A Stochastic Design Approach for Aircraft Affordability

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Abstract

A novel approach to assessing aircraft system feasibility and viability over time is presented, with special emphasis on modeling and estimating the impact of new technologies. The approach is an integral part of an overall stochastic, life-cycle design process under development by the authors, which is to address the new measure for system value, *affordability*. Stochastic methods are proposed since the design process is immersed in ambiguity and uncertainty, both of which vary with time as knowledge increases about the system behavior. The specific task of examining system feasibility and viability is encapsulated and explained in five steps in this paper. The probabilistic approach contained in these steps is compared to more traditional, deterministic means for examining a design space and evaluating technology impacts. Finally, the techniques are implemented on an example problem to highlight the additional realism and information that is obtained. The example is based on a High Speed Civil Transport vehicle design, and is meant to illustrate the power of the technique on a current problem of significant interest to the international aerospace community.

Introduction & Motivation

Since its inception, the field of multidisciplinary analysis and design optimization (MDA/MDO) has operated under a deterministic paradigm. In this setting, a design objective is identified along with an associated set of design parameters which are varied to determine the settings which result in an extremal value for the design objective. Since these elementary parameters often arise from multiple disciplines, addressing their interactions while seeking their optimal values has potentially important benefits and thus has been the charter of the MDO community. It is the authors' contention that the design process must not only address interactions between traditional aerospace disciplines (e.g. aerodynamics, structures, controls, propulsion), but should also account for "life cycle" disciplines (e.g. economics, reliability, manufacturability, safety, supportability, etc.). These disciplines can bring a variety of uncertainties of differing natures to the design problem, especially as innovation occurs within and amongst the disciplines. It is the presence of uncertainty which demands the use of a *probabilistic approach to design synthesis*. Further, since the representations of these uncertainties can vary in time, a *stochastic treatment of the design activity is more appropriate.*

As these new life cycle disciplines join the traditional ones in the realm of aerospace systems analysis, new measures of goodness (objectives) are needed. Traditional choices such as gross take-off weight, acquisition cost, and payload individually fail to fully capture all of the life cycle characteristics of a system. A new measure has been proposed to fill this void, affordability. *Affordability* may be viewed as a measure of value balancing the product's effectiveness against its associated cost and risk, for a given schedule. From a product user's viewpoint, effectiveness includes characteristics such as capability (performance), reliability, maintainability, safety, and other such system attributes, while the costs (those incurred throughout the life cycle) include acquisition, operation, support, financing, and disposal. Clearly, affordability is a multi-attribute as well as multidisciplinary figure of merit. From a manufacturer/developer viewpoint, effectiveness includes the same characteristics as stated while cost in this case encompasses the engineering research, design, development, manufacture, and testing costs (i.e., the investment needed to bring the product to market).

The "design process" in the most generic sense is a continuum of decisions made with the intent of reaching an acceptable value of some objective while satisfying a set of constraints. Accurately assessing attributes of affordability, especially in the early stages of design, is difficult due to the ambiguity of requirements and the

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uncertainty in the analyses. However, as several authors have noted (Ref. 1), decisions made during these early stages often commit a large portion of the eventual life cycle cost. The process is beset by significant uncertainty, especially at the conceptual design stage. In searching for good design solutions, one is interested in both feasibility (which deals with constraints) and viability (which deals with objectives) in a probabilistic way to account for the uncertainty. The notion of design evolution with time is illustrated in Figure 1. A generic objective, or measure of value for the design process, is displayed as a random variable with a time-dependent probability distribution. As the design evolves, it is desirable to shrink the variability of this objective, as well as shift its mean to more desirable levels (Figure 1 depicts a "lower the better" scenario). This description is analogous to the concept of "process capability indices" which are commonly used in manufacturing to indicate process control.

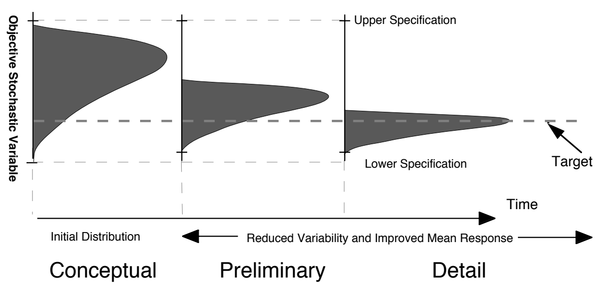


Figure 1: Product Design Objective Evolution

The key goal as outlined in Figure 1 is to shift the objective distribution mean and control its variance (i.e. identify, model, and mitigate uncertainty). This goal for the design evolves through: 1) small perturbations in existing designs, and/or 2) large shifts in the underlying nature of the system through the application of technologies. Design optimization or down selection begins with a baseline system. Selected design variables are then adjusted through search techniques to arrive at the optimal solution. However, instances will occur when even the "optimal" solution does not satisfy the customer/market desires. In this case, changes of a more fundamental nature are required. These changes take the form of technology infusions, and have the potential to significantly increase the feasible and viable design spaces. However, these advances are associated with significant development expenses, production, and/or support costs. Further, the technologies benefits are accompanied by uncertainty, specifically the uncertainty associated with readiness, or the chance they will perform as currently estimated. The delineation between incremental improvements through design variable perturbations and the shifting of the entire design space through technology infusion is exemplified in Figure 2, in one dimension. Revolutionary designs are characterized by the introduction of totally new variables and new engineering solutions which were inconceivable under the limits of previous designs. The problem becomes more complicated when the interactions between multiple technologies are to be modeled and their impact evaluated. This complication is addressed in the method to be presented and illustrated.

As an example, one can consider the propeller driven, piston engine aircraft as a baseline concept. This baseline is shown the lower left corner in Figure 2 and represents a "1st Generation" concept. The design space around the baseline is multidimensional, though it is shown in one dimension in the figure, and represents the possible design alternatives. Eventually, a new technology, for example an advanced propeller, is introduced which has the effect of providing a step increase in thrust/weight. This is an "evolutionary" improvement.

However, the introduction of a new type of engine cycle, the turboprop engine, was "revolutionary" in nature resulting in significant increases in engine thrust/weight ratio through new levels of overall efficiency. The turboprop then became the "2nd generation" baseline. Once again evolutionary improvements were made, shifting the design space to new levels of thrust/weight but not significantly changing the nature of the space itself (i.e. how the various design variables relate to each other). With time, a second revolution took place, this time in the drive mechanism, where the jet replaced the propeller, and the "3rd generation" baseline is formed. The turbojet engine then evolved through the addition of a fan (single or multiple stage) and improvements in stage design and flow mixing technology resulting in the turbofan engine with even greater thrust/weight and overall efficiency levels.

