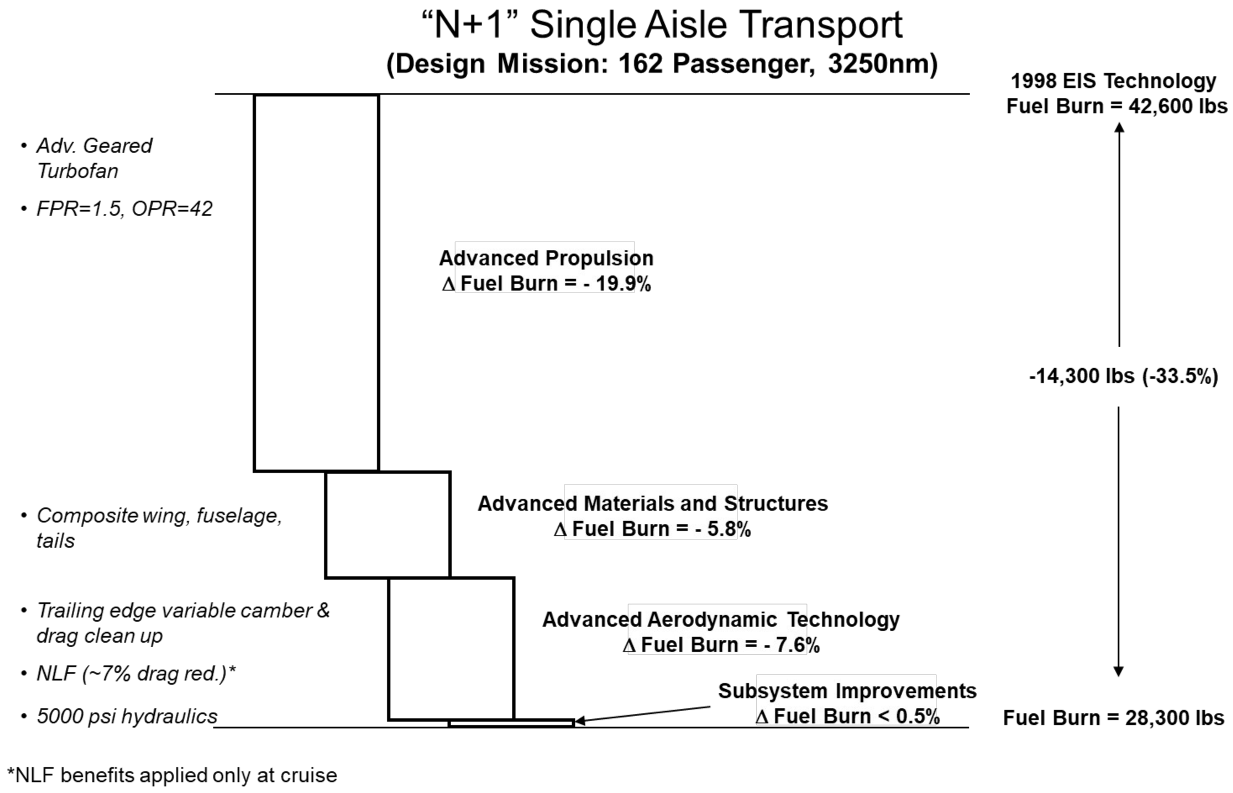

Figure 1. Potential Fuel Burn Reduction[4]

A Stage 4 (FAA standard) cumulative margin of 29 Estimated Perceived Noise in decibels (EPNdB) was the result of the N+1 airframe and engine model assumptions (3 dB short of the 32 EPNdB goal). Significant noise reduction was achieved from the advanced engine cycle and high bypass ratio assumptions.

