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A Technique for Selecting Emerging Technologies for a Fleet of Commercial Aircraft to Maximize R&D Investment

Michelle R. Kirby and Dimitri N. Mavris
Aerospace Systems Design Laboratory
Georgia Institute of Technology

ABSTRACT

A solid business case is highly dependent upon a strategic technology research and development plan in the early phases of product design. The embodiment of a strategic technology development plan is the identification and subsequent funding of high payoff technology programs that can maximize a company's return on investment, which entails both performance and economic objectives. This paper describes a technique whereby the high payoff technologies may be identified across multiple platforms to quantitatively justify resource allocation decisions and investment opportunities. A proof of concept investigation was performed on a fleet of subsonic, commercial aircraft.

INTRODUCTION

For the success of any organization, a solid strategic plan must guide the decision-making process for all spending ventures. "Strategic planning can be defined as a structured process through which an organization translates a vision and makes fundamental decisions that shape and guide what the organization is and what it does."[1] The strategic plan is then compiled into a decision package, in the form of a business case or project request, to justify capital project endeavors. A solid plan includes documentation and analysis that support the proposed investment opportunities, especially with regards to technology development programs.

Unfortunately in the aerospace industry, traditional methods of investment in technology development programs or closing the business case are ad hoc and lack rigor. "Many Research and Development (R&D) selection techniques have been developed in the last 30-40 years, but few have been used by R&D companies in industry. In fact, the methods used aren't much more advanced than two or three decades ago, even though the state of the art has advanced rapidly."[2]

The allocation of resources considered herein is for technology development programs, as applied to potential product development plans. "Product development entails the design and manufacture of a product, such as an airplane, a car, or a satellite, as an end item for delivery to a customer. Technology development fosters technological advances for potential application to a product development."[3] Cetron observes five traditional approaches of allocating R&D resources for technology development [4]:

1. *Squeaking Wheel*: cut resources from every area and then wait and see which area complains the most. Based on the loudest and most insistent, then restore budget until ceiling is hit.
2. *Level Funding*: budget perturbations minimized and status quo maintained; if this approach continues within a rapidly changing technology field, the company, group, or agency will end up in serious trouble.
3. *Glorious Past*: "once successful, always successful". Assign resources solely on past record of achievement.
4. *White Charger*: best speaker or last person to brief the boss wins the money or whichever department has the best presentation.
5. *Committee*: a committee tells the decision-maker how to allocate resources.

Cetron points out that the scientific and objective foundations of these approaches are lacking and naïve, but widely used. Thus, the business case that is developed is lacking in substance and strongly suggests the need for a means by which more informed and substantiated decisions can be made. Froham notes that most R&D technology developments are allocated resources based on past activities, "glorious past" approach, in the specific research area rather than the potential bottom line contributions to the competitiveness of the end product [5]. Short-term funding tends to be the driver for allocating resources which leads to projects and endeavors that are not broader-range or do not have long-term or high payoffs for the particular company [5].

In lieu of the traditional R&D allocation approaches, one should ask the following questions prior to committing scarce R&D resources [6]: Does the technology fit within the companies present and future business strategies and plans? Are the resources, both technical and monetary, available or accessible? Does the technology possess superior performance and/or economical characteristics of which commercial attractiveness is heightened? Will the resources spent on the technology development be recouped as profit when the technology is matured? Are there multiple uses (cross-fertilization) for the technology to reduce investment risks? The focus of the current investigation is to address these issues and provide a means by which product design decisions may be more quantitatively justified and high payoff technologies may be identified rapidly in the early phases of multiple product designs.

BACKGROUND

The goal of any organization's design and development of a new product is to deliver a superior system relative to the current state of the art. The drivers for the new design are to gain market share over a competitor, to provide increased capability for future threats, to respond to various societal needs, or to comply with government regulations. However, to accomplish this end, significant technical advances over the current state of the art capabilities must be pursued and infused to the end product.

Additionally, in lieu of just one product being the focal point for technology infusion, a diverse group of products should be considered to cross-fertilize the technologies and maximize the return on investment. In doing so, the R&D investment cost could be distributed amongst numerous products and the risk of investment minimized for each. In addition, some of the technologies that may have been disregarded for a particular investigation may in fact have a significant impact on different product concepts. Thus, if a company was attempting to identify how to distribute a limited R&D budget, the applicability of a technology across many potential future concepts should be considered in the context of long-term strategic planning.

FORECASTING TECHNICAL ADVANCES - There exist two avenues by which technologies may be infused into a system as depicted in Figure 1. One is to look forward and ask the question: *With the specific technologies that are being developed within the organization today, how will the end product compare to the design specifications of the future or compete with future systems?* This approach is an exploratory forecasting technique that considers current technology development trends and extrapolates into the future to predict what may happen [7]. This approach depends upon the assumption that the progress of a technology will be evolutionary and the R&D funding will be continuous [8]. An approach of this nature was created for specific technology assessments in aerospace systems and is called the Technology Identification, Evaluation, and Selection (TIES) method [9].

The other avenue is to look back in time from the future and ask the question: *What technology developments should be pursued by the organization today to meet or exceed the design specifications or system requirements of the future?* This approach is a normative forecasting method that begins with future goals and works backward to identify the levels of performance or economics needed to obtain the desired goals, if at all achievable with the resources available. This approach was also formalized into a method for aerospace applications and is called the Technology Impact Forecasting (TIF) environment [10,11].

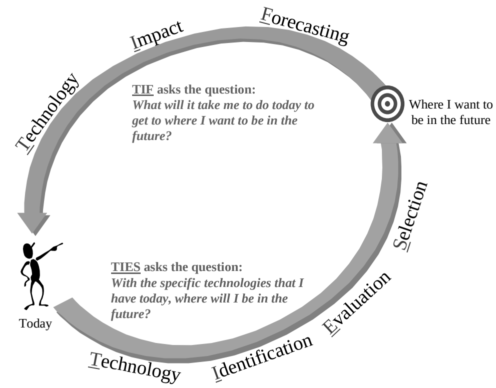

Figure 1: Avenues for Infusing New Technologies

TECHNICAL APPROACH

The technical approach taken herein is a subset of the comprehensive and detailed TIES method described in Reference [9,12,13,14]. The development of TIES focused on the application of a set of technologies for a single vehicle concept and the identification of the highest payoff technology combinations within that set. The method is an eight step process, as shown in Figure 2, which begins with defining the problem, in terms of the customer requirements that drive the product design, to selecting the best family alternatives, in terms of design attributes and technology sets, that best satisfies the customer requirements.

The focus of the current investigation is to extend the current capabilities of the TIES method through an application of a set of technologies across a notional subsonic fleet. For the current investigation, the following steps are excluded: define concept space, investigate design space, and evaluate system feasibility. A brief description of the executed steps is provided for the intended reader's edification.

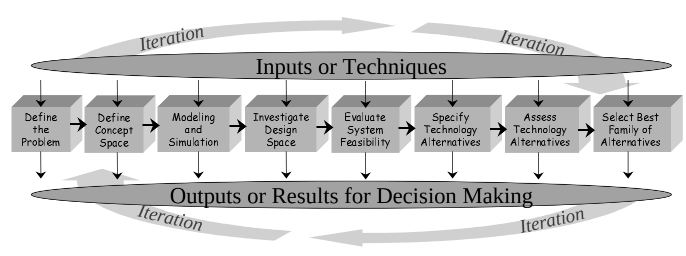

Figure 2: TIES Technical Approach

DEFINE THE PROBLEM - TIES begins with the definition of the problem through a mapping of the customer requirements into quantitative evaluation criteria. For a commercial system, the definition of the customer requirements must capture the needs of the airframe and engine manufacturer, airlines, airports, passengers, and society as a whole through operational and environmental regulations. The requirements may be objectives or constraints and in the context of this research will be defined as system metrics, or a system attribute that is tracked for the purpose of decision-making. In essence, the system metrics are the thresholds by which the system under consideration can be measured as successful. If multiple products are under consideration, each system may have its own set of customer requirements. If the system(s) can meet all imposed metric thresholds, then the system(s) should be considered for launch, else, the program should be cancelled or an alternative system considered.