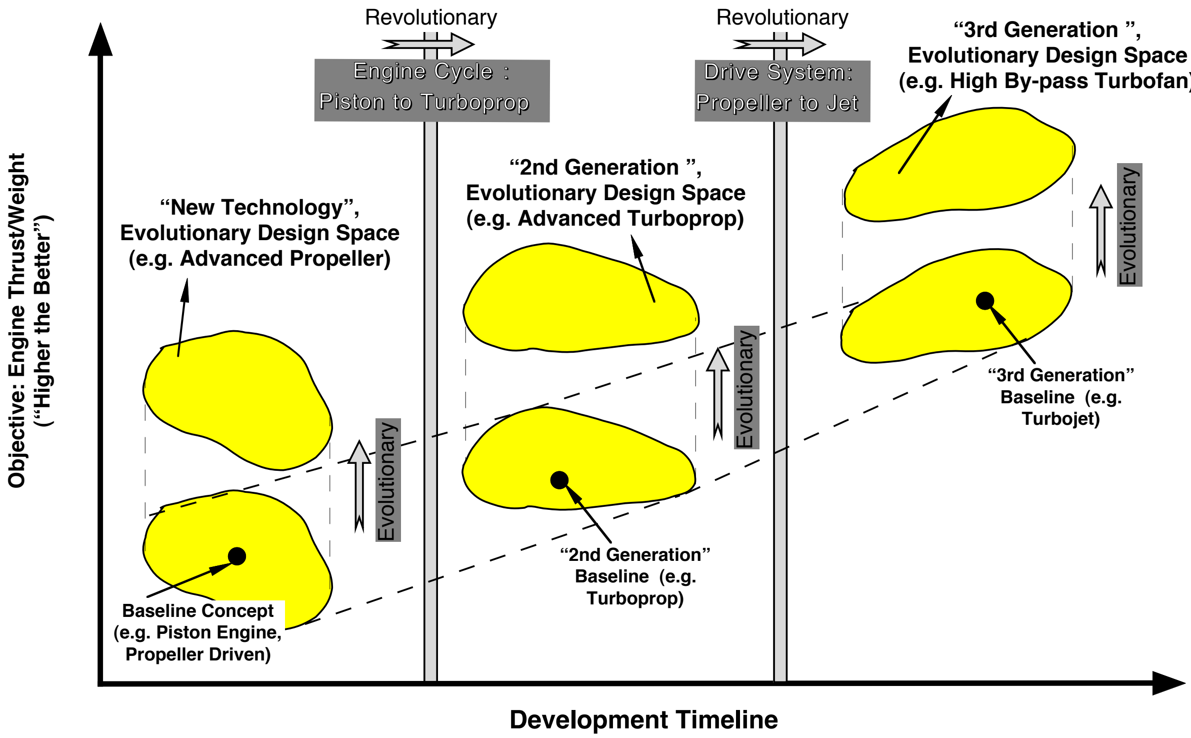


Figure 2: Design Space Evolution: Representation in One Dimension

For the designer, in the setting just described, the goal is to find the "location" in the design evolution which maximizes the affordability to the customer. Given risk and technology readiness information and the needs of the customer, a revolutionary design may not provide the most affordable solution. *There appears to be a lack of a formal methodology for system evaluation and design which accounts for all these components: uncertainty, life cycle design, feasibility, and technology infusion*. The design methodology described in this paper is an initial attempt to tackle this problem. Subsequent to the description, the method is illustrated in an example problem involving a High Speed Civil Transport (HSCT) concept. The HSCT is an excellent example in that it will require a combination of both incremental and breakthrough improvements, working in unison, to yield a feasible and it will be very sensitive to cost and economic issues, which are both key to affordability.

Definitions

Since many of the concepts discussed in this paper are relatively new to the design community, a few key definitions are offered for clarity:

System Affordability: The ultimate goal of the design process, affordability represents value to the customer, including a balance between benefits, costs, availability, and risks.

Synthesis: The recomposition of various parts or disciplines into a design alternative through some formal algorithm. An example is aircraft synthesis through fuel balance, mission-based sizing.

Metric: A Figure of Merit that characterizes a discipline or function or their related technologies (e.g. L/D for aerodynamics, SFC for propulsion).

Feasible Alternative: A design alternative which is physically realizable and satisfies all imposed constraints.

Viable Alternative: A design alternative which is feasible **and** meets or exceeds the customer objective(s) (i.e. it is technically feasible and affordable).

Metamodel: An approximation of a complex analysis model. Typical metamodels include regression models of complex computer programs based on experimental designs (e.g. the Response Surface Method), artificial neural networks, or fuzzy sets.

Uncertainty: An estimate of the difference between models and reality. Uncertainty is manifested when quantities associated with the product cannot be determined exactly.

Probabilistic Analysis: Analysis which allows for the examination of systems with imprecise or incomplete information (i.e. uncertainty and ambiguity). In other words, a means of forming relationships between input and output variables, accounting for the variability of the inputs.

Fast Probability Integration (FPI) [Ref. 2]: A family of probabilistic analysis techniques characterized by better efficiency and transparency than "brute force" probabilistic techniques such as the Monte Carlo (MC) Simulation.

The focus of this paper is a step-by-step approach to the search for feasible and viable design spaces in a probabilistic fashion, possibly incorporating the infusion of new technologies. This particular task can be described in five main steps, which are the subject of the next section and are shown in Figure 3.

The Five Steps for Investigating System Feasibility and Viability

1. *Define the Problem to be Tackled*

Rationale: Identify objectives, constraints, design variables (and associated ranges), analyses, uncertainty models, and metrics for each discipline and for the system level. This involves translating the customer requirements to the items listed.

Description: Techniques such as the Quality Function Deployment (QFD), Pugh and Tree Diagrams, morphological matrices, and activity network diagrams are often used to assist in defining the engineering problem to be addressed by mapping the customer's requirements and desirements into engineering terms. This includes establishing relationships, metrics, and the relative importance amongst the requirements.

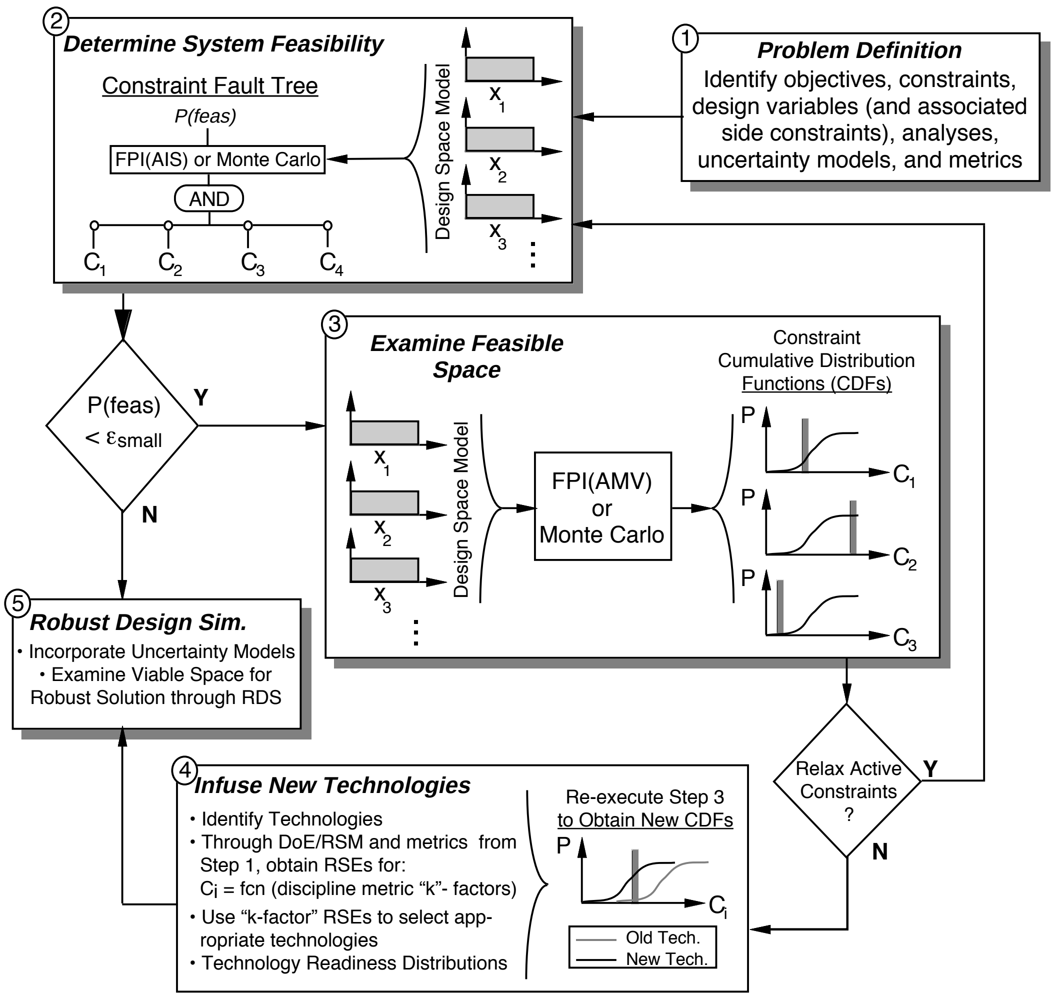


Figure 3: Five Steps to Investigating Feasibility and Viability of Multidisciplinary Systems

