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Georgia Institute of Technology

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Technology Impact Forecasting for a High Speed Civil Transport

Dimitri N. Mavris, Michelle R. Kirby, Songtao Qiu
Aerospace Systems Design Laboratory (ASDL)
Georgia Institute of Technology

ABSTRACT

This paper outlines a comprehensive, structured, and robust methodology for decision making in the early phases of aircraft design. The proposed approach is referred to as the Technology Identification, Evaluation, and Selection (TIES) method. The seven-step process provides the decision maker/designer with an ability to easily assess and trade-off the impact of various technologies in the absence of sophisticated, time-consuming mathematical formulations. The method also provides a framework where *technically feasible alternatives* can be identified with accuracy and speed. This goal is achieved through the use of various probabilistic methods, such as Response Surface Methodology and Monte Carlo Simulations. Furthermore, structured and systematic techniques are utilized to identify possible concepts and evaluation criteria by which comparisons could be made. This objective is achieved by employing the use of Morphological Matrices, Pugh Evaluation Matrices, and Multi-Attribute Decision Making methods. Through the implementation of each step, the best alternative for a given evaluation metric/criterion can be identified and assessed subjectively or objectively. This method was applied to a High Speed Civil Transport as a proof of concept investigation. The TIES method identified that a conventional (present day technology) configuration could not meet imposed FAR 36 Stage III sideline noise requirements. Through the infusion of new technologies, a technically feasible design space was created. The TIES method identified a single notional concept for further investigation. This concept has a composite wing structure, Circulation Control for low speed flight, Hybrid Laminar Flow Control for cruise, and advanced engines for reduced fuel consumption and noise emissions.

INTRODUCTION

The design of complex systems, such as commercial aircraft, has shifted its focus from the traditional design for performance to design for affordability. Global and national budgetary requirements, operational restrictions, and airline deregulation have been the major impetus for this shift. In the United States, this paradigm shift calls for solutions outside of the traditional, historical evolutionary databases, while maintaining the importance of safe and affordable technology, and demands the consideration of all life cycle associated implications [1]. The life cycle phases of an aircraft include conceptual, preliminary, and detailed design, production, service, and retirement. Each of these phases has a considerable impact on the aircraft system in question. In particular, there is a strong "cost-knowledge-freedom" dependency from conceptual design to production which can significantly impact the entire life cycle of a system, specifically, the life cycle costs. The most design freedom exists in the conceptual phase and the beginning stages of the preliminary phase before a configuration is "frozen" and detailed design commences. Hence, "making educated decisions (increased knowledge) early on, and maintaining the ability to carry along a family of alternatives (design freedom) is the key to success" [1] of the paradigm shift. This can be achieved through system forecasting of the technical feasibility and economic viability in the early phases of design. Various initiatives have been developed by industry, government, and academia (such as Integrated Product and Process Development, Multi-disciplinary Design Optimization, and Concurrent Engineering) which address the above issues from a top level. However, this paper addresses the details on how to implement aspects of the paradigm shift.

The methodology presented will establish a comprehensive, structured, and robust decision making process for "design for affordability". The overall goal is to *formulate a stochastic, modeling and simulation-based decision making process which yields robust solutions and maintains a technically open system for as long as possible in the design process*. This method accounts for the multi-attribute, multi-objective, multi-constraint problems in the presence of operational and economic uncertainty, requirement ambiguity, and conflicting objectives. Furthermore, the process allows for the infusion and subsequent affordability assessment of new technologies while considering technological and economic risk. The process utilizes various techniques developed in other technical/operational/mathematical fields. These techniques include Response Surface Methods [2, 3, 4], Robust Design Simulation [4, 5, 6], use of a Morphological Matrix [7], a Pugh Evaluation Matrix [8], and Multi-Attribute Decision Making [9].

The methodology described herein is probabilistic in nature. Traditionally, uncertainty in knowledge about structural loads, mathematical models, economic assumptions, potential technological risks, etc., has been simulated deterministically through factors of safety [10]. Yet, the aspects of the virtual stochastic, life cycle design method presented by the authors herein and in Refs. [1, 11] maintains that the design of an aircraft system is immersed in ambiguity, conflict, uncertainty, and risk. The evolving modern aircraft design *must be* probabilistic in nature rather than the traditional deterministic approach.

METHODOLOGY

The methodology developed by the Aerospace Systems Design Laboratory (ASDL) to address the decision making process for the "design for affordability" initiative is depicted in Figure 1. The Technology Identification, Evaluation, and Selection (TIES) methodology contains seven steps for implementation. These steps are:

1. Problem definition
2. Baseline and alternative concepts identification
3. Modeling and simulation
4. Design space exploration
5. Determination of system feasibility: probability of success
6. Population of the Pugh evaluation matrix
7. Best alternative concept determination

The goal of the TIES methodology is to provide a framework where technically feasible alternatives can be identified with accuracy and speed. A feasible alternative is one which satisfies all imposed constraints and is physically realizable [1]. This methodology allows for more information (knowledge) to be brought into the earlier phases of the design process and will have direct implications on the affordability of the system. *This paper will focus on the technological feasibility aspects of aircraft concepts.* For the intended reader, the economic viability of various aircraft concepts is addressed in References [4, 11, 12].

PROBLEM DEFINITION (STEP 1)

The first step in the TIES process is to define the problem in question. In order to formulate the problem, a customer or societal need must exist or a request for proposal must be stated to drive the design of a new product. This need is often termed the "voice of the customer" and is typically qualitative, or ambiguous, in nature. For example, a commercial airline performs a market study and identifies that a majority of potential passengers wish to have lower fares and more flight time options. These are subjective and qualitative "wants" that must be mapped into some economic, engineering, or mathematically quantifiable terminology. A very efficient and organized method for translating the "voice of the customer" to the "voice of the engineer/designer" is the Quality Function Deployment (QFD) method [13]. With this method, the qualitative needs/requirements are mapped into system product and process parameters. These parameters can be ambiguous (passenger seat comfort), uncertain (daily cost of fuel), and/or deterministic (wing aspect ratio). For the example of more flight time options, the mapped voice of the engineer would be a higher utilization which implies a higher vehicle availability and, hence, component reliability.

From QFD and other brainstorming activities, system level metrics (objectives, constraints, and evaluation criteria) can be established. For a commercial system, the definition of the metrics must capture the needs of the airframe manufacturer, airlines, airports, passengers, and society as a whole through operational/environmental regulations. Furthermore, the evaluation criteria are those metrics of importance to the decision maker and which may significantly impact the design. The evaluation criteria are used in the Pugh matrix and the objectives, constraints, and metrics are used in the Modeling and Simulation step as illustrated in Figure 1.

These top level metrics can be further decomposed into product and process characteristics. Primary product characteristics include the physical design parameters which describe a system (e.g., wing area, engine fan pressure ratio, number of passengers). In the conceptual design phase, all of these parameters are not fixed but can vary, and thus be traded off, within some specified range until a configuration is "frozen". The process characteristics include manufacturing, economic, and operational parameters (e.g., production learning curves, passenger load factors, fuel cost) which are inherently uncertain. For the TIES methodology, the product characteristics are the key design variables (with associated ranges) which define the design space of interest. These design variables are often referred to as "control" factors, or variables that are within the designers control [12]. These key design variables, and associated ranges, define the design space in which technical feasibility is sought.

