JOURNAL OF AIRCRAFT
Vol. 42, No. 6, November–December 2005

Multi-Attribute Value Approach to Business Airplane Product Assessment

Troy D. Downen,* Deborah J. Nightingale,† and Christopher L. Magee‡
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139-4307

A new approach to airplane product specification and assessment is introduced for the early, fuzzy front-end product development process. A highly adaptable and generalizable multi-attribute method is developed for rapidly assessing the value of new product designs relative to proposed or existing product portfolios. A process for determining the empirical role product attributes have played in differentiating products in competitive markets is introduced through the use of consumer-revealed preference data. The value approach is applied specifically to the business airplane industry with a discussion of how model parameters were selected, a sensitivity analysis, and comments on the data used in the analysis. Advantages of the new approach vis à vis existing aircraft industry assessment methods include the simplicity of the method, its adaptability to the changing needs of designers, and its ability to more correctly portray aspects of the current and historical business aviation market.

Nomenclature

A	=	repair cost of a part or product, dollars
D	=	annual product demand
D_T	=	total annual demand in a segment
E_p	=	price elasticity
g	=	product attribute level
g_C	=	critical attribute level
g_I	=	ideal attribute level
g_0	=	nominal attribute level
i	=	index for number of products in the kth segment ($i = 1 \ldots N_k$)
j	=	index for number of attributes used in the relative-value-index (RVI) model ($j = 1 \ldots n$)
K	=	constant based on product segment price elasticity
k	=	index for number of segments ($k = 1 \ldots s$)
N_k	=	number of products competing in segment k
n	=	number of attributes contributing to total product value in the RVI model
P	=	product price, dollars
pax	=	passengers
$Q(g)$	=	quality level of a part or product due to attribute level g
Q_I	=	ideal quality level of a part or product
RV_{ik}	=	revealed value for the ith product in segment k
r	=	correlation coefficient
s	=	number of product segments
V	=	total absolute value of a product, dollars
V_0	=	absolute value of a baseline product, dollars
VI_{ik}	=	value index for the ith product in segment k, dollars
$v(g_j)$	=	part-worth value contribution due to jth attribute
γ_j	=	exponential weighting factor for jth attribute

Introduction

ONE of the most challenging and critical aspects of product development (PD) is the so-called fuzzy front-end process: the specification and conceptual design of new products. In this phase of development, interdisciplinary teams of product designers require the ability to rapidly explore the tradespace of possible product attributes within the context of consumer preferences, pricing, and technical performance. Product assessment methods must be able to provide designers a reasonable facsimile of the effects of modifying product features while also adhering to Little's modeling criteria of being simple to use, easy to control, robust, complete on important issues, adaptable, and easy to communicate with.[1]

Business aviation, sometimes referred to as corporate aviation, is an active and high dollar-value sector of the general aviation industry, which claimed nearly $10 billion in billings in 2003.[2] In today's business and general aviation industry specifications can naturally be driven by available technologies or capabilities, be based upon product platforms that already exist and can be conveniently modified, result from pressures to align with competitor product portfolios, or be the result of perceived niches in loosely representative market segmentations. At this level of ambiguity, the desires of one or more dominant personalities within the company or an important customer can be excessively important, particularly if quantitative assessment tools are lacking. Thus, product specification might not reflect the true needs of the overall market and can be absent of an integrated, interdisciplinary systems engineering approach. Typical industry methods for assessing consumer preferences and for quantitatively evaluating proposed designs tend to be either cumbersome and unsuitable for rapid tradespace exploration or oversimplified and lacking a basis in the appropriate literature and theory. Existing tools also tend to be developed and utilized within disciplinary departments (i.e., engineering, marketing), often resulting in suboptimization of product attributes by a single dominant individual or group within the organization and without full consideration of a broader range of stakeholder interests.

In this paper a new method for business aircraft product assessment that seeks to balance the needs for a simple figure of merit suitable for rapid tradespace exploration while also having a firm theoretical basis and providing realistic assessments of potential product technical and market performance is proposed. A mathematical model that incorporates a highly adaptable, quantitative, multi-attribute approach to product specification and conceptual design is developed. Though generalizable to both service and physical products, in this paper a version of the model is specifically developed for business airplane products within the business aviation industry.

Current Product Assessment Approaches

Interviews with PD managers in the business aviation industry indicate that at least two separate approaches are commonly used

Received 20 August 2004; revision received 19 December 2004; accepted for publication 23 December 2004.

*Research Assistant, MIT Lean Aerospace Initiative, 77 Massachusetts Avenue, Room 41-205; downen@alum.mit.edu. Associate Fellow AIAA.

†Director, MIT Lean Aerospace Initiative, 77 Massachusetts Avenue, Room 41-205; dnight@mit.edu.

‡Director, MIT Center for Innovation and Product Development, 77 Massachusetts Avenue, Room E60-275C; cmagee@mit.edu.

in the early product specification and assessment phase: marketing research using consumer-stated preference data and multi-attribute figures of merit.

Marketing Science Methods

Marketing science methods have their origins in the need to solve important industry questions regarding anticipated market share for a new product and ways to improve the product's appeal to consumers. In 1971 Green and Rao[3] published ground-breaking research in which the importance of various product attributes to consumers were identified and rank ordered for the purpose of product development based on consumer-stated preferences for the attributes. Such methods are now known as conjoint analysis, and a flood of marketing research has since explored this approach. (Cattin and Wittink[4] and Wittink and Cattin[5] review the historical application of this research.) Some of the most recently developed approaches to conjoint studies are presented by Urban and Hauser,[§] Toubia, Simester and Hauser,[§] and Louviere et al.[6] An expository discussion of the current state of conjoint analysis and related marketing science methods for use in product development can be found in Hauser and Rao.[7]

The reliance on stated preferences (which can vary from actual preferences), as well as limitations in the number of attributes that can be studied as a result of respondent fatigue, remain major weaknesses of the approach despite considerable advances.[7,8] Interviews with industry marketing managers indicate that conjoint studies can be costly, require several months to complete, and typically require the help of outside consultants to most effectively execute and analyze the collected data. Though unarguably valuable to refining a product in later design phases and for exploring preferences for novel features, the time and financial requirements of conjoint analysis does not make it suitable for standard use in the early PD phase.