MODELING AND SIMULATION - In the conceptual stages of product design, a rapid assessment is desired so that trade-offs can be performed with minimal time and monetary expenditures. The advent of the computer has greatly facilitated this objective via Modeling and Simulation (M&S) environments. The Defense Systems Management College defines a model as "a physical, mathematical, or logical representation of a system entity, phenomenon, or process", while a simulation is "the implementation of a model over time…and a simulation brings a model to life and shows how a particular object or phenomenon will behave."[15]

Table I: Required Features Needed for an M&S Environment

Feature	Importance	Purpose
Parametric inputs	High	To quantify outputs in terms of inputs and facilitate the use of Response Surface Methods
Physics based	*Very High*	To analyze and model evolutionary or revolutionary concepts based on desired fidelity and operational environment
Synthesis capability	*Average*	To quantify the various disciplines (aerodynamics, structure, and propulsion) for a given configuration or could use table look-ups created off-line
Mission analysis not constrained	*Very High*	To "size" the system from an algorithm based on physical principles for a given system and provide responses, or customer requirements, in an unconstrained manner so as to employ the use of metamodels
Robust input definition	*High*	To allow for a wide range of configurations or missions to be analyzed
Economic analysis	*Very High*	To immediately quantify the impact of design changes on the economic requirements of the system
Quantifiable responses	*Medium High*	To functionally relate the responses of interest to the variations of inputs
Disciplinary technical metric impact factors	*Very High*	To simulate the discontinuity associated with the addition of new technologies, also called technology "k" factors
Automation capability	*Average*	To facilitate probabilistic design methods and to have a "wrapper" around the tool
Rapid Assessments	*Average*	To facilitate reduced cycle time
Access to source code	*Average*	To modify fidelity or physical principle deficiencies of different disciplines as needed and understand internal control laws or to add technical metric "k" factors

Most companies have an in-house developed M&S environment to perform the design trades. However, *the TIES method is not code specific or system specific*, but, the M&S tool utilized must have some basic features as outlined in Table I. One cannot underestimate the importance of having a cohesive M&S environment. Without this environment, application of the TIES method is arduous and would be qualitative in nature. A principle requirement for any decision making process is the ability to quantitatively assess the customer requirements that drive a design. This can only be achieved through an M&S environment. In fact, the Defense Systems Management College states that use of an M&S environment provides four benefits to the design process and includes cost savings, accelerated schedule, improved product quality, and cost avoidance [15].

A few issues regarding the M&S environment must be addressed to properly implement the TIES method, in particular, a more detailed discussion of some of the features rated with a "very high" importance. First, a physics-based analysis is essential to accurately model the designs of interest. This implies that the level of fidelity desired by the decision-maker must be reflected in the analysis. For example, if one were to consider a derivative of a commercial transport, the analysis of the design must be able to capture, within the desired fidelity, all of the pertinent customer requirements. Thus, the physics governing the evaluation must model the aerodynamics, propulsion, and structures of a subsonic vehicle. If a supersonic vehicle is of interest, the M&S environment must be able to capture the physics associated with supersonic flight. Additionally, if the design were of a hypersonic vehicle, a different set of governing equations must be used. The designer must take into consideration what physics are required to accurately asses the system when creating or identifying the proper M&S environment. Thus, the needed capabilities are problem dependent and should be determined based on the system(s) under consideration and in some instances, may need to be created from scratch.

The unconstrained mission analysis is an important feature required if the Response Surface Methodology (RSM) is to be utilized. "Response Surface Methodology (RSM) comprises a group of statistical techniques for empirical model building and model exploitation. By careful design and analysis of experiments, it seeks to relate a response, or output variable to the levels of a number of predictors, or input variables, that affect it."[16] RSM has been a successful technique for efficiently building and optimizing empirical models of continuous functions since the 1950's in chemical and mechanical engineering, chemistry, and agriculture [17]. The use of RSM provides significant insight to a previously unknown or complicated response behavior in an efficient manner. RSM approximates the dependency of output metrics to input parameters with an empirical polynomial relationship. In general, the approximation is a second order Taylor series model, called a Response Surface Equation (RSE). An assumption made with the RSM approach to model building is that the input parameters are continuous. Thus, if the input to the analysis, based on applying RSM techniques, is modified from the original setting, the accuracy of the resulting model and response behavior would be in question. The modification of an input parameter would occur if the governing equations of the sizing or synthesis algorithm had constraint values, such that the input value was reset or changed to a value other than that which was input during the execution.

The modification due to an internal constraint may originate from limitations of physical principles. For example, an input to an analysis tool may be the inlet temperature to the engine turbine. If the temperature value input to the tool exceeded the allowable temperature of the blade materials, a limitation would be imposed with the intention that the blades do not melt and the input value adjusted to compensate. The physical limitation, or constraint, imposed on the analysis would skew or bias the output results. Although this is the appropriate engineering approach, limitations of this nature may inhibit application of the RSM. A potential solution for this dilemma would be to modify the analysis tool to provide an error message when a physical limitation was violated and state that the results are not physically realizable. At that time, the decision-maker could modify the analysis capability to handle the physics of the problem under investigation or adjust the assumptions of the investigation.

Next, the ability to quantify design changes on the economics of the system is very important, since a key driver for the success of any new design is a measure of the system's affordability. Thus, a means to quantify the affordability as a function of varying design configurations must be created. The economics of an aircraft system are essentially the life cycle costs. The life cycle costs are a summation of the Research, Development, Testing and Evaluation (RDT&E), acquisition price, operation and support costs, and disposal costs. Two approaches to quantifying the RDT&E costs and acquisition price include the use of cost estimating relationships and activity-based costing. The former approach is based on historical trends of component costs as a function of component weights, while the latter is based on the cost of the specific activities associated with the design and production of the system. On the other hand, the operation and support costs are determined based on the acquisition price, stage length, utilization, tax and interest rates, and desired yields over the life of the system. There are many approaches for the determination of operation and support costs, but an ability to quantify the costs must exist to properly capture the operator's expenses and revenues (if applicable) of the system.

Finally, since breakthrough technologies will be infused to the system(s) of interest, an ability must exist to quantify the technology impacts. A standard practice for modeling technologies in the aerospace industry is through incremental changes in disciplinary metrics such as drag, component weights, and fuel consumption within an M&S environment. The incremental changes are determined from more detailed, higher fidelity analysis or experiments at the disciplinary level and rolled up to the system at the decision maker's level. The incremental changes simulate the discontinuities associated with the addition of new technologies. Thus, to model the incremental changes of the disciplinary metrics, a multiplicative factor, denoted as "k" factor or technology impact factor, on those metrics must be added within the synthesis or sizing algorithm. Most analysis tools already have these factors built into the source code as calibration factors. However, if the factors are not inputs to the analysis tool, the internal logic must be modified such that the factors can be input directly.

SPECIFY TECHNOLOGY ALTERNATIVES – If an organization is currently investing in the development of multiple technology R&D programs, a logical strategic plan dictates that potential applications of said technologies be identified in Step 1 of the TIES method. Subsequently, to facilitate the assessment and selection of the most appropriate technology set to meet the customer requirements, the following must be defined:

- Create technology vectors for technology R&D programs that describe the impact to the system(s) of interest
- Create a Technology Impact Matrix (TIM)
- Define a Technology Compatibility Matrix (TCM)

<u>Technology Vectors</u> - For each technology funded or pursued within the organization, an ability must exist to quantify the technology impacts. As mentioned previously, a standard practice for modeling technologies in the aerospace industry is through incremental changes in disciplinary metrics such as drag, component weights, and fuel consumption within a M&S environment. The technology metrics, which defined the impact of the given technology, can be combined into a technology vector, $\vec{k}$. The elements, k_i, of the vector constitute the impact of the specific technology on a specific disciplinary metrics. Each element of the vector has an estimated impact value as established via expert questionnaires as derived from experiments or physics-based modeling [18]. For example, a technologists is developing an arbitrary technology (T1) that is expected to increase cruise drag by 4% (k_{drag} = +4%) while reducing Operation and Support (O&S) costs by 1% ($k_{O\&S}$ = -1%) and RDT&E costs by 2% ($k_{RDT\&E}$ = -2%). The incremental percent changes are *relative to a datum point or a baseline value as declared by the technologist*. Another technologists is developing a technology (T2) that will reduce fuel burn by 3% ($k_{fuel\text{-}burn}$ = -3%) and O&S costs by 2% ($k_{O\&S}$ = -2%). This process continues until all funded technologies are defined.