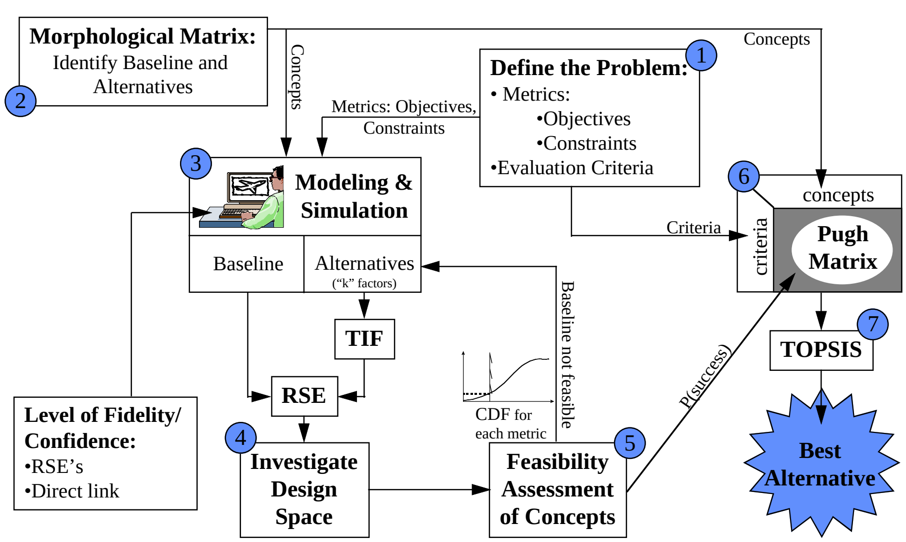

FIGURE 1: TECHNOLOGY IDENTIFICATION, EVALUATION, AND SELECTION METHODOLOGY

BASELINE AND ALTERNATIVE CONCEPTS IDENTIFICATION (STEP 2)

In the design of any complex system, there exists a plethora of combinations of particular subsystems or attributes which may satisfy the problem at hand. For example, how many engines are needed? What is the cruise speed? What type of high lift system? Is a horizontal stabilizer preferred over a canard? A functional and structured means of decomposing the system is through the use of a Morphological Matrix [7]. This matrix aids the decision maker/designer in identifying possible new combinations of subsystems to meet the customer needs. An example Morphological Matrix is depicted in Figure 2 for a pen. The circled items denote the combination of various attributes which comprise a single concept. For example, the circled characteristics define a ball point pen which has a metal casing and writes a medium black line. Typically, a conventional configuration (one which contains present day technology) is usually chosen as a datum point to begin the feasibility investigation. Other combinations of attributes constitute the alternatives. All of these concepts are supplied to the Pugh matrix (see Figure 1) and will be evaluated in subsequent steps.

Alternatives

Characteristics	1	2	3
Casing	Plastic	Metal	Hybrid
Writing Tip	Felt	Ball	
Color	Black	Red	Blue
Line Width	Fine	Medium	Heavy

FIGURE 2: EXAMPLE MORPHOLOGICAL MATRIX

MODELING AND SIMULATION (STEP 3)

A modeling and simulation environment is needed to quantitatively assess the metric values for the concepts identified from the Morphological Matrix. In the conceptual stages of design, rapid assessments are desired so that trade-offs can be performed with minimal time and monetary expenditures. These trade-offs are typically performed in a monolithic or legacy sizing and synthesis code. Most of the existing public domain codes, such as the Flight Optimization System (FLOPS) [14], are based on historical data for evolutionary concepts. If the designs of interest fall within this range, the sizing and synthesis codes can accurately assess the objectives. Yet, for a revolutionary concept, such as a High Speed Civil Transport (HSCT), the validity of the results will be questionable. This inability can be overcome through direct linking of more physics-based analytical models, or through the use of metamodels to represent the physics-based analysis tool [15.]. This process yields a preliminary design vehicle specific sizing/synthesis tool. For brevity, the reader is directed to Reference [1] for a more detailed description of the Modeling and Simulation step.

DESIGN SPACE EXPLORATION (STEP 4)

The design space exploration begins with the establishment of datum values for all metrics of interest. The design space (represented by the design parameter variation) of a conventional configuration is initially investigated and baseline values quantified. Similar to the aircraft attributes of the Morphological Matrix, there exists an infinite number of design variable combinations or settings. There are three methods by which this space can be investigated for feasible solutions: 1) linkage of an actual simulation code with a Monte Carlo simulation; 2) creation of a Metamodel and linkage to a Monte Carlo model; and 3) Fast Probability Integration (FPI) [12, 16]. Due to uncertainty in the design process, each of the methods are probabilistic in nature rather than deterministic. The end result of each method is a cumulative distribution function (CDF) for each metric as seen in Figure 1. The first method is the most accurate and most computationally intense since the analysis tool is executed directly. Typically, ten thousand random simulations must be executed for a reasonable CDF. The second method uses a particular metamodel called a Response Surface Equation (RSE) to approximate the analysis tool and a Monte Carlo is performed on this equation. This method has been applied for various investigations [4, 5, 6, 15] and is limited to a maximum of sixteen variables for a second-order approximation. The third method is a recent extension of the design methodology research conducted at ASDL. FPI approximates the CDF of the metrics directly using the analysis tool with fewer simulations. This technique is very efficient and accurate and has been applied in References [12, 16]. It is the designer's discretion as to which method is most suitable.

DETERMINATION OF SYSTEM FEASIBILITY: PROBABILITY OF SUCCESS (STEP 5)

The evaluation of concept feasibility is based on the value of the probability of a given metric for the specified target value on the CDF. For example, if a metric has an 80% chance of achieving the target, the decision-maker may assume that it is no longer a constraint and does not warrant further investigation. Yet, a low probability value (or small confidence) of achieving a solution that satisfies the constraints implies that a means of improvement must be identified. This includes, but is not limited to, the infusion of new technologies. The need for the infusion of a technology is required when the manipulation of the variable ranges has been exhausted, optimization is ineffective, constraints are relaxed to an extremal limit, and the maximum performance attainable from a given level of technology is achieved. The maximum level of a given technology is essentially the natural limit of the benefit. This implies that the maturation variation with time remains constant. When this limit is reached, there is *no other alternative* but to infuse a new technology.

Unfortunately, advanced technologies are difficult to assess. As mentioned earlier, sizing/synthesis tools are typically based on regressed historical data which limits or removes the applicability to exotic/revolutionary concepts or technologies. However, the impact of a technology can be qualitatively assessed through the use of technology metric "k" factors. These "k" factors modify disciplinary technical metrics, such as specific fuel consumption, cruise drag, and/or component weights, that result from some analysis or sizing tool. The modification is essentially a change in the technical metric, either enhancement or degradation. In effect, the "k" factors simulate the discontinuity in benefits and/or penalties associated with the addition of a new technology.

Based on the possible technologies (or characteristic alternatives) identified in the Morphological Matrix, ranges of applicability of the "k" factors must be established. These ranges must capture not only the benefits to a system but also the primary and secondary penalties to other subsystems. Once the "k" factors are identified, the geometric baseline may be optimized, if desired, and Steps 3 and 4 are repeated for a fixed configuration. For completeness, Steps 3 and 4 should be repeated for each concept in the Morphological Matrix.

The impact of new technologies on the system level metrics can be assessed qualitatively through a linear or higher order sensitivity analysis depending on the level of detail desired. If a "k" factor for a given technological metric is shown to improve the system objectives relative to the constraints, that technology impact can be identified as worthy of further investigation. An actual technology must be identified which can provide the "k" factor projections. For example, if a 10% reduction in cruise drag is required to meet a takeoff gross weight constraint, then a specific technology must be identified which can provide this benefit; perhaps, hybrid laminar flow control. Furthermore, the penalties to other systems must be determined and subsequently applied. The process is described in more detail in References [11] for an HSCT concept and [12] for a high capacity commercial transport. This technique is in essence the forecasting of the impact of a technology, also known as Technology Impact Forecasting (TIF). This ASDL-developed technique provides a very efficient means of identifying design alternatives around concept "show-stoppers". As a result, the identification of technologies capable of counteracting the show-stoppers will aid the decision maker in the correct allocation of resources for further research and development of a project.