Figures of Merit

Design engineers use preliminary techniques such as those in Roskam[9] to assess in detail the technical performance of proposed airplane designs. In the early fuzzy front-end phase of PD, both engineers and managers require a simplified yet meaningful metric for more rapidly evaluating designs that are not yet well enough detailed in their definition for more advanced methods. This has resulted in a number of less resource intensive and simplified productivity or value metrics being developed throughout the aviation industry. McMasters and Cummings[10] combine factors of speed, useful load, and maximum takeoff weight to estimate the efficiency of commercial transport aircraft in their productivity index (PI_1):

$$PI_1 = \text{Speed} \cdot \frac{\text{Useful Load}}{\text{Max Takeoff Weight}} \tag{1}$$

Though perhaps useful for large commercial aircraft, this measure of transport capacity neglects attributes of importance to the business aviation community such as airplane range, field performance, and the comfort of passengers. Mead et al.[11] propose one measure of productivity specifically for business jets that also includes the airplane purchase price:

$$PI_2 = \frac{\text{Purchase Price}}{\text{Passengers} \cdot \text{Range} \cdot \text{Cruise Speed}} \tag{2}$$

Conventional economic theory, however, indicates that productivity (or value) should be weighed against price rather being a function of price,[12] and one should also note that the form of this index counterintuitively indicates a lower value of PI_2 for more highly productive products. Furthermore, the index fails to indicate meaningful trends in product value as current-day business aircraft are assessed across their respective market segments and does not indicate any overall advancement of business aircraft productivity over the past 40 years, a result at variance with reality (Fig. 1).

§Data available online at http://mitsloan.mit.edu/vc.

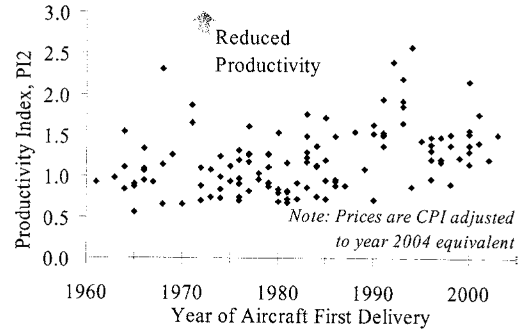

Fig. 1 History of business aircraft productivity using PI_2 figure of merit.

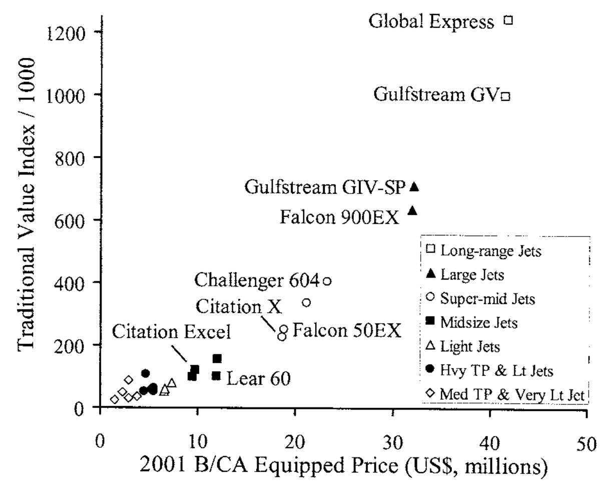

Fig. 2 Traditional value index for the business airplane market, 2001.

In the business airplane industry the most common figure of merit is the so-called traditional value index (TVI), a mathematical model first publicly documented by Norris[13,14] in the 1990s but widely used for decades:

$$\text{TVI} = \frac{\text{Range} \cdot \text{Speed} \cdot \text{Cabin Volume}}{\text{Field Length}} \tag{3}$$

The "value" of a proposed or existing business airplane in terms of technical utility and consumer appeal can ostensibly be assessed using the TVI approach. The appeal of the TVI is obvious; the mathematics are straightforward, and the data required are minimal and readily accessible for existing business airplanes in publications such as *Business and Commercial Aviation*.[15] The weaknesses of the TVI include the inability to weight the importance of the attributes relative to one another and the high correlation of the attributes used in the model, making redundant much of the information provided by the model's parameters (e.g., range and cabin volume, $r = 0.94$; field length and speed, $r = 0.84$; based on business airplane data in Ref. 15 for the 2004 market).

The fundamental value/price trend reflected in the TVI results, shown in Fig. 2 for the 2001 business airplane market, is also problematic. The figure indicates a strong exponential relationship between product value and price, largely a result of the aircraft range and cabin volume multiplication in the TVI. The trend would imply that products of increasing value should be delivered with diminishing price increases and that perhaps, at the extreme, infinite value can be delivered at some asymptotic price. This mathematical trendline holds true even if entire upper-level segments were to be neglected. The theoretical ability of a manufacturer to profit by pursuing improvements in technical performance is strictly limited by the TVI approach. ("B/CA Equipped Price" in Fig. 2 refers to the *Business and Commercial Aviation* equipped price.[15])

Another concern is that the TVI model does not accurately represent some important historical events, calling into question its

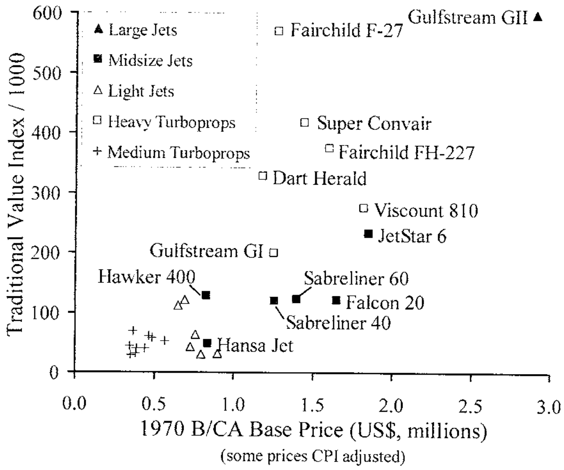

Fig. 3 Traditional value index for the business airplane market, 1965–1970.

suitability for assessing current industry developments. One such example is the ascendance in the late 1960s of the first generation of jet-driven business airplanes (for example, the Lockheed JetStar and the North American Sabreliner) over established heavy turboprop models. Figure 3 indicates that, had contemporary designers used the TVI model to assess the potential of business jet designs, those designers would have concluded that higher-valued, similarly priced heavy turboprops adapted from airline use, such as the Dart Herald and Super Convair, would continue to dominate the business airplane market. Students of history know, however, that within five years of their introduction in 1965 the first generation of business jets had completely driven their heavy turboprop competitors from the business airplane market.[15,16] [To make a direct comparison possible, all product prices in Fig. 3 are set to a 1970 equivalent using the consumer price index].

A number of permutations of the TVI exist in industry with slight variations in the parameters considered and with parameter weightings implemented in some form. The alternate forms of the TVI still do not address the issue of parameter correlation and offer no systematic method for selection of the weighting factors. Problems continue to exist with the fundamental trends indicated by the models and with the models' inability to replicate important historical events.

Relative Value Index Model

The deficiencies of existing methods warrant development of a new tool to aid in the early phase of business airplane product specification and assessment. In this section, a generalizable model suitable for use in the fuzzy front-end PD process that is simple in structure and computation while remaining adaptable to the changing needs of designers is developed.

