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CONCEPTUAL DESIGN OF A FAMILY OF PRODUCTS THROUGH THE USE OF THE ROBUST CONCEPT EXPLORATION METHOD

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ABSTRACT

In this paper, we present a method for designing a *family* of products, namely, a family of General Aviation aircraft around a given noise factor - the number of passengers. Principles from robust design embodied in the Robust Concept Exploration Method (RCEM) are used to determine a *ranged* set of top-level design specifications around which a family of aircraft can be developed. The robustness of the solutions found using the RCEM is examined and also compared to the appropriate baseline designs. Our focus in this paper is on describing some foundational principles for designing a family of products and not on the results of the example problem, *per se*.

NOMENCLATURE

AF	Engine Activity Factor
AR	Aspect Ratio
CSPD	Aircraft Cruise Speed, Mach
d_i^+, d_i^-	Positive and negative deviation variables in compromise DSP
DOC	Direct Operating Cost, $/hr
DPROP	Propeller Diameter, ft
DSIDES	Computer software for Decision Support in Designing Engineering Systems which is used to solve compromise DSPs.
DSP	Decision Support Problem
GAA	General Aviation Aircraft
GASP	General Aviation Synthesis Program
LDMAX	Maximum Lift to Drag Ratio
NOISE	Take-off Noise, dbA
nmu	No Meaningful Units
PAX	Number of Passengers
PURCH	Aircraft Purchase Price, $
RANGE	Maximum Cruise Range, nautical miles
RCEM	Robust Concept Exploration Method
ROUGH	Ride Roughness Factor
SW	Sweep Angle of Aircraft Wing, degrees
TPSPD	Propeller Tip Speed, ft/sec
VCRMX	Maximum Cruise Speed, kts
WEMP	Aircraft Empty Weight, lbs
WFUEL	Aircraft Fuel Weight, lbs
WL	Wing Loading Estimate, lb/ft^2
WS	Seat Width, in

1. FRAME OF REFERENCE

The United States, despite possessing abundant resources of all kinds and having at one time, "made half the manufactured products sold anywhere in the world," (Dobbins and Crawford-Mason, 1991) now faces an agile and unforgiving global marketplace in which the formerly all-important concept of economies of scale is now a thing of the past. Producers must offer a variety of products in addition to enhanced system flexibility in order to remain competitive in the marketplace. This raises the following question, *how can product realization teams provide product variety and enhanced flexibility for today's (and tomorrow's) highly competitive, global marketplace?*

Answers to this question vary in the literature. Wheelwright and Clark (1992) suggest designing "platform projects" which are capable of meeting the needs of a core group of customers but are easily modified into derivatives through addition, substitution, or removal of features. Similarly, Uzumeri and Sanderson (1995) emphasize standardization and flexibility as a means for enhancing *product flexibility*. Most recently, Ishii, et al. (1995) introduced the variety importance-cost map to help minimize the life-cycle cost associated with offering product variety. Chen and her coathors (1994) suggest designing *flexible products* which can be readily adapted in response to large changes in customer requirements by changing a small number of components or modules. This idea is further expanded in (Simpson, et al., 1996) in which we introduce *open engineering systems*; systems which are readily adaptable to changes in their environment and enable producers to remain competitive through indefinite growth and continuous improvement of an existing technological base. Finally, Rothwell and Gardiner (1988) advocate robust designs as a means to improve system flexibility. They assert that robust designs have sufficient inherent *design flexibility* or "technological slack" to enable them to evolve into a *design family of variants* which meet a variety of changing market requirements.

Our focus in this paper is on the use of the Robust Concept Exploration Method (RCEM) to design a *family of products* as shown in Figure 1. On the left hand side of Figure 1, we list existing philosophies or approaches which facilitate designing a family of products, e.g., standardization, modularity, robustness, etc. In the dashed box in the middle of Figure 1 we illustrate our approach, namely, the implementation of robust design principles embodied in the RCEM to develop *a family of products around a common noise factor.* Specifically, we invoke the Robust Concept Exploration Method (Chen, et al., 1995b) to develop a *ranged* set of top-level design specifications for a *family* of products. Our approach is applied to an example problem, namely, the conceptual design of a family of General Aviation aircraft. The family of aircraft consists of three models: a two (2), a four (4), and a six (6) seater aircraft, and the number of passengers serves as the noise factor in the design as outlined in Section 3. To begin, we introduce the Robust Concept Exploration Method and its components in the next section. In Section 3, we present our example problem.