POPULATION OF THE PUGH EVALUATION MATRIX (STEP 6)

The Pugh Evaluation Matrix [8] is a method where concept formulation and evaluation is performed in an organized manner. The concepts identified in Step 2 form the columns, and the evaluation criteria (or important metrics) in Step 1 form the rows. The elements of the matrix are populated from the feasibility assessment for each concept and criteria. Since the metrics are in the form of CDFs, the decision maker has the ability to select a confidence level associated with a given metric. The confidence level is also related to the risk or uncertainty associated with a particular technology and the selection of these levels is purely subjective. The corresponding value of the metric (for a fixed confidence level) is then inserted into the appropriate cell of the matrix. This process is repeated for each metric and concept.

BEST ALTERNATIVE CONCEPT DETERMINATION (STEP 7)

Once the Pugh Matrix is populated, the next step is to determine the best alternative concept. This decision making process is facilitated through the use of Multiple Attribute Decision Making (MADM) techniques. For the purpose of the TIES methodology, a Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is utilized [9]. TOPSIS provides an indisputable preference order of the solutions obtained in the Pugh Matrix with the end result being the best alternative concept. This best alternative is established as described below.

First, a decision matrix is formed from the transpose of the Pugh Matrix. If any of the evaluation criteria are subjective in nature, an interval scale may be utilized. For example, if one of the qualitative criteria is the reliability of a particular component, a range of values from 1 to 9 (i.e., very low to very high) may be used. From this matrix, each criteria for a given alternative is nondimensionalized from the norm of the total outcome vector of a particular criterion. If so desired, subjective weights may be placed on each criterion to establish a relative importance. Next, each criterion must be classified as a "benefit" or a "cost" whereby a maximum of a benefit and a minimum of a cost are desired. A positive and negative ideal solution vector is established for each criterion based on the above classification. Next, the Euclidean distance of each alternative is measured with respect to both the positive and negative ideal solutions. And finally, the concepts are ranked based on the "closeness" to the positive ideal solution and the distance from the negative ideal solution. The result is a ranking from "best" to "worst" of the concepts considered. These rankings can change depending upon the level of confidence and criterion weightings assumed.

Finally, the robustness of the best alternative can be evaluated with various techniques. One method developed by researchers at ASDL is the Robust Design Simulation. This method has been implemented for various concepts, and the reader is referred to References [11, 17,18] for more information. Additionally, the "best alternative(s)" should be re-investigated with regards to the design variable settings, i.e., Steps 3 through 5 are repeated.

IMPLEMENTATION

A proof of concept vehicle for the TIES methodology is the High Speed Civil Transport (HSCT) initiative. This concept has received world-wide attention since its renewed interest in the commercial industry in the mid-1980's. An HSCT is a primary candidate for the application of the TIES method as will be described below.

PROBLEM DEFINITION (STEP 1)

<u>Voice of the Customer</u>

Travelers have always welcomed the idea of reaching distant destinations in less time without having to spend a great deal of money. However, with the exception of the Concorde, the speed of commercial aircraft has not significantly increased over the last 20 years because of the enormous technical difficulties associated with faster-than-sound travel. During the late 1960's, an attempt to create a supersonic commercial transport aircraft resulted in the Concorde. Although the Concorde was a technological triumph, it was something less than an economic success. The ticket fare (approximately $6,500 for New York to London [19]) is as much as eight times higher than current commercial subsonic transports. At the time of its inception, the Concorde represented an innovative solution to one of the most challenging commercial transport endeavors, that of supersonic transportation. However, this supersonic transport had many short-comings: poor reliability, high specific fuel consumption, and low payload capacity [20]. Moreover, the Concorde does not adhere to any of the environmental restrictions imposed in recent years, such as NO_X emission and FAR 36 Stage III noise requirements.

From a manufacturer's point of view, the Concorde was a challenging task full of technological unknowns which forced a move into uncharted territories. This led to over-designing in order to avoid unexpected surprises which added to the weight and cost of the aircraft. As a result, the Concorde received a weak response from commercial airlines who were reluctant to accept the high acquisition price and narrow or non-existent profitability. In addition, market studies have indicated that the required ticket fare for this aircraft was too high for most passengers to pay (average required yield per Revenue Passenger Mile, $/RPM $\approx$ 0.8). The engine's poor reliability record has also contributed to the poor operational performance. In addition, recognition of the environmental impact of high flying aircraft to the upper atmospheric ozone concentration has resulted in de-facto limitations on the emission of certain compounds, most notably, NO_X. At the time of the Concorde's inception, this upper atmospheric concern was not an issue; therefore, it was not designed to meet any type of emissions standard. Also, the Concorde is powered by turbojet engines, which are inherently noisy. Most airports have been forced to ban the Concorde due to noise complaints from surrounding residential neighborhoods.

Since the introduction of the Concorde in 1975, many changes have occurred in technology readiness and the international air travel market. Some researcher predict that current technology has now reached a stage where it will soon be possible to build a commercially viable supersonic aircraft. Furthermore, the Concorde is expected to reach its life-cycle limit within the next ten to fifteen years. In addition, the number of people traveling abroad has increased steadily [21]. These changes warrant a very serious re-examination of the market and the technological potential for a second generation supersonic transport [22].

An HSCT is the United States' response to this growing need for a next-generation supersonic aircraft. The most evident benefit that an HSCT brings to the traveling community is the travel time reduction that results from flying at high supersonic speeds. The travel time for a passenger on a typical New York to Paris flight can be reduced by as much as 65% and a Los Angeles to Tokyo reduction of 150% [23]. Such time savings will have a strong appeal to the business executive who has limited time to spend away from the office; and the number of days required for business trips would be substantially reduced. The increase in international flights for business interactions will help promote the "door-to-door" policy [24] that seems to be dwindling in an era of e-mail, faxes, and modems. Recent market forecasts predict the strongest growth in international air travel will occur in the Pacific Basin region [25, 26] although this may not be the case for the current woes of the Asian economy. An HSCT concept could also have an enormous impact for the country that produces the aircraft. The United States, if it were to produce this vehicle, could ensure that aerospace technical superiority remains within the U.S. and provide an estimated 140,000 jobs [27, 28] for a $200 billion HSCT market to stimulate the aerospace industry.

The greatest challenge facing an HSCT is the necessity to go farther with a greater payload capacity than the Concorde at an operating cost for the airline comparable to that of current subsonic transports. This translates to an increase in vehicle range and passenger capacity while minimizing the fuel cost per trip. Furthermore, recent research studies have revealed that the success of an HSCT will require significant technological advances in order to provide the needed environmental compatibility and economic viability [29]. Based on the current NASA High Speed Research program effort, an HSCT is a Mach 2.4, 300 passenger aircraft with a 5,000 nm range [28] and four mixed-flow turbofan engines [30]. The aircraft is restricted to subsonic flight over land due to the impact of sonic boom and must abide by all FAA regulations. Previous studies have shown that an HSCT is not technically feasible nor economically viable with conventional technologies [31, 32, 33]; where feasibility and viability are measured by compliance with noise levels, takeoff and landing field length requirements, gross weight limitations, and affordability goals. Various technologies have been proposed to address these issues including composite materials to reduce component weights [31, 34], advanced engines to reduce fuel consumption and noise emissions [30, 31, 32], laminar flow devices to reduce cruise drag [31], and circulation control to improve low speed flight characteristics [35].