Taguchi's Loss Function

The relative-value-index (RVI) mathematical model is based on Taguchi's loss function, adapted from statistical process control methods.[17] Traditional manufacturing practices strive to produce products within a specification $\pm\Delta$ of a nominal attribute level g_0. A loss of quality is assumed only when products fall outside the specification and is typically quantified in terms of the repair cost A (Fig. 4). As long as the attribute g is within $g_0 \pm \Delta$, then the quality level is treated as if it were at g_0 and no losses are assumed. Taguchi repudiates the mindset that loss only occurs when a product falls outside the specification limits $\pm\Delta$. Instead, the importance of producing products as close to the nominal specification as possible is emphasized in the loss function by representing a continual loss of quality as a result of any deviation from g_0. The total quality of the part or product $Q(g)$ is then based on the level of attribute g as shown in Fig. 4. Note that in this case $Q(g_0) = Q_I$ has been selected such that some residual nonzero quality exists even at $g = g_0 \pm \Delta$.

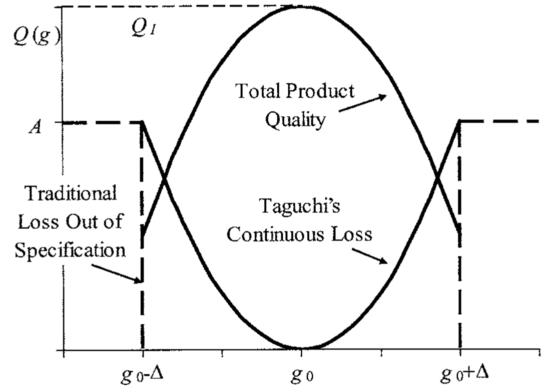

Fig. 4 Traditional and Taguchi losses.

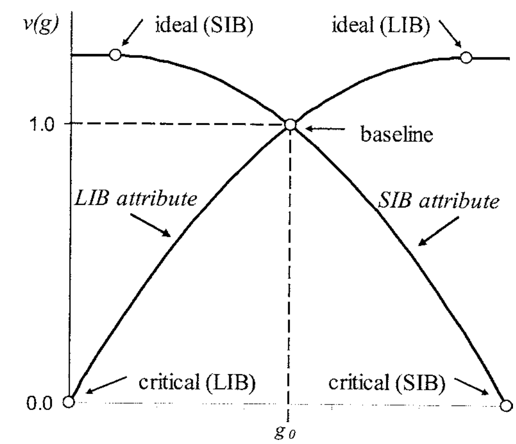

Fig. 5 Examples of attribute types LIB and SIB.

Cook's Extension to Value

Cook[18] extends the concept of a *quality* loss function to that of a *value* loss function and makes a number of contributions to the manner in which value can be modeled for products. The "value" terminology is important in that, unlike "utility," it connotes an economic tradeoff for consumers (monetary value is received in exchange for monetary units such as dollars) and because value can extend beyond conventional manufacturing "quality" or technical "performance."

In addition to a nominal attribute level g_0, Cook introduces the concept of an ideal attribute level g_I at which further improvement in the attribute is of no additional value to the stakeholder and the critical attribute level g_C at which further degradation in the attribute renders the product as a whole worthless to the stakeholder. The requirement for specifying an ideal value $v(g_0) = v_I$ is also eliminated by referencing value to a baseline product $v(g_0) = 1.0$. The relative value of a product as a result of a single attribute at level g located between g_C and g_I is then given by Cook's value equation:

$$v(g) = \left[\frac{(g_C - g_I)^2 - (g - g_I)^2}{(g_C - g_I)^2 - (g_0 - g_I)^2}\right] \tag{4}$$

Attributes can consist of any number of product features or functions such as noise, speed, reliability, etc. Sketches of representative smaller-is-better (SIB) and larger-is-better (LIB) type attributes are shown in Fig. 5. For LIB type attributes $v(g) = 0$ if $g < g_C$ and $v(g) = v(g_I)$ if $g > g_I$. For SIB type attributes $v(g) = 0$ if $g > g_C$ and $v(g) = v(g_I)$ if $g < g_I$. Note that $v(g) \geq 0$ and is typically, though not necessarily, within an order of magnitude of 1.0.

Use of the Taguchi loss function with added ideal and critical attributes is an intuitively appealing approach to the measurement of attributes and reflects the economic theory of diminishing marginal value (or benefit) caused by consumer saturation in the attribute. Cook's augmentation of Taguchi's loss function marks an important contribution to the science of value modeling.

Multi-Attribute Value

The value of the most complex products is influenced by multiple attributes, all of which must be considered by the value model simultaneously. A multi-attribute figure of merit for the total value of the ith product in a competitive market, where the value is composed of $j = 1, 2, 3 \ldots n$ attributes, will be hereafter referred to as the RVI equation:

$$\mathrm{RVI}_i = v(g_{i1})^{\gamma_1} v(g_{i2})^{\gamma_2} v(g_{i3})^{\gamma_3} \ldots v(g_{\mathrm{in}})^{\gamma_n} \tag{5}$$

Cook's S-Model is of this same form, but Cook has not yet established a name for the value equation itself. The relative-value-index nomenclature is used in this study for purposes of clarity in reference and to maintain some connection with the well-known and established business aviation traditional value index.

The exponential weighting factors in the RVI equation γ_j reflect the relative importance to the overall product RVI of the attributes g_j. The form of this equation is the well-known Cobb–Douglas utility function from economic theory, and in this form the system is rendered worthless if any single attribute reaches a critical point g_C. The multiplicative relationship among the attributes also provides that the effect of a specific product attribute depends not only upon its own level but also on the levels of the other attributes. The RVI metric is dimensionless and nonnegative.

A value index (VI) can also be expressed in absolute terms, such as dollars, by multiplying the RVI equation with the absolute value of a baseline product V_0:

$$\mathrm{VI}_i = V_0 \left\lfloor v(g_{i1})^{\gamma_1} v(g_{i2})^{\gamma_2} v(g_{i3})^{\gamma_3} \ldots v(g_{\mathrm{in}})^{\gamma_n} \right\rfloor \tag{6}$$

Using a uniform baseline value across all products in a segment holds because all product values are relative to the same set of nominal attribute levels for the j attributes g_{0j}, and V_0 thus acts as a scaling factor. Note, however, that the baseline product value V_0 (e.g., \$45 million for an aircraft) is distinct from the nominal attribute level g_0 (e.g., 391 kn airspeed for an aircraft). Determination of V_0 based on customer-revealed value will be discussed in the next section. Equation (6) represents a bottoms-up (or compositional) approach to product value estimation that depends only on the attributes of the products under consideration.