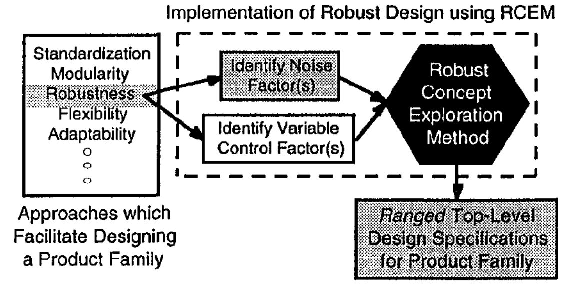

Figure 1 -- Pictorial Overview of Approach for Designing a Family of Products using RCEM

2. DESIGNING A FAMILY OF PRODUCTS: OUR FOUNDATION

2.1. Robust Concept Exploration Method

The RCEM is developed to facilitate quick evaluation of different design alternatives and generation of top-level design specifications with quality considerations in the early stages of design (Chen, et al., 1995b). It is primarily useful for designing complex systems and for computationally expensive design analysis. The RCEM is created by integrating several methods and tools, i.e., robust design methods (Phadke, 1989), the Response Surface Methodology (Box and Draper, 1987; Khuri and Cornell, 1987), and Suh's Design Axioms (Suh, 1990), within one mathematical construct, namely, the compromise Decision Support Problem (Mistree, et al., 1993). A complete description of the RCEM is presented in (Chen, 1995a), and its usefulness for designing families of products is discussed thoroughly in (Simpson, 1995). The RCEM is a four step process with the corresponding computer infrastructure illustrated in Figure 2.

Step 1: Classify Design Parameters - Given the overall design requirements, this step involves the use of Processor A (Figure 2) from the RCEM computer infrastructure to (a) classify different design parameters as either control factors, noise factors, or responses following the terminology used in robust design and (b) define the concept exploration space.

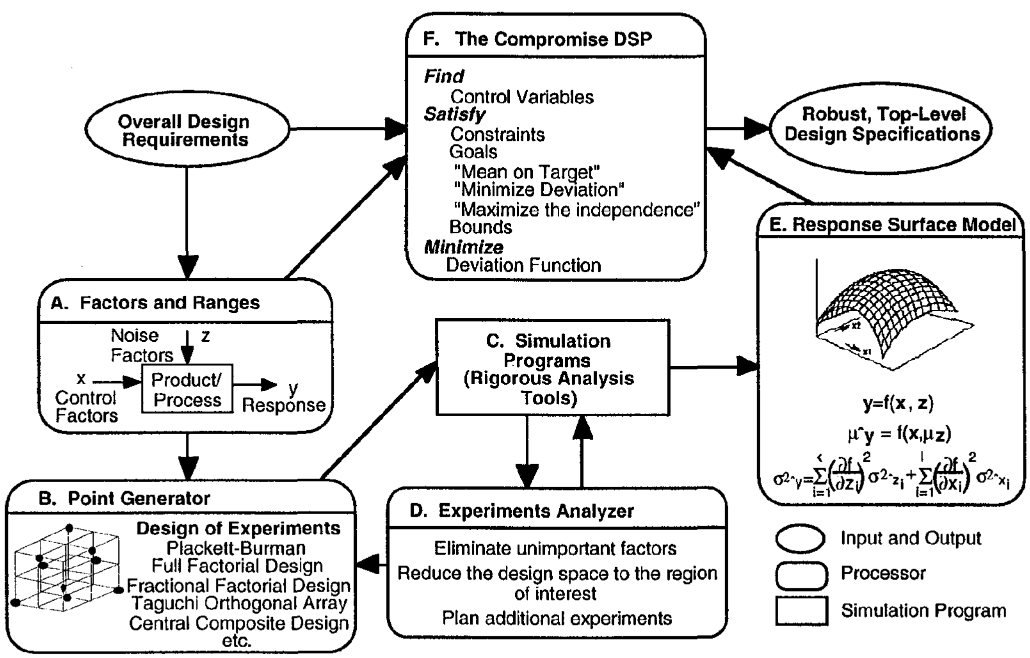

Figure 2 -- Computer Infrastructure of the RCEM

Step 2: Screening Experiments - This step requires the use of a point generator (Processor B), simulation programs (Processor C), and an experiment analyzer (Processor D) as shown in Figure 2 to set up and perform *initial screening experiments* and analyze the results. The results of the screening experiments are used to (a) fit low order response surface models, (b) identify the significance of main effects and omit those factors which have little or no influence on the design, and (c) reduce the design region.

Step 3: Elaborate the Response Surface Model - This step also requires the use of the point generator (Processor B), simulation programs (Processor C), and experiment analyzer (Processor D) from Figure 2 to set up and perform *secondary experiments* and analyze the results. The results from the secondary experiments are used to (a) fit high order response surface models (using Processor E) which replace the original (computationally expensive) analysis programs, (b) identify key design drivers and the significance of different design factors and their interactions, and (c) quickly evaluate different design alternatives and answer "what-if" questions in Step 4.