2. *Determine System Feasibility*

Rationale: This step is focused on obtaining an aggregate estimate of the percentage of the design space which contains feasible alternatives, or the probability of feasibility, *P(feas)*. This information is essential, since if there is very little chance of obtaining a *feasible* design, there is no use in searching for *viable/optimal* ones.

Description: The design space is investigated for occurrences of combinations of design parameters which result in the satisfaction of *all constraints*. This is formulated as a reliability problem, utilizing fault tree analysis.[2] Uniform frequency distributions are assigned for each design variable, indicating that all the points within the space are equally likely to be selected during the feasibility computation. However, if uncertainty is to modeled at this stage, separate distributions for each uncertain variable can be used. The box labeled "2" in Figure 3 depicts the computation of *P(feas)*.

P(feas) is normally computed through a Monte Carlo simulation using the above mentioned distributions and an analysis code which computes the constraint values given settings of the variables. This task may be computationally expensive (especially if the required analyses are complex and a standard Monte Carlo approach is used to select points). However, through the use of the Adaptive Importance Sampling (AIS) technique from the FPI family described in Ref. 3, the search efficiency can be improved. If the computational effort remains a problem, a metamodel/Monte Carlo approach can be used, as described in Ref. 4. In any case, the result of this step is a single number: the probability of feasibility, *P(feas)*.

3. *Investigate Active Constraints*

Rationale: As indicated in Figure 3, a decision node occurs at the end of Step 2. If the system achieves an acceptable *P(feas),* then proceed to Step 5, which involves the search for robust design solutions. If the system achieves an unacceptably low (or zero) *P(feas),* an investigation must be performed to find out which constraints are active and most restrictive. Crisp definitions for the fuzzy modifiers "acceptable" and "unacceptably low" are at the discretion of the designer.

Description: If *P(feas)* is low, the constraints are investigated on an *individual* basis. Thus, unlike the system feasibility problem, there is no fault tree structure. The design variables are once again given uniform distributions and a cumulative distribution function (CDF) for each constraint is formed which represents the probability of achieving specific values for the constraint. When the current constraint values for the specific problem at hand are overlaid on the CDFs, the active constraints are clearly discovered. Once this identification is made, there are two avenues available to "open the feasible space" (i.e. increase *P(feas)*):

a) Relax the current active constraints (and return to Step 2)
b) Infuse new technologies in hopes of shifting the design space to overlap the feasible space (proceed to Step 4)

4. *Infuse New Technologies (and perform Technology Impact Forecast)*

Rationale: The infusion of new technologies may be required to increase the *P(feas)* value. New technologies almost always affect the underlying physics of the design space, but not necessarily the geometry of the space itself, as defined through the design variable ranges (see Figure 2). New technologies contain three elements whose impact must be accounted for: benefits, penalties, and confidence estimates.

Description: For complex systems, the search for feasible and viable solutions often will involve the application of multiple new technologies. The ability to accurately predict the tradeoffs between (and within) alternative technologies from a benefit, risk, and affordability viewpoint is of tremendous value to the designer/decision maker. This ability first requires the identification of appropriate metrics related to each new technology. Normally, design parameters are used to feed an analysis routine to generate metric values. For example, wing planform and airfoil geometry are inputs to an aerodynamics routine which computes forces and moments which are subsequently integrated to form lift and drag estimates. For a "new" aerodynamic technology, such as Circulation Control, there *may not be an analysis routine* which can translate these conventional inputs into lift and drag estimates which represent the performance of the technology. An interim solution is to define metrics for the new technology as a delta with respect to a current technology baseline. This is done through the introduction of technology "k-factors". These factors modify the technology metrics as computed during analysis, simulating technology benefits (and penalties). Subsequently, the Response Surface Method (RSM) is used to form relationships between the constraints and the various metric "k-factors", so that Response Surface Equations (RSEs) are obtained for constraints as a function of technology "k-factors". These RSEs allow for rapid sensitivity computation and for conducting benefit/cost investigations for new technologies.

While the "k-factors" represent technology improvements in a generic way, a time comes when *specific* technologies are proposed. This new information must be modeled and utilized to create more confident technology impact assessments. The new information provided by specific technologies comes in two forms: 1) numerical benefits and penalties to system metrics as estimated from research by the technologists and evaluation by designers 2) the relative readiness of the technology as measured from a standard scale.[5]

The infusion of new technologies are targeted towards opening the feasible design space by affecting the constraints. However, in doing so, penalties may be incurred in other disciplines as the "price" of the benefits. For example, any type of auxiliary blowing or suction on the wing to improve aerodynamic performance requires extra weight for ducting, possible bleed mass flow from the engine(s), and additional research, production, and maintenance costs. Thus, "k-factors" for penalties as well as benefits must be employed to provide as accurate a picture as possible of the worth of a technology or set of technologies.

Benefit/penalties by themselves still do not complete the modeling required. The projected benefits of new technologies contain an element of uncertainty; thus the estimated target benefit level is based on incomplete knowledge. This type of information is represented through probability distributions based on the best available information on the readiness of the technology. Also, since these technology benefits/penalties are estimates, it is logical to treat their effects probabilistically instead of deterministically.

Figure 4 summarizes the technology modeling process, where benefits/penalties are modeled as step changes in the mean of a distribution formed to capture the confidence estimate. The technology metrics shown for illustration purposes are typical of those used for commercial aircraft: lift-to-drag ratios, maximum lift coefficients, component weights, specific fuel consumption, and maintenance man hours per flight hour.

Once selected, new technologies are used in a re-execution of Step 3 to obtain new cumulative distribution functions for the constraints. These new CDFs should show an increased probability of meeting the constraints.

5. Robust Design Simulation

Steps 1-4 are concerned with feasibility, since only constraints are considered. When a large enough feasible space is found, this space can be searched for robust solutions. Here, the objective function is introduced, as well as any uncertainty models to be considered in the problem. RDS is a systematic procedure for finding settings of design variables which maximize the probability of meeting or surpassing a target for the objective, while satisfying the constraints. Step 5 is not covered in this paper, but the reader is encouraged to review Refs. 6 and 7 for detailed description of the RDS.