Consumer-Revealed Value

Although the RVI model estimates product value through a compositional attribute part-worths approach, value can also be estimated based on consumer-revealed preferences. ("Part-worths" in the marketing literature typically indicates a summation figure of merit. Here we refer to a product, but believe the terminology is still useful.) Traditional economic theory of consumer demand holds that quantity demanded is a function of the consumer's value function, product prices, and constraints on consumer income.[12] In his 1890 *Principles of Economics* Alfred Marshall first proposed the concept that the price at which consumers are willing to forego consumption of a product is treated as a measure of the value of the product to the individual.[19] This price point V is considered in this research to be the product's value as revealed by the consumer's preferences and is noted in Fig. 6. A linear consumer demand function is used

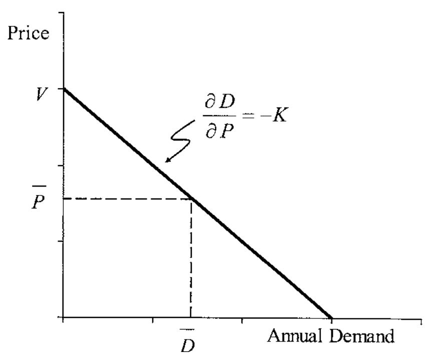

Fig. 6 Demand as a function of price (linear approximation).

to operationalize the relationship between demand D, price P, and value V for the ith product in a competitive market (this approach assumes that the markets under consideration are not monopolistic):

$$D_i = K(V_i - P_i) \tag{7}$$

The coefficient K can be estimated from the price elasticity E_p and the average demand and price $\bar{D}$ and $\bar{P}$ of the market segment for which demand is being estimated:

$$K = E_p \frac{\bar{D}}{\bar{P}}, \qquad E_p = \frac{\%\text{ change in unit sales}}{\%\text{ change in unit price}} \tag{8}$$

The linear demand model neglects how the actions of competitors can influence the demand for a product. Cook and Kolli[20] propose an approximate method for considering the effects of competitors by adding a new term to the ith product's estimated annual demand:

$$D_i = K \left\{ (V_i - P_i) - \frac{1}{N_k} \sum_{l \neq i} (V_l - P_l) \right\} \tag{9}$$

Errors in this linear model grow as competing products within a segment deviate from $\bar{D}$ and $\bar{P}$. To minimize errors, it is best to consider product segment groupings as those having $(V - P)$ levels within 15–20% of the product with the largest $(V - P)$ in the segment.

A set of simultaneous demand equations for the N_k products in a segment can be written based on Eq. (9).

$$\begin{bmatrix} D_1 \\ D_2 \\ \vdots \\ D_{N_k} \end{bmatrix} = \frac{K}{N_k} \begin{bmatrix} N_k & -1 & \cdots & -1 \\ -1 & N_k & & \vdots \\ \vdots & & \ddots & -1 \\ -1 & \cdots & -1 & N_k \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_{N_k} \end{bmatrix} - \frac{K}{N_k} \begin{bmatrix} N_k & -1 & \cdots & -1 \\ -1 & N_k & & \vdots \\ \vdots & & \ddots & -1 \\ -1 & \cdots & -1 & N_k \end{bmatrix} \begin{bmatrix} P_1 \\ P_2 \\ \vdots \\ P_{N_k} \end{bmatrix} \tag{10}$$

Solving for the product value vector yields the revealed value (RV) (in dollars) of the ith product based on the demand and price of that product and the total segment demand D_T:

$$\mathrm{RV}_i = [N_k/(N_k + 1)K](D_i + D_T) + P_i \tag{11}$$

Equation (11) represents a top-down approach to product value estimation that depends only on empirical market data for the products under consideration.

Determining Attribute Weights

The results of the attribute bottoms-up value index and the top-down revealed-value calculations for any product should ideally be identical; VI = RV. If V_0 represents the average revealed value of all competing products in the s market segment, then the only unknown quantities when equating VI and RV are the attribute weights γ_j. These weights can be determined by a best fit (ordinary least squares or other method) of individual product RV and VI results, either among competing products in one market segment or among multiple market segments. In the business aviation model the sum-squared error cost function will be minimized by varying γ_i using a generalized-reduced-gradient method:

$$J = \sum_{k=1}^{s} \sum_{i=1}^{N_k} (\mathrm{RV}_{ik} - \mathrm{VI}_{ik})^2 \tag{12}$$

where s is the number of market segments under consideration.

General Model Considerations

Note that by equating VI to the revealed value, the resulting set of attribute weighting factors indicates only what attributes make products differentiable in the current market. The optimization routine leverages the attributes to minimize the cost function J and only those attributes that cause a product to be distinguished from another can be utilized by the optimization. Therefore higher numerical values for weighting factors do not necessarily indicate the importance of that attribute to the customer, but instead the contribution of that attribute to making products differentiable. An attribute with a weighting factor of zero can be quite important to the customer but fairly uniform across the competing products, making them nondifferentiable on that attribute alone (e.g., an aircraft having received a type certification from the U.S. federal government). The process represented by Eq. (12) directly links, for the first time, Cook's compositional RVI method to empirical market data and permits analysis of what attributes serve as determinants of competition in a free market.

Fulfilling Little's criteria for good decision models, the preceding model development is simple to use, simple to control, and easy with which to communicate. It is easily implemented on a common PC using spreadsheet software such as MS Excel. Built-in optimization routines such as Excel Solver are well suited for determining the best fits for attribute weights, and the graphing capabilities of spreadsheets are useful in better understanding the model's behavior.

Application to the Business Airplane Industry

Cook's RVI method is extended to the domain of business aviation for the first time in this study. Business aviation is defined by the National Business Aviation Association as consisting of "companies and individuals using aircraft as tools in the conduct of their business."[21] The airplanes implemented in the model are those listed in *Business and Commercial Aviation*[15] for appropriate years. An in-depth discussion of the application to the business airplane industry, as well as listings of all data used, is available in Downen.[22]

Identification and Bounding of Attributes

Interviews with industry marketing and product managers indicate a wide belief that the parameters in the TVI model address some of the primary technical attributes of interest to business airplane customers, though additional important attributes include operating costs and load-carrying capability. Data are available for current and historical business airplane products for each of these attributes,[15] though fuel consumption per hour was used as a proxy for direct operating costs because of a lack of consistent historical data for costs. More attributes, some nontechnical in nature, are thought to be of importance but not implemented in the model at this time. These will be further discussed at the end of this section.

Nominal attribute levels g_0 were determined based on historical averages for the industry. Critical levels were typically estimated as being just below minimum values for the industry based on the supposition that products introduced with performance lower than historical minimums would be likely to compete poorly in the market. One exception is maximum speed for which the critical level is based on the maximum speed of the nearest competing form of transportation most popular in North America: the automobile. In a similar fashion the ideal levels were also estimated from the data at hand with exceptions such as the theoretical ideal of zero fuel consumption. Maximum speed was based on a round trip to any location on Earth within a 12-h business day (10 h round trip flying time with a minimum of two hours on the ground for a meeting).