TABLE I: HSCT SYSTEM LEVEL METRICS

Parameter	Target/ Constraint	Units
Performance		
Approach Speed (V_{app})	≤ 155	kts
FAR 36 Stage III Flyover Noise (FON)	≤ 106	EPNLdB
Landing Field Length (Landing FL)	≤ 11,000	ft
FAR 36 Stage III Sideline Noise (SLN)	≤ 103	EPNLdB
Takeoff Field Length (TOFL)	≤ 11,000	ft
Takeoff Gross Weight (TOGW)	≤ 1,000,000	lbs
Economics		
Acquisition Price (Acq $)	*minimize*	FY98 $M
Average Required Yield per Revenue Passenger Mile ($/RPM)	≤ $ 0.13	FY98
Direct Operating Cost per Trip (DOC/trip)	*minimize*	FY98 $
Research, Development, Testing, and Evaluation Costs (RDT&E)	*minimize*	FY98 $M

TABLE II: DESIGN SPACE VARIABLES

Variable	Minimum	Maximum	Units	Description
SW	7500	9000	ft^2	Wing area
TWR	0.29	0.33	~	Thrust-to-weight ratio
TIT	3000	3400	°R	Turbine Inlet Temperature
FPR	3.5	4.5	~	Fan Pressure Ratio
OPR	18	21	~	Overall Pressure Ratio
CLdes	0.08	0.12	~	Design lift coefficient
X2	1.54	1.69	~	LE kink x-location*
X3	2.1	2.36	~	LE tip x-location*
X4	2.4	2.58	~	TE tip x-location*
X5	2.19	2.37	~	TE kink x-location*
X6	2.18	2.5	~	TE root x-location*
Y2	0.44	0.58	~	LE kink y-location*
t/c_root	3	5	%	Wing root t/c ratio
t/c_tip	2	4	%	Wing tip t/c ratio
SHref	400	700	ft^2	Horizontal Tail area
SVref	350	550	ft^2	Vertical Tail area

* Variables Nondimensionalized by wing semi-span

Voice of the Engineer

In accordance with the TIES methodology, the "voice of the customer" previously described must be translated into the "voice of the engineer" in the form of quantifiable metrics. For this study, the metrics are extracted from previous work and are summarized in Table I. The performance metrics are constrained by either FAA regulations (Vapp, FON, and SLN) or airport compatibility requirements (Landing FL, TOFL, and TOGW). Whereas the economic metrics are not constrained only minimized, yet the $/RPM has a target value of $0.13/RPM. The economic results obtained herein are optimistic since the infusion of new techologies did not penalize the economics. This will be the focus of future investigations. The metrics defined above can be further decomposed into product characteristics. These characteristics are the key design variables which define the design space of interest and will directly affect the metric values. Based on previous work performed in industry and at ASDL, important geometric and propulsive design variables were identified. These variables are listed in Table II with the associated ranges of interest. The nondimensional wing parameters will be further described in Step 3.

BASELINE AND ALTERNATIVE CONCEPTS IDENTIFICATION (STEP 2)

Baseline and alternative concepts are identified through the use of a Morphological Matrix. An HSCT system is decomposed into subcomponents, and through brainstorming activities or literature reviews, various alternatives can be associated with each characteristic. No limit should be placed on the number of alternatives, nor should the alternatives exclude exotic ideas. The Morphological Matrix is a tool for which ideas and creativity are preferred. The matrix utilized in this investigation is shown in Figure 3. As stated previously, a datum point must be established from this matrix. This datum is assumed to be the combination of alternatives which represent conventional (or present day) technologies and consists of the circled characteristics in Figure 3.

	Characteristics \ Alternatives	1	2	3	4
Config	Vehicle	Wing & Tail	Wing & Canard	Wing, Tail & Canard	Wing
	Fuselage	Cylindrical	Area Ruled	Oval	
	Pilot Visibility	Synthetic Vision	Conventional	Conventional & Nose Droop	
Mission	Range (nmi)	5000	6000	6500	
	Passengers	250	300	320	
	Mach Number	2	2.2	2.4	2.7
Propulsion	Type	MFTF	Turbine Bypass	Mid Tandem Fan	Flade
	Fan	None	1 Stage	2 Stage	3 Stage
	Combustor	Conventional	RQL	LPP	
	Nozzle	Conventional	Conventional & Acoustic Liner	Mixed Ejector	Mixer Ejector & Acoustic Liner
Aero	Low Speed	Conventional Flaps	Conventional Flaps & Slots	C C	
	High Speed	Conventional	LFC	NLFC	HLFC
Struct	Materials	Aluminum	Titanium	High Temp. Composite	
	Process	Chordwise Stiffened	Spanwise Stiffened	Monocoque	Hybrid

FIGURE 3: HSCT MORPHOLOGICAL MATRIX

The alternative concepts considered for this study include combinations of four subcomponent characteristics: high speed aerodynamics, low speed aerodynamics, structures, and propulsion. From the Morphological Matrix in Figure 3, the possible technology concepts include Hybrid Laminar Flow Control (HLFC), Circulation Control (CC), high temperature composite structures for the wing, and a propulsive system with a Lean, Premixed, Prevaporized (LPP) combustor and a mixer ejector and acoustical liner nozzle. A full factorial combination of these technologies results in fourteen different concept alternatives, in addition to the baseline previously described. The distinction of the various concepts is listed in Table III. The remaining characteristics are identical to the baseline.

The configurations analyzed in this study are sized for a 5,000 nm mission with the primary cruise altitude of 67,000 ft at Mach 2.4. A subsonic cruise portion precedes the primary cruise segment at an altitude of 35,000 ft at Mach 0.9. The payload of the aircraft is assumed to be 300 passengers with baggage and a flight crew of two.

MODELING AND SIMULATION (STEP 3)

The metrics for the concepts described above must be quantitatively assessed. This was done via a modeling and simulation environment. This environment was created with the aid of the public domain synthesis and sizing tool FLOPS [14]. FLOPS is a multidisciplinary system of computer programs used for the conceptual and preliminary design and analysis of aircraft configurations. This tool was developed by the NASA Langley Research Center. FLOPS was linked to an Aircraft Life Cycle Cost Analysis, ALCCA, program used for the prediction of all life-cycle costs associated with commercial aircraft and was originally developed by NASA Ames and further enhanced by ASDL [36]. The direct link of FLOPS and ALCCA provided the capability to create a conceptual aircraft design with immediate evaluation of life-cycle cost elements.

TABLE III: HSCT CONCEPT ALTERNATIVES

Alternative	Tech #1 Composite Wing	Tech #2 CC	Tech #3 HLFC	Tech #4 Advanced Engine
Baseline				
1	X			
2		X		
3			X	
4				X
5	X	X		
6	X		X	
7	X			X
8		X	X	
9		X		X
10			X	X
11	X	X	X	
12	X	X		X
13		X	X	X
14	X	X	X	X