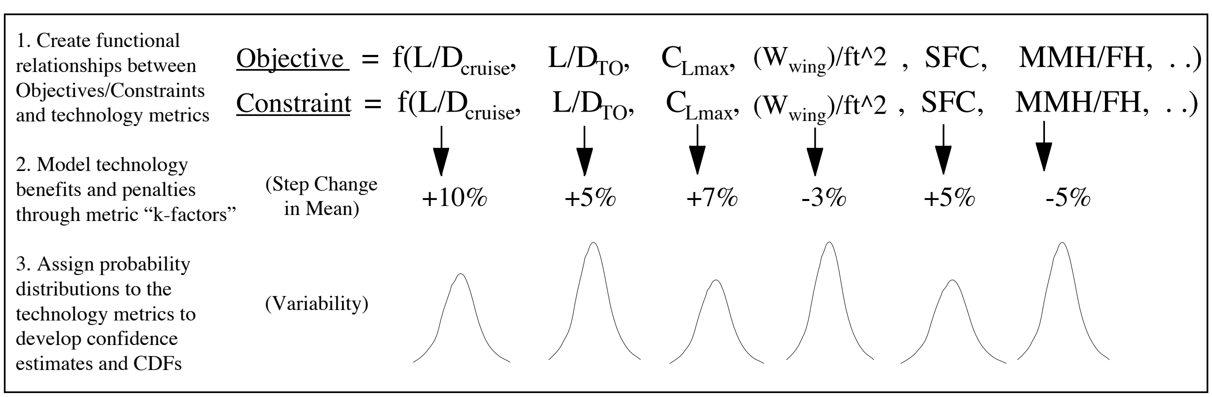


Figure 4: Addressing Technology Benefits, Penalties and Confidence

This 5-step process embodies a probabilistic methodology for technology impact forecasting for feasibility and viability, resource allocation, etc. Function approximation techniques, probabilistic analysis methods, and optimization are all used in the appropriate places throughout the five steps.

Method Implementation

The implementation involves the system level design of an High Speed Civil Transport (HSCT), to expand on the concepts introduced and to show how relevant the method is to current problems of interest. Once again, the HSCT problem centers on determining design feasibility first and then economic viability through the RDS. A detailed application of this method for a subsonic, Very Large Transport (VLT) can be found in Ref. 8. General references on the HSCT aircraft and the use of the Response Surface Methodology (RSM) in its design include Refs. 9, 10, and numerous others found therein.

Step 1: Previous studies by the authors and their colleagues have been carried out, such as those in Refs. 6, 9, and 11, which document a detailed problem formulation for the HSCT design. The following serves as a brief summary of the problem description for the HSCT conceptual synthesis/design application:

Objective: *min Average Required Yield per Revenue Passenger Mile ($/RPM)*

A measure of Affordability for commercial aircraft, the $/RPM is the minimum (average) price, on a per paying passenger mile basis, the airline must charge in order to achieve specified return on investments (ROI) for the manufacturer and the airline itself. In this study, this metric is calculated using the Aircraft Life Cycle Cost Analysis (ALCCA) program, developed jointly by the Aerospace Systems Design Laboratory at Georgia Tech and NASA Ames System Analysis Branch.[12] Acquisition Price (ACQ$) is also tracked as an alternative objective.

Constraints: *Takeoff Field Length (TOFL), FAR 36 Flyover Noise (FON), FAR 36 Sideline Noise (SLN), Landing Approach Speed (VAPP)*

In order to be economically viable, the HSCT must be certified to operate at all airports that its subsonic competitors utilize. This translates to several performance constraints, four of which are studied here. The constraint values are all in the Federal Aviation Regulations (FARs). The TOFL constraint is the maximum of 115% of the all-engine operating takeoff distance and the balanced field length. The balance field length is the maximum of the following distances: One engine-out aborted takeoff distance, all engines operating aborted takeoff distance, and the one engine out takeoff distance.

The FON and SLN are computed at takeoff at observer locations as described in the FAR Part 36 regulations.[13] The unit of measure is the Effective Perceived Noise Level in decibels (EPNLdb). This unit captures both the frequency and time integrated effect of a noise source. The limits for these two constraints are a function of gross weight, to an upper limit where they become invariant with gross weight. For our purposes, the limits will be treated as constant as described in Table 1. Ref. 14 is an excellent reference on HSCT noise issues and possible solutions. The approach speed constraint is mainly a function of the allowable maximum lift coefficient (C_{Lmax}) available in landing configuration (i.e. leading and trailing edge flaps deflected). This maximum C_L as well as a landing drag polar are required inputs to the synthesis code, with the main landing-related outputs being the approach speed and the landing field length. The maximum angle of attack for landing can also limit the C_{Lmax}. Table 1 summarizes the objectives and constraints.

Design Variables: *Wing geometry, engine cycle parameters, thrust-to-weight ratio, wing area*

The wing geometry is defined parametrically through a set of Cartesian coordinates with origin at the wing root leading edge. All of these values are normalized by the wing semi-span.

Table 1: Constraints and Objectives

Response	Requirement
Avg. Req. Yield/Rev. Psg. Mile (¢/RPM)	minimize
Takeoff Field Length (TOFL)	< 11,000 ft
FAR 36 Flyover Noise (FON)	< 106 EPNLdB
FAR 36 Sideline Noise (SLN)	< 103 EPNLdB
Approach Speed(VAPP)	< 155 kts

Metrics: *Allowable* C_{Lmax} *,*C_{Dsup}*, , Noise Suppression,* W_{nozzle}*, Acquisition cost complexity factor, Production cost complexity factor, O&S cost complexity factor*

Tools: Sizing/Synthesis code (specifically the FLight OPtimization System, FLOPS)[15], various aerodynamic analysis, airline/manufacturer economics

The symbols, ranges, and limits for the design variables appear in Table 2. The HSCT baseline is assumed to have a cranked delta wing planform, as shown in Figure 5. Thus, the "kink" location (the point of discontinuity in leading edge sweep) is an important design parameter. Variables *X1* and *Y1*, which define the kink location, are normalized by the semi-span. The engine cycle is a Mixed Flow Turbofan type and the thrust per engine is in the 50-75,000 pound class. There are four engines.

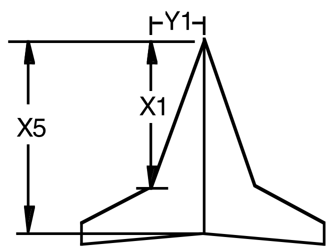


Figure 5: HSCT Wing Planform Variable Definitions

Step 2: Using the DoE/RSM method, a set of system level response surface equations (RSEs) for the HSCT design space was obtained. This set of metamodels is used in this step to investigate system feasibility by computing *P(feas)* via Monte Carlo Simulation. Prediction profiles for the models are given in Figure 6.