The final bounds on the selected attributes are listed in Table 1, but before implementing the attributes in the RVI model the issue of *multicollinearity* needs to be addressed. Parameters with high correlations, typically considered $r \geq 0.85$, provide redundant information and, though inclusion of the parameters might provide better predictive capability in mathematical models, they reduce the explanatory power of the model as the user is not able to properly apportion the part-worth contributions of the correlated parameters. All attributes considered for the model are important, but because of physical laws and design tradeoffs some attributes are forced into dependency with others. An example is field length growing proportionally with aircraft range caused by a common dependence on aircraft weight. Because the attributes are not independent, they are not both meaningful and should be combined into alternative, meaningful parameters with lower correlation coefficients. Another option is to eliminate all but one of the correlated parameters, but this strategy is problematic as one does not want to eliminate design considerations.

Variable correlations are addressed by combining several variables into three new but meaningful attributes: available passenger seat miles (n miles-*pax*; a measure of load-carrying capability as well as range), cabin volume per passenger (ft$^3/pax$; a measure of passenger comfort), and fuel consumption per passenger seat mile (lb/n miles/*pax*; a proxy for operating costs as well as range and payload capability).

$$\text{available seat miles} = \text{range} \cdot \text{seating} \tag{13}$$

$$\text{cabin volume per passenger} = \frac{\text{cabin volume}}{\text{seating}} \tag{14}$$

$$\text{fuel consumption per seat mile} = \frac{\text{fuel consumption}}{\text{speed} \cdot \text{seating}} \tag{15}$$

The new attribute bounds were estimated based on historical data for the business aviation industry. The final list of attributes selected for the RVI model is shown in Table 1 along with the critical and ideal bounds placed on the parameters (the weights and sensitivity $\partial J/\partial \gamma$ will be discussed shortly). The sum-squared error cost function for the fit that results in the listed attribute weighting factors is $J = 141.9$ and the multiple coefficient of determination $R^2 = 0.99$.

Comments on the Data Used

It is appropriate to briefly comment on the data used in this model for the aircraft characteristics. All technical and pricing data are from

Table 1 Business airplane relative-value-index model attributes

		Attribute bounds				
Attribute	Type	Critical	Baseline	Ideal	Weight[a] γ	$\partial J/\partial \gamma$[a]
Max. cruise speed, ktas[b]	LIB	61[c]	391	2,866[d]	0.25	10.7
Runway field length, ft	SIB	10,000[e]	4,000	3,000	0.00	36.1
Fuel cons./seat-mile, lb/n miles/*pax*	SIB	1.0	0.4	0.0	0.00	62.6
Cabin vol./passenger, ft$^3/pax$	LIB	20	60	150	0.23	43.6
Available seat miles, *pax*-n miles	LIB	900	21,000	100,000	0.15	54.4

[a]Weighting factors and sensitivities valid for 2001 business airplane market only.
[b]ktas = knots true airspeed.
[c]Top speed of alternative travel mode: automobile (70 mph).
[d]Mach 5.0 at altitudes $\geq 36{,}089$ ft. Enables aircraft of nonstop range to reach any point on Earth in ≤ 5 h, allowing 12-h travel day with minimum 2 h on ground for meeting.
[e]Approximate longest runway lengths in North America.

Business and Commercial Aviation[15] of various years except for annual unit shipments, which are taken from the *Weekly of Business Aviation*[23] and GAMA shipment reports.[2] Technical parameters vary from year to year based on what the equipment manufacturers report to the publisher, but efforts have been made to preserve consistency in the parameters and to verify any that are in question with alternative sources. When comparing historical airplanes, with current airplanes, one needs to be aware that measurement and reporting methods have changed over the years even though *Business and Commercial Aviation* has been the consistent source of data publication. Some modification in parameter values will be necessary for a valid comparison using historical business airplane data.

Although unit shipments were employed in this model as equivalent to consumer demand, in reality annual unit shipments are set by a number of factors such as manufacturer capacity and order backlogs. Ideally one would use orders booked rather than unit shipments, but such data are typically not made public. The last year for which complete and detailed unit shipments data are available for the industry is 2001, thus all analysis referred to as "current day" is for the 2001 market. Additionally, the prices used in the model are those listed as average "equipped" prices in Ref. 15 (see the reference for details on the equipped price). Actual sales prices can be discounted by as much as 10–20% according to industry experts, but such data are closely held by both the manufacturers and customers and are unavailable for this analysis.

Attribute Weights

For purposes of determining the attribute weights, business airplanes offered in the 2001 market (the last year for which complete shipments data are available) were grouped into the seven competitive segments ($s = 7$) shown in Table 2. (Note that both the Raytheon Premier I and Dassault Falcon 900C are omitted from consideration. The year 2001 was the first year of shipments for the Premier, thus insufficient data existed to determine the true market appeal for the aircraft, and the Falcon 900C experienced unusually low shipments, perhaps as a consequence of manufacturer-imposed limits and not a reflection of the true market appeal of the aircraft.) These product segments are partially the result of ensuring $(V - P)$ levels remained within 20% of each other within a given segment (see discussion under consumer-revealed-value section) and might not exactly represent traditional industry segments that more closely follow list price. The revealed value of each aircraft within the seven segments was determined from known pricing and annual unit shipments data (averaged over three years to smooth the data) and with an estimated price elasticity of $E_p = 1.5$ (uniform across all segments) based on interviews with industry marketing experts and confirmed by data in Rukstad and Einav ("The Demand for Gulfstream Aircraft: A Quantitative Analysis of the Business Jet Market," unpublished working paper, Harvard Graduate School of Business Administration, Cambridge, MA, 17 May 2001). All parameters in the value index for each airplane, with the exception of the attribute weighting factors, were determined based on the attribute bounds in Table 1 and known airplane characteristics. Excel Solver (a generalized reduced gradient optimization routine) was used to minimize the sum-squared error cost function J by manipulating the attribute exponential weighting factors γ_j.

The resulting unique attribute weights for the VI = RV best fit are shown in Table 1.

Table 2 2001 market competitive segments

Segment ($s = 7$)	Airplanes
Medium turboprops and very light jets ($N_1 = 5$)	Socata TBM 700 Cessna Caravan I Pilatus PC-12 Raytheon King Air C90B Cessna CJ1
Heavy turboprops and light jets ($N_2 = 5$)	Piaggio P-180 Raytheon King Air B200 Raytheon King Air 350 Cessna CJ2 Cessna Citation Bravo
Light ($N_3 = 3$)	Bombardier Lear 31A Cessna Citation Encore Raytheon Beechjet 400A
Midsize ($N_4 = 4$)	Bombardier Lear 45 Bombardier Lear 60 Cessna Citation Excel Raytheon Hawker 800XP
Super midsize ($N_5 = 4$)	Dassault Falcon 50EX Bombardier Challenger 604 Dassault Falcon 2000 Cessna Citation X
Large ($N_6 = 2$)	Dassault Falcon 900EX Gulfstream G-IV-SP
Long range ($N_7 = 2$)	Bombardier Global Express Gulfstream G-V

Model Results

Sample RVI calculations for four representative modern business airplanes are shown in Table 3. Results for the 2001 business airplane market are graphed in Fig. 7 with some airplanes labeled for reference.