Step 4: Generate Top-Level Design Specifications with Quality Considerations - Once an accurate response surface model has been created, Step 4 involves the use of the compromise DSP (Processor F in Figure 2) to determine top-level design specifications with quality considerations. In Step 4, the original analysis or simulation program(s) is replaced by response surfaces which are functions of both control and noise factors. Different quality considerations and multiple objectives are incorporated in the compromise DSP which is then solved to determine the appropriate top-level design specifications.

2.2. Overview of Robust Design Principles

One of the main components of the RCEM is an *adaptation* of robust design methods which relies on modeling the robust design objectives of "bringing the mean on target" and "minimizing the deviation" as separate goals in a compromise DSP (Chen, et al., 1995b). In robust design, a designer adjusts control factors, x, to dampen variations caused by the noise factor, z, as illustrated in Figure 3. If the objective is to achieve a performance as close as possible to the target, M, the designs at levels x = a and x = b are both acceptable because their means are on target. However, introducing *robustness*, when x = a, the performance varies significantly with the deviation of the noise factor, z; however, when x = b, the performance deviates considerable less. Therefore, x = b is more robust than x = a as a design solution because x = b dampens the effect of the noise factors more than x = a. By selecting the control factor settings which best minimize the effects of noise on the system performance, we can *develop a set of specifications which is robust with respect to a given noise factor.*

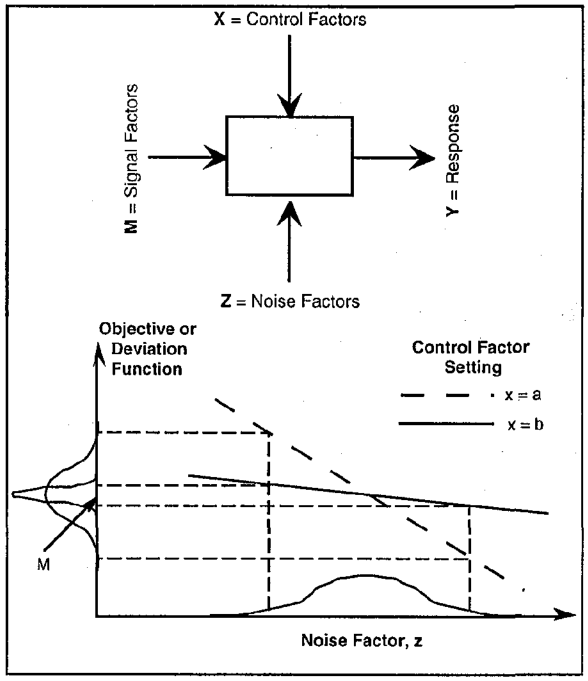

Figure 3 -- Taguchi's Robust Design

2.3. Response Surface Methodology

To facilitate the implementation of robust design, response surface models are created and used in the RCEM to approximate the design space. The major elements of the response surface model approach (Welch, et al., 1990; Shoemaker, et al., 1991) are:

- combining control and noise factors in a single array instead of using Taguchi's inner- and outer-array approach,
- modeling the response itself rather than expected loss, and
- approximating a prediction model for loss based on the fitted-response model.

Central composite designs are employed to fit second-order response surface models based on design simulations. This process is facilitated through the use of experimental sequencing software entitled NORMAN®. In general, the response surface model postulates a single, formal model of the type:

$$\widehat{y} = f(\mathbf{x},\mathbf{z}) \tag{1}$$

where $\widehat{y}$ is the estimated response and **x** and **z** represent the settings of the control and noise variables. From the response surface model, it is possible to estimate the mean and variance of the response. For applications in which the deviations of noise factors are the source of variation, the mean and variance of the response can be approximated by:

- Mean of the response:

$$\mu_{\hat{y}} = f(\mathbf{x}, \mu_{\mathbf{z}}) \tag{2}$$

- Variance of the response:

$$\sigma^2_{\hat{y}_i} = \sum_{i=1}^{k} \left(\frac{\partial f}{\partial z_i}\right)^2 \sigma^2_{z_i} \tag{3}$$

where μ represents the mean values, k is the number of noise factors in the response model and σ_{Zi} is the standard deviation associated with each noise factor.

2.4. The Compromise DSP

The compromise DSP is the mathematical construct through which the various metrics and tools of the RCEM are integrated. The compromise DSP is a multiobjective decision model which is a hybrid formulation based on Mathematical Programming and Goal Programming (Mistree, et al., 1993). It is used to determine the values of design variables which satisfy a set of constraints while achieving a set of conflicting goals as well as possible. The compromise DSP has been successfully used in designing aircraft, thermal energy systems, mechanisms, damage tolerant structural systems, ships, and material composite design.