## 4.0 New Baseline – 2015 Best-in-Fleet

As stated earlier, the N+1 studies were used to set performance goals and define high-payoff technology portfolios for the 2015 timeframe. At the beginning of the N+1 studies, the analysis baseline models were updated from the 1997 best in fleet to 2005 best in fleet. Moving ahead to 2015, the single-aisle aircraft baseline best in fleet, the Boeing 737-8 (MAX) and CFM LEAP engines were modeled to assess the overall performance and noise characteristics. Reference 16 describes the methodology and the results will be used to update the NASA goals relative to the 2015 baseline. In parallel, this retrospective of the N+1 studies (primarily regarding the technology paths) was conducted, and insights into how assumptions and procedures might be improved in future studies of this nature were produced.

Most of the N+1 engine-technology paths assumed in the N+1 studies did not require completely new aircraft designs and were equally likely to be deployed with re-engineering

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[4] Emissions reductions and fuel-burn reductions are proportional, which led to the use of fuel burn as an indicator for emissions as well.

retrofit programs. Many of the engine technologies also offered economic benefits, which further motivated their inclusion. However, many of the airframe technology paths (e.g., 50% composite structures and materials) were dependent on new aircraft programs which did not materialize for this class aircraft by the 2015 timeframe. Noise reduction technology paths included engine and airframe changes, thereby, falling into both program types.

### 4.1 Propulsion System

The 2005 baseline used the CFM56 engines and the 2015 baseline used LEAP-1B28 engines, like those on the MAX. The LEAP engine is a CFM high bypass, separate flow, turbofan engine. Given the economic incentive of many of the engine technology paths assumed in the setting of goals, many of the N+1 engine-technology paths were present in the LEAP engine design.

It is difficult to determine exactly which of the N+1 technology assumptions were incorporated into the LEAP-1B engine, as the modeling remains in the final stages of completion. The propulsion system has not been in production a long time, and few engine performance details are in the open literature. As such, technical judgement was employed. The N+1 material assumptions (see Appendix A) seem plausible based on public comments from vendors supporting the engine's manufacture. Composites are used in construction of the fan blades, and the use of high temperature nickel alloys also seems reasonable; however, there is less confidence in the assumption that Titanium-Metal Matrix Composite (MMC) compressors are part of the LEAP-1B engine. NASA's LEAP-1B representation is employing turbomachinery improvements of similar magnitude to what was assumed in the N+1 engine study. Again, based on the NASA in-house model, it doesn't appear that the turbine cooling has been reduced 25%, but may be closer to 5-10%. That would translate to a 100 degree increase to the turbine design temperature T41. The OPR value used in the N+1 engine study is close to what has been stated in the literature for the LEAP-1B, so the T3 increase seems reasonable.

The emissions results for the in-house LEAP-1B engine models are quite close (<3% difference) to the publicly available data found in the International Civil Aviation Organization (ICAO) Databank (see Table 3). While the cycle model for the LEAP engine is not fully validated, these results are a step in that direction.

Table 3. ICAO Engine Exhaust Emissions Databank.

| | | | | | | |
|---|---|---|---|---|---|---|
| ENGINE IDENTIFICATION: | LEAP-1B28 | | | BYPASS RATIO: | 8.6 | |
| UNIQUE ID NUMBER: | 18CM084 | | | PRESSURE RATIO: | 41.5 | |
| ENGINE TYPE: | TF | | | RATED OUTPUT (kN) | 130.4 | |
| | | | | | | |
| REGULATORY DATA | | | | | | |
| CHARACTERISTIC VALUE: | | | HC | CO | NOx | SMOKE NUMBER |
| Dp/Foo (g/kN) or SN | | | 1.2 | 21.9 | 67 | 1.5 |
| AS % OF ORIGINAL LIMIT | | | 5.90% | 18.60% | 54.40% | 6.80% |
| AS % OF CAEP/2 LIMIT (NOx) | | | | | 68.00% | |
| AS % OF CAEP/4 LIMIT (NOx) | | | | | 74.40% | |
| AS % OF CAEP/6 LIMIT (NOx) | | | | | 81.70% | |
| AS % OF CAEP/8 LIMIT (NOx) | | | | | 91.60% | |