The value results in Fig. 7 show an intuitive trend consistent with industry perceptions and actual sales experiences for the various airplanes. The relative value/price position of aircraft in the figure represents an approximation of actual technical and market performance experienced by each airplane relative to competing products. Given this assessment of the current business airplane market, designers can use the RVI approach to place proposed new products or modified designs on such a graph for a rapid, intuitive evaluation of both the anticipated market and technical performance for that design. The potential market share captures for new products can also be estimated using Eq. (9), which leads to a rapid method of assessing the marketability impacts as a result of changing product technical parameters.

Table 3 Sample RVI calculations for 2001 business airplanes

	Attribute level (relative value)					
Airplane	Max cruise speed	Field length	Fuel cons./ seat-miles	Cabin vol/*pax*	Avail. seat miles	RVI
Bombardier Chall. 604	468 (1.050)	5840 (1.000)	0.48 (1.000)	141.7 (1.161)	35,757 (1.073)	1.307
Cessna CJ1	377 (0.990)	3280 (1.000)	0.45 (1.000)	63.4 (1.015)	4,093 (0.767)	0.771
Gulfstream GV	488 (1.061)	5150 (1.000)	0.35 (1.000)	122.5 (1.150)	85,358 (1.161)	1.417
Raytheon 800XP	447 (1.037)	5032 (1.000)	0.38 (1.000)	91.1 (1.102)	19,256 (0.988)	1.129

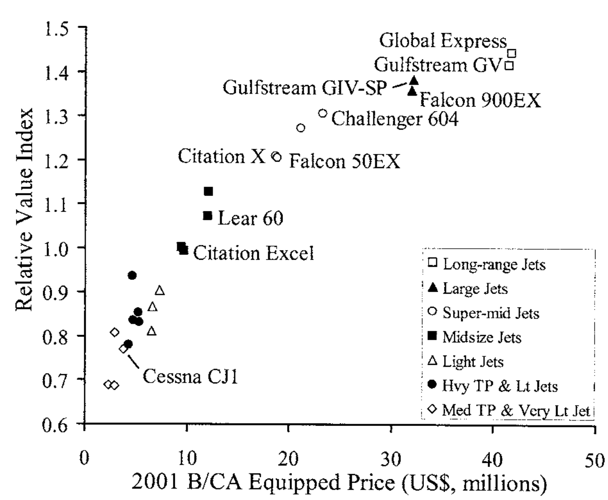

Fig. 7 Relative value index for the 2001 business airplane market.

A graph such as Fig. 7 provides designers a clear and easy approach to communicating anticipated product appeal and the impact of design decisions to project management. Nontechnical audiences are more likely to find Cook's RVI method, with its simple mathematics and intuitive use of concepts such as "ideal" and "critical" attribute levels, approachable and available for their own use in estimating effects such as product pricing changes with respect to existing competitive segment portfolios.

In contrast to the TVI approach, the value/price relationship shown in Fig. 7 is logarithmic, indicating a clear theoretical ability for manufacturers to profit by pursuing improvements in technical performance. The tendency to an asymptotic RVI level is attributable to a saturation of consumer needs in some technical attributes as they have been bounded for this study. Extending the ideal levels g_I of some attributes would make the curve more nearly linear, but would not alter the relative price/value relationship of the products.

Another advantage of the RVI model is its ability to better represent aspects of the historical evolution of the business airplane industry, enhancing its credibility for current-day product evaluation. Recalling the earlier criticism of the TVI model regarding the late 1960s introduction of business jets, in Fig. 8 one can see that RVI results for this time period point to a new family of business jets at higher values but equivalent or lower prices.

A new set of attribute weights, noted in the figure, was determined as just discussed using the averaged 1964–1966 market data. These weighting factors are the earliest that can be determined with statistical significance given the sparse business aircraft shipments data for the early 1960s. Business jets had just been introduced at this time, so that the weighting factor data do include some initial effect of the jets' introduction. Although it could be argued that the RVI results will be retrospective and only reflective of what the market actually decided regarding the value of the new business jets, it is felt that the data are still useful in showing a forecast of the coming effect the business jets would have on the existing heavy turboprops. At a minimum, the RVI method is capable of showing this effect, whereas existing methods such as the traditional value index are not capable of showing it.

The data in Fig. 8 show another important consideration in using the RVI method. Note that the HFB Hansa Jet, a failed design, is highly valued as the RVI model is currently structured around technical attributes. The design failed in part from negative market perceptions because of crashes of the prototype in flight test and also from a lack of access to the important North American market.[16] These are attributes, although difficult to quantify, that should be added to the RVI model for a more full and proper assessment of the early business airplane market.

It has been contended that existing figures of merit could simply be reformulated with exponential weighting factors to improve their performance vis à vis historical data and avoid transitioning to a new value assessment method. Such reformulations would, however, still lack important features contributed by the RVI approach, including its firm grounding in economic and consumer behavioral theory (e.g., Marshall's value of the product, diminishing marginal value), the intuitively attractive concepts of critical and ideal attribute levels, and an analytic basis for selecting the attribute weighting factors based on empirical determinants of competition.

Sensitivity Analysis

With the attribute weighting factors estimated in Table 1, the next question for users of the RVI approach should center on the reliability of the estimates. The sum-squared error cost function and the multiple coefficient of determination both indicate a good fit of the RV and VI equations, but do not directly speak to the consistency of the attribute weighting factors, particularly in light of uncertainties in the attribute levels themselves as well as the aircraft sales prices and demand.

The sensitivity of the sum-squared error J to changes in each of the attribute weighting factors $\partial J/\partial\gamma$ is shown in Table 1. The relatively low sensitivity of the cost function to changes in the maximum speed weighting factor indicates that the airplanes under consideration are less differentiable in this model on that attribute than on the others. This results from the fact that most business jets, a considerable proportion of all business aircraft today, cruise in approximately the same speed range, Mach 0.75–0.85. These sensitivity results indicate that the maximum speed weighting factor could be set to alternative values (for example, zero) without greatly altering the stance of one airplane's value relative to another. Designers should not interpret these results as meaning that the maximum speed attribute is unimportant, but only that it is not a differentiable attribute in the 2001 market. As a counterexample, historically one finds that maximum speed was a differentiable attribute in the mid-1960s as the first generation of business jets was introduced.