Due to the non-conventional nature of an HSCT configuration, many of the historically based, regressed equations within FLOPS are not accurate, nor valid. Previous work performed by researchers at ASDL have corrected some of these inadequacies, in particular, the aerodynamics and wing weight calculations. These capabilities were enhanced through the use of metamodels which approximated more sophisticated aerodynamic and structural analysis tools. These metamodels, in the form of Response Surface Equations (RSE), were inserted into the FLOPS source code and utilized for the preliminary system level study. The reader is referred to Ref. [37] for more detailed information on the structural enhancements, to Ref. [15] for the aerodynamics, and Refs. [6, 38] for the general description of the methodology for the RSE generation. For this study, the aerodynamic RSEs were enhanced from the description contained in Reference [15]. The enhancements include an increase in the number of variables forming the RSEs, inclusion of the vertical tail, different wing thickness-to-chord ratios at the root and tip, and slightly different ranges of the variables. The aerodynamic RSEs are of the form:

$$C_D = C_{D_0} + K_1 \cdot C_L + K_2 \cdot C_L^2 \qquad (1)$$

where C_{Do} is a function of operating Mach number, altitude, and geometric variables; K_1 and K_2 are functions of operating Mach number and geometric variables. The variables utilized for the RSE generation are shown in Figure 4. A screening test was performed with these variables for the subsonic and supersonic operating regimes. A maximum of fifteen and sixteen variables were used for each of the coefficients in EQ (1) for each Mach-altitude combination. The fifteen and sixteen variable Design of Experiments (DoE) employed for these RSEs is a face-centered Central Composite Design (CCD) with a Resolution IV fractional factorial design. Commonly available fractional factorial designs are listed or described by their confounding rules for up to eleven variables [39]. But with the strong need for a DoE with 15 or 16 variables and no possibility for further screening, a new design was created by one of the researchers at ASDL that allows for estimates of all main effects as well as all interactions between main effects (Resolution IV). This fractional factorial design was then merged with a center point in the hyper-cube and a set of face-centered axial points to form the CCD employed for this study.

The screening procedure and the aerodynamic RSEs integration into FLOPS are identical to the methods described in Reference [15]. The reader is referred there for more information. The important variables forming the subsonic and supersonic coefficient of EQ (1) consist of the geometric variables in Table II and also those listed in Table IV. The aerodynamic analysis tools utilized to estimate the coefficients in EQ (1) are listed in Table V [40,41,42].

TABLE IV: ADDITIONAL AERODYNAMIC RSE VARIABLES

Variable	Minimum	Maximum	Description
XW	0.22	0.28	Wing Apex Location on Fuselage
Y5	0.43	0.6	TE kink y-location*
NACSCAL	0.9	1.1	Percent Nacelle Scaling
YD2**	0.49	0.55	Outboard Nacelle Location*

* Variables Nondimensionalized by wing semi-span
** Variable only used for supersonic regime

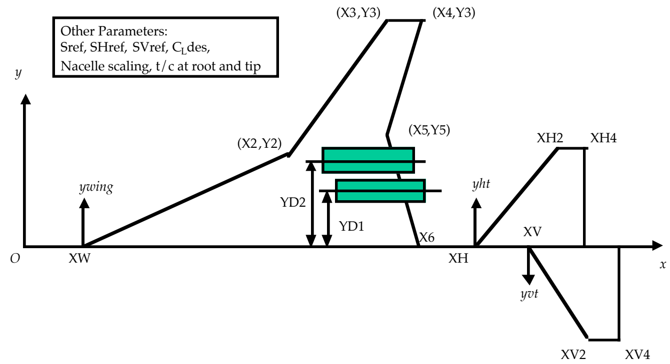

FIGURE 4: HSCT AERODYNAMIC RSEs VARIABLES

TABLE V: AERODYNAMIC ANALYSIS TOOLS

Tool	Purpose
AERO2S	Low speed induced drag
AWAVE	Fuselage area-ruling distribution
BDAP	Skin friction and wave drag
VORLAX	Subsonic and supersonic induced drag
WingDes	Optimal wing twist and camber for specified design lift coefficient

DESIGN SPACE EXPLORATION (STEP 4)

As stated previously, the design space of the conventional configuration, i.e., baseline concept, must initially be investigated. This investigation is performed to establish if a feasible space exists and, if so, how much. For this study, the second method described in the methodology section will be utilized: metamodel representation of the metrics with a Monte Carlo simulation. The design space under investigation is created by the control variables and associated ranges listed in Table II. These parameters will vary between the stated minimum and maximum values to provide data whereby the metric metamodels listed in Table I may be approximated. The sixteen variable DoE described in Step 3 will be utilized to build these models. A quadratic form of the RSEs is assumed.

FLOPS is executed based on the settings prescribed by the DoE; appropriate data is extracted; and the RSEs are formed with the aid of the statistical package JMP [43]. The accuracy of the RSEs are confirmed with the R^2 value and verified with random cases. All metric RSEs had an R^2 value greater than 99% and a confidence interval of ±5%. Once the RSEs were generated and validated, a Monte Carlo simulation was performed on each equation with the software package Crystal Ball [44]. The random number generator in Crystal Ball generated values for the design variables based on assumed uniform distributions. Crystal Ball then used those values to determine the metric values through the RSEs. This procedure was repeated 10,000 times to obtain the cumulative distributions functions (CDF) of the design space for each metric.

DETERMINATION OF SYSTEM FEASIBILITY: PROBABILITY OF SUCCESS (STEP 5)

A CDF displays the probability or confidence of achieving values less than or greater than a given amount [39]. With the CDFs of each metric, the decision maker may readily determine the probability of meeting a metric constraint or target. For the ten metrics listed in Table I, six are constrained. The design space investigation performed in Step 4 of the TIES method resulted in the probability values listed in Table VI. As is evident, some of the design space will satisfy the constraints: Vapp of 20.1%, TOGW of 84.1%, etc. Yet, the sideline noise (SLN) has a 0% probability of meeting the 103 EPNLdB constraint. This metric is essentially a "show-stopper" and new technologies must be infused. The infusion of technology may increase the probability of success of the SLN if, and only if, the technologies considered in Step 2 benefit the system more than degrade. An initial estimate to the impact of the technologies is through Technology Impact Forecasting (TIF).

To implement the TIF method, disciplinary technology metric "k" factors associated with the technologies identified in Step 2 must be established. The range of applicability of the "k" factors must consider the benefits and penalties to various vehicle subsystems. Eleven possible "k" factors were identified and are summarized in Table VII. A value of 100% corresponds to no change in a technical/economic metric (present day technology).

Prior to the application of the TIF technique, the baseline concept was optimized so as to minimize the metric values listed in Table I using the desirability feature of JMP. The desirability feature translates a multi-objective problem to one objective in the form of a "desirability" function and was pioneered by Derringer and Suich [45]. Consider the prediction profile illustrated in Figure 5, there are ten different objective functions (i.e., metrics) defined on the ordinate. On the right of the figure is the desirability of each objective. The slopes of each individual objective shows the direction of highest desirability, e.g., a negative slope implies minimization. As is evident, minimization of the individual metrics is the goal. Yet, the TOGW, TOFL, Landing FL, and Vapp are constrained. The $/RPM was constrained just for the geometric optimization. The SLN and FON are not considered as constraints in this process due to complete violation of the constraint values for the design space and are minimized, not constrained. For the constraints shown, the mean value of the desirability is set to zero at the constraint value. For the TOGW and the economic metrics, minimization is also desired as evident by the negative slope. The variable settings which maximized the desirability are listed in Table VIII and represent the datum point (or optimal baseline) for the Pugh Matrix. This optimal configuration is illustrated in Figure 6.

