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Method to Assess Commercial Aircraft Technologies

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Increasing competition in the commercial aircraft industry requires that airframe manufacturers be judicious with technology research and development efforts. Currently, technology development strategies for commercial aircraft appear to be lacking; a methodology is presented to assess new technologies in terms of both cost and performance. This methodology encompasses technologies that can be applied to the aircraft design and technologies that improve the development, manufacturing, and testing of the aircraft. This differs from past studies that focused on a small number of performance-based technologies. The method is divided into two phases. The first phase evaluates technologies based on cost measures alone. The second phase redesigns an aircraft with new technologies, assesses the relative importance of performance-based technologies, and recognizes technology interactions using Taguchi's design of experiments. For a wide-body transport aircraft example, the methodology identifies promising technologies for further study. Recommendations and conclusions about the methodology are made based on the results.

Introduction

OVER the past two decades, the focus of transport aircraft design has shifted from performance driven to operating-cost driven and, more recently, to life-cycle-cost driven. As the commercial aircraft industry matures, new technological advancements are difficult to identify and develop. In efforts to improve corporate performance, airframe manufacturers are spending more on production and less for technology research and development. Therefore, decisions must be made about which research areas will provide the highest return on investment for the airframe manufacturer, as well as for the airlines.

This paper presents a method for evaluating a large number of technologies for commercial transport aircraft without requiring a large expenditure of time or budget. This method encompasses technologies that can be applied to the aircraft design and technologies that improve the development, manufacturing, and testing of the product. This departs from previous studies that focused on a small number of performance-based technologies.

Related Work

Previous efforts have investigated various techniques for evaluating aircraft technologies and their potential impacts on aircraft (and aircraft subsystem) performance and cost. Other related efforts have investigated the use of fuzzy logic and Taguchi's design of experiments as techniques to assist in technology evaluations. Many of these efforts relied heavily on surveys of experts.

Aircraft Technology Evaluation

In 1972, NASA published a study detailing benefits of over 50 commercial aircraft technologies.[1] For this study, engineers redesigned several aircraft with and without technology enhancements to perform a cost/benefit analysis. The work also detailed the development timeline and costs for each technology. The study recommended that almost all of the technologies be funded at an average level of $55 million per year over a 10-year period. The study also recommended implementation of all of the technologies on a transport to be built in 1985. Because of high costs and demanding schedules, commercial aircraft manufacturers have not followed many of these recommendations.

Beginning in 1975, Boeing Commercial Aircraft Group worked as a subcontractor to American Airlines to study the impact of technology on airline operating and maintenance costs. In 1978, the final version of the resulting report recommended further study of several technologies.[2]

For the NASA sponsored study, "Integrated Wing Design and Technology Integration and Environmental Impact," Boeing experts in several engineering disciplines rated new technologies directly as a change in cost or performance. The impact categories were weight, drag, specific fuel consumption, airframe maintenance cost, engine maintenance cost, nonrecurring cost, and recurring cost. Respondents provided three ratings for each category, numerical values with a high, medium, and low probability of obtaining benefits. A high probability value was one the respondent believed was obtainable with minimal research and development breakthroughs, whereas a low probability value was optimistic and indicated that the technology required additional research and development. After completing individual surveys, team members agreed on a single set of high, medium, and low probability values for each technology and then redesigned the aircraft using these impact values as modifiers. For each technology, three different designs resulted corresponding to the high, medium, and low probability values. Technologies were not combined in the redesigned aircraft. Figures of merit for the technologies were changes in airline profit and manufacturer profit.

Evaluation Methodologies and Techniques

Technology evaluation approaches have been attempted for other aerospace systems. Reference 3 describes a technique to assess aircraft propulsion technologies. This work applied fuzzy logic to address uncertainty in the knowledge base of experts judging technologies. Experts evaluated the cost of technologies on a verbal, relative scale. These descriptions were given numerical values by a method known as a repertory grid. Using these values, the system cost was estimated with new technologies included.

Bell and Pringle explored aircraft weapons systems and enabling technologies.[4] Instead of gathering expert inputs, the authors derived figure of merit values from published literature. Assessments were based on cost, probability of survival, probability of kill, and maintainability. From these figures of merit, a system effectiveness equation measured total system performance. The system effectiveness results enabled separation of the technologies into four groups: developing, mature, nearly mature, and dependent technologies. Developing technologies showed promise for application to all of the weapons systems and significantly increased each system's effectiveness; these were recommended for further investigation. The

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work also recommended future studies of the interactions between systems and of the impact of technological advances on mission type.

The assessment methodology developed for this paper makes use of Taguchi's design of experiments (DOE). This technique has been applied successfully to preliminary aerospace system design by several authors. Taguchi's DOE and response surface methodology have been used to search an aircraft design space more efficiently for optimum configurations[5]; this work focused less on technology implementation, but still considered design for life-cycle cost. The conceptual design of a combined-cycle single stage to orbit launch vehicle, which incorporates advanced technologies using Taguchi's DOE approach, is described by Olds and Walberg.[6] The DOE approach for design of optimum wing structures is discussed by Yurkovich.[7] This approach is becoming recognized as a useful tool in many design studies.

Methodology

The technology assessment methodology developed in this effort can evaluate a set of technologies that impact both airplane performance (aircraft technologies) and airframe development (process technologies). Aircraft technologies may be physically incorporated into an airframe, and process technologies apply to the manufacture and development of the aircraft. To address both types of technologies, the method consists of two phases. Phase 1 involves assessing all aircraft and process technologies in terms of several cost measures. Phase 2 examines the cost and performance impacts of aircraft technologies and considers possible interactions between technologies.

Four tools are used in this methodology. Like many other technology assessment approaches, input is obtained by surveying engineering experts. The survey data produces cost and performance increments that are used in two additional tools: a cost relationship model and an aircraft sizing code. The cost relationship model predicts the impact of each technology on airline profit, recurring cost to build, and nonrecurring cost to build in phase 1 of the methodology. In phase 2, the aircraft sizing code computes performance and weight of an aircraft, as well as operating and unit costs. The sizing code results enable Taguchi's DOE to determine an optimal set of aircraft technologies and identify possible technology interactions.