Table 2: Design Space Definition

Variable	Range "-1"	Range "+1"
Thrust to Weight Ratio (TWR)	0.28	0.32
Wing Area, sq. ft. (SW)	8500	9500
Longitudinal Kink Location (X1)	1.54	1.62
Spanwise Kink Location (Y1)	0.5	0.58
Root Chord (X5)	2.19	2.35
Overall Pressure Ratio (OPR)	19	21
Turbine Inlet Temperature (TIT), °R	3000	3250
Fan Pressure Ratio (FPR)	3.5	4.5

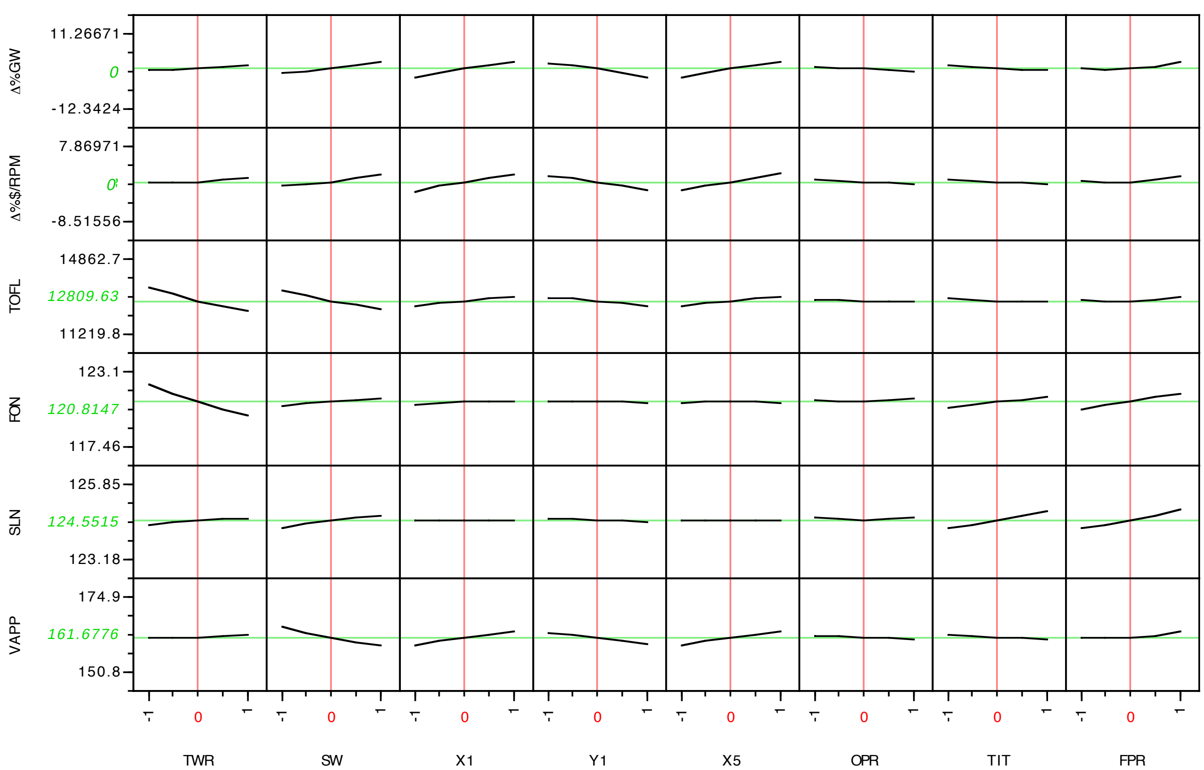


Figure 6: Prediction Profiles for HSCT System Level Constraints

Takeoff and landing drag polars were not modified from case to case, but the field lengths and approach speed vary due to the weight variation. Results for the gross weight and $/RPM responses are normalized to a baseline vehicle, due to the competition sensitive nature of these metrics. The baseline was chosen to be the vehicle corresponding to center point settings for the design variables. To compute *P(feas),* uniform distributions are assigned to the control variables and the noise variables are fixed at their expected value. The value of *P(feas)* is quite important here, since it is difficult to estimate the feasibility ratio graphically or by other means. However, one can still look at a traditional, deterministic design plot. Such a plot is shown in Figure 7. After the simulation is run, the computed probability is found as *P(feas)≈0*.

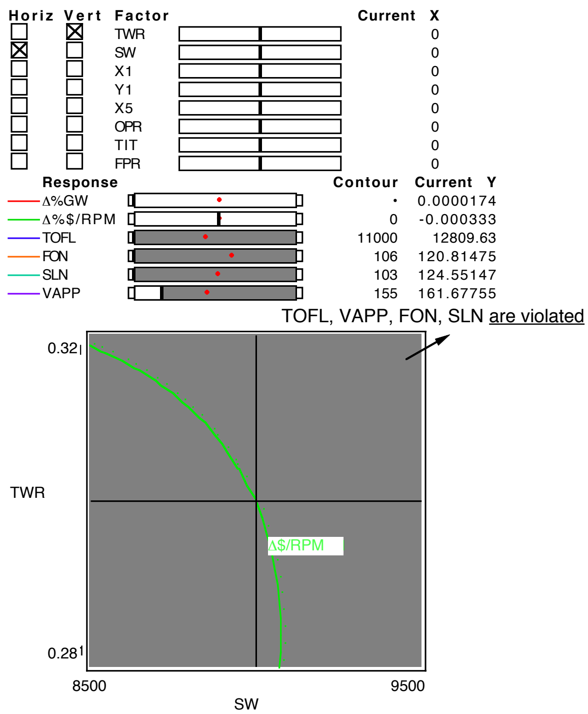


Figure 7: Design Space Snapshot: Multiple Constraint Violation

Step 3: Since there is no feasible space, the individual constraints must be investigated to see which are the most restrictive. There are three options at this point to compute the constraint CDFs: 1) perform a MC simulation using the actual synthesis code, 2) perform a MC simulation using the above RSEs, or 3) use one of the FPI family of techniques. Option 1 will almost always be impractical due to inordinate computing time. In the current case, the second option of using a Monte Carlo simulation (5,000 samples) in conjunction with FLOPS to create CDFs for *TOFL, FON, SLN, and VAPP* is selected. Refs. 2 and 16 are recommended for details on the AMV method and instances when it is of most usefulness. Figure 8 below displays the CDFs for the four HSCT constraints under study. The individual probability within this design space of achieving the *TOFL*, *FON, SLN, and VAPP* constraints was found to be approximately zero. Clearly, then, the nil value for *P(feas)* is not surprising.