TABLE VI: HSCT METRIC PROBABILITY OF SUCCESS

Metrics	Probability of Success
Performance	
Vapp	20.1 %
FON	13.7 %
Landing FL	95.1 %
SLN	0 %
TOFL	35.8 %
TOGW	84.1 %

TABLE VII: TECHNOLOGY METRIC "K" FACTORS

Parameter	Minimum (-1)	Maximum (+1)
Subsonic drag (k_Drag_sub)	85%	100%
Supersonic drag (k_Drag_sup)	85%	100%
Wing weight (k_Wing_wt)	80%	105%
Nozzle weight (k_Nozzle_wt)	95%	200%
Supersonic fuel flow (k_FF_sup)	95%	103%
Subsonic fuel flow (k_FF_sub)	95%	103%
CLmax allowable (k_CLmax)	100%	130%
Noise supression (k_noise_supp)	90 %	100%
Utilization (k_U)	3000 hrs/yr	4500 hrs/yr
RDT&E (k_RDT&E)	90 %	110%
Operation and Support Costs (k_O&S)	90 %	110%

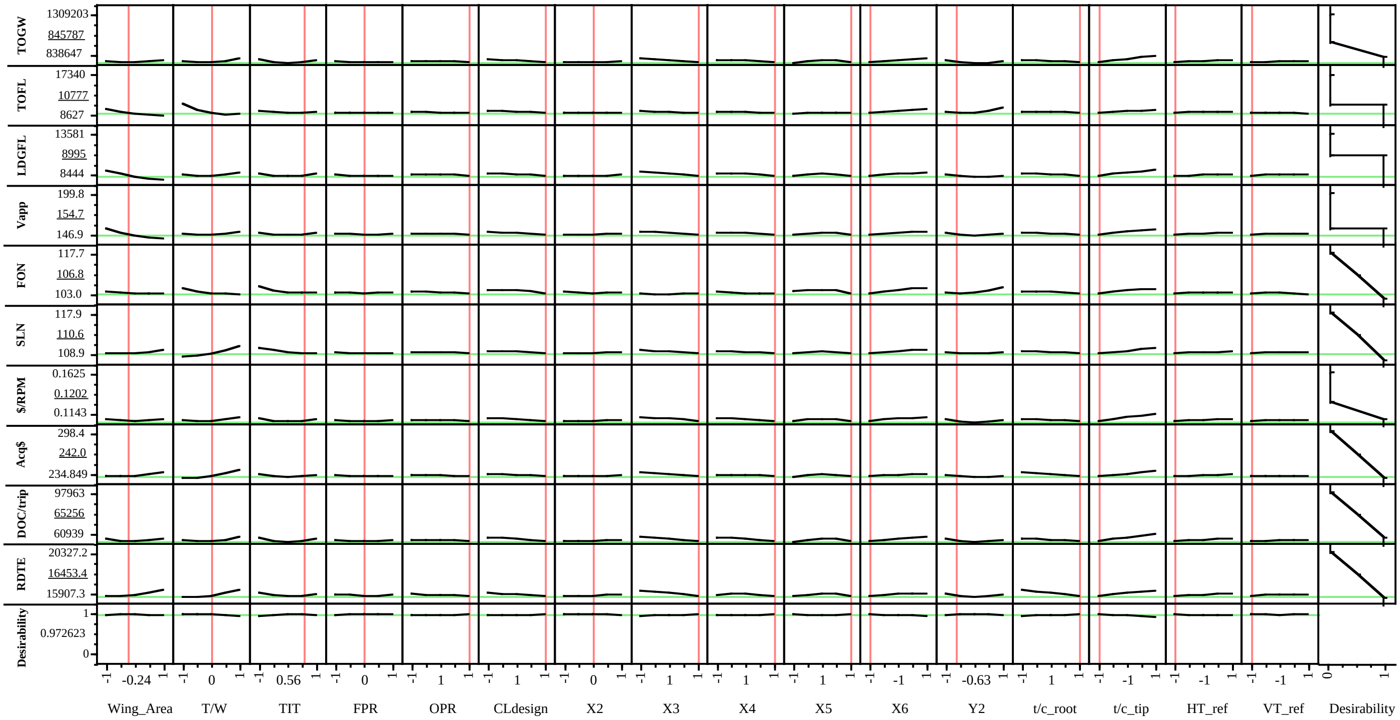

FIGURE 5: DETERMINATION OF OPTIMAL CONVENTIONAL HSCT

TABLE VIII: OPTIMAL HSCT BASELINE (DATUM POINT)

Parameter	Value	Parameter	Value
SW	8070 ft^2	X4	2.58
T/W	0.31	X5	2.37
TIT	3312 °R	X6	2.18
FPR	4	Y2	0.4659
OPR	21	t/c_root	5%
CLdes	0.12	t/c_tip	2%
X2	1.615	SHref	400 ft^2
X3	2.36	SVref	350 ft^2

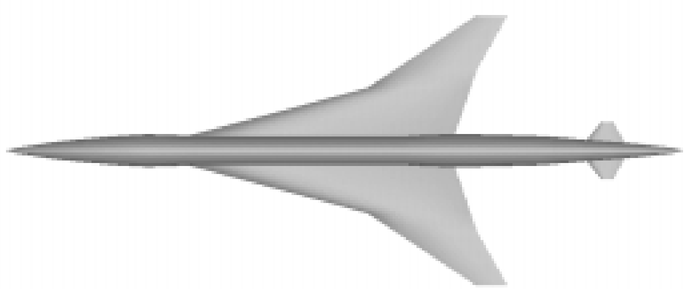

FIGURE 6: OPTIMAL GEOMETRIC HSCT CONFIGURATION

The purpose of the TIF method is to investigate whether the infusion of technologies will overcome any "show-stoppers". This procedure is implemented with a DoE on the optimal baseline concept. The RSEs for the metrics are now a function of the "k" factor parameters listed in Table VII for a fixed geometry. The wing area and thrust-to-weight ratio are included to allow for scaling of the vehicle. Once again, FLOPS is executed based on the settings prescribed by the DoE; appropriate data is extracted; and the RSEs are formed with the aid of JMP. The impact that the "k" factors have on the metrics can be visualized through the prediction profile feature of JMP. The prediction profile, shown in Figure 7, is evaluated based on the magnitude and direction of the slope, where the "-1" and "1" values shown above the "k" factors are normalized values with respect to the ranges identified in Table VII. The larger the slope, the greater the influence of the given parameter. If a parameter, listed on the abscissa, does not contribute significantly to the response listed on the ordinate, the slope is approximately zero. The sign of the slope, either positive or negative, depicts the direction of influence of the parameter on the response. Furthermore, the limits of the metrics can be readily obtained, e.g., the SLN varies between 96.5 and 112.9 EPNLdB; the TOFL varies between 6,494 and 13,971 ft. As is evident, the infusion of technology *can* create a feasible design from the ranges of the technology metrics shown in Figure 7. In particular, the SLN constraint of 103 EPNLdB can be met with some combination of the "k" factor settings.

The question at hand is: "What are the "k" factor settings and associated technology (or combination of technologies) which creates a feasible solution?" The answer to this question is achieved through the use of the alternative concepts identified with the Morphological Matrix in Step 2 and listed in Table III. The next aspect of the TIF method is to establish confidence estimates for each technology metric which includes primary benefits and secondary penalties. Based on the four technologies identified previously, deterministic mean values of the "k" factor benefits and penalties for each technology were identified and are listed in Table IX. For a given combination of technologies (i.e., one alternative concept), a technology "k" factor mean is summed for a given row to simulate the technology impact on that alternative. For example, Alternative 5 has a composite wing and Circulation Control (CC). This combination of technologies results in a 1% reduction in cruise drag, 18% reduction in wing weight, 1% increase in subsonic fuel flow, 30% increase in C_{Lmax} at takeoff and landing, 3% reduction in utilization, etc. For the aircraft utilization, a value of 4,500 hrs/yr was assumed to be present day, i.e., 0%, and the percent reductions listed imply a reduction from present day levels.