The sensitivity in Table 1 also indicates that the best fit varies most because of changes in the last four attributes. Despite this, the optimization routine was unable to utilize the first two of these attributes ($\gamma = 0$), runway field length and fuel consumption per passenger seat mile, in finding a best fit between revealed and estimated product values. The reasons for this are different for each of the attributes. As shown in Fig. 9, there is a strong correlation between increasing revealed value for the products in the 2001 market and increasing values of the aircraft's takeoff field lengths. Higher revealed values tend to correspond to larger aircraft, which, in turn, typically require longer runway distances to take off because of their higher weights. We have noted, however, that runway field length is a smaller-is-better attribute, so that the optimization routine, at least for the products in the 2001 market, cannot leverage this attribute to improve the RV and VI best fits.

In Fig. 10 it becomes apparent that the rate of fuel consumption per passenger seat mile is uncorrelated with revealed value. Fuel consumption is highly dependent on the aerodynamic properties of

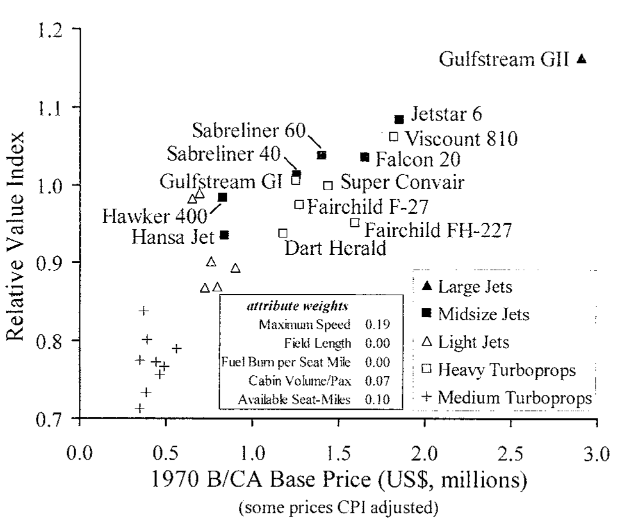

Fig. 8 Relative value index for the business airplane market, 1965–1970.

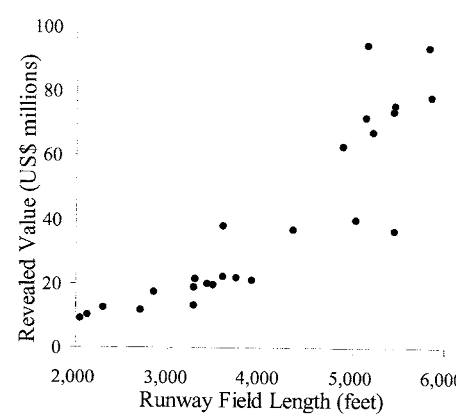

Fig. 9 Correlation of runway field length attribute and revealed value, 2001 market.

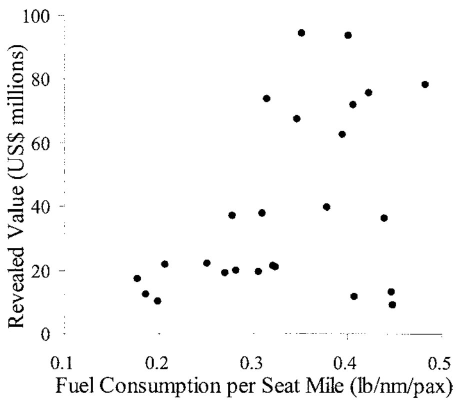

Fig. 10 Correlation of fuel consumption attribute and revealed value, 2001 market.

the aircraft (i.e., drag) and the efficiency of the engines. Turboprop-driven aircraft do tend to have higher fuel efficiencies within their low-speed cruise regimes, accounting for some of the low RV, low fuel consumption per seat mile data points in the figure. But for the majority of the jet-driven aircraft in the 2001 market, no aircraft type (i.e., light jet, long-range jet) tends to have a monopoly on fuel efficiency per passenger seat mile. For this reason the optimization routine is unable to leverage this attribute in the RV = VI best fit.

To address uncertainties in the attribute levels as well as in the aircraft sales prices and demand, a Monte Carlo analysis was performed to determine how the attribute weighting factors would change because of these uncertainties. Each of the five attributes and the product demand parameter were treated as normal random variables with 90% of their values falling within ±5% of their mean (deterministic) values (i.e., $1.65\sigma = 0.05\mu$). Because few customers would be expected to pay more than list price, the price parameter was treated an asymmetric B(2, 4) beta distribution with the bounds 0 and 20% representing the discount consumers would receive on the B/CA equipped price. With this distribution the average customer receives a 7% discount, and 90% of customers receive a 12% discount or less. The analysis was performed by randomizing each of the seven parameters for each of the aircraft in the 2001 market (Table 2) and then determining the new attribute weighting factors for the best fit. One thousand such randomizations and best fits were performed for the analysis.

The resulting $N(\mu, \sigma)$ distributions for the cabin volume and seat-miles weighting factors were $N(0.21, 0.06)$ and $N(0.14, 0.04)$ for each of the attributes, respectively. This indicates that the deterministic weighting factors for each of these attributes (i.e., $\mu = 0.23$ and 0.15) are reliable even amid uncertainties in the model inputs. The field length and fuel consumption weighting factor distributions were asymmetric with ($\mu = 0$, $\sigma = 0.04$) and ($\mu = 0$, $\sigma = 0.01$) for each of the attributes, respectively. In nearly every instance these attributes remain unused by the best fit routine, with only rare and negligible nonzero weighting factor values that do not alter the relative value standing of the aircraft under consideration. The maximum speed weighting factor demonstrated the greatest variation with a $N(0.21, 0.13)$ distribution. As noted before in examining the $\partial J/\partial\gamma$ sensitivity, this attribute does not facilitate differentiation in the 2001 business airplane market and can vary considerably without significantly impacting the RV and VI best fit. In effect, the Monte Carlo analysis serves as a confirmation of the $\partial J/\partial\gamma$ sensitivity analysis in indicating which attributes are of the greatest leverage in differentiating business airplanes in the 2001 market.

Missing Attributes and Model Adaptability

Industry marketing and product managers have indicated their belief that additional attributes, particularly dispatch reliability and after-sales customer support, are of increasing importance to the customer purchase decision. Unfortunately reliability statistics have not, until very recently, been formally collected in the business airplane industry and are currently not publicly available. Quantification of customer support levels is also difficult as they can vary widely from product to product even within the same manufacturer's product line. At least one manufacturer has tried to quantify customer support through factors such as the number of manufacturer-approved service centers in North America, but to date these data have failed to improve the best-fit results or the explanatory power of the RVI method. Two publications currently issue annual customer support surveys based on reader feedback.[24,25] Unfortunately the surveys are highly variable in the number of participants for each type of aircraft, and as a result the data are not statistically reliable enough for meaningful analysis in this research.