The system descriptors, namely, system and deviation variables, system constraints, system goals, bounds and the deviation function are described in detail in (Mistree, et al., 1993) and are therefore not repeated here. The mathematical form of the compromise DSP is shown in Figure 4. Notice that the d_i^+ deviation is used to minimize a goal to a target whereas d_i^- is used to maximize a goal to a target; we make extensive use of this feature in Section 3.

In the compromise DSP, goals may be rank-ordered into priority levels using a Preemptive formulation to effect a solution on the basis of preference. We use the lexicographic minimum concept (Ignizio, 1985) to evaluate quickly different design scenarios by changing the priority levels of the goals to be achieved. This is demonstrated in Section 3.2 in our example problem. The compromise DSP is solved using the ALP algorithm (Mistree, et al., 1993), a part of DSIDES (Decision Support in Designing Engineering Systems (Reddy, et al., 1992)).

A solution to the compromise DSP is called a *satisficing* solution* since it is a *feasible point that achieves the system goals to the extent that is possible.* This notion of *satisficing* solutions is philosophically in harmony with the notion of developing a *broad and robust set of top-level design specifications.* The efficacy of the compromise DSP in creating ranged sets of top-level design specifications has been demonstrated in both aircraft design (Lewis, et al., 1994) and ship design (Smith and Mistree, 1994). By finding ranged sets of top-level design specifications

* Satisficing solutions are "good enough" but not necessarily the "best" (Simon, 1981).

Given

An alternative to be improved. Assumptions used to model the domain of interest.

The system parameters:

n number of system variables, q inequality constraints

p + q	number of system constraints,
m	number of system goals
$g_i(X)$	system constraint function
$f_k(d_i)$	function of deviation variables to be

minimized at priority level k for the preemptive case.

Find $X_i \quad i = 1, \ldots, n; \quad d_i^-, d_i^+ \quad i = 1, \ldots, m$

Satisfy

System constraints (linear, nonlinear)

$g_i(X) = 0 \; ; i = 1, .., p$

$g_i(X) \geq 0 \; ; i = p+1, ..., p+q$

System goals (linear, nonlinear)

$A_i(X) + d_i^- - d_i^+ = G_i \; ; i = 1, \ldots, m$

Bounds

$X_i^{min} \leq X_i \leq X_i^{max} \; ; \quad i = 1, \ldots, n$

$d_i^-, d_i^+ \geq 0 \; ; i = 1, \ldots, m$

$d_i^- \cdot d_i^+ = 0 \; ; i = 1, \ldots, m$

Minimize: *deviation function*

$Z = [\, f_1(d_i^-, d_i^+), \ldots, f_k(d_i^-, d_i^+) \,]$

Figure 4 -- Mathematical Form of a Compromise DSP

rather than point solutions, we can maintain design flexibility which enables the system to be readily adapted to changing design requirements. Use of the compromise DSP in the RCEM to develop a ranged set of specifications is demonstrated in the next section.

3. EXAMPLE : CONCEPTUAL DESIGN OF A FAMILY OF GENERAL AVIATION AIRCRAFT

To demonstrate the use of the RCEM to design a family of products, we present an example problem, namely, the conceptual design of a family of General Aviation aircraft (GAA) around the 2, 4, and 6 seater configurations. Background information can be found in (Simpson, 1995). Simply stated, our objective in the example problem is to develop a *ranged set of top-level design specifications† which are robust with respect to the number of passengers to facilitate developing a family of GAA around a common set of specifications.*

† Top-level design specifications are used to define the overall system configuration, e.g., wing area, aspect ratio, sweep angle, etc., and subsystems at an abstract level. They can be either continuous, e.g., aspect ratio = 7 - 11, sweep angle = 0° - 6°, etc., or they can be discrete, e.g., single- or twin-engine, high or low wing, etc.

This is achieved by introducing the number of passengers as a noise factor in the design and using robust design principles embodied in the RCEM to find a "common and good" ranged set of top-level design specifications for the family of GAA, Figure 1. In our simulation program, GASP (the General Aviation Synthesis Program (NASA, 1978)), aircraft seats must be specified in pairs, and the number of seats is equal to the number of passengers plus one pilot. An aircraft is then sized in GASP using a weight of 200 lbs per passenger; therefore, using the number of passengers, PAX, as a noise factor ranging from 1 to 5 allows us to size a *family* of aircraft for passenger weights varying from 200-1000 lbs which we consider as *noise* during the design process. We begin our example problem by formulating a compromise DSP for our family of General Aviation aircraft.

3.1. Formulation of GAA Compromise DSP

We are interested in finding the appropriate *ranged* values for the following top-level design specifications for the family of GAA.