Survey of Experts

Predicting the ways technologies are applied to aerospace systems and the consequences of those implementations is difficult. Expert opinions are often the most reliable input available. Participants for the example in this study were Boeing Commercial Aircraft Group employees who are considered experts in one or more of the technologies under consideration. Nine technical disciplines were represented, with various numbers of respondents in each discipline. The technologies for consideration were identified and described before the survey was distributed. The technologies assessed in the following example are presented in the Appendix and are indicative of improvements possible in commercial aircraft.

To complete the surveys, respondents provided a percentage change that each technology would produce in cost, weight, or performance from a baseline aircraft without any of the technologies. This approach was used for two reasons. First, participants were familiar with technology impacts in terms of relative differences from the state of the art. Secondly, most engineers do not have access to absolute aircraft costs, but they may have an idea of how much relative change can be affected from the current baseline. For the work reported here, the baseline aircraft was a 300-passenger, twin-engine, wide-body transport between the 767 and 777 in terms of size, passengers, and technology level. Participants completed the surveys with this aircraft in mind.

Participants were also asked to rate their own experience in each technology on a subjective scale of 1 (little experience) to 5 (expert). The experience rating serves as the weighting for each participant's input for a technology impact similar to the concept of weighted objectives.[8] The respondents' input increments are multiplied by their experience rating, and these products are summed for all respondents to evaluate an impact of each technology. To gain a multidisciplinary insight, participants were asked to respond to all of the various areas, regardless of their expertise in a field.

Cost Relationship Model

To estimate technology effects on aircraft costs, Boeing provided the tool, cost measures for the evaluation of technology (CoMET), which was developed as part of a Boeing internal research and development effort. CoMET is a set of relationships between cost categories and cost measures for wide-body, subsonic commercial aircraft. This tool was originally created to give engineers a sense of which categories were important in terms of bottom line measures. Additionally, these relationships can evaluate the effect of each cost category on the total cost.

Figure 1 is a graphical representation of CoMET. Cost categories appear in the outer cells, influence ratios on the connecting lines, and cost measures at various levels marked by letters. The product of the ratios along a path from a cost category to a cost measure represents the impact of the corresponding cost category on the measures.

Aircraft Sizing and Cost Prediction

The third tool required by the technology evaluation methodology is an aircraft sizing and cost prediction tool. Following the approach outlined by Raymer,[9] a simple sizing code was developed to determine an aircraft's gross weight for a given set of design parameters and a design mission. A rubber engine is scaled during the sizing process to predict the fuel used. The empty weight of the aircraft is estimated using a component weight buildup method based on empirical equations.

In CoMET, airplane operating cost is presented as total airplane-related operating cost (TAROC). For this study, the direct operating cost plus interest (DOC + I) prediction of Ref. 10 estimated TAROC; this DOC + I measure is based on statistical data from current commercial transport aircraft and is essentially the same as TAROC, making it well suited to this study. Operating costs predictions include contributions of empty weight, landing weight, as well as takeoff gross weight. Additionally, cockpit crew, cabin crew, and maintenance cost contributions to operating cost rely heavily on trip times calculated by the sizing routine.

In this cost model, a statistically based relationship in which airframe weight is the independent parameter predicts airframe acquisition cost. Engine price is calculated on a dollar value per pound of thrust. The sum of these quantities is the aircraft unit acquisition cost. The number of trips per year is an important assumption for the cost model. Increasing the number of trips per year or the fuel cost will increase the predicted TAROC.

Taguchi's DOE

The fourth tool needed in the technology evaluation method identifies an optimal set of technologies and allows recognition of interactions between candidate technologies. Preliminary results may be obtained by only considering the cost impact of the aircraft and process technologies. However, the cost survey and CoMET alone do not capture weight- and performance-related impacts of the aircraft technologies. Additionally, the CoMET relationships are linear, so considering interactions with the CoMET predictions alone yields simple sums of the predicted impacts. The step of resizing the aircraft with new technologies must be performed to recognize interactions more complicated than those obtained from the CoMET tool. Taguchi's DOE[11] is a disciplined approach that allows technology interactions to be considered.

DOE is applied in two stages for this method. The first stage involves designating all aircraft technologies as factors and then conducting experiments (aircraft sizing and cost modeling) with technologies either on or off the baseline aircraft. These experiments are conducted by applying the empty weight and performance increments from the surveys to the sizing and cost prediction input. The results of the experiments are gross weight, unit cost, and TAROC. The second stage of DOE identifies interactions between technologies based on the first set of experiments. After potential interactions