A preliminary analysis of model results for competitive segments throughout the past decade indicates that the products of some manufacturers are consistently under- or overvalued by the model, indicating in a quantitative fashion the possibility that there are important nontechnical manufacturer-related attributes not yet considered in the analysis. Customer support might be one factor, and it is anticipated that price discounting, warranty packages, delivery squawks (faults), and other as-yet difficult-to-quantify features will be proven to play an important role in the product value equation.

There are, unarguably, important attributes missing from the RVI model, and the authors agree that the RVI model's usefulness in practical applications is limited, for the time being, without the inclusion of at least some of the nontechnical attributes that have been discussed here. Nevertheless, the RVI method demonstrates an improved ability over existing value methods to replicate important historical market events and provides intuitively more correct price/value trends for current markets. The approach also enables the extension of value methods to market share analysis and engineering conceptual design studies. This study indicates that further development of Cook's RVI method with a focus on nontechnical attributes (vetted with empirical data) is well warranted.

Another merit of Cook's RVI approach are its ability to accommodate situations in which only sparse data are available. Designers can easily incorporate additional existing or novel product attributes if it is felt that a proposed product might be differentiable on those features. To assess a new proposal, the designer would need only to estimate the attribute bounds (critical, baseline, and ideal) and also the weighting factor, which it might be preferable to treat parametrically. Demand estimates should, in these situations, be made as market share capture estimates rather than as unit demand estimates as was discussed earlier. Such trade studies using the RVI method can be rapidly conducted using conventional computing resources.

Conclusions

Cook's relative value index is a new approach to business airplane product value assessment for the early, fuzzy front end of product development. The approach, while firmly rooted in economic and marketing science theory, adheres to Little's criteria for good models in being simple to use, easy to control, robust, adaptable, and easy to communicate with. Although not yet complete on important issues, this is because of the lack of reliable quantified data for certain important product attributes and not because of deficiencies in the method itself. Further research into quantifying nontechnical product attributes is warranted by the demonstrated potential of the method.

The RVI approach has a number of features that provide it an advantage in the early PD phase over existing industry product specification and assessment methods. The simplicity of the model structure and its minimal data requirements enable designers and decision makers to rapidly explore the tradespace of possible product attributes and their potential impact on the marketability of the product. The concept of ideal and critical attribute levels is an intuitively appealing characteristic that better meets established economic theory than exiting business aircraft industry figures of merit. The method also has demonstrated advantages over existing techniques in portraying historical industry developments as well as in the fundamental value/price relationship it represents.

References

[1]Little, J. D. C., "Models and Managers: The Concept of A Decision Calculus," *Management Science*, Vol. 16, No. 8, 1970, pp. B466–B485.

[2]"General Aviation Airplane Shipment Report 2003," General Aviation Manufacturers Association, Washington, DC, March 2004, URL: http://www.gama.aero.

[3]Green, P. E., and Rao, V. R., "Conjoint Measurement for Quantifying Judgmental Data," *Journal of Marketing Research*, Vol. 8, No. 3, 1971, pp. 355–363.

[4]Cattin, P., and Wittink, D. R., "Commercial Use of Conjoint Analysis: A Survey," *Journal of Marketing*, Vol. 46, No. 3, 1982, pp. 44–53.

[5]Wittink, D. R., and Cattin, P., "Commercial Use of Conjoint Analysis: an Update," *Journal of Marketing*, Vol. 53, No. 3, 1989, pp. 91–96.

[6]Louviere, J. J., Hensher, D. A., and Swait, J. D., *Stated Choice Methods: Analysis and Application*, Cambridge Univ. Press, New York, 2000.

[7]Hauser, J. R., and Rao, V. R., "Conjoint Analysis, Related Modeling, and Applications," *Advances in Marketing Research and Modeling: The Contributions of Paul E. Green*, edited by P. E. Green, Kluwer Academic, Norwell, MA, 2004.

[8]Carmone, F. J., Green, P. E., and Jain, A. K., "Robustness of Conjoint Analysis: Some Monte Carlo Results," *Journal of Marketing Research*, Vol. 15, No. 2, 1978, pp. 300–303.

[9]Roskam, J., *Airplane Design, Vols. I–VIII*, DAR Corp., Lawrence, KS, 1990.

[10]McMasters, J. H., and Cummings, R. M., "Airplane Design—Past, Present, and Future," *Journal of Aircraft*, Vol. 39, No. 1, 2002, pp. 10–17.

[11]Mead, L. M., Coppi, C., and Strakosch, J., "The Grumman Aerospace and Gulfstream American Gulfstream III Case Study in Aircraft Design," AIAA Professional Study Series, AIAA, Reston, VA, 1980.

[12]Nicholson, W., *Microeconomic Theory: Basic Principles and Extensions*, 6th ed., Dryden Press, New York, 1995.

[13]Norris, R., "Measuring the Relative Value of Business Aircraft," *Professional Pilot*, Jan. 1999, pp. 48–54.

[14]Norris, R., "Relative Value of Business Aircraft-Part 2," *Professional Pilot*, Feb. 1999, pp. 50–54.

[15]*Business and Commercial Aviation, Purchase Planning Handbook*, McGraw–Hill, New York, April Issue 1960–1973; May Issue 1974–2004.

[16]Pattillo, D. M., *A History in the Making: 80 Turbulent Years in the American General Aviation Industry*, McGraw–Hill, New York, 1998.

[17]Taguchi, G., Yokoyama, Y., and Wu, Y., *Taguchi Methods*, Quality Engineering Series, Vols. 1–4, Japanese Standards Association, American Supplier Inst. Press, Dearborn, MI, 1993.

[18]Cook, H. E., *Product Management: Value, Quality, Cost, Price, Profits, and Organization*, Chapman and Hall, New York, 1997.

[19]Marshall, A., "What is Experimental Design for Quality?" *Principles of Economics*, 9th ed., annotations by C. W. Guillebaud, Vol. 4, Taguchi Methods, Quality Engineering Series, MacMillan, New York, 1961, Chap. 1.

[20]Cook, H. E., and Kolli, R. P., "Using Value Benchmarking to Plan and Price New Products and Processes," *Manufacturing Review*, Vol. 7, No. 2, 1994, pp. 134–147.

[21]"NBAA Business Aviation Fact Book 2004," National Business Aviation Association, Washington, DC, 2004, p. 2.

[22]Downen, T. D., "A Multi-Attribute Value Assessment Method for the Early Product Development Phase with Application to the Business Aviation Industry," Ph.D. Dissertation, Engineering Systems Div., Massachusetts Inst. of Technology, Cambridge, MA, Feb. 2005.

[23]*Weekly of Business Aviation*, McGraw–Hill, New York, 1966–2004.

[24]"Product Support Survey," *Aviation International News*, The Convention News Co., Inc., Midland Park, NJ, Aug. 2004, pp. 18–24.

[25]"Corporate Aircraft Product Support Survey," *Professional Pilot*, Queensmith Communications Corp., Alexandria, VA, Sept. 2004, pp. 54–72.