1. Cruise speed, CSPD ($0.24 \leq$ CSPD $\leq$ to 0.48)
2. Aspect ratio, AR ($7 \leq$ AR ≤ 11)
3. Propeller diameter, DPROP ($5.5 \leq$ DPROP ≤ 6.8 ft)
4. Wing loading, WL ($19 \leq$ WL ≤ 25 lb/ft^2)
5. Wing sweep angle, SW ($0 \leq$ SW $\leq 6.0°$)
6. Engine activity factor, AF ($85 \leq$ AF ≤ 110)
7. Seat width, WS ($10 \leq$ WS ≤ 20.0 in)
8. Tail length to diameter ratio, ELODT ($3.0 \leq$ ELODT ≤ 3.75)

The compromise DSP for the GAA example problem is included in the Appendix. The individual constraints and goal target values for the different aircraft are summarized in Tables 1 and 2, respectively. For example, the take-off noise (NOISE) for all three aircraft must be less than 75 dbA, Table 1, while the empty weight (WEMP) of each aircraft should be 1900 lbs, 1950 lbs, and 2000 lbs for the 2, 4, and 6 seater aircraft, respectively. Worst case scenarios are used when satisfying the constraints while individual goals are created for "bringing the mean on target" and "minimizing the deviation" of each response since we are using robust design techniques in the RCEM to develop our family of aircraft. For example, the target for the mean of the fuel weight (WFUEL) goal is simply

$$\mu_{\text{WFUEL, Target}} = \frac{450 + 400 + 350}{3} = 400 \text{ lb} \qquad (4)$$

while the target for its deviation is

$$\sigma_{\text{WFUEL, Target}} = \frac{450 - 350}{6} = 16.65 \text{ lb} \qquad (5)$$

which is the permissible range for WFUEL divided by $\pm 3\sigma$, i.e., six standard deviations. The remaining mean and deviation targets are computed in a similar manner.

Table 1 -- GAA Compromise DSP Constraints for 2, 4, and 6 Seater GAA

Constraint	Acronym	2 Seater GAA	4 Seater GAA	6 Seater GAA
Take-off noise	NOISE	75 dbA	75 dbA	75 dbA
Propeller tip speed	TPSPD	850 ft/sec	850 ft/sec	850 ft/sec
Direct operating cost	DOC	\$80/hr	\$80/hr	\$80/hr
Ride roughness coefficient	ROUGH	2.0	2.0	2.0
Aircraft empty weight	WEMP	2200 lbs	2200 lbs	2200 lbs
Aircraft fuel weight	WFUEL	450 lbs	475 lbs	500 lbs

Table 2 -- GAA Compromise DSP Goal Targets for 2, 4, and 6 Seater GAA

Goal	Acronym	2 Seater GAA	4 Seater GAA	6 Seater GAA
Fuel weight	WFUEL	450 lbs	400 lbs	350 lbs
Empty weight	WEMP	1900 lbs	1950 lbs	2000 lbs
Direct operating cost	DOC	\$60/hr	\$60/hr	\$60/hr
Purchase price	PURCH	\$41,000	\$42,000	\$43,000
Max. lift to drag ratio	LDMAX	17	17	17
Max. cruise speed	VCRMX	200 kts	200 kts	200 kts
Max. range	RANGE	2500 nm	2500 nm	2500 nm

To facilitate the implementation of robust design, second order response surface models, which include the number of passengers as a noise factor, are created using an experiment sequencer/analyzer, NORMAN®. The response surface models are based on simulations from GASP (NASA, 1978) which performs parametric analysis necessary for preliminary aircraft design. Development and validation of the response surface models is detailed in (Simpson, 1995) and is not included here. These second order response surface models are used as the fast analysis module for solving the GAA compromise DSP in DSIDES as discussed in Section 2. Use of the second order response surface models facilitates estimating system response means and standard deviations, refer to Eqns. 2 and 3. For example, in GAA example problem, the mean of fuel weight (WFUEL) is computed as the average of the fuel weights for the 2, 4, and 6 seater GAA, i.e., and the standard deviation is approximated using a first order Taylor series expansion, e.g.,

$$\sigma_{WFUEL} \approx \sqrt{\sum_{1}^{i}\left(\frac{\partial f}{\partial z_i}\right)^2 \sigma_{z_i}^{\,2}} = \left|\left(\frac{\partial WFUEL}{\partial PAX}\right)\sigma_{PAX}\right| \qquad (6)$$

The first part of Eqn. 6 is the basic Taylor expansion for f(**x**) with noise factors, z_i, each with a standard deviation, σ_{zi}. Since the number of passengers, PAX, is the only noise factor in our example problem, there is only one partial derivative, ∂PAX, and the square root can be dropped. In this manner, we can approximate the means and standard deviations for all of the system responses and find a ranged set of top-level design specifications for our family of aircraft.