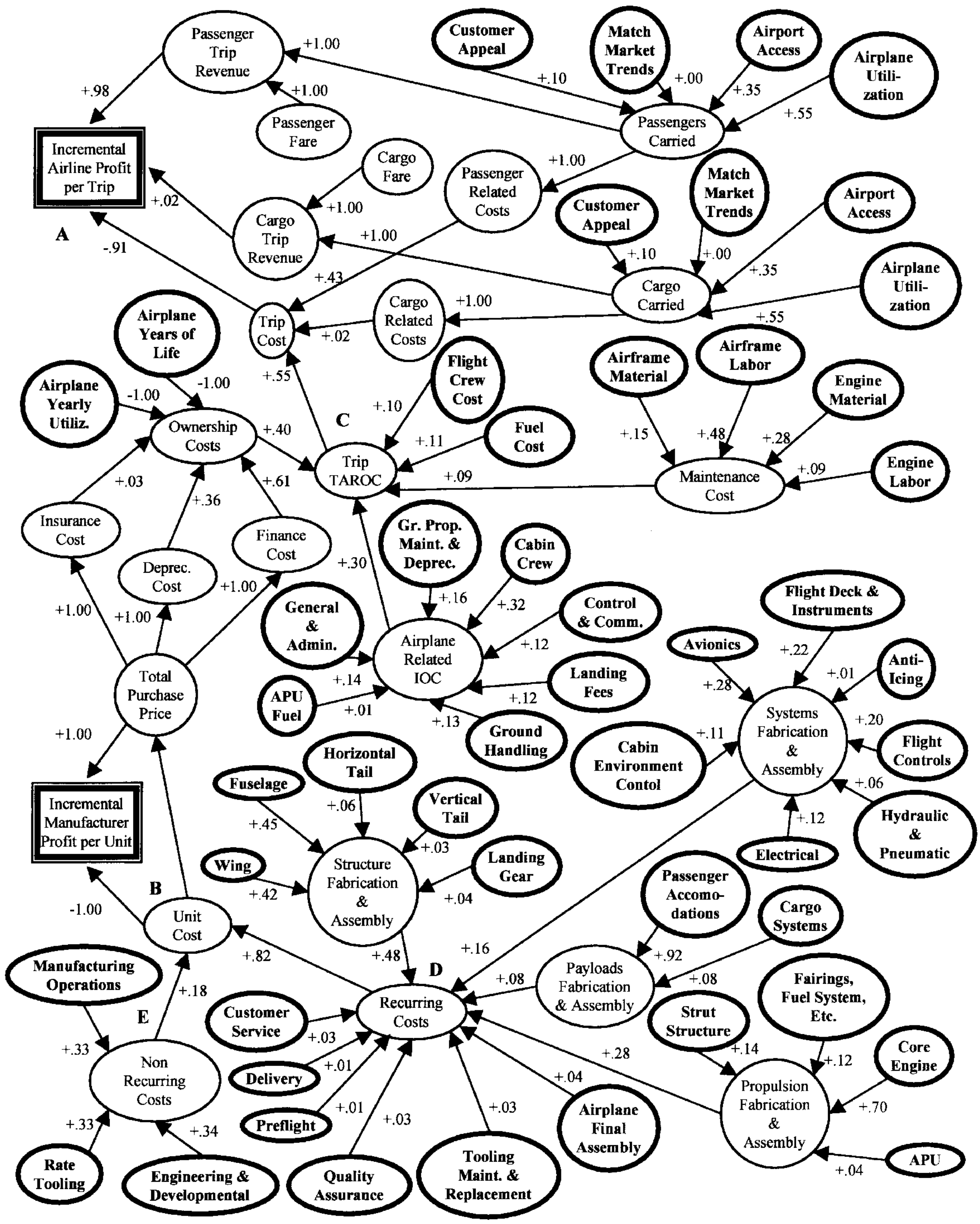

Fig. 1 CoMET relational diagram.

are identified, a second set of experiments determines if these interactions are significant.

Implementation

The four tools just described were combined to assess the impacts of the 29 different technologies in the Appendix on a baseline 300-passenger, long-range, wide-body commercial transport aircraft whose design mission is presented in Fig. 2. The aircraft was assumed to fly 590 trips per year of 4000-n mile distance each trip. In service, aircraft with this type of design mission often operate over shorter routes. In addition, jet fuel was assumed to cost \$0.63/gallon. This implementation illustrates how the technology evaluation methodology works. Results based upon this wide-body transport example are presented and discussed.

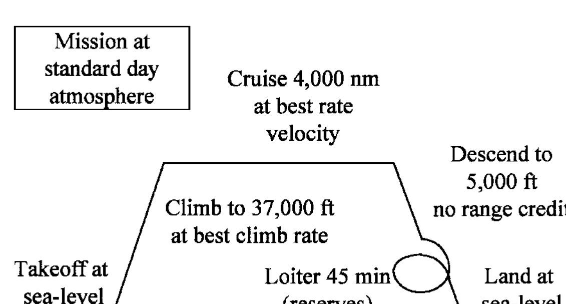

Fig. 2 Design mission for baseline transport aircraft.

Table 1 CoMET technology impact ranking for unit cost and trip TAROC

Unit cost technology ranking	% Impact	Trip TAROC technology ranking	% Impact
Toolless assembly	−6.11	Toolless assembly	−2.93
Monolithic structure	−4.30	**Monolithic structure**	−2.00
Automated fastening/assembly	−3.58	Automated fastening/assembly	−1.72
Flexible tooling	−3.52	Flexible tooling	−1.69
Automated factory floor control	−3.46	Automated factory floor control	−1.66
Data-driven process analysis	−2.16	Data-driven process analysis	−1.04
Fiber optics	−1.51	**Fiber optics**	−0.93
Simple high-lift devices	−1.46	**Simple high-lift devices**	−0.77
Cross functional integrated design	−1.35	Cross functional integrated design	−0.65
KBE tool design	−1.08	KBE tool design	−0.52

Technologies for Consideration

The technologies considered are representative of areas of current research undertaken by airframe manufacturers. Several technologies, such as composites and hybrid laminar flow control, have been studied for years. Others represent more recent developments. The distinction between aircraft and process technologies is a key element of this methodology. Aircraft technologies can be incorporated into the airframe; composites and fly by wire are examples of this type of technology. Process technologies apply to the development and manufacture of the aircraft. Examples of process technologies include toolless assembly and pressure paint loads analysis.

The focus of the technologies varies widely. For example, hybrid laminar flow control is under consideration to improve fuel efficiency, which reduces TAROC. Often, TAROC measures the value of a technology; however, new technologies, such as cross-functional integrated design, have little direct impact on TAROC. Instead, the focus of this type of technology is reduction in internal development costs. These savings can potentially reduce acquisition and finance costs for the airline customer. This methodology evaluates aircraft and process technologies with quantifiable cost measures.

Surveys and Data Reduction

Two surveys were used to gather expert opinions. The first addressed the effect of each technology on each of the CoMET cost categories. Areas of expected impact were highlighted on the survey, but respondents were free to enter any impacts. Technology impacts were given as a percentage change in cost from a baseline aircraft. The second survey requested input needed to redesign an aircraft with new technologies. Participants first considered the impact of each technology on several empty weight categories, such as avionics weight or wing weight. Performance impacts were considered in terms of specific fuel consumption, maximum lift coefficient, and total drag. Again, the input was given in terms of a percentage change from the current baseline aircraft.