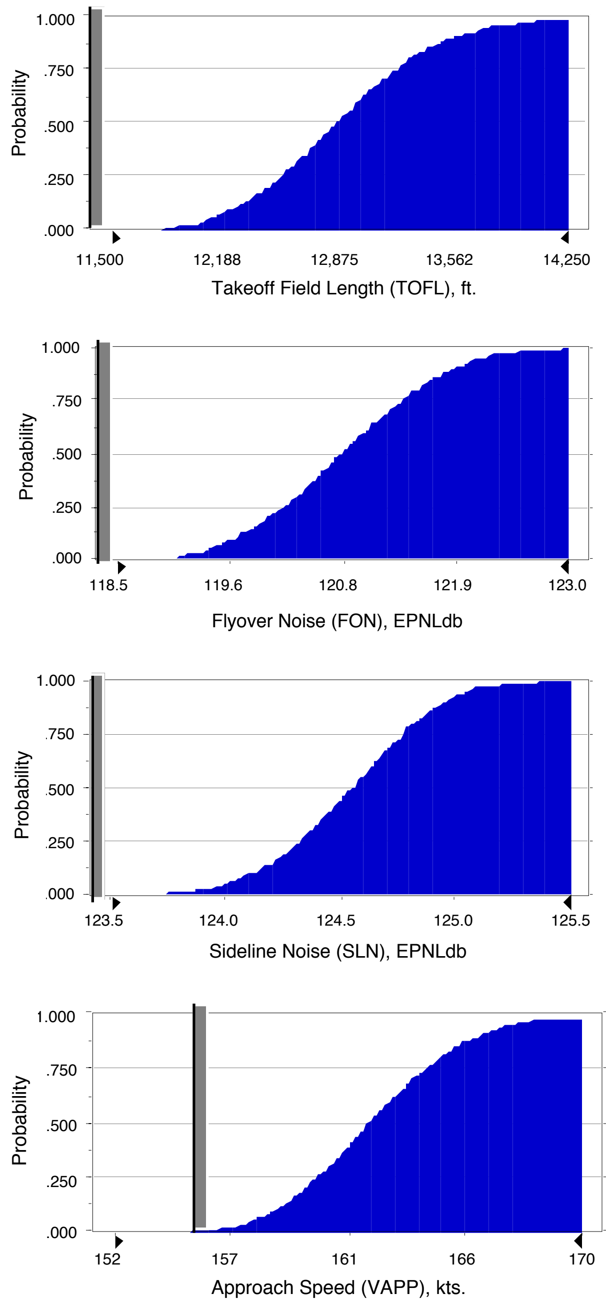


Figure 8: CDFs for the Four Constraints, Monte Carlo Simulation

Step 4: In step 3, it was found that there are four constraints which are causing the feasible design space to be empty. In light of this, technologies can be proposed in an effort to open the feasible space. The "k-factor" approach described earlier is now applied in order to determine which technologies might offer the greatest assistance in meeting the *TOFL, FON, SLN,* and *VAPP* constraints. For example, tackling the *TOFL* and *VAPP* constraints directly might entail a more complex flap system or a blowing technology such as Circulation Control. However, a technology which increased the supersonic cruise L/D might be a better alternative, even though it affects VAPP indirectly (through a reduction in landing weight). More likely, combinations of technologies will be required. The "k-factor" approach makes these investigations possible. Possible penalties associated with a technology to improve the allowable C_{Lmax} include a higher wing weight and additional development and support cost. Thus, "k-factors" for these are also employed. The wing weight factor ranges from a 10% decrease to a 10% increase, as advanced technology composites were already modeled in the baseline. The noise constraints are alleviated through the application of suppression. For example, the largest source of noise on the HSCT is the jet noise, and noise from this source can be reduced through a complex and heavy` mixer-ejector nozzle. So "k-factors" are introduced for noise suppression (the benefit) and the weight of each nozzle (the penalty).

Since all technologies are likely to have some impact on the research and development, production, or operations and support cost, "k-factors" for these quantities are included in the formulation. The final economic responses will thus be a function of the technology's effect on the vehicle (likely a positive effect) and the technology's effect on the manufacture/operator's economics (likely a negative effect). Finally, since indirect effects can at times be more significant than direct effects, a supersonic drag reduction technology is added to see how such a reduction might translate to impacts on the binding constraints. The selected technology metric "k-factors" and their ranges are summarized in Table 3. In all cases, "0%" represents the baseline case (i.e. no new technologies). The exception is the noise suppression, which varies in the dimensional units of EPNLdb described earlier.

Table 3: Technology "k-factor" Ranges

Technology "k-factor"	Impact Range
Allowable C_{Lmax} ("k_CLmax")	0% to 60%
Wing Weight ("k_WingWt")	-10% to 10%
Supersonic Drag ("k_CDsup")	-15% to 0%
Noise Suppression ("k_Supp")	0 to 20 dB
Nozzle Weight ("k_NozWt.")	0% to 600%
RDTE Cost ("k_RDTE$")	-20% to 10%
Production Cost ("k_Prod$")	-20% to 10%
Operations & Support Cost ("k_O&S$")	-20% to 10%

These eight "k-factors" are now used in a new DoE and the resulting data is regressed, providing response surface equations which capture the relation between the constraints and the technology "k-factor" levels. The "k-factor" RSEs appear in Figure 9, with their ranges displayed as listed in Table 3. From the figure, it is apparent that infusing a technology that increases allowable C_{Lmax} will have the greatest impact on the efforts to meet the *TOFL* and *VAPP* constraint. These prediction profiles are interactive, i.e. the values of the "k-factors" can be adjusted and the update values of the response will be immediately displayed. So the designer can play "what-if" games with the benefits/penalties of the various technologies. Further, these profiles can be checked for sensitivities which do make engineering sense, indicating an error in the analysis.

Finally, it is important to note that the "k-factor" equations are constructed using a *fixed aircraft*, in the sense that the design variables of Table 2 are fixed to their midpoint values during the construction the "k-factor" RSEs. A truly complete problem formulation entails the following: *search the space of design variables* ***and*** *technology levels for the settings of each which maximize the feasible (and viable) design space.* This problem is currently under research by the authors.