If information of this nature is collected for each technology development program, one may cross-reference the elements of each technology vector to establish a common set. Thus, the common set defines a *generic technology impact vector*, T_i, for which all technologies under consideration may be defined. In the example above, the generic technology impact vector would be a function of drag, fuel burn, RDT&E costs, and O&S costs, such that

$$T_i = f\,(k_{drag}, k_{fuel\text{-}burn}, k_{RDT\&E}, k_{O\&S})$$

Not all technologies will affect each element of the generic vector, but the vector must capture all the disciplinary metrics that the technologies influence.

For T1, the generic vector would become

$$T1 = f(k_{drag}= +4\%, k_{fuel\text{-}burn}=0\%, k_{RDT\&E}= -1\%, k_{O\&S}= -2\%)$$

When multiple systems are considered for infusion, the impact vector for a given technology *may not* be consistent across platforms. For instance, the impact values defined for T1 above may only be valid for subsonic commercial transports. However, the technology may be applied to supersonic transports but with a different impact vector. To accommodate this situation, a new derivative technology vector should be defined, T1′, which describes the impact of T1 in the new system or operational regime. Additionally, using this nomenclature ensures proper tracking of the impact of like technologies across multiple systems.

<u>Technology Impact Matrix</u> – Each of the specific technology vectors can be combined into a Technology Impact Matrix (TIM). An example matrix for four technologies that influence four technical metrics is shown in Figure 3, where T1, T1′, and T3 affect all impact factors except for the second, while T2 does not affect the first or third. A disciplinary metric reduction from a datum point or baseline is represented as a negative percentage (-%), an increase is a positive percentage (+%), and present day technologies are no change (0% or ~), where present day technologies implies the current state-of-the-art design capabilities. The vectors *must* include benefits *and* degradations to accurately assess the impact of technologies. If significant variations in the product applications of the technology impacts exist, one may need to create a TIM for each product. In general, the TIM will not be an *nxn* matrix nor will the impacts always be percent changes from a baseline value as in this example.

Disciplinary Metrics	Technology Impact Factors	Technologies Considered: T1	T1′	T2	T3
	K-factor 1 (Drag)	+4%	+2%	~	-10%
	K-factor 2 (Fuel burn)	~	~	-3%	~
	K-factor 3 (RDT&E)	-1%	-1%	~	-2%
	K-factor 4 (O&S)	-2%	+1%	-2%	+3%

Figure 3: Example Technology Impact Matrix

<u>Technology Compatibility Matrix</u> – With the technologies specified, physical compatibility rules between technologies are established to prevent non-realistic combinations from biasing the selection process. The compatibility results are formalized in a Technology Compatibility Matrix (TCM). A group of technologists or disciplinary experts familiar with the intended function and application of each of the selected technologies best prepare this matrix. The purpose of this matrix is to eliminate combinations that are not physically realizable and, as a by-product, usually results in a downsizing of the evaluation problem. Incompatibilities arise when technologies are competing for the same application or functionality, one technology severely degrades the intended function or integrity of another, or the technologies are only applicable for a specific product application or operational regime. Additionally, one could have another measure for compatibility that included enabling technologies such that a technology is not physically realizable without an additional technology being developed.

An example TCM is depicted in Figure 4 for three arbitrary technologies (T1,T2,T3) and one technology only applicable in a specific operational regime, T1′. A "1" implies compatibility and a "0" implies incompatibility. It should be noted that the limiting case of compatibility is assumed to be a combination of two technologies. This implies that if two technologies are not compatible, then adding another technology, which may be independently compatible with the others, will not change the compatibility of the first two - the mix of the three would still be incompatible. In this matrix, T1 applied with T2 and T2 with T3 are not compatible mixes. Meanwhile, T1′ is not compatible with T2, just as the case with T1, since it is simply a derivative of T1 with a different operational regime. As an example of functional degradation, a composite wing structure could not have a hybrid laminar flow technology. Due to the nature of composite structures, the micro-holes needed for the boundary layer suction of hybrid laminar flow control would severely compromise the composite matrix and create structural integrity problems. Competing technologies are rather intuitive.

Compatibility Matrix 1: compatible 0: incompatible	T1	T1′	T2	T3
T1	1	0	0	1
T1′		1	0	1
T2			1	0
T3				1

Figure 4: Example Technology Compatibility Matrix

ASSESS TECHNOLOGY ALTERNATIVES - In this step, the specified technologies are applied to the baseline system(s) of interest and the impacts assessed. The evaluation provides data and information to the decision-maker whereby selection of the proper mix of technologies across the systems is performed in Step 8. Yet, generating the data needed to conduct the search is dominated by the *curse of dimensionality*. Depending upon the number of technologies (n) and the number of systems (m) considered, the combinatorial problem could be enormous. If all combinations are physically compatible and assuming only an "on" or "off" condition for all systems, then $m2^n$ combinations would exist. If the computational expense of the analysis is acceptable, a full-factorial investigation could ensue for each system. Yet, if the computational expense is too high (e.g., a finite element analysis), an alternate evaluation method is needed. One potential method is a genetic algorithm formulation. Gen defines genetic algorithms as "a class of general-purpose search methods…which can make a remarkable balance between exploration and exploitation of the search [of the design or technology] space" to find the best family of alternatives [19]. This approach would allow for a reduction in the technology space under examination such that a more detailed investigation could be pursued on a smaller set of technology combinations.

Other traditional techniques for technology assessments for a high number of technologies include: one on-one off, one on at a time, and all on-one off. The one on-one off approach infuses one technology to the system, assesses the impact through changes in the system metrics, and then removes the technology. This process is repeated for each technology, and the changes in the system metrics are tabulated. If a combination of technologies is of interest, the change in the metrics for the individual technologies are summed together for the given combination. The drawback of this approach is that the interactions amongst technologies at the disciplinary level are not captured in the changes to the system metrics since the incremental changes were determined in isolation. The next technique for technology assessments is to infuse one technology at a time until all technologies have been infused and tabulate the changes in the system metrics with the addition of each technology. The identical limitations with the one on-one off technique exist with this approach, however, the order in which the technologies are infused to the system may affect the percentage changes to the system metrics. Finally, the last technique for technology assessments is to infuse all the technologies to the baseline at once and remove one technology at a time and establish the impact to the system metrics as before. Again, the same drawbacks exist in this approach. The limitations of the traditional technology assessment approaches may be overcome with the aid of Response Surface Methods.

Consider the TIM in Figure 3. If one were to put bounds on each impact factor element of the generic technology impact vector, a metamodel in the form of a second-order Response Surface Equation (RSE), Equation 1, could be generated for each of the system metrics for 'n' "k" factors [18].

$$R = b_o + \sum_{i=1}^{n} b_i k_i + \sum_{i=1}^{n} b_{ii} k_i^2 + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} b_{ij} k_i k_j \quad (1)$$

The independent variable ranges, k_i, are defined from the TIM. A summation of all the "+" values (increases to disciplinary metrics) in a given row defines the *upper limit* and summing all of the "-"values (decreases to disciplinary metrics) defines the *lower limit*. Hence, the system metrics can be defined as a function of "k" factors for a fixed geometry using Equation 1 as derived from RSM application. The impact of a technology on a system metric can be evaluated via a simple calculation of Equation 1 with the appropriate technology vector values.