Based on the experience level of each individual, the individual assessment of each technology can be combined with other respondents. First, a weighting factor for each individual is obtained for each technology by taking that individual's experience rating and dividing it by the sum of ratings for that technology. Then, an individuals input percentage change is multiplied by the weighting factor. Finally, these products for all individuals are added together to compute a predicted effect.

Cost Impact of Technologies

After the effect is determined from the survey data reduction, that effect is related to a cost measure via CoMET. Figure 3 shows an excerpt of the CoMET chart that includes trip TAROC. Airframe labor makes up 48% of the total maintenance cost, and maintenance cost is 9% of trip TAROC. If the survey suggests that composite materials increase labor cost by 8.33%, then this technology would result in a 0.36% (8.33% $\times$0.48 $\times$0.09) increase in trip TAROC. Through this process, each technology (aircraft and process) can be compared in terms of cost measures.

Table 1 shows the top 10 technologies and their predicted impacts on unit cost and TAROC based on the CoMET evaluation. The bold

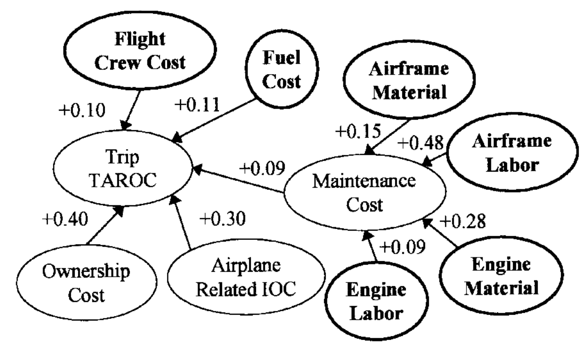

Fig. 3 Trip TAROC excerpt of CoMET diagram.

type indicates aircraft technologies. Impacts are measured as a percentage change in cost from the baseline aircraft. Many aircraft technologies, typically thought to reduce operating costs, rank low in this evaluation.

The top 10 technologies for impact on airline profit, recurring cost to build, and nonrecurring cost to build, are ranked in Table 2. In Table 2, an increase in airline profit is desirable; in the other measures, reduction is desired. Unlike the other cost measures, airline profit has several aircraft technologies at the top of the ranking. The recurring cost ranking is similar to the ranking for trip TAROC. The top technologies for nonrecurring cost to build are process related.

Performance- and Weight-Related Cost Impact of Technologies

Although the preceding section used the cost survey results and the CoMET methodology to estimate changes in several cost measures, the aircraft technologies can also have performance- and weight-related impacts that indirectly affect airplane costs. For example, a technology that increases an aircraft's cruise speed may reduce operating cost contributions that are related to trip times. To evaluate these impacts, results from the weight and performance survey were used to modify predictions of empty weight, fuel efficiency, etc. in the sizing code. The baseline aircraft was then resized incorporating the effects of each aircraft technology. Cost predictions were modified using the cost impacts determined in the preceding section. Table 3 presents a rank-ordered list of the top 10 technology impacts on unit cost and trip TAROC evaluated using this approach; as before, aircraft technologies are bold face.

Using the resizing approach, performance- and weight-based impacts of each aircraft technology are highlighted. One example is the advanced ducted fan technology that ranked low in the cost-only evaluation (unit cost increment of +0.78% and trip TAROC increment of +0.23%). However, including the performance-based effects of this technology suggests a beneficial impact (−0.87% on unit cost and −1.96% on trip TAROC). The process technologies listed in Table 3 do not affect the aircraft sizing, and so their impact values remain unchanged from Table 1.

Design of Experiments to Evaluate Technologies

The preceding evaluation did not evaluate combinations of technologies, nor does it allow for identification of potential interactions between technologies. Thus, a second phase of the methodology

Table 2 CoMET technology impact ranking for airline profit, recurring cost, and nonrecurring cost

Airline profit technology ranking	% Impact	Recurring cost technology ranking	% Impact	Nonrecurring cost technology ranking	% Impact
Terminal four-dimensional navigation	2.99	Toolless assembly	−6.26	Data-driven process analysis	−11.98
GPS direct routing	1.95	**Monolithic structure**	−5.16	Cross functional integrated design	−7.46
Rapid wind-tunnel testing	1.08	Automated fastening/assembly	−4.74	KBE tool design	−6.00
Toolless assembly	0.86	Automated factory floor control	−4.07	Toolless assembly	−5.42
Advanced flex zones	0.77	Flexible tooling	−3.83	KBE design	−3.87
Slotted/advanced/ adaptive airfoils	0.67	**Fiber optics**	−2.29	Flexible tooling	−2.08
Monolithic structure	0.62	**Simple high-lift devices**	−1.52	Rapid wind-tunnel testing	−1.83
Active landing gear load suppression	0.60	**Multiplex architecture**	−0.53	**Simple high-lift devices**	−1.19
Active noise suppression	0.54	KBE design	−0.24	Pressure paint loads analysis	−1.03
Flexible tooling	0.51	Rapid wind-tunnel testing	−0.01	Automated factory floor control	−0.68

Table 3 Top ten unit cost and trip TAROC technology impacts with aircraft resizing

Unit cost technology ranking	% Impact	Trip TAROC technology ranking	% Impact
Monolithic structure	−6.24	**Composite primary structure**	−3.93
Toolless assembly	−6.11	**Monolithic structure**	−3.23
Composite primary structure	−4.97	Toolless assembly	−2.93
Automated fastening/assembly	−3.58	**Advanced ducted fan**	−1.96
Flexible tooling	−3.52	Automated fastening/assembly	−1.72
Automated factory floor control	−3.46	Flexible tooling	−1.69
Data-driven process analysis	−2.16	Automated factory floor control	−1.66
Simple high-lift devices	−2.01	**Ultrahigh bypass ratio engine**	−1.57
Fiber optics	−1.52	**Simple high-lift devices**	−1.11
Multiplex architecture	−1.38	Data-driven process analysis	−1.04