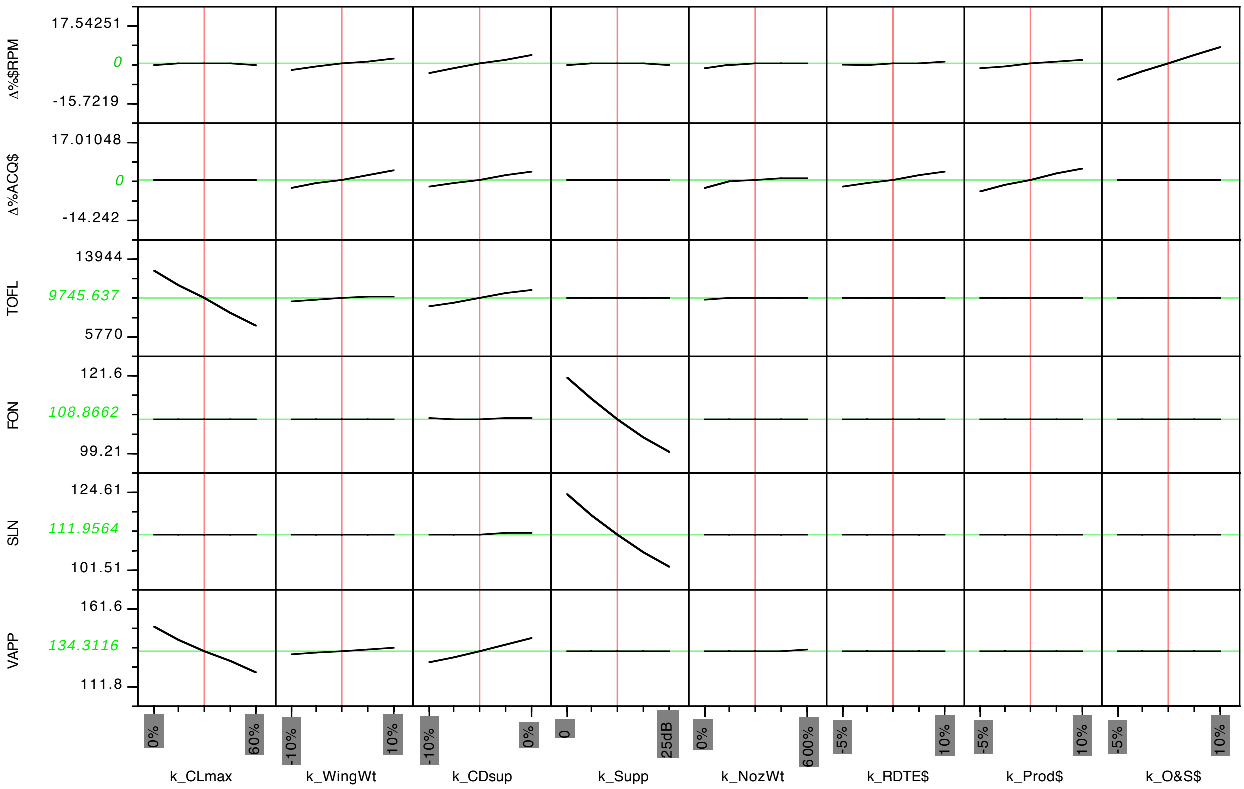


Figure 9: Interactive "k-Factor" Response Surface Equations

Incorporating Technology Confidence Estimates: The actual benefits/penalties of proposed technologies are uncertain, due to the fact that the estimates are based on the readiness. The lower the readiness, the higher the uncertainty in the estimate. As mentioned earlier, technology confidence information can be modeled by assigning probability distributions for each of the metric "k-factors". In this way, the factors are modeled as random variables with specific distribution characteristics. Subsequently, a Monte Carlo simulation is performed for a *fixed airplane*, but with variability in the responses due to the "k-factor" distributions. Figure 9 indicates that technologies which provided noise suppression and increased C_{Lmax} may create feasible space by affecting the HSCT's binding noise, *TOFL* and *VAPP* constraints, respectively. An advanced mixer-ejector nozzle would be a likely candidate technology to supply the noise suppression while the use of Circulation Control has been proposed as a potentially efficient low speed lift augmentation system.[17] The addition of a Hybrid Laminar Flow Control (HLFC) technology in supersonic flight helps in all areas by reducing the overall vehicle weight, though it will, along with Circulation Control, require bleed flow from the engines which may impact the engine sizing activity. At this stage, in an actual technology impact forecast effort, specialists in these three technologies would be queried for their opinion on the benefits, penalties, readiness of the three concepts. With this information, frequency distributions for the eight "k-factors" in the HSCT problem are constructed, as shown in Table 4. Of course, some "k-factors" will not be affected by some technologies. The expert opinion of the technologists are key to forming these distributions in a meaningful way, as they are intended to represent a forecast of the possible impacts of specific technologies. For now, the percentages in Table 4 are notional, and research is continuing in search of efficient ways of estimating technology benefits/penalties.

Accurate estimates for the RDT&E, Production, and O&S cost penalties can be especially difficult, even for individuals most involved in a specific technology development program. One approach which can add insight into the formation of cost penalty estimates involves a decomposition of the major categories into their components and sub-components. For example, the RDT&E investment for a specific technology consists of such items as engineering man hours cost, initial tooling cost, project management costs, etc. These categories may be much easier to estimate than the total RDT&E cost for a given technology. This "zooming" approach to new technology cost impact estimation is currently under investigation by the authors.

If only the deterministic information in Table 4 is used, the effect of technology infusion is seen through an update of the design space as displayed in Figure 7. The effective increase of 60% in allowable C_{Lmax} and full suppression for the jet and fan are included in the aircraft sizing analysis. The new, or "evolutionary" design space snapshot is displayed in Figure 10. The feasible space has been increased tremendously, with regards to all the formerly binding constraints. This is indicated by the "white space" region. However, for other combinations of design variables, the feasible space may be small, even with the infusion of new technologies. And, the additional information provided by the confidence estimates is not accounted for at all in such a plot.

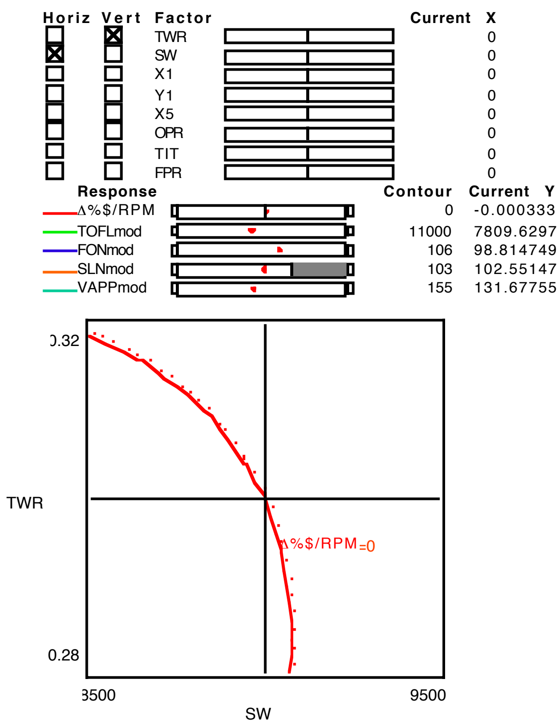
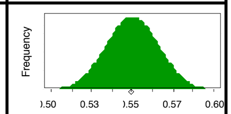
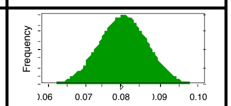
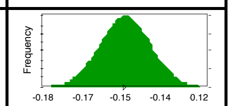
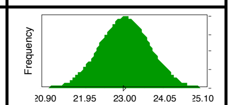
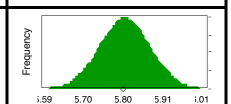
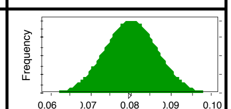
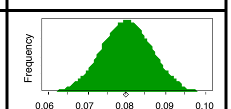
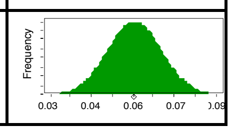


Figure 10: New Design Space Plot, Showing the Opening of Feasible Space

Table 4: Technology Estimate Distributions, An Example Scenario

K-Factor	Tech#1 Mixer-Ejector Nozzle	Tech #2 CC	Tech# 3 HLFC	Confidence Estimate Frequency Distribution
Δk_CLmax	-	+60%	-	
Δk_WingWt	+3%	+3%	+2%	
Δk_CDsup	-	-	-15%-	
Δk_Supp	19db	4db	-	
Δk_NozWt	+580%	-	-	
Δk_RDTE$	+5%	+2%	+1%	
Δk_Prod$	+5%	+1%	+2%	
Δk_O&S$	+2%	+2%	+2%	

To more completely examine the effects of this technology infusion on the HSCT, a Monte Carlo simulation consisting of 5,000 samples was performed using the RSEs shown in Figure 9 and the random variable distributions in Table 4. The key results are contained in the CDFs for the four active constraints *(TOFL, FON, SLN, VAPP),* which appear in Figure 11. Under this technology scenario, the baseline vehicle has a probability of one (in the limit) of meeting all but the SLN constraints. The probability of meeting the *SLN* constraint is about 30%. The usefulness of the CDF representation is apparent, in that they give a estimate of the confidence in satisfying the constraints through the probability measure. This type of information is not available in the traditional deterministic design plot as in Figure 10.

In addition to feasibility, system viability objectives can be investigated simultaneously. For the

HSCT, these technology improvements come with a price: an increase in the ticket price required to ensure economic success of the aircraft. This can be seen in Figure 12, which contains the CDF for Δ%$/RPM which resulted from the Monte Carlo simulation used to generate the constraint CDFs. For example, there is a probability of about 50% that the percentage increase for this objective would be about 4%, a modest but not insignificant increase.