3.2. Top-Level Design Specifications for the Family of General Aviation Aircraft

A total of eight different design scenarios, see Table 3, are used when solving the GAA compromise DSP to develop a ranged set of top-level design specifications for the family of aircraft. The design scenarios consist of equally weighted deviation functions at each priority level (Preemptive formulation). The deviation variables d_1 - d_7 are for "bringing the mean on target" whereas the deviation variables d_8 - d_{14} are for "minimizing the variance". For example, in Scenario 2, the economic goals (d_2^+ and d_9^+ for WEMP, d_3^+ and d_{10}^+ for DOC, and d_4^+ and d_{11}^+ for PURCH) are equally weighted at the first priority level while the performance goals (d_1^+ and d_8^+ for WFUEL, d_5^- and d_{12}^+ for LDMAX, d_6^- and d_{13}^+ for d_7^- and d_{14}^+ for RANGE) are equally weighted at the second priority level. The goals for "bringing the mean on target" and "minimizing the variance" are placed at the same priority level whereas in reality they could be placed at different levels depending on the preference of the designer. A description of each group of design scenarios follows the table.

Table 3 -- GAA Compromise DSP Design Scenarios

Scenario	Deviation Function: *Priority Level 1*	*Priority Level 2*	*Priority Level 3*	*Priority Level 4*
Group I: Trade-offs				
1. **Overall trade-off study** (All goals equally weighted)	$1/14*(d_1^+ + d_2^+ + d_3^+ + d_4^+ + d_5^- + d_6^- + d_7^- + d_8^+ + d_9^+ + d_{10}^+ + d_{11}^+ + d_{12}^+ + d_{13}^+ + d_{14}^+)$			d_1 and d_8 are for fuel weight d_2 and d_9 are for empty weight d_3 and d_{10} are for direct operator cost d_4 and d_{11} are for purchase price d_5 and d_{12} are for lift to drag ratio d_6 and d_{13} are for cruise speed d_7 and d_{14} are for range
2. **Economic trade-off study** (DOC, WEMP, & PURCH ranked first)	$1/6*(d_2^+ + d_3^+ + d_4^+ + d_9^+ + d_{10}^+ + d_{11}^+)$	$1/8*(d_1^+ + d_5^- + d_6^- + d_7^- + d_8^+ + d_{12}^+ + d_{13}^+ + d_{14}^+)$		
3. **Performance trade-off study** (WFUEL, VCRMX, WFUEL, & LDMAX ranked first)	$1/8*(d_1^+ + d_5^- + d_6^- + d_7^- + d_8^+ + d_{12}^+ + d_{13}^+ + d_{14}^+)$	$1/6*(d_2^+ + d_3^+ + d_4^+ + d_9^+ + d_{10}^+ + d_{11}^+)$		
Group II: Economics				
4. **Economic driver:** WEMP & PURCH ranked first	$1/4*(d_2^+ + d_9^+ + d_4^+ + d_{11}^+)$	$1/2*(d_3^+ + d_{10}^+)$	$1/8*(d_1^+ + d_5^- + d_6^- + d_7^- + d_8^+ + d_{12}^+ + d_{13}^+ + d_{14}^+)$	
5. **Economic driver:** DOC ranked first	$1/2*(d_3^+ + d_{10}^+)$	$1/4*(d_2^+ + d_9^+ + d_4^+ + d_{11}^+)$	$1/8*(d_1^+ + d_5^- + d_6^- + d_7^- + d_8^+ + d_{12}^+ + d_{13}^+ + d_{14}^+)$	
Group III: Performances				
6. **Performance driver**: VCRMX & WFUEL ranked first	$1/4*(d_1^+ + d_6^- + d_8^+ + d_{13}^+)$	$1/4*(d_5^- + d_7^- + d_{12}^+ + d_{14}^+)$	$1/6*(d_2^+ + d_3^+ + d_4^+ + d_9^+ + d_{10}^+ + d_{11}^+)$	
7. **Performance driver**: LDMAX ranked first	$1/2*(d_5^- + d_{12}^+)$	$1/2*(d_7^- + d_{14}^+)$	$1/4*(d_1^+ + d_6^- + d_8^+ + d_{13}^+)$	$1/6*(d_2^+ + d_3^+ + d_4^+ + d_9^+ + d_{10}^+ + d_{11}^+)$
8. **Performance driver**: RANGE ranked first	$1/2*(d_7^- + d_{14}^+)$	$1/2*(d_5^- + d_{12}^+)$	$1/4*(d_1^+ + d_6^- + d_8^+ + d_{13}^+)$	$1/6*(d_2^+ + d_3^+ + d_4^+ + d_9^+ + d_{10}^+ + d_{11}^+)$