Table 4 Unit cost ANOVA

Technology (experimental factor)	Degrees of freedom	Sum of squares, %	Variance, %	Percentage contribution
Monolithic structure	1	1.3732	1.3732	51.6192
Composite primary structure	1	0.8378	0.8378	31.4951
Simple high-lift devices	1	0.1503	0.1503	5.6487
Hybrid laminar flow control	1	0.1016	0.1016	3.8210
Fiber optics	1	0.0885	0.0885	3.3285
Slotted/advanced/adaptive airfoils	1	0.0367	0.0367	1.3810
Active controls	1	0.0328	0.0328	1.2317
Advanced ducted fan	1	0.0195	0.0195	0.7347
Direct satellite link	1	0.0081	0.0081	0.3058
Active noise suppression	1	0.0073	0.0073	0.2740
Ultrahigh bypass ratio engine	1	0.0033	0.0033	0.1256
GPS direct routing	1	0.0005	0.0005	0.0204
Active landing gear load suppression	1	0.0004	0.0004	0.0140
Terminal four-dimensional navigation	1	0.0000	0.0000	0.0003
Error	1	0.0000	0.0000	0.0001
Sum	——	2.6601	——	100.0000

was pursued. Using Taguchi's DOE approach helps identify potential cost interactions between technologies and provides a measure of which technologies have the largest impacts. Furthermore, using Taguchi's DOE results in a set of optimal technologies for various cost measures.

To apply DOE in the assessment methodology, the aircraft technologies are treated as factors. These factors are given two levels indicating if the technology is on the aircraft or off the aircraft. An experiment involves resizing the baseline aircraft with appropriate on technologies. Experimental results include gross weight, unit cost, and operating cost. Two stages of DOE are applied. In the first stage, all aircraft technologies are treated as independent factors, providing the optimal technology sets and identifying potential interactions. In the second stage interactions are investigated.

Technology Significance

In the first stage of the DOE application, 14 aircraft technologies were considered, so that 16 experiments provided measures of aircraft unit cost and trip TAROC using an L_{16} orthogonal array.[11] An analysis of variance (ANOVA) for the results determines the technologies with the greatest cost impacts. Table 4 shows the ANOVA for unit cost, and Table 5 shows the ANOVA for operating cost. The

Table 5 Operating cost ANOVA

Technology (experimental factor)	Degrees of freedom	Sum of squares, %	Variance, %	Percentage contribution
Composite primary structure	1	0.5089	0.5089	42.9239
Monolithic structure	1	0.3645	0.3645	30.7378
Advanced ducted fan	1	0.1218	0.1218	10.2704
Ultrahigh bypass ratio engine	1	0.0772	0.0772	6.5107
Simple high-lift devices	1	0.0455	0.0455	3.8346
Fiber optics	1	0.0371	0.0371	3.1321
Active controls	1	0.0161	0.0161	1.3592
GPS direct routing	1	0.0069	0.0069	0.5831
Active noise suppression	1	0.0025	0.0025	0.2104
Terminal four-dimensional navigation	1	0.0022	0.0022	0.1845
Direct satellite link	1	0.0021	0.0021	0.1732
Slotted/advanced/adaptive airfoils	1	0.0007	0.0007	0.0632
Hybrid laminar flow control	1	0.0001	0.0001	0.0099
Error	1	0.0001	0.0001	0.0060
Active landing gear load suppression	1	0.0000	0.0000	0.0009
Sum	——	1.1857	——	100.0000

Table 6 Taguchi optimal technology sets

Technologies and performance metrics	Unit cost	Trip TAROC	MTOGW
Terminal four-dimensional navigation	off	on	on
GPS direct routing	off	on	on
Active landing gear load suppression	off	on	on
Simple high-lift devices	on	on	on
Slotted/advanced/adaptive airfoils	off	on	on
Hybrid laminar flow control	off	on	on
Active noise suppression	off	off	off
Advanced ducted fan	on	on	on
Ultrahigh bypass ratio engine	on	on	on
Composite primary structure	on	on	on
Monolithic structure	on	on	on
Active controls	on	on	on
Direct satellite link	off	off	on
Fiber optics	on	on	on
Unit cost, % change	−15.48	−12.35	−13.09
TAROC, % change	−12.36	−12.64	−14.49
MTOGW, % change	−11.91	−12.37	−14.45

technologies are listed in descending order of percentage contribution to the total sum of squares; this indicates the significance or importance of each technology. The top five factors for each cost measure were investigated for interactions in the second stage of the DOE application.

Using the L_{16} array with 14 technologies allows one factor to measure error in the experiments. The orthogonal arrays used in Taguchi's DOE reduce the number of experiments needed; however, the results are most reliable when the performance is directly proportional to the linear combination of factors. Because the computer-based experiments are exactly replicable, the error factors in the ANOVA tables measure nonlinearity in the problem. The small but nonzero percentage contribution of error indicates that the problem is minimally nonlinear. In addition, the error contribution indicates factors that appear to have no meaningful impact. For example, active landing gear load suppression contribution is smaller than the error contribution in Table 5.

Taguchi Optimal Technologies

The first stage of the DOE application also provides the main effects of each technology. If the average "on" effect is better than the average "off" effect for a technology, then this technology provides a benefit to the aircraft. These main effects determine a set of optimal technologies for each measure of unit cost, trip operating cost, and maximum takeoff gross weight (MTOGW). The three Taguchi optimal technology sets were evaluated through resizing to provide a measure of improvement over the baseline aircraft. Table 6 presents these technology sets and their improvements.

For optimal unit cost, fewer technologies are applied than for operating cost or gross weight. The performance of each design in unit cost, trip TAROC, and gross weight is better than or approximately equal to the other experiments conducted. In addition, the best design for each objective has the largest reduction in its respective measure. A slight exception occurs for the minimum trip TAROC design, which is actually slightly better in MTOGW than the minimum gross weight design. This difference is very small, and the effect is attributed to noise in the iterative sizing code because the difference in gross weight is less than the convergence tolerance. One caveat is that conflicting technologies are suggested. For example, it may not be possible to fully include monolithic structure and composite primary structure on the same aircraft.