Single Technology Assessment - The impact of a single technology can be evaluated via a calculation of the RSE's with the appropriate technology impact vector values from the TIM. Consider a case where an RSE was generated for 3 "k" factors (k_1=total drag, k_2=SFC, k_3=O&S). If the impact of technology T1 was to reduce drag by 10% ($k_{1,T1}$ = -10%), increase O&S by 3% ($k_{3,T1}$ = +3%), and had no impact on SFC ($k_{2,T1}$ = 0%), the RSE would become

$$R_{|T1} = b_o + \left(\sum_{i=1}^{3} b_i k_i + \sum_{i=1}^{3} b_{ii} k_i^2 + \sum_{i=1}^{2} \sum_{j=i+1}^{3} b_{ij} k_i k_j \right)_{T1} \quad (2)$$

$$R_{|T1} = b_o + b_1 k_1 + b_2 k_2 + b_3 k_3 + b_{11} k_1^2 + b_{22} k_2^2 + b_{33} k_3^2 + b_{12} k_1 k_2 + b_{13} k_1 k_3 + b_{23} k_2 k_3 \quad (3)$$

but, $k_{1,T1}$ = -10%, $k_{2,T1}$ = 0%, and $k_{3,T1}$ = +3%, such that

$$R_{|T1} = b_o + b_1(-10\%) + b_3(+3\%) + b_{11}(-10\%)^2 + b_{33}(+3\%)^2 + b_{13}(-10\%)(+3\%) \quad (4)$$

This procedure is repeated for as many technologies, metrics, and systems under consideration and is virtually an instantaneous calculation.

Multiple Technology Assessment - The evaluation of a combination of technologies assumes that the impacts of the individual technologies are additive. The additive nature was assumed as a valid approach since the technology impacts are modeled at a disciplinary level and the interactions between technologies would be captured. Although other sophisticated techniques could be used to evaluate the impact of multiple technologies, an additive approach was straightforward. Moreover, the interactions amongst different technologies were captured through the simple summation of the corresponding disciplinary factors. At present, no technology combination can be employed that violates this assumption. The assessment of multiple technologies is best explained through example. Consider the RSE example for the single technology case described above. Let T1 and T2 be defined as in Equation 5. Assuming the technologies are additive implies that the impact on a metric due to the combination of T1+T2 is the summation of the individual impact factors and Equation 6 is obtained. The same procedure performed to calculate the single technology is applicable for the new technology vector in Equation 6. The method of calculation may be repeated for all compatible combinations for all systems.

$$T1 = f\begin{Bmatrix} k_{1,T1} = k_{drag} = -10\% \\ k_{2,T1} = k_{SFC} = 0\% \\ k_{3,T1} = k_{O\&S} = +3\% \end{Bmatrix} \qquad T2 = f\begin{Bmatrix} k_{1,T2} = k_{drag} = +3\% \\ k_{2,T2} = k_{SFC} = +5\% \\ k_{3,T2} = k_{O\&S} = -5\% \end{Bmatrix} \quad (5)$$

$$R_{|T1+T2} = f\begin{Bmatrix} k_{1,T1} + k_{1,T2} \\ k_{2,T1} + k_{2,T2} \\ k_{3,T1} + k_{3,T2} \end{Bmatrix} = f\begin{Bmatrix} k_{1,T1+T2} = -10\% + 3\% \\ k_{2,T1+T2} = 0\% + 5\% \\ k_{3,T1+T2} = +3\% - 5\% \end{Bmatrix} = f\begin{Bmatrix} k_{1,T1+T2} = -7\% \\ k_{2,T1+T2} = 5\% \\ k_{3,T1+T2} = -2\% \end{Bmatrix} \quad (6)$$

Populate Decision Matrices - Prior to selecting the highest payoff technologies that respond to the customer requirements, a Decision Matrix (DM) is formed for each product under consideration. The compatible technology alternatives form the rows and the systems metrics populate the columns. A single matrix may be created for all the products or a DM may be created for each product. The decision matrices will be manipulated in the selection process.

SELECTION OF BEST FAMILY OF ALTERNATIVES – For any multiple attribute, constraint, or criteria problem, the selection of the "best" family of alternatives is inherently subjective due to the personal preferences of the final decision-makers. As a result, no single answer will ever exist that fulfills all requirements. Since the identification of the highest payoff technologies is the goal for a strategic technology R&D plan, a cross-section of different selection techniques should be used to capture the decision-maker's subjectivity and guide the allocation of R&D resources. Three techniques are utilized herein and include:

1. Technology Sensitivities
2. Multi-Attribute Decision-Making techniques
3. Technology Frontiers

<u>Technology Sensitivities</u> - The decision-maker may desire insight to the sensitivity of the system metrics to the technologies. This can be accomplished with a full-factorial evaluation of the technologies. A full factorial procedure based on 2 levels - "on" and "off", constitutes $m2^n$ evaluations for "n" technologies and "*m*" systems. Although this may appear to be an enormous amount of technology combinations to consider, the power of representing the system metrics as a RSE is evident since the required execution time for a single technology combination is on the order of 10^{-4} seconds using Microsoft Excel® on a 750MHz personal computer.

The commercial statistical program, JMP© [20], may be used for visualization of the technology sensitivities with the Prediction Profiler feature. An example Prediction Profiler is shown in Figure 5 and depicts the *prediction traces* for each technology impact. The prediction trace is defined as the predicted response in which one variable (or technology) is changed while the others are held at their current values, effectively, it shows the sensitivity of the response to the input variables. In the dynamic environment, moving the vertical hairline with the mouse turns "on" or "off" the technology and JMP® recomputes the underlying functional relationship and updates the prediction traces and values. Effects of the technologies in the Prediction Profiler are evaluated based on the magnitude and direction of the slope. The larger the slope, the greater the influence of a given technology. If a technology does not contribute significantly to the system metrics, the slope is approximately zero. The sign of the slope, either positive or negative, depicts the direction of influence of the technology. As a technology is turned "on" or "off", the slope of the other technologies will change if an interaction exists. The interactions amongst the technologies are inherent in the functional relationship behind the Prediction Profiler. Although for the technology sensitivities, a full factorial functional relationship is established, inherent behind that relationship are the original RSE's as described previously.

A couple of interesting aspects of information can be obtained from the technology sensitivities. First, one can evaluate how much fidelity is required in an analysis tool to model a technology or the accuracy of an experimental result. For example, since T2 minimally affects the performance metrics, a lower fidelity analysis code or a simplified experiment could be used to predict the performance impact of T2 due to the very small prediction trace slope as seen in Figure 5. However, a higher fidelity analysis code or a detailed experiment should be used to quantify the impact of T1 due the higher sensitivity of the metrics to this technology. The slopes of the prediction traces inform the decision-maker which technology impact values need to be "nailed" in the analysis to minimize the influence of code fidelity to the technological uncertainty. Also of importance from the technology mapping is the effect that degradation in technology performance would have on the operational life of the system. For example, an arbitrary technology was infused to reduce performance metric 1 and was designed for a specific threshold value. If the ability of that technology to reduce that performance metric were to degrade rapidly over the life of the vehicle, one may interpret that the performance expectations might not be met as the technology degrades due to the large sensitivity of the performance metrics to the impact of T1.

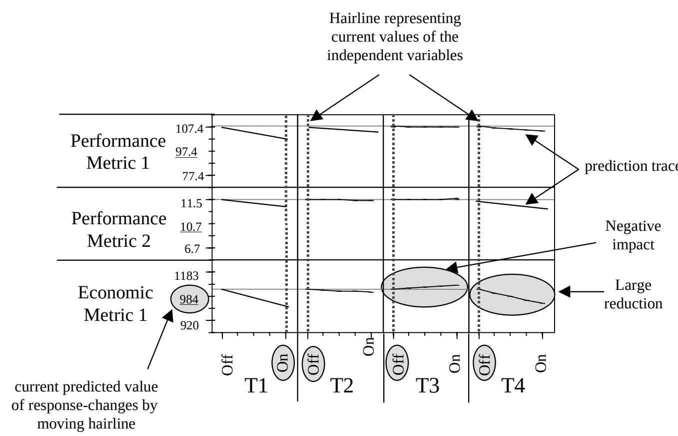

Figure 5: Sample Technology Sensitivities

<u>Multi-Attribute Decision-Making (MADM) techniques</u> - MADM techniques are product selection techniques in which the multiple attributes are processed to arrive at a single choice for the best product. Within the MADM category, the means by which the attributes are processed may be classified as noncompensatory or compensatory. Noncompensatory models *do not* allow for trade-offs between attributes and "comparisons are made on a criterion by criterion basis."[21] This category is not applicable for the current research since the aircraft design, or any complex systems design, problem inherently involves trade-offs amongst attributes. In contrast, compensatory models *do* permit attribute trade-offs. With these models, a single number is usually assigned to each multidimensional characterization representing a design alternative. Based on the manner in which this number is calculated, MADM techniques may be further decomposed into scoring models, compromising models, or concordance models [22].