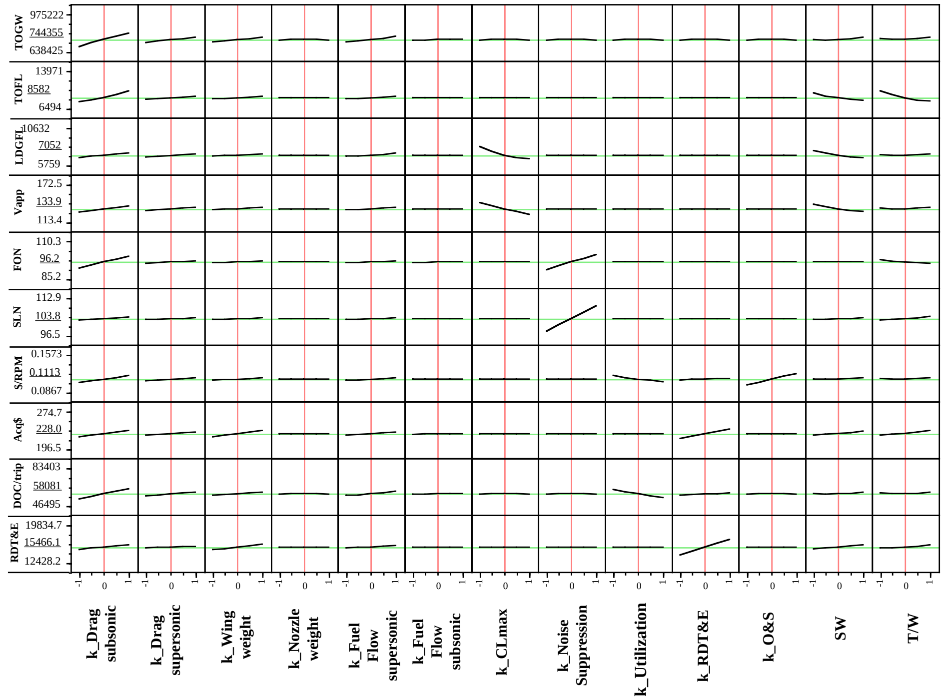

FIGURE 7: HSCT TIF ENVIRONMENT

For each alternative, a mean value of each "k" factor was established, as described for Alternative 5, to estimate the impact of specific technologies. Since this method is an estimation of the impact, there is some uncertainty that the estimated mean may be achieved. If one assumes that the deviation from the deterministic mean is of the form of a normal distribution, a variance may be established. For this study, the variance for each technology "k" factor is listed in Table X. With the confidence estimate distributions established, a Monte Carlo simulation was executed for all fourteen alternatives and each metric RSE. Once again, 10,000 combinations were simulated and metric CDFs obtained.

POPULATION OF THE PUGH EVALUATION MATRIX (STEP 6)

The sixth step in the TIES method is the population of the Pugh Evaluation Matrix. At this point, the decision maker's discretion is used to select a probability/confidence level for the metrics. Once a level is chosen, the corresponding metric values from the CDFs generated in Step 5 are supplied to the Pugh Matrix. For the purposes of this study, a 75% confidence level of achieving the metrics was assumed. The metric values associated with this confidence level are listed in Table XI. Furthermore, each constraint that was violated is underlined and italicized.

BEST ALTERNATIVE CONCEPT DETERMINATION (STEP 7)

The final step in the TIES methodology is the identification of the best alternative concept. This concept was established via a MADM technique, TOPSIS, as described in the methodology section. The results shown are for a confidence level of 75%. The TOPSIS method was applied to the results in Table XI. Subjective weightings were placed on the ten metrics and the alternatives were ranked from best to worst. The top seven ranking alternative concepts for various metric weighting scenarios in each column are listed in Table XII. The metric weighting factor scenarios are listed at the top, and the alternative rankings, from best to worst, are below each weighting column. Furthermore, as read from left to right, the subjective weighting factors vary from increased importance of performance on the left, to increased economics on the right. As is evident, if the performance metrics are the primary decision making drivers in the first four columns, Alternative 14 is the best solution. As the importance of the economic metrics increases, Alternative 14 remains as the best solution, but the ranking of other alternatives changes. It appears that Alternative 14 is the best solution for minimizing and meeting the imposed metric targets/constraints. These results were consistent with other CDF confidence levels and were for a fixed concept geometry.

TABLE IX: TECHNOLOGY "K" FACTOR ASSUMED IMPACT

Parameter	Tech #1 Composite Wing	Tech #2 CC	Tech #3 HLFC	Tech #4 Advanced Engine
Δ k_Drag_sub	-1%	-	-10%	-
Δ k_Drag_sup	-1%	-	-10%	-
Δ k_Wing wt	-20%	+2%	+2%	-
Δ k_Nozzle wt	-	-	-	+50%
Δ k_FF_sub	-	+1%	+1%	-2%
Δ k_FF_sup	-	-	+1%	-2%
Δ C_{Lmax}	-	+30%	-	-
Δ k_Noise Supp	-1%	-	-	-10%
Δ k_U	-2%	-1%	-2%	-1%
Δ k_RDT&E	+2%	+1%	+2%	+3%
Δ k_O&S	+2%	+2%	+2%	+2%

TABLE X: ASSUMED VARIANCE OF TECHNOLOGY "K" FACTORS

Parameter	Assumed Variance	Parameter	Assumed Variance
Δ k_Drag_sub	0.010	Δ C_{Lmax}	0.010
Δ k_Drag_sup	0.010	Δ k_Noise Supp	0.010
Δ k_Wing wt	0.010	Δ k_U	3.000
Δ k_Nozzle wt	3.000	Δ k_RDT&E	0.005
Δ k_FF_sub	0.010	Δ k_O&S	0.005
Δ k_FF_sup	0.010		

TABLE XI: HSCT PUGH MATRIX (75% CONFIDENCE LEVEL)*

Metric	Optimal Baseline	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5	Alternative 6	Alternative 7	Alternative 8	Alternative 9	Alternative 10	Alternative 11	Alternative 12	Alternative 13	Alternative 14
TOGW	845787	801981	861001	747608	837082	807039	700700	788695	754809	841026	734669	704926	789666	737721	690532
TOFL	10777	10223	10957	8745	10771	10215	8194	10072	8733	10791	8583	8158	10069	8574	8022
LDGFL	8995	8670	7379	8377	8950	7038	8000	8556	6815	7258	8277	6490	6914	6707	6383
Vapp	154.7	150.9	136.8	145.8	154.1	132.5	141.3	149.7	128.2	135.2	144.6	124.0	131.1	126.8	122.8
FON	*107*	104.8	*107.8*	101.3	96.4	104.9	98.6	93.9	101.4	96.5	90.8	98.7	93.9	90.9	88.3
SLN	*111*	*109.5*	*111.4*	*110.0*	100.0	*109.6*	*108.3*	98.3	*110.1*	100.1	98.9	*108.4*	98.4	98.9	97.3
$/RPM	0.1202	0.1166	0.1217	0.1098	0.1195	0.1195	0.1080	0.1176	0.1129	0.1223	0.1110	0.1106	0.1201	0.1136	0.1113
Acq $	242	232	245	233	244	235	223	234	235	246	234	225	235	236	225
DOC/trip	65256	60708	64679	55552	62926	61312	52668	59989	56325	63431	54873	53200	60265	55319	52326
RDT&E	16453	15811	16838	16071	16898	16079	15374	16170	16359	17168	16435	15626	16403	16689	15800

* Economic penalties associated with manufacturing not included, economic metrics are optimistic