### 4.2 Aircraft

The 2005 baseline used the B737-800 as its reference model. The 2015 baseline used the 737 MAX-8 variant as the reference model. It was assumed in the N+1 studies that the advancement of airframe technology would be primarily through the extensive use of composite materials for the airframe structures. New airframe programs at the time of the N+1 studies were using composites for up to 50% aircraft structures (reference 11). Since a new airframe program did not materialize for the single-aisle aircraft during that period, many of the technology paths assumed when setting the goals were not deployed.

Some minor technology paths modeled in the 2015 baseline (MAX-8 model) were longer landing gear lengths to accommodate the increased diameter of the underwing nacelles, and a re-contoured tail cone. The 2015 baseline was calibrated assuming that the cruise $L/D$ ratio was equal to, or better than, the previous model. The result of this assumption was that the MAX-8 model had lower drag across all Mach numbers when compared with the -800 model of 2005. The justification for this assumption was that even though the aircraft was heavier and had larger engines, Boeing would not produce an aircraft that went backwards in terms of drag performance. The fuel burn results from the NASA models also closely match the publicly available data. The results showed a reduction of 13% in Specific Fuel Consumption (SFC) over the 2005 baseline.

### 4.3 Noise Reduction

Detailed takeoff and landing performance models were necessary for determining noise levels of the new 2015 baseline. Two noise analyses were run; one was a macro-level analysis of takeoff and landing distance, and the second was a detailed profile of takeoff and approach. Models were calibrated to airport planning guide noise data and Boeing proprietary B737-800 performance data. Two missions were modeled: takeoff at Maximum Take-Off Weight (MTOW) and landing at maximum design landing weight.

Although there are strong economic incentives for aircraft and engine manufacturers to implement new technologies for fuel burn reductions, incentives for noise reduction are more indirect and complex. Generally, aircraft that are recently entered-into-service will exhibit noise levels at or below current noise certification limits and subsequent projected certification limits (due to the aircraft service life). New aircraft generate noise at levels similar to those of close competitors, and are able to meet noise limits imposed by key individual airports. Meeting the noise certifications caps relaxes noise design constraints, and eliminates further design penalties on the aircraft design performance, weight, or maintenance needs. Thus, many noise reduction technologies assumed in the N+ studies, including over-the-rotor treatment, soft vane, porous flap side edges, etc., have not materialized because economic and design factors do not drive efforts to overcome the implementation challenges and costs.

For the assessed configurations, the results turned out acceptably close to the published 737 MAX-8 certification noise levels. The maximum attainable noise reduction of 32 dB below Stage 4 assumed aggressive increases in engine bypass ratios (and corresponding decreases in fan pressure ratios), lighter airframe construction, and the application of a full range of noise reduction technology which mostly are not yet in service. In addition, Boeing's decision to not redesign the 737 MAX-8 airframe led to a lesser bypass ratio improvement (restricted diameter due to ground clearance), as evidenced by comparing the 737 MAX-8 Bypass Ratio (BPR) = 9 engine compared to the comparable A320 BPR=11 engine. The metrics and target values still represent appropriate goals for NASA, to provide benchmarks for the necessary development of noise reduction technology beyond the FAA's mandated limits. For more on the noise level of the 737 MAX-8, refer to the type-certificate data sheet (reference 20). The NASA goals may also be updated to reflect the recent implementation of Stage 5 standards.

## 5.0 Summary – Lessons Learned

Analytical tools used in the N+1 studies were validated with various configurations and no major gaps were found regarding analytical capabilities. Although evolutionary improvements in accuracy always take place, the tools used in the earlier studies contain the necessary accuracy for setting goals and projecting performance. Lessons learned regarding the systems analysis assumptions and the study design are presented in the following subsections for the purpose of establishing goals, projecting performance, and the overall study structure and study approach.