Technology Interactions for Cost Measures

Interactions describe conditions when one factor's influence of on the result is dependent on the level of another factor. The interaction between two factors may be determined by averaging the performance of several experiments that involve the two factors and examining the main effects of these two factors. For this implementation, interactions were investigated by examining combinations of the five most significant technologies identified in the preceding step. Using these technologies, interaction charts were constructed for each possible combination of two technologies. Only two potential cost interactions were found for the unit cost metric; these were between simple high-lift devices and fiber optics and between composite primary structure and fiber optics. Figure 4 presents these interaction charts. These charts illustrate interactions because the two curves intersect, suggesting that one factor's setting affects the desired setting of the other factor. For example, if simple high-lift devices are left off the aircraft, then including fiber optics creates a larger reduction in unit cost. The converse is true; if simple high-lift devices are incorporated into the aircraft, then the fiber optics should be left off.

For the TAROC cost measure, two possible interactions appeared. The technologies involved in these were simple high-lift devices and composite primary structure, and simple high-lift devices and advanced ducted fan (illustrated in Fig. 5). These interactions are likely small, because the lines are not parallel but do not intersect.

To determine the degree of an interaction, further experiments were designed that account for interactions as separate factors. Guidelines for selecting the interaction columns are described by Taguchi's DOE approach.[11] After the interaction columns are chosen, other factors can be assigned to the remaining columns; in this case the other factors were the five most significant factors determined from the first stage of the DOE. After running the second stage of experiments, pooled ANOVA tables were constructed for both cost measures. Abbreviated tables for unit cost and TAROC are shown in Tables 7 and 8, respectively.

Following the guidelines for pooling results, both interactions and the monolithic structure technology have been pooled for the unit cost measure, which indicates that they do not have significant

Table 7 Pooled ANOVA for unit cost measure including interactions

Technologies and interactions	Degrees of freedom	Sum of squares, %	Variance, %	Percentage contribution
Simple high-lift devices	1	0.0901	0.0901	3.5374
Hybrid laminar flow control	1	0.4413	0.4413	19.6715
Composite primary structure	1	1.3308	1.3308	60.5305
Simple high-lift devices × fiber optics	−1	0.0016	Pooled	——
Fiber optics	1	0.2359	0.2359	10.2349
Composite primary structure × fiber optics	−1	0.0004	Pooled	——
Monolithic structure	−1	0.0374	Pooled	——
Error	3	0.0394	0.0131	6.0257
Total	4	2.1769	——	100.0000

Table 8 Pooled ANOVA for TAROC measure including interactions

Technologies and interactions	Degrees of freedom	Sum of squares, %	Variance, %	Percentage contribution
Simple high-lift devices	1	0.3744	0.3744	38.0498
Advanced ducted fan	−1	0.0161	Pooled	——
Simple high-lift devices × advanced ducted fan	−1	0.0000	Pooled	——
Simple high-lift devices × composite primary structure	−1	0.0015	Pooled	——
Composite primary structure	1	0.4959	0.4959	50.5933
Monolithic structure	1	0.0263	0.0263	2.1083
Ultrahigh bypass ratio engine	1	0.0365	0.0365	3.1635
Error	3	0.0177	0.0059	6.0851
Total	4	0.9685	——	100.0000

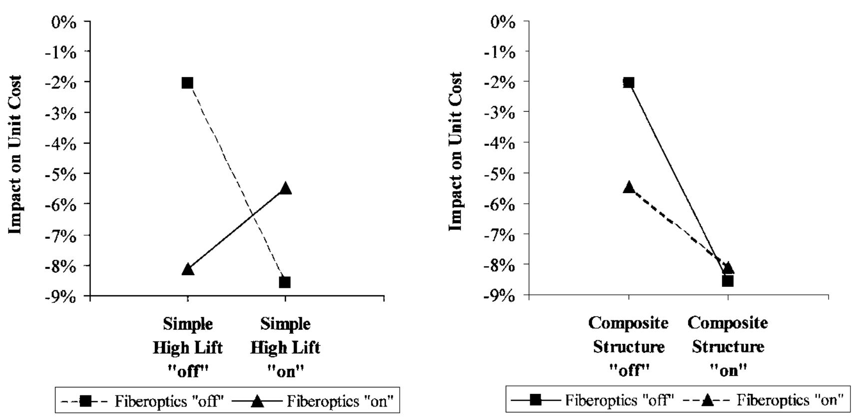

Fig. 4 Unit cost interaction charts: simple high-lift devices and fiber optics (left) and composite structure and fiber optics (right).

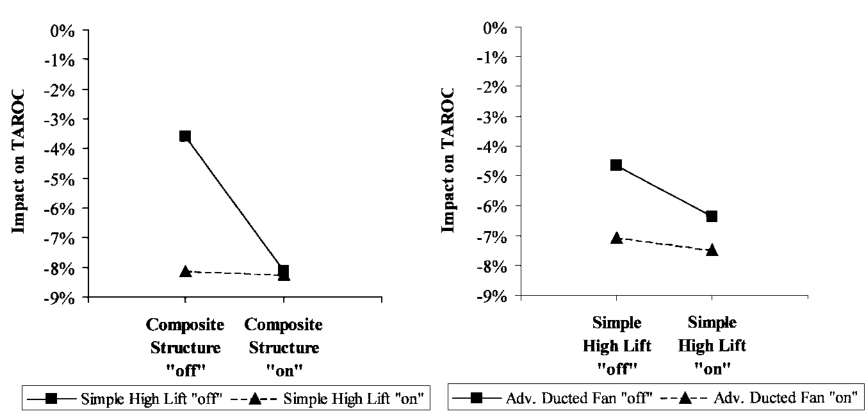

Fig. 5 TAROC interaction charts: composite structure and simple high-lift devices (left) and simple high-lift devices and advanced ducted fan (right).

impact. Additionally, the simple high-lift device technology contributes less than the pooled error term, so that this technology also contributes minimally to the unit cost. For the TAROC cost measure, both interactions have been pooled, along with the advanced ducted fan technology. Furthermore both the monolithic structure and ultrahigh bypass ratio engine technologies have contributions lower than the pooled error, suggesting that these may also have little impact on TAROC.