d_1^+ drives minimizing the *mean* fuel weight (WFUEL)
d_2^+ drives minimizing the *mean* empty weight (WEMP)
d_3^+ drives minimizing the *mean* direct operating cost (DOC)
d_4^+ drives minimizing the *mean* purchase price (PURCH)
d_5^- drives maximizing the *mean* lift to drag ratio (LDMAX)
d_6^- drives maximizing the *mean* cruise speed (VCRMX)
d_7^- drives maximizing the *mean* range (RANGE)

d_8^+ drives minimizing the fuel weight *std. deviation*
d_9^+ drives minimizing the empty weight *std. deviation*
d_{10}^+ drives minimizing direct operating cost *std. deviation*
d_{11}^+ drives minimizing the purchase price *std. deviation*
d_{12}^+ drives minimizing lift to drag ratio *std. deviation*
d_{13}^+ drives minimizing cruise speed *std. deviation*
d_{14}^+ drives minimizing the range *std. deviation*

Group I - Trade-off studies - includes Scenarios 1, 2 and 3. An overall trade-off study with all goals weighted equally is performed in the first scenario. The second scenario is an economic trade-off study with WEMP, PURCH, and DOC given first priority. A performance trade-off study with WFUEL, VCRMX, RANGE, and LDMAX ranked first is the third scenario. The deviation function formulations for Scenarios 1 through 3 are summarized in Table 3. Information regarding the deviation variables, d_i^+ and d_i^-, is provided at the bottom of the table.

Group II - Economic studies - includes Scenarios 4 and 5. In these two scenarios, economics plays the lead role while performance takes a back seat. Two scenarios are considered, one with manufacturing (WEMP and PURCH) as the main driver, Scenario 4, and one with operating cost (DOC) as the main driver, Scenario 5. The deviation function formulations for these scenarios are also summarized in Table 3.

Group III - Performance studies - includes Scenarios 6, 7, and 8. In these scenarios performance takes the lead rather than economics. Scenario 6 is based on speed considerations with VCRMX and WFUEL ranked first, Scenario 7 is based on aerodynamic considerations with LDMAX ranked first, and Scenario 8 is based on the flight distance with RANGE ranked first. The deviation functions for these scenarios are listed in Table 3.

The GAA compromise DSP is solved under the aforementioned design scenarios, and the resulting top-level design specifications and system performance means are plotted in Figures 5 and 6, respectively. All final solutions are feasible; therefore, final constraint values are not included. By examining the changes in the design variables, it is possible to assess the stability of the results when different design considerations are introduced. This information is used to determine a ranged set of top-level design specifications to maintain design flexibility.

In Figure 5, each design variable is plotted against its lower and upper bounds to help identify trends. A jump in cruise speed (CSPD) occurs in Scenarios 3, 6, 7, and 8 when economics are ranked highest, see key in figure. Aspect ratio (AR) fluctuates between a low of 7 and a high of 9. Sweep angle (SW) and tail length to diameter ratio (ELODT) both converge to their upper bounds and remain there for 7 out of 8 scenarios. Wing loading (WL) fluctuates between 21 lb/ft^2 and 25 lb/ft^2. Propeller diameter (DPROP) varies between 5.5 ft and 5.96 ft while engine activity factor (AF) remains below 95. Seat width (WS) is the most erratic, fluctuating between 15.5 in. and 19 in.

The final achieved means of the system performance responses and their target values are plotted in Figure 6. The standard deviations of the system responses are not included since all of the targets for maximum allowable deviation are met. As specified in the key, the fuel weight (WFUEL), empty weight (WEMP), direct operating cost (DOC), and purchase price (PURCH) means are to be minimized, while the maximum lift to drag ratio (LDMAX), maximum cruise speed (VCRMX), and maximum range (RANGE) means are to be maximized.