### 5.1 Establishing Goals

It is a common practice in research and development to set "stretch" goals to incentivize efforts. NASA's goals, through metrics such as 32 dB, 42 dB, and 52 dB below Stage 4, provided incentive for research and development of technology solutions that can provide a step change in noise reduction to the benefit of the public and the air transportation system, rather than the incremental improvements already undertaken by industry to keep up with certification requirements.

Single-point targets for metrics have several advantages when establishing goals, since many interpret ranges as projections, not targets. That is, the use of ranges introduces the concept of uncertainty that does not contribute to clear goal setting, as done in the latest version of the SIP (see Table 2). Compounding the confusion in the latest metrics table was the use of ranges for dates. Does the first date correspond to the minimum goal value and the last date the maximum goal value? The continued use of “timeframe” with a single year provides the precision and appropriate level of accuracy for the tools and methodologies being used to establish goals.

### 5.2 Projecting Performance

As discussed in the previous subsection, single point results are sufficient when establishing goals, however, single-point results are often insufficient when projecting performance. With single point projections, there will be no indication of the likelihood or probability of the generated performance results.

A probability distribution depicts the expected outcomes of possible values for a given data generating process (reference 21). In this case, the abscissa is the range from min to max and the ordinate is the probability. Distribution shape should be dependent on a technology classification system (framework). While the distributions for each technology “type” was not examined in detail during this retrospective, an illustrative framework is provided.[5]

In this sample distribution framework, distributions are dependent on whether the technology needs a new aircraft design and whether it has an economic motivation (e.g., fuel burn). As discussed in this paper, the likelihood for applications on new aircraft programs is significantly less than retrofit programs. Therefore, technologies dependent on new aircraft programs should apply probability distributions that are strongly weighted at the minimum likelihood value, and lightly weighted at the maximum value. This is illustrated by the left column of Figure 2. Given the higher likelihood of technologies that are not dependent on new aircraft programs, the right column in the framework shows distributions skewed toward the maximum values.

Technology paths with economic motivations are more likely to “buy their way into the system” than those that do not. As can be seen in the distribution framework rows, more weight should be toward the maximum value for those technologies with economic motivation or at least, not skewed toward the minimum value. Ideally, the cells defining the distribution for technologies with no economic value and not dependent on a new airframe program should be based on the historical penetration rates of such technologies.[6]

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[5] Further examination of probability distributions is suggested before progressing with any framework.

[6] Research to generate this type of distribution has not be done.