Scoring models are based on the principle that the design alternative with the highest score of a user-defined utility function is the best alternative. These models are popular for subjectively evaluating multiple objectives [23]. Some examples of scoring models include simple additive weighting and hierarchical additive weighting. Compromising models select an alternative that is closest to an ideal solution based on various algorithms and include TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) and LINear programming techniques for Multidimensional Analysis of Preference. Finally, a concordance model arranges a set of preference ranking which most satisfies a given concordance measure and include permutation method, linear assignment method, and Elimination et Choice Translating Reality [22].

One particular MADM technique that is very simple and easy to implement is TOPSIS [22]. TOPSIS is based on the notion that the best alternative amongst a finite set should have the shortest Euclidean distance to the ideal solution and farthest from the negative-ideal solution. TOPSIS provides a preference order of the values contained in the DM resulting in a ranking of the best alternative concepts. However, the numerical values obtained from the ranking of design alternatives are not intuitive to the decision-maker, especially for visual representations.

<u>Technology Frontiers</u> – Technology Frontiers are defined as the limiting threshold of an intuitive "effectiveness" parameter. An Effectiveness Parameter (EP) is a user-defined utility function for which maximization is desired and preference of the different criteria is introduced through weighting factors. Two intuitive parameters may be defined as Performance Effectiveness (PE) and Economics Effectiveness (EE). Examples of performance parameters include weight, range, speed, etc., while economic parameters include acquisition price, ROI, and so on. Subjectivity is introduced through weights on each criterion that defines the PE and EE.

Once the PE's and EE's are determined for each alternative, the technology space for each product may be compared. This approach is similar to the notion of "system cost effectiveness" proposed by Mavris [24], which is the ratio of the benefit to the system, in terms of PE, relative to the cost of achieving those benefits, in terms of EE. A similar approach to TOPSIS can be used to define the ideal solution for the technology space. A "best compromise" solution may be established based on the technology alternative that is closest to the ideal solution. The "best compromise" solution is similar to a Pareto optimal solution which implies that one system metric cannot be improved any further without degrading another [25]. Finally, the Technology Frontier is established by placing a threshold curve around all of the technology alternatives and is analogous to a Pareto front [26]. The frontier implies that no alternative falls outside of the established boundary.

<u>Identification of Highest Payoff Technologies</u> –The highest payoff technology combinations are readily identified from a comparison of the different selection techniques. In previous applications of the TIES method, dominant technologies have appeared regardless of the selection method used [14]. An interesting result of the current investigation is to determine if this trend is constant for multiple products. Once the highest payoff technologies are identified through this process, a decision-maker has quantitative justification for the continued development of those technology R&D programs. Unlike the traditional methods of resource allocation mentioned previously, the approach taken here is more rigorous and quantitative, such that investment decisions made regarding a particular technology development may be justified and tracked.

IMPLEMENTATION

A proof of concept investigation was performed on a fleet of subsonic commercial aircraft to test the validity of the TIES approach for multiple systems and identify any short-comings of the matured approach.

DEFINE THE PROBLEM – In 1997, Daniel Goldin, the NASA Administrator, gave a speech entitled "The Three Pillars of Success for Aviation and Space Transportation in the 21st Century" [27]. The focus of this speech was to provide a roadmap to focus U.S. aerospace endeavors for the next 20 years in accordance with the changing environment of future aviation and access to space. In the "Three Pillars for Success" program that followed, the pillars were concentrated on Global Civil Aviation, Revolutionary Technology Leaps, and Access to Space.

Under the Global Civil Aviation pillar, the affordability goal focus was to reduce the cost of air travel by 25% in 2007 and 50% in 2022 from the levels achievable in 1997. The two system metrics that defined the affordability were the acquisition price (Acq$) of future vehicle systems and the Direct Operating Cost plus Interest (DOC+I). The Acq$ represents the cost to manufacture the aircraft, including engine price, and the profit margin for the airframe manufacturer. DOC+I constitutes approximately 55% of the passenger ticket price and includes: flight and cabin crew salaries, engine and airframe maintenance, fuel and APU costs, insurance, depreciation, interest, and landing fees. For this investigation, the customer requirements were defined by specifically, reduction of Direct Operating Costs plus Interest (DOC+I) and acquisition cost in 10 years and 25 years in the future. The system metrics, including technical and economic, of interest to this investigation are outlined in Table II.

Table II: System Level Metrics

Parameter	Target/ Constraint For 10 year goal	Target/ Constraint For 25 year goal
<u>Technical</u>		
Approach Speed (Vapp)	130 kts	130 kts
Landing Field Length (LdgFL)	7,000 ft	7,000 ft
Takeoff Field Length (TOFL)	7,000	7,000 ft
Takeoff Gross Weight (TOGW)	minimize	minimize
<u>Economic</u>		
Acquisition Price (Acq $)	-25%	-50%
Research, Development, Testing, and Evaluation Costs (RDT&E)	minimize	minimize
Average Required Yield per Revenue Passenger Mile ($/RPM)	minimize	minimize
Direct Operating Cost plus Interest (DOC+I)	-25%	-50%

In the “Three Pillars for Success” program, a multitude of notional vehicle concepts have been considered as benchmarks for all research efforts within NASA. Four of those systems are considered herein and are derived from an existing subsonic commercial fleet. The vehicles include a long range Boeing 777-200 class (300pax), a medium range intra-continental Boeing 767-200 class (225pax), an intra-continental Boeing 737-800 class (150pax), and a short range Embraer-190-100 class (100pax). A description of the major attributes of each vehicle is listed in Table II.

MODELING AND SIMULATION - All aircraft sizing and analysis tasks for this study utilized the FLight OPtimization System, FLOPS, a multidisciplinary system of computer programs used for the conceptual and preliminary design and analysis of aircraft configurations [28]. This tool was developed by the NASA Langley Research Center. FLOPS was linked to the Aircraft Life Cycle Cost Analysis, ALCCA, program used for the prediction of all life-cycle costs associated with commercial aircraft. ALCCA was originally developed by NASA Ames and further enhanced by Aerospace Systems Design Laboratory (ASDL) [29]. The combination of FLOPS and ALCCA meets the required features necessary for a good M&S environment as outlined in Table I.

The economic assumptions used in this study are summarized in Table IV and the baseline metric values for each aircraft are listed in Table V as obtained from a FLOPS/ALCCA simulation. The baseline configurations can meet all imposed technical constraints, except for the 300pax takeoff Field Length. The economic metric values are the points of departure for technology infusion. That is, the Acq$ and the DOC+I target values for the future are percent reductions from the baseline values listed.

SPECIFY TECHNOLOGY ALTERNATIVES - To improve the affordability of the current systems, specific breakthrough technologies must be infused. To accomplish this end, applicable technologies or programs must be identified. For this investigation, 11 technologies were provided from NASA Langley under grant NAG-1-2235. The 11 technologies and the intended function are listed in Table VI.

Each of the technologies under consideration is not a fully matured technology, where maturity is defined with a qualitative scale known as the Technology Readiness Level. (TRL) [30,31]. The TRLs describe the maturation and development process of a technology and provide a basis by which different technologies can be compared as they progress through the gates of maturation. In general, the impact of a technology is probabilistic in nature, even possibly stochastic. The probabilistic nature arises from various contributing factors. If the technology to be applied has not matured to the point of full-scale application, the primary impact on the system is not certain and must be estimated via an analysis tool or an experiment. Each impact estimation introduces uncertainty to the system. An extensive investigation was performed by Kirby to quantifying the impact of technological uncertainty [9]. In the current investigation, the technological impacts are assumed to be deterministic, or “theoretical” values.

Technology Vectors - For each of the technologies listed in Table VI, the primary benefits to a 150 passenger aircraft were supplied by NASA Langley under grant NAG-1-2235. However, the penalties associated with each technology were estimated based on the description of the technology and potential integration difficulties to the actual system.