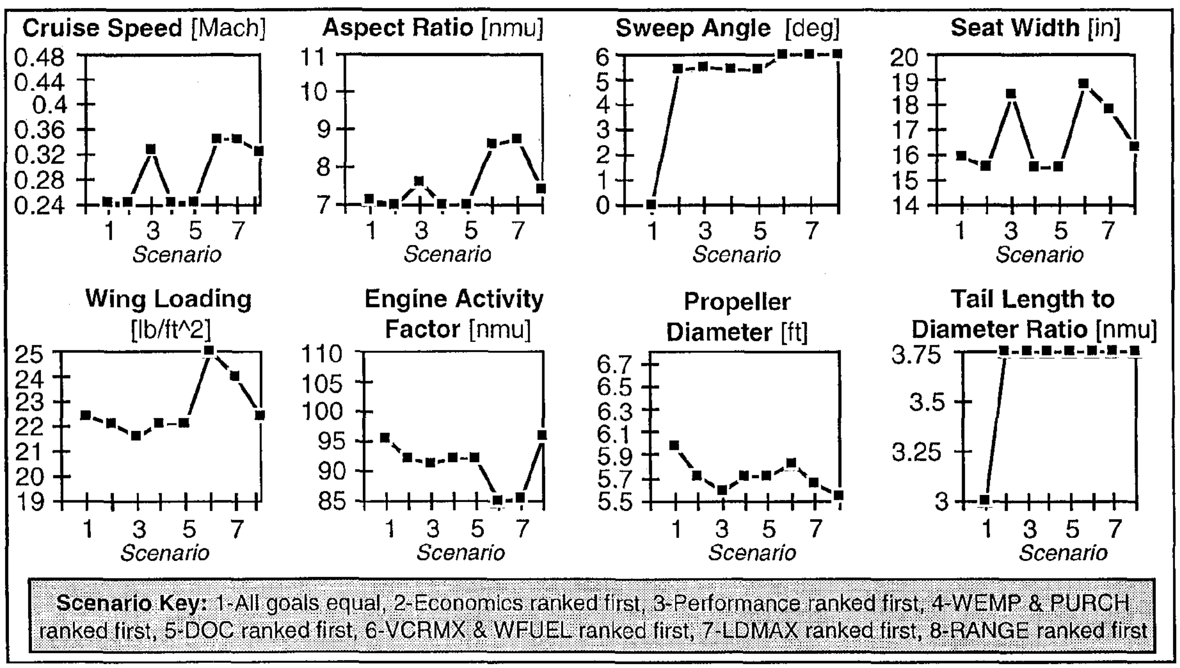

Figure 5 -- Final Values of the System Variables Using RCEM

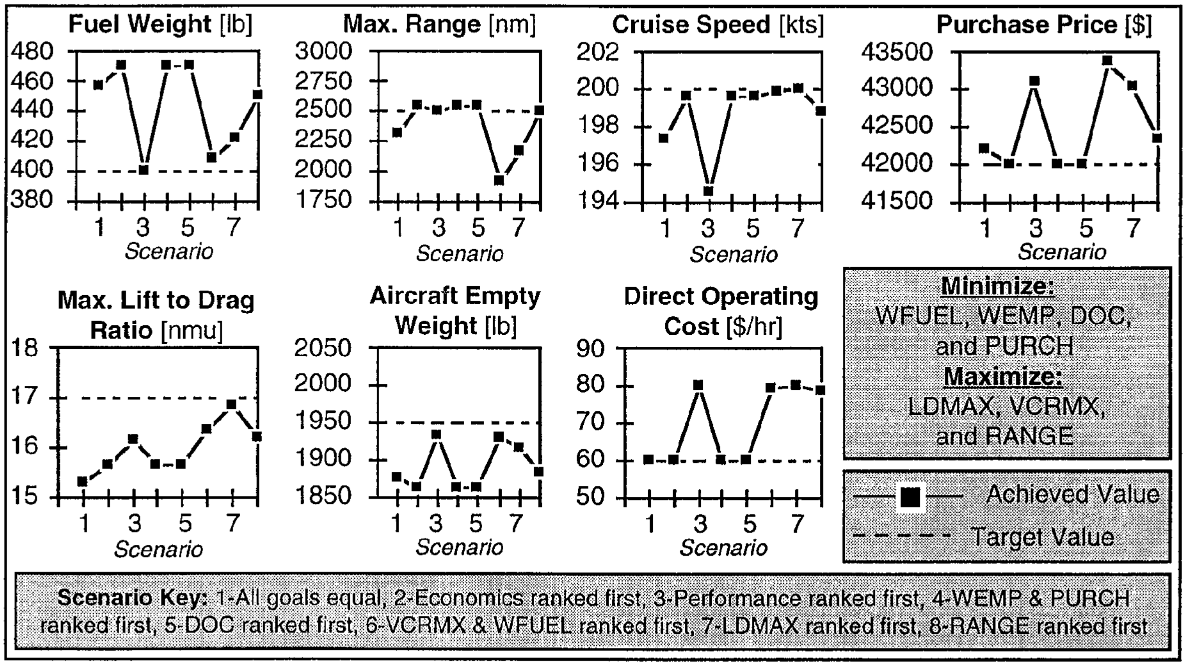

Figure 6 -- Final Means of the System Performance Using RCEM

Mean empty weight (WEMP) reaches its target in all scenarios whereas mean fuel weight (WFUEL) only hits its target in Scenario 3. Mean purchase price (