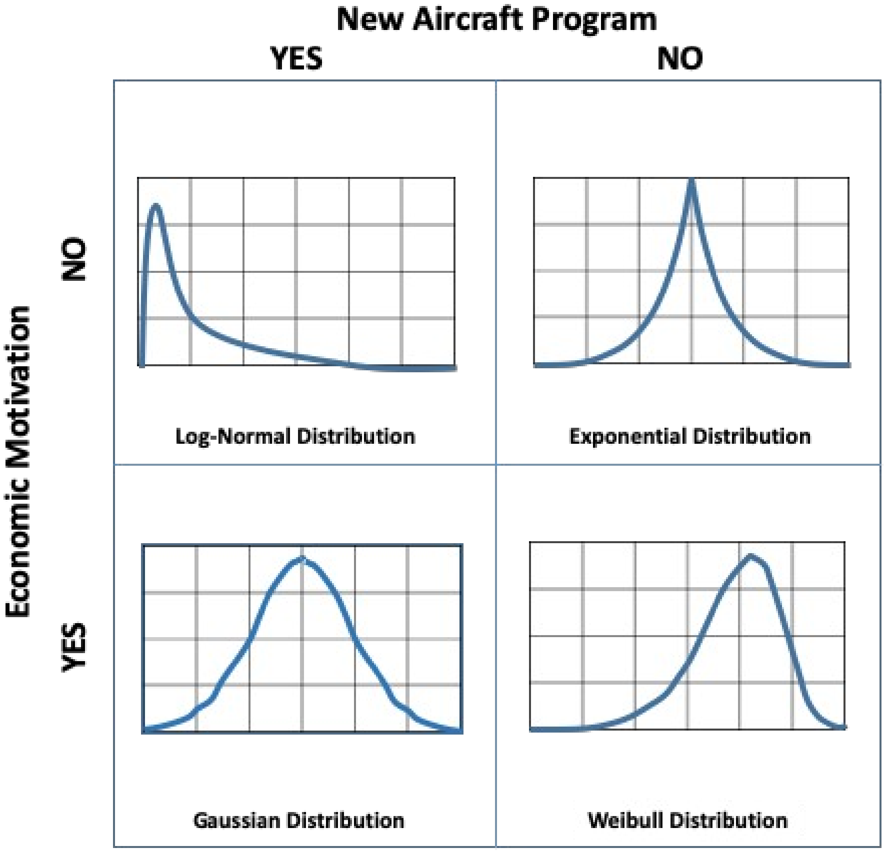

Figure 2. Example probability distribution framework.

### 5.3 Study Design Reviews

Empirically, efforts are taken before experiments to minimize expenses and maximize the value (usefulness) of the results. This is commonly done through a two-phase experimental design review. In phase one, the hypothesis, or question being addressed is scrutinized and prioritized among the options for the funds to determine whether to proceed. If proceeding, the second-phase review looks at the specific study design to maximize the applicability of the results.

While analytical studies are commonly far less expensive than empirical studies, there are still many advantages of pre-analysis design reviews. The advantages include less studies resulting in the category of "shelf filler," and increased ability to draw from the comparisons and contrasts with other studies of similar intent or domain. The exact process and construction of the reviews should be determined internally, but a few thoughts on the process are provided for consideration.

Within a project, there is a strong desire and motivation for consistency across studies, especially internal studies. The projects often were noted to have found value in getting outside opinions on the assumptions, baselines, etc. with contracted studies rather than dictating that they use the same as the internal studies. That creates difficulties because the results are no longer easily comparable. In the N+3 studies, the contractors were free to come to their own conclusions about the appropriate technology assumptions, vehicle-mission requirements, etc. In some cases, NASA adopted the contractor’s assumptions for future internal studies to provide a basis of consistency. A possible compromise is to design a process that includes the primary contractors when establishing the analytical assumptions, baselines, etc.

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# Appendix A: N+1 Engine Material Assumptions

| | Advanced Materials Used (projected 2015 technology) | | | |
|---|---|---|---|---|
| **Component** | **Blade** | **Vane** | **Disk** | **Case** |
| Fan | Polymer matrix composite | Polymer matrix composite | | Polymer matrix composite wrapped by Zylon |
| LPC | Titanium metal matrix composite | Titanium metal matrix composite | | Polymer matrix composite |
| HPC (hot section) | Titanium metal matrix composite | Titanium metal matrix composite | | Titanium metal matrix composite |
| HPT | 5th gen. nickel-based alloy | 5th gen. nickel-based alloy | Nickel-based powder metallurgy alloy | |
| LPT | 5th gen. nickel-based alloy | 5th gen. nickel-based alloy | Nickel-based powder metallurgy alloy | |
| Inlet/Nacelle | | | | Polymer matrix composite |

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Analytical tools used in the N+1 studies were validated with various configurations and no major gaps were found regarding analytical capabilities. The tools used in the earlier studies contained the necessary accuracy for setting goals and projecting performance. Lessons learned regarding the systems analysis assumptions and the study design were presented relative to establishing goals or projecting performance, and the overall study design and approach were examined.

**15. SUBJECT TERMS**

Systems Analysis, Concept Development, Aeronautics, NASA, Lessons Learned, Aircraft Modeling and Analysis, Aeronautics Research Mission Directorate

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