Table III: Aircraft Attributes

Attribute	100 Pax	150 Pax	225 Pax	300 Pax
Design Range (nm)	1,500	3,000	6,000	7,500
Cruise Mach #	0.8	0.785	0.8	0.85
Max Cruise Altitude (ft)	40,000	40,000	40,000	40,000
Engine Thrust Class (lbs)	20,230	25,805	58,469	85,199
Wing Area (ft^2)	885	1,310	3,090	5,912
First Class passengers	8	12	18	24
Tourist Class passengers	92	138	207	276
Economic Range (nm)	500	1,000	2,000	3,000
Daily utilization (hrs/day)	8.09	10.69	13.46	14.58

Table IV: Economic Assumptions

Parameter	Value	Parameter	Value
Airframe spares (% of airframe price)	6%	Fiscal year dollars	1996
Airline ROI	10%	Fuel cost	$0.70/gal
Average annual inflation	8%	Hull insurance (% aircraft price)	0.35%
Residual value	10%	Manufacturer learning curve	78%
Downpayment	0%	Passenger load factor	65%
Economic life	20 years	Maintenance burden (% direct labor)	200%
Engine spares (% of engine price)	6%	Maintenance labor rate	$25/hr
Engine units produced	2000 units	Manufacturer ROI	12%
Engineering labor rate	$89.68/hr	Airframe units produced	800 units
Entry into service date	2006	Tooling labor rate	$54.68/hr
Financing period	20 years	Years of production	15 years

Table V: System Level Metrics

Parameter	100 Pax	150 Pax	225 Pax	300 Pax
Performance				
Vapp (kts)	121.9	106.2	109.8	112.9
LdgFL (ft)	5627	4873	5038	5179
TOFL (ft)	6114	5304	6804	7181
TOGW (lbs)	100372	146899	376344	681734
Economics				
Acq $ ($M FY96)	48.337	58.735	105.613	162.321
RDT&E ($M FY96)	3912.4	4681.7	8273.9	13057.6
$/RPM ($ FY96)	0.22621	0.14409	0.14071	0.12804
DOC+I (¢ FY96)	8.961	5.455	5.811	5.243

Technology Impact Matrix - The Technology Impact Matrix (TIM) was constructed for the 11 technologies. The TIM, shown in Table VII, contains the predicted impact values if each technology were matured to the point of full-scale application (TRL of 9). The values shown were assumed to be the "theoretical" upper limits of the technologies. The elements of the technical impact factor vector are listed on the left. The elements encompassed all technology impacts, although not all technologies contributed to every element. The technical impact vector consisted of 12 elements and included benefits and degradations to both performance and economic metrics. For example, the infusion of a composite wing could reduce the sized vehicle wing weight by 15% and the cruise drag (due to a smoother wing surface) by 2%. Yet, the costs associated with manufacturing and maintaining this type of wing were more than a conventional aluminum wing structure due to increased complexity. This penalty was simulated with increased Research, Development, Testing, and Evaluation (RDT&E), production, and Operation and Support (O&S) costs. Except for T5 and T9, no explicit economic impacts were found regarding the other technologies. Thus, an educated "guesstimate" impact to the economic metrics was assumed for these technologies.

Technology Compatibility - Once the technologies were identified, physical compatibility rules between technologies were established and formalized in a Technology Compatibility Matrix (TCM). The compatibility rules for these technologies were determined from brainstorming activities and literature reviews and are listed in Table VIII. If all the technologies were compatible, 2,048 combinations would exist. Only 288 technology combinations existed after the compatibility logic was applied.

ASSESS TECHNOLOGY ALTERNATIVES - A metamodel, or RSE, was created for each system metric defined in Table II via a Design of Experiments by bounding the impact vector element ranges in the TIM as listed in Table IX. The "0" implies no change in the technical metric while a negative value denotes a reduction and a positive value an increase from the baseline values. Once Equation 1 was determined for each vehicle metric, the RSEs were used to rapidly evaluate the impact of the various technologies based on a particular impact vector setting in lieu of executing FLOPS/ALCCA directly. References [9,12,13] provide a more detailed description of the use of Response Surface Methods for technology assessments.

Since the vehicle metrics were modeled as RSE's, a full factorial investigation was pursued due to the speed with which a technology alternative could be evaluated. Additionally, a decision matrix was created for each vehicle for only the compatible technology combinations. Each matrix was 288 by 8, where 288 represented the number of alternatives and 8 the number of system metrics.

Table VI: Technologies to Infuse

(Identifier) Technology	Purpose
(T1) Composite Wing	Total wing weight reduction
(T2) Composite Fuselage	Total fuselage weight reduction
(T3) Natural Laminar Flow Control	Drag reduction through natural shaping of the wing
(T4) Hybrid Laminar Flow Control	Drag reduction with boundary layer suction and wing shaping
(T5) Advanced Subsonic Technology (AST) Engine	Improved fuel efficiency and weight reduction
(T6) IHPTET Engine	Improved fuel efficiency and weight reduction
(T7) Antenna Systems	Reduced excursion drag
(T8) Russian Aluminum Lithium fuselage skin	Alternative material for fuselage skin weight reduction
(T9) Integrally Stiffened Aluminum Wing Structure	Manufacturing process to reduce wing weight and production costs
(T10) Active Load Alleviation on Wing	Reduce flutter and wing weight through wing shaping
(T11) Active Load Alleviation on Tail	Reduce flutter and tail weight through tail shaping

Table VII:Technology Impact Matrix for Subsonic Fleet

Technology Impact Factor	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11
Wing Weight	-15			+4					-15	-5	
Fuselage Weight		-25						-2			
Subsonic Fuel Flow				+1	-10	-5				+0.5	
Total Drag	-2	-2	-5	-10			-1				
Avionics Weight							-45			+5	+2
Engine Weight				+0.5	-30	-20					
Electrical Weight				+2	+3					+10	+3
Empennage Weight											-5
O&S costs	+2	+2		+3	-3	-3		+2	-2	+2	+2
RDT&E costs	+2	+2	+2	+4	-4	+3	+1	+2		+3	+3
Production Costs	+10	+10	+1	+1	-3			+2	-2.5		
Utilization	-2	-2		-2	+3	+2			+2	-2	-2

Table VIII: Technology Compatibility Matrix

Compatible (1): Incompatible (0)

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11
T1	1	1	0	0	1	1	1	1	0	0	1
T2		1	1	1	1	1	1	0	1	1	1
T3			1	0	1	1	1	1	1	0	1
T4				1	1	1	1	1	0	0	1
T5					1	0	1	1	1	1	1
T6						1	1	1	1	1	1
T7			Upper Triangular				1	1	1	1	1
T8			Matrix					1	1	1	1
T9									1	1	1
T10										1	1
T11											1

Table IX: Bounded Nondimensional Impact Factors

Technology Impact Elements	Minimum	Maximum
Wing Weight	-35%	+4%
Fuselage Weight	-27%	0%
Subsonic Fuel Flow	-15%	+1.5%
Total Drag	-20%	0%
Avionics Weight	-45%	+7%
Engine Weight	-50%	+0.5%
Electrical Weight	0%	+18%
Empennage Weight	-5%	0%
O&S costs	-8%	+13%
RDT&E costs	-4%	+22%
Production costs	-5.5%	+24%
Utilization	-10%	+7%

SELCTION OF BEST FAMILY OF ALTERNATIVES – The best alternatives to respond to the affordability goals were established from a balance of the three selection approaches: technology sensitivities, MADM techniques, and technology frontiers. The result of each approach is described below.

Technology Sensitivities - The Prediction Profiler for the full-factorial combination of the 11 technologies is depicted in Figure 6. The decision-maker can readily identify the technologies that most significantly impact the system metrics. For the technologies considered, T5 provided the most substantial benefits for all metrics, both performance and economic. In general, this is not the case. T1 and T2 have opposing impacts where the reductions in performance were countered by increases in the economics as would be expected from the technology impact vectors that describe both T1 and T2. T5, T6, and T9 provided the most positive impact of the 11 technologies considered.