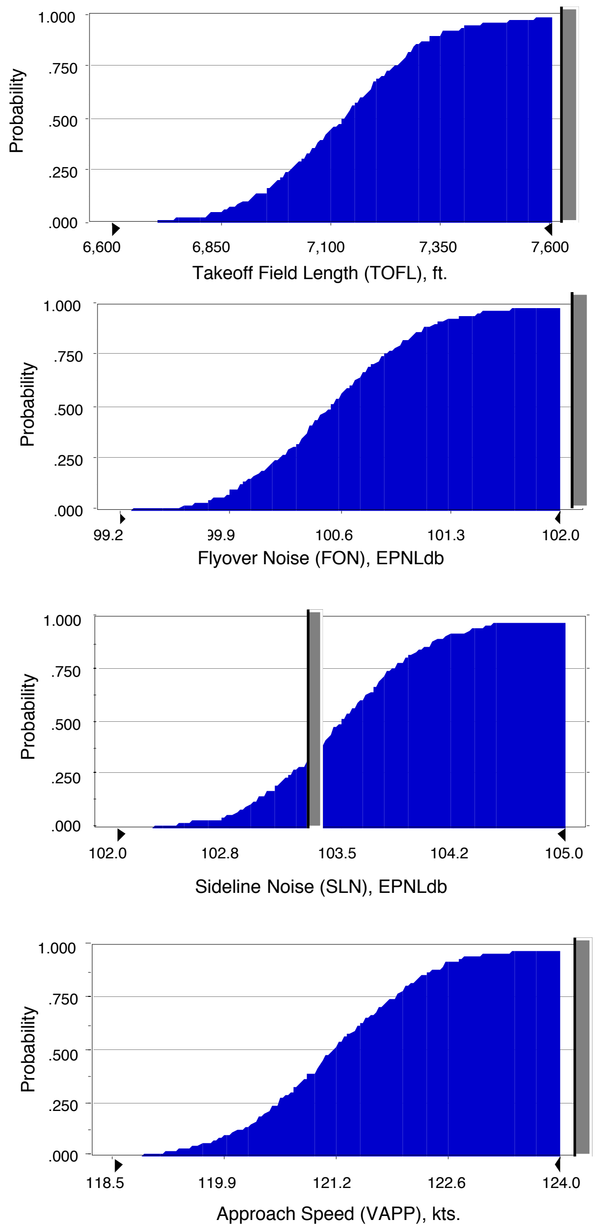


Figure 11: Technology Impact Forecast, Including Confidence Estimates: Constraint CDFs for Baseline Aircraft

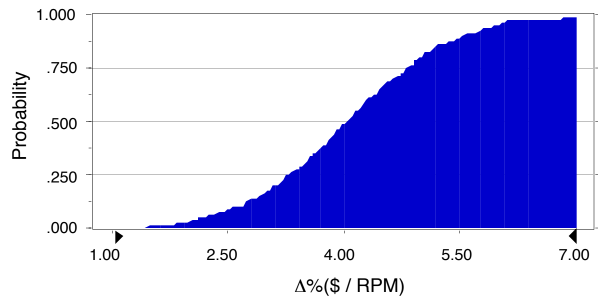


Figure 12: CDF for Δ%($/RPM) Objective

Step 5: Having created a feasible space through the use of technology infusion, the designer's next task is to search in this space for robust design solutions. This done through execution of the Robust Design Simulation (RDS) methods. The performance of the RDS for the HSCT is outside the scope of this paper, but is described in the aforementioned references.

Current and Future Work

Key further developments in this approach include research into the simultaneous examination of design variables and technology levels in the search for feasible and viable design spaces, in the presence of technological uncertainty. Also, investigations are under way with regards to methods for consistent and accurate predictions of technology benefits, penalties, and readiness levels.

Conclusions

This paper described elements of a novel approach in aerospace systems design, specifically for the task of searching for feasible and viable design spaces in a probabilistic fashion, including the possibility of incorporating new technologies. A five step procedure was described, including steps for problem formulation, system feasibility estimation, individual constraint investigation, technology identification and impact forecasting, and robust optimization. A key focus was the ability to identify and choose among a group of new technologies whose infusion could benefit the system performance, while simultaneously accounting for their penalties and the relative confidence in their ultimate performance .

Overall, the primary benefits gained from this new approach are:

- A comprehensive, step-by-step algorithm for determining system feasibility and viability

- An intuitive and graphical examination of system feasibility without excessive analysis requirements
- Accessibility of information on the most influential and binding constraints, and
- A logical, accurate way to assess the *benefits and penalties* of new technologies (including confidence estimates) in early design stages

The ease of implementation of the approach was demonstrated on an example problem involving the design space investigation for a High Speed Civil Transport aircraft. Since the original design space for the baseline vehicle was found to have a very small probability of feasibility, technology "k-factors" were used to identify technologies which could alleviate the binding constraints. The effects of the identified technologies were simulated and the probability of achieving feasible solutions was increased by the infusion of new technologies, accounting for benefits, penalties, and confidence estimates in the forecast.

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References

[1] Schrage, D. P., and Mavris, D. N., "Recomposition: The Other Half of the MDO Equation," *Multidisciplinary Design Optimization: State-of-the-Art, in Proceedings in Applied Mathematics- SIAM*, Vol. 80, 1997, pp. 432-447.

[2] Southwest Research Institute (SwRI), FPI User's and Theoretical Manual, San Antonio, TX, 1995.

[3] Wu, Y.T., "Computational Methods for Efficient Structural Reliability and Reliability Sensitivity Analysis," *AIAA Journal*, Vol. 32, No. 8, Aug. 1995. pp. 1717-1723.

[4] Bandte, O., Mavris, D. N., "A Probabilistic Approach to Multivariate Constrained Robust Design Simulation," Oct. 1997, AIAA/SAE Paper 97-5508.

[5] Mavris, D.N., Bandte, O., "A Method for the Identification and Assessment of Critical Technologies Needed for and Economically Viable HSCT," Sept. 1995, AIAA 95-3887.

[6] Mavris, D.N., Bandte, O., and Schrage, D.P., "Application of Probabilistic Methods for the Determination of an Economically Robust HSCT Configuration," 6th AIAA/USAF/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Bellevue, WA, 1996.

[7] DeLaurentis, D.A., Calise, A., Schrage, D.P., Mavris, D.N., "Reduced Order Guidance Methods and Probabilistic Techniques in Addressing Mission Uncertainty", Sept., 1996, AIAA 96-4174.

[8] Mavris, D.N., Mantis, G.C., Kirby, M.R., "Demonstration of a Probabilistic Technique for the Determination of Aircraft Economic Viability", Oct. 1997, AIAA/SAE 97-5585.

[9] DeLaurentis, D.A., Mavris, D.N., and Schrage, D.P., "System Synthesis In Preliminary Aircraft Design Using Statistical Methods," Proceedings of the 20th International Congress of the Aeronautical Sciences (ICAS), Sorrento, Italy, September, 1996, pp. 866-878.

[10] Mavris, D.N., Bandte, O., and Schrage, D.P., "Effect of Mission Requirements on the Economic Robustness of an HSCT," *Journal of Parametrics*, Vol. 17, No. 1, Spring 1997, pp. 53-77.

[11] National Research Council, U.S. Supersonic Commercial Aircraft- Assessing NASA's High Speed Research Program, National Academy Press, Washington, D.C., 1997.

[12] Galloway, T.L., and Mavris, D.N., *Aircraft Life Cycle Cost Analysis (ALCCA) Program*, NASA Ames Research Center, September 1993.

[13] DOT/FAA Noise standards: Aircraft Type and Airworthiness Certification, FAR Part 36, January 1, 1990.

[14] Olson, E.D., "Advanced Takeoff Procedures for High Speed Civil Transport Community Noise Reduction," SAE-92-1939, Oct. 1992.

[15] McCullers, L.A. *Flight Optimization System* User's Guide, Version 5.7, NASA Langley Research Center, 1995.

[16] Wu, J.T., Millwater, H.R., Cruse, T.A., "Advanced Probabilistic Structural Analysis Method for Implicit Performance Functions," *AIAA Journal,* Vol. 28., No. 9, Sept. 1990. pp. 1663-1669.

[17] Englar, R.J., Niebur, C.S., Gregory, S.D., "Pneumatic Lift and Control Surface Technology Applied to High Speed Civil Transport Configurations," Jan. 1997, AIAA 97-0036.