Using Taguchi's DOE readily accommodates the discrete choice of technologies on or off the aircraft. The underlying orthogonal arrays greatly reduce the number of experiments needed to provide technology evaluations, especially compared with a full-factorial design. This DOE approach also furnished optimal technology sets for various cost measures. Taguchi's approach allows for recognition of interactions and some investigation of these interactions.

However, assumptions of the orthogonal arrays can lead to inaccurate results in the presence of nonlinearity or complicated interactions. In the aforementioned implementation, interactions were identified, and they appear to be minimal. This approach generated inconsistent results, illustrating some of the inaccuracies. For example, the monolithic structure technology was identified as the largest contributor to unit cost during the first-stage application (Table 4), yet when included with potential interactions in the second stage, its contribution was pooled into the error term (Table 7). The first and second DOE stages required sizing of aircraft with different sets of on technologies, and so these differing results are not completely surprising. The difference in calculated percent contribution is large, which suggests that applying monolithic structures to an aircraft may have nonlinear effects on the cost measures.

Some interactions presented are nonintuitive because they have been examined in terms of cost measures. The interaction between simple high-lift devices and fiber optics is one unexpected result indicating that cost interactions may exist where there is no obvious physical interaction between technologies.

Discussion

The methodology described and implemented provides quantitative values that allow assessment of both process and aircraft technologies. From these values, recommendations about technologies for development may be made. As with any technology evaluation methodology, some limitations exist.

Recommended Technologies

The methodology allows several ways to recommend technologies for further development. Recommendations can be based on cost measures deemed most appropriate by the user; for example, an airframe manufacturer may decide that unit cost is the most important measure and would select technologies with the largest predicted reduction in unit cost. Determining a single measure may not be possible, or practical, because many cost measures affect the acceptance of an aircraft by airlines. The approach suggested here selects technologies that appear in the top of their ranked performance for all cost measures under consideration. For the cost measures of airline profit, recurring cost, and nonrecurring cost, only the CoMET technology tool provides these measures. However, for unit cost and operating cost (TAROC), the results generated from the aircraft resizing incorporate performance- and weight-related impacts, and so these results are preferred.

An example of this can be made using Table 3. If five technologies are to be selected for further development, monolithic structure, toolless assembly, composite primary structure, automated fastening/assembly, and flexible tooling would be chosen, because these technologies are ranked in the top six for both unit cost and trip TAROC.

Using the cost impact with resizing approach allows assessment of both process and aircraft technologies. Monolithic structure, composite primary structure, and simple high-lift devices appear in the top ten of the unit cost and trip TAROC rankings using resizing. Taguchi's DOE also supports these as the most significant aircraft technologies for unit cost and among the five most significant technologies for trip TAROC. Two of these, monolithic structure and simple high-lift devices, improve performance and also simplify manufacturing and maintenance to reduce costs, and so these results appear rational.

The DOE step also identified three optimal sets of aircraft technologies for minimum unit cost, trip TAROC, and takeoff gross weight. If one objective was deemed most important, development of the optimal technology set corresponding to that objective could be pursued. However, it may be desirable to develop technologies that appear in more than one optimal set. Keeping with the earlier discussion, simple high-lift devices, advanced ducted fan, ultrahigh bypass ratio engine, composite primary structure, monolithic structure, active controls, and fiber optics appear in the optimal sets for both unit cost and trip TAROC. This list includes the three aircraft technologies identified earlier.

Although Taguchi's DOE provides a means to select technologies for further development, in the form used here, the DOE step does not allow for process technologies to be evaluated. Based on the results in Table 3, process technologies are also important, and so using a combination of means to identify technologies for further development seems prudent.

Limitations

The methodology has limitations that deserve discussion because these may affect interpretation of the results. These limitations exist primarily in the definition of the technologies for evaluation and in the survey to gather expert opinions.

Many of the technologies in this study cannot logically be paired. For example, primary composite structure and monolithic provide dissimilar alternatives for primary airframe structure and are not fully compatible. Similarly, simple high-lift devices and advanced/slotted airfoils are incompatible. In cases where physically incompatible technologies are promising, development of both technologies could be pursued, but a later choice is needed to determine which technology would be applied to an aircraft.

The self-rating system for technology experience was effective for weighting the survey input of different participants. This method is susceptible to differences in perception when the individuals judge their experience in relation to their colleagues in the discipline. The survey format also allows for the resulting evaluations to be somewhat sensitive to the input of each respondent. To examine these effects, one respondent's experience ratings for the top ten unit cost technologies in Table 1 were lowered by one (a 4 rating became a 3, etc.). The impact values did change, but only slightly; for example, the impact for monolithic structure changed from −4.298 to −4.295%. Larger variations in the experience rankings or outlying responses will impact the results, but this appears to be minimal.

Several survey participants felt that they did not have enough exposure to cost in their present positions; but they did have a good understanding of weight and performance increments and suggested only completing the weight/performance survey. However, process technologies could not have been evaluated or ranked against the aircraft technologies without the cost survey.

Participants also expressed concern about responding to the cost survey at different levels of abstraction, and survey input may have been based on the respondent mentally resizing the aircraft. For example, one participant may conclude that composites will reduce the aircraft weight, so that the fuel required and operating cost will decrease. The composite wing may cost more to build and increase unit cost. This participant would enter the corresponding increments in both cost categories. Another participant may not consider the effect on fuel cost and only enter input for wing labor cost.

Expansion of the Method

Different aircraft sizing codes and cost models such as ACSYNT[12] or FLOPS[13] may provide higher accuracy and can easily replace the models used here. An obvious expansion is the inclusion of more survey participants. By gathering results from more people, noise associated with experience ratings and outlying inputs may be reduced. The scope of this study was limited to 29 technologies; however, the methodology can incorporate more technologies.

This approach could be extended easily to other types of aircraft. The performance and cost models would differ as needed, but the survey, data reduction, and analysis would be essentially the same. Other engineering systems that may benefit from this method include automobiles, electronics, and others requiring large-scale manufacturing/assembly operations. The connecting and crucial element of these industries is that the application of technology directly affects the performance and manufacturing of the product.