The 10 year goal for the percent reduction from the baseline values for the fleet was 25%. As is evident, only the 225pax and 300pax can achieve the 10 year goal for the DOC+I with some mix of technologies. Unfortunately, the 25 year goal of a 50% reduction in the economic metrics *cannot be achieved* with any mix of technologies, even incompatible combinations. If the goals are rigid targets that cannot be relaxed, the decision-maker has a few options. First, different technologies could be pursued that could further improve the vehicle systems. Or, the decision maker could raise the bar on the currently funded technologies to obtain higher levels of impacts. For example, the Advanced Subsonic Technology engine (T5) is a significant contributor to the reduction of Acq$ and DOC+I. At present, the primary impact is to reduce fuel flow by 10% and engine weight by 30%. If the two impacts could be pushed to more aggressive values, the gap between what is achievable and what is desired would be reduced. Since the 10 and 25 years goals cannot be achieved with the technology set considered, the selection of the best mix of technologies across the fleet focused on the identification of which mix was closest to the goals.

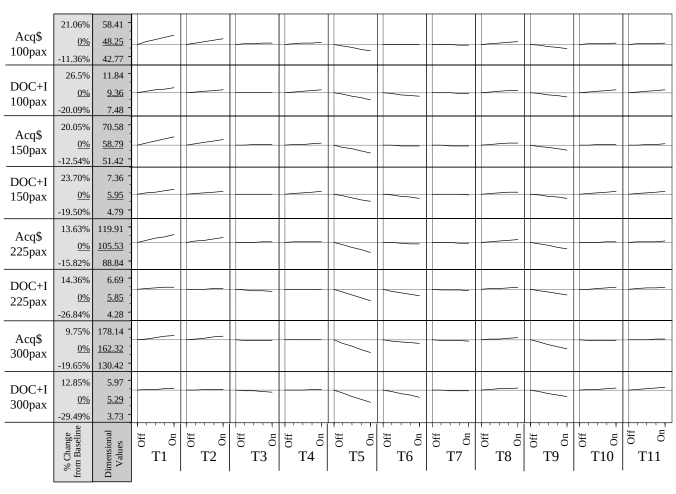

Figure 6: Full Factorial Technology Impact

The usefulness of a TIES approach to technology assessments over traditional techniques is evident. TIES provides a realistic technology assessment to substantiate critical program decisions, such as:

- “Should the company continue to fund the current set of technologies, although they are not providing the needed improvements, or find alternate technologies?”
- “Should the company fund the current set of technologies and demand that a higher level of performance be obtained from each?”
- “Are the goals of the future set too high?”

MADM Techniques – For the current study, the TOPSIS technique was applied to the four decision matrices to identify the best mix of technologies. Each metric was classified as a “cost” since minimization was desired. Various weighting scenarios were considered in the ranking process, and ranged from heavy performance to heavy economics, as listed in Table X. This approach simulated the subjectivity of the decision-maker. Note, $/RPM was not given any preference in this instance. Some interesting results were obtained from applying TOPSIS. First, the top 20 of the 288 compatible technology combinations were compared for each vehicle weighting scenario. The same 6 combinations ranked in the top 20 regardless of the weighting scenario as listed in Table XI. Although the absolute ranking order and closeness to the ideal solution varied, the same technology mixes appeared. The six technology combinations were compared based on the relative closeness values for all 10 weighting scenarios to determine the “best” compromise solution across the scenarios and the fleet.

Table X: TOPSIS Weighting Scenarios

	Preference Weighting Scenario									
	Heavy Performance →								Heavy Economics	
Metric	1	2	3	4	5	6	7	8	9	10
Vapp	0.2	0.2	0.15	0.1	0.1	0.1	0.05	0.05	0	0
LdgFL	0.3	0.2	0.2	0.2	0.15	0.1	0.05	0.05	0.05	0
TOFL	0.25	0.2	0.2	0.15	0.15	0.1	0.1	0.05	0.05	0
TOGW	0.25	0.2	0.2	0.15	0.15	0.1	0.1	0.05	0.05	0
Acq$	0	0.1	0.15	0.15	0.15	0.2	0.25	0.3	0.3	0.5
RDT&E	0	0	0	0.1	0.15	0.2	0.2	0.2	0.25	0
$/RPM	0	0	0	0	0	0	0	0	0	0
DOC+I	0	0.1	0.1	0.15	0.15	0.2	0.25	0.3	0.3	0.5

Table XI: Dominant Technology Mixes Across the Fleet

Concept Number	Technology Mix	Scenarios that Concept Ranked
69	T5+T9	Economic
85	T5+T7+T9	Economic
325	T3+T5+T9	Economic
341	T3+T5+T7+T9	All
597	T2+T5+T7+T9	All
853	T2+T3+T5+T7+T9	All

A spider chart or radargram is an appropriate visualization tool for the TOPSIS scenarios across the fleet. A sample of a radargram result for combined TOPSIS weighting scenarios #5 and #10 is depicted in Figure 7. The most significant technology combination was the mix that maximized the radargram area. For the weighting scenarios considered, the "best" compromise solution was the combination of T3, T5, T7, and T9. The inclusion of T5 and T9 was an expected result based on the sensitivity of the metrics to the two technologies in Figure 6. The next best combination was T5+T7+T9. A comparison of the influence of the preference of the different criteria is evident with the shift in Euclidean distance toward an ideal solution value of 1 for weighting scenario #10 which had only two criteria; unlike scenario #5 which decreased in Euclidean distances since more compromise was made for multiple criteria (7 criteria) than scenario #10. The radargram is a very visual means of rapidly identifying the highest payoff technology mix across various weightings of the attributes.

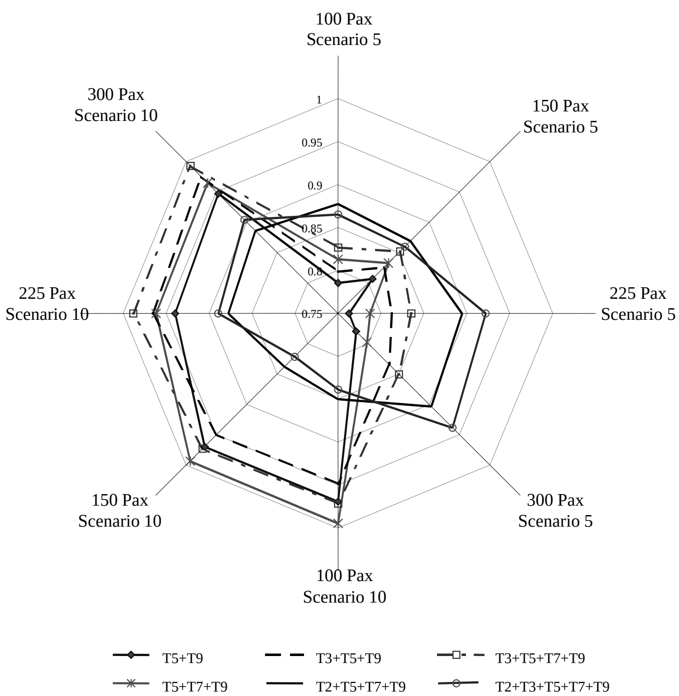

Figure 7: Radargram of TOPSIS Weighting Scenario #5

Technology Frontiers – The technology frontier technique was applied to the four decision matrices, one for each vehicle. The performance effectiveness parameter, PE, was defined as a function of Vapp, LdgFL, TOFL, and TOGW, and the economic effectiveness parameter, EE, was defined using RDT&E, Acq$ and DOC+I. Subsequently, a simplified additive weighting utility function was used to represent the Effectiveness Parameters. The PE was defined as:

$$PE_{Alt_i} = \frac{1}{4}\frac{Vapp_{BL}}{Vapp_{Alt_i}} + \frac{1}{4}\frac{LDGFL_{BL}}{LDGFL_{Alt_i}}\frac{1}{4}\frac{TOFL_{BL}}{TOFL_{Alt_i}} + \frac{1}{4}\frac{TOGW_{BL}}{TOGW_{Alt_i}}$$

Similarly, the EE was defined as

$$EE_{Alt_i} = \frac{1}{5}\frac{Acq\$_{BL}}{Acq\$_{Alt_i}} + \frac{1}{5}\frac{RDT\ \&\ E_{BL}}{RDT\ \&\ E_{Alt_i}} + \frac{2}{5}\frac{DOC + I_{BL}}{DOC + I_{Alt_i}}$$

The PE was equally weighted since all configurations could meet the imposed technical requirements and each metric was of equal importance. However, the EE was weighted more heavily towards DOC+I, since the Acq$ and the RDT&E were only capturing the manufacturing portion of the affordability of the fleet.