TABLE XII: RANKED ALTERNATIVES FOR DIFFERENT WEIGHTING SCENARIOS

	Weighting Factor Scenarios				
Attribute	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
TOGW	0.1	0.1	0.05	0.025	0.025
TOFL	0.25	0.2	0.1	0.1	0.05
LDGFL	0.1	0.075	0.05	0.025	0.025
Vapp	0.1	0.1	0.1	0.1	0.05
FON	0.2	0.2	0.2	0.15	0.15
SLN	0.2	0.225	0.2	0.15	0.15
$/RPM	0.05	0.05	0.1	0.15	0.15
Acq $	0	0.025	0.1	0.1	0.15
DOC/trip	0	0.025	0.05	0.1	0.1
RDT&E	0	0	0.05	0.1	0.15
Best Alternative	14	14	14	14	14
	13	13	13	13	10
	11	10	10	10	13
	10	11	11	11	11
	6	6	12	6	6
	8	8	6	8	7
Worst Alternative	3	12	7	12	12

Finally, as a confirmation of the alternative rankings, Steps 3 through 5 were repeated for Alternative 14 with the technologies fixed and the design variables in Table II allowed to vary. Once again, RSEs for the metrics were generated and Monte Carlo simulations performed. From the conventional design space investigation, the two noise constraints, FON and SLN, had the lowest probability of success with 13.7% and 0%, respectively. In comparison, Alternatives 14 shifted the CDF curve for these constraints into the technically feasible region (to the left of the constraint) as seen in Figure 8 (SLN) and Figure 9 (FON). The design space for Alternative 14 could meet the FON and SLN constraints with 100% of the designs. The shifting of the metric CDF curves was consistent for all metrics. The initial investigation of the "k" factors (Figure 7) showed that the SLN constraint could be met. This step confirmed that the benefits of the particular technologies considered *could* supply the needed enhancements to create a technically feasible alternative. A summary of the probability of success of the six constrained metrics is listed in Table XIII. Alternative 14 could meet all metric targets with 100% probability except for TOFL at 94.9%. Once again, the optimal geometry was determined via the desirability option in JMP. The resulting design parameters are listed in Table XIV and also illustrated in Figure 10 with Alternative 14 represented as the solid body, and the optimal conventional geometry as a wireframe. The variation of the optimal settings is due to the influence of the "simulated" technologies on the converged vehicles. Alternative 14 will be the foundation for future studies in robust design and economic viability investigations.

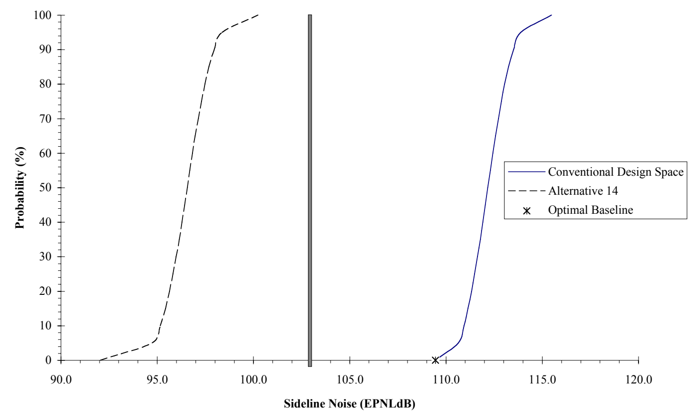

FIGURE 8: CONCEPT COMPARISON FOR SLN

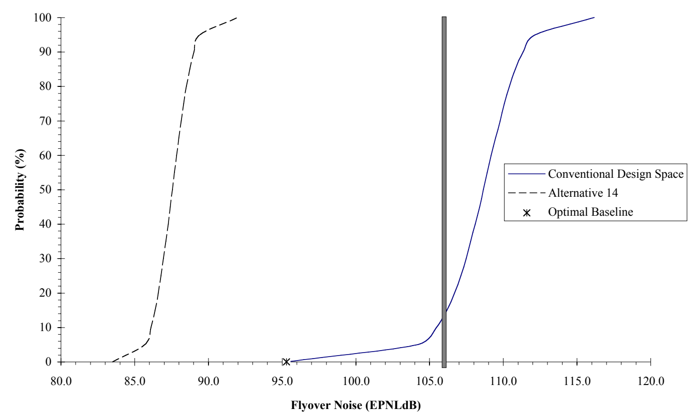

FIGURE 9: CONCEPT COMPARISON FOR FON

TABLE XIII: ALTERNATIVE COMPARISON OF PROBABILITY OF SUCCESS

	Probability of Success	
Metrics	Optimal Conventional Baseline	Alternative 14
Performance		
Vapp	20.1 %	100 %
FON	13.7 %	100 %
Landing FL	95.1 %	100 %
SLN	0 %	100 %
TOFL	35.8 %	94.9 %
TOGW	84.1 %	100 %

TABLE XIV: CONCEPT OPTIMAL GEOMETRY COMPARISONS

Parameter	Optimal Conventional Baseline	Alternative 14
SW	8070 ft^2	8332 ft^2
T/W	0.31	0.295
TIT	3312 °R	3368 °R
FPR	4	4.5
OPR	21	21
CLdes	0.12	0.12
X2	1.615	1.609
X3	2.36	2.36
X4	2.58	2.58
X5	2.37	2.19
X6	2.18	2.18
Y2	0.4659	0.51
t/c_root	5%	5%
t/c_tip	2%	2%
SHref	400 ft^2	400 ft^2
SVref	350 ft^2	350 ft^2

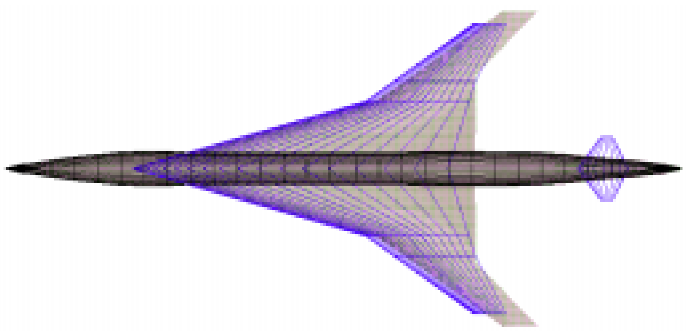

FIGURE 10: GEOMETRIC COMPARISON OF HSCT CONFIGURATIONS

CONCLUSIONS

This paper described a methodology under development at the Aerospace Systems Design Laboratory which is in response to the "design for affordability" initiative sweeping through the aerospace industry. The method focused on the identification, evaluation, and selection of alternative technological concepts in the early phases of the design cycle. The method is called the Technology Identification, Evaluation, and Selection (TIES) method. A comprehensive and structured seven-step method was described which begins at the problem definition and proceeds through to the identification of the best alternative(s) for further study. The TIES method utilizes various techniques developed in other technical/operational/mathematical fields. These techniques include Response Surface Methodology, Morphological Matrix, Pugh Evaluation Matrix, and Multi-Attribute Decision Making.

One of the goals of the TIES methodology was to create a process whereby the decision maker/designer could identify feasible alternatives worthy of further investigation and resource allocation. This goal was achieved through application of the TIES method to a High Speed Civil Transport concept. Each step was implemented and four technologies identified as worthy of further investigation. The technologies include composite wing structures, hybrid laminar flow control for cruise drag reduction, circulation control for low speed flight lift augmentation, and advanced engines for specific fuel consumption and noise emissions reductions. The FAR 36 Stage III sideline noise requirement was shown to be the concept "show-stopper". This constraint could be met with the concept alternative which had all four technologies. All remaining metrics, including field lengths, weight limits, and approach speed, could be achieved with high levels of confidence for the entire design space investigated. Technical feasibility required a 2% reduction in fuel flow, 10% reduction in cruise drag, 10% reduction in noise levels, 20% reduction in wing weight, and a 30% increase in low speed maximum lift coefficient.

Future work in the development of this methodology will be proof of concept studies of economic viability and robust design on various vehicles and the introduction of time dependencies on the decision-making process.

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