Conclusions

The purpose of this effort was to develop a method to evaluate technologies in a manner that could lead to a research and development strategy for a commercial airframe manufacturing company. The implementation presented here illustrates that this is possible.

Through the use of a defined methodology to evaluate the impact of technology, strategists can prioritize the study of these technologies. The methodology presented identifies promising commercial aircraft technologies at a minimum study cost. This method should contribute to aircraft technology assessment and design in several ways.

First, this methodology can simultaneously assess both process and aircraft technologies in terms of cost metrics. Previous technology studies have primarily focused on a small number of performance-based technologies.

Second, the methodology considers technologies with a multidisciplinary view. Many technical experts from several disciplines provided input to this study, and the weighted objectives approach for experience ratings allowed inputs from experts in different disciplines to be combined. Typically, previous studies only gathered input from a few individuals in a limited range of fields.

Finally, the application of Taguchi's DOE as part of the methodology is novel compared to other DOE applications. By using this approach, several technologies are evaluated in combination to provide a measure of each technology's importance and to identify a set of optimal technologies for various objectives. In addition, technology interactions can be recognized in terms of cost measures.

For the notional transport aircraft in the implementation, the technology assessment methodology results allowed recommendation of technologies for further development. This method appears to work well for commercial aircraft and should be applicable to other types of aircraft and other products.

Appendix: Commercial Aircraft Technologies for Evaluation

1) Terminal four-dimensional navigation uses four-dimensional trajectory generation for real time optimal path control of time/space in the airport terminal control area (TCA). It increases the capability to manage large numbers of aircraft and minimize times in the air and fuel burn in the TCA.

2) GPS direct routing uses GPS positioning to permit direct routing to destination airports without flying vector airways. It provides in route four-dimensional navigation for minimum airtime and/or fuel burn.

3) Active landing gear load suppression uses an active control system to alleviate dynamic landing gear loads through pressure manipulation within the oleo.

4) Simple high-lift devices are mechanically simple leading- and trailing-edge approaches to produce high lift for takeoff/climb and approach/landing. They avoid complex rigging and actuation with substantial reduction in maintenance.

5) Slotted/advanced/adaptive airfoils provide optimization of three-dimensional geometry to reduce drag, increase lift, or increase cruise speed, as well as providing variation of three-dimensional geometry with leading or trailing devices at different flight conditions to optimize aerodynamic performance.

6) Rapid wind-tunnel testing is the process of accelerated model design, fabrication, instrumentation, testing, and data reduction to rapidly obtain aerodynamic and loads data. Different paradigms in instrumentation and data reduction may be required.

7) Hybrid laminar flow control uses a porous skin with suction over regions of the wing or airframe to reduce skin-friction drag by maintaining large areas of laminar flow.

8) Active noise suppression is noise suppression utilizing a noise source(s), sensors, and feedback control to actively attenuate engine and cabin noise.

9) An advanced ducted fan results in engine cycles with variable pitch fan blades to improve the high-speed performance of the fan stage.

10) An ultrahigh bypass ratio engine results in engine cycles with fan bypass ratios significantly higher (>10) than those currently in use.

11) Composite primary structure is the use of composite material in the primary load-carrying structure, such as the wing box, engine strut, and fuselage pressure vessel.

12) Monolithic structure is the use of single piece castings rather than built-up structure in areas such as bulkheads, ribs, doorframes, fuselage frames, floor beams, etc.

13) Knowledge-based engineering (KBE) design is the automation of airplane/structure/systems/tooling geometry definition through engineering rules in an intelligent computer aided design-like environment.

14) Active controls are instrumental in achieving artificial structural stiffness using active control surfaces for gust load alleviation, maneuver load control, flutter suppression, and relaxed stability.

15) Pressure paint loads analysis refers to the utilization of pressure sensitive paint to quantify aerodynamic load distribution rather than using pressure ported models.

16) A direct satellite link provides the capability of direct high-bandwidth communication with satellites by transmitters and receivers onboard the aircraft.

17) Fiber optics refers to fiber optic cables for data connection rather than conventional wiring.

18) Multiplex architecture refers to the substitution of pin-to-pin connections in conventional wiring harnesses with multiplex networking of system components.

19) Advanced flex zones are a payload architecture allowing maximum movement of galleys, lavatories, and seating based on self-contained interior packaging and widespread plumbing and power networking.

20) Automated cargo handling is system automation in cargo handling to reduce ground crew support. Includes cabin consumables and galley service.

21) Upgradable in-flight entertainment systems refer to a flexible bus architecture allowing commercial standard interfaces and software for entertainment system vendor upgrades. Enables an Internet connection at each seat terminal via direct satellite link.

22) Toolless assembly refers to control of key part interface characteristics to permit subassembly and final assembly without the requirements of fixtures or alignment tools.

23) Automated factory floor control refers to closed-loop decision support for planning/replanning and scheduling/rescheduling of anticipated/unanticipated events on the shop floor. Establishes on-line coordination of the factory.

24) KBE tool design is the use of design rules to define tool geometry from configuration geometry. It permits automated tool design changes based on airplane geometry changes.

25) Automated fastening/assembly is the robotic tooling enabling automated drilling, fastening, and assembly of airframe structure such as wings and fuselage sections.

26) Flexible tooling refers to computer adjustable tooling fixtures such as a wing jig that can vary the geometry of the structure to be assembled. Different wings within a geometry envelope may be produced on the same tool.

27) The near-real-time parameter estimation is a maximum likelihood parameter estimation in flight test for rapid determination of aerodynamic coefficients, stability and control derivatives, aeroelastic characteristics, and engine performance. Estimation occurs near real time during maneuvering flight by matching nonlinear model dynamics.

28) Cross functional integrated design is the integration of discipline methods and tools in a database environment to facilitate movement and maintain data consistency through the preliminary design process. It structures the design process as data driven.

29) Data-driven process analysis is the use of data-driven methodology to eliminate out-of-sequence rework and to identify opportunities for parallel or concurrent tasks. It is capable of hierarchical planning and management to generate integrated plans and schedules.

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