With the technology frontier approach, the affordability, or system cost effectiveness, could be quantified as the ratio of benefit supplied to the system, in terms of PE, to the cost to achieve that effectiveness in terms of EE. Hence, the affordability of the technology combinations considered could be compared based on the PE values versus the EE values and a technology frontier representing the system affordability could be established. The PE and EE for each compatible alternative and each vehicle was calculated. The 300pax technology frontier is shown in Figure 8. The alternatives were grouped by how many technologies were contained within the alternative, i.e., 1 to 6 technologies. The maximum value of PE (1.2673) and EE (1.2693) determined the "ideal" solution.

A few interesting results were obtained from the technology frontier. Clusters of alternatives were evident that shared the same number of technologies. All of the combinations that had 2 technology were clustered at low PE values and had a moderate range of EE. The group cluster increased in PE and varied over a larger range of EE as the number of technologies increased. This trend was also evident with the combinations that had 5 technologies. This result was anticipated since the addition of more technologies should increase the benefit to the system. This trend was consistent across all vehicles. The "best compromise" technology combination was determined based on the closeness to the ideal solution. For the 300pax vehicle, the combination of T2+T3+T5+T7+T9 maximized the system cost effectiveness.

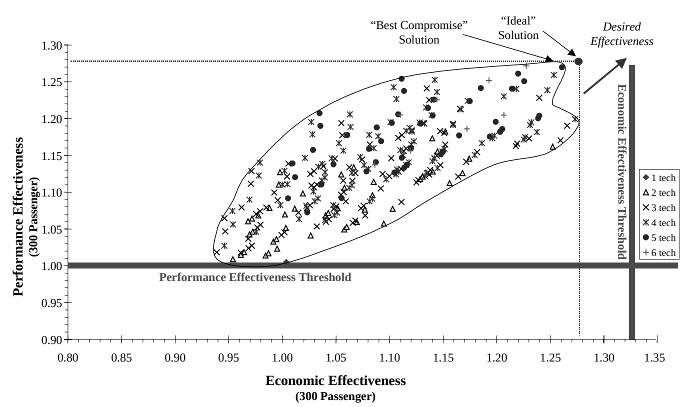

Figure 8: Technology Frontier for 300pax Vehicle

For each of the vehicles, the frontiers were compared to determine how the technology payoffs varied across the vehicles as shown in Figure 9. For the lower capacity vehicles, the payoff of the technology infusion was relatively small in terms of effectiveness parameters. At larger capacities, the payoff was much more substantial as the frontiers shift to higher values. The “ideal” solution for each vehicle frontier was established from the maximum of both the PE and the EE values within the decision matrices. Interestingly, two alternatives were the “best compromise” solutions for each frontier and included a mix of T2+T3+T5+T9 and T2+T3+T5+T7+T9. For the 100pax and the 150pax, the combination of T2+T3+T5+T7+T9 provided the most benefit, while for the 225pax and the 300pax, the combination of T2+T3+T5+T9 provided the most payoff. As with the case with the technology sensitivities and the MADM approach, T5 and T9 appeared in all the high ranking technology alternatives across the fleet. One could infer that the benefit of these technologies is substantial across multiple platforms.

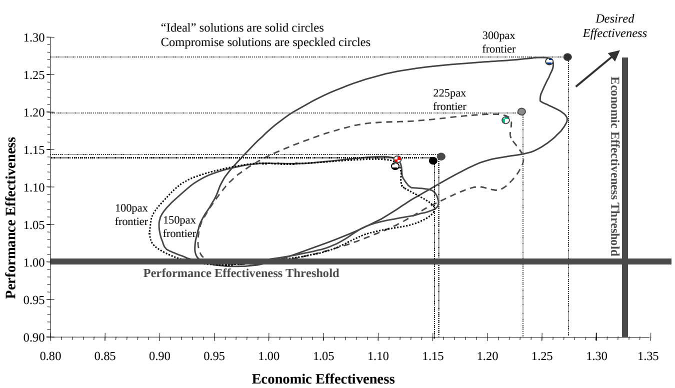

Figure 9: Fleet Comparison of Technology Frontiers

Highest Payoff Technologies - The three selection approaches resulted in the following “best” alternatives:

Technology Sensitivities

Result also showed that T5 and T9 provided the most benefit, while T1 and T2 degraded the affordability

MADM (TOPSIS):

Highest performers across all preference weighting scenarios were T3+T5+T7+T9, T2+T5+T7+T9, T2+T3+T5+T7+T9

Technology Frontiers:

Two major payoff combinations across all vehicles were a mix of T2+T3+T5+T9 and T2+T3+T5+T7+T9

From the three selection approaches, four technologies were identified as significant contributors to the fleet. The technologies are Natural Laminar Flow Control (T3), Advanced Subsonic Technology engine (T5), Antenna Systems (T7), and Integrally Stiffened Aluminum wing structure (T9). The explanation of the payoff of these technologies can be determined from the TIM in Table VII. Each of the four technologies provided technical improvements with no significant cost penalties. However, none of the technology combinations considered herein can meet the 10 year or 25 year affordability goals. Thus, the decision maker has two options. First, the affordability goals of the future could be relaxed, but this is not a viable option from a strategic marketing perspective. The alternative path should be taken and includes identification of more aggressive technologies to infuse to the vehicle concept.

A Final Comparison – Traditional techniques for technology assessments for strategic decision making were mentioned previously. A simple comparison of one of the significant technology combinations across the fleet to the traditional methods provided some insight as to the accuracy of traditional assessments to the method presented herein. Specifically, the one on-one off, one technology at a time, and finally, the approach utilized for the current investigation were compared. The technology combination consisting of T3+T5+T7+T9 was used as the point for comparison. For each approach to assessing the technologies, the end percent change of each system metric in Table II was determined and compared. In general, the difference between the approaches for technical metrics was relatively low. However, for the economic metrics, the difference between the approaches varied more substantially, as shown in Figure 10. For the 300pax vehicle, the difference between the technology assessment approaches was more significant than for the 100pax. One might conclude that a four or five percent difference in the approaches is insignificant and the evaluator’s preference would be the ultimate factor. However, the difference between the technology assessment approaches will likely vary significantly when technological uncertainty is introduced, especially with large variations in the maturity levels of the diverse technologies.

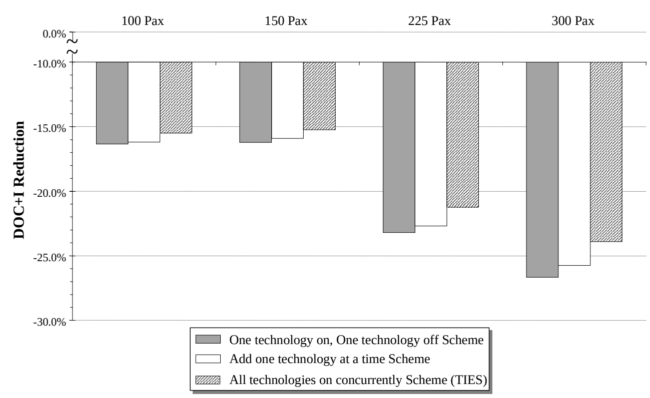

Figure 10: Technology Assessment Approaches

CONCLUSION

An approach was presented to guide the decision-maker and quantitatively justify decisions so as to create a more rigorous and solid business case for strategic technology development planning across multiple systems. A matured TIES method was extended to a new application and provided insight as to the effect of a set of technologies across a fleet of aircraft systems. Future efforts of the research will be to investigate the impact of technological uncertainty across the fleet and identify any short-comings of the TIES approach to technology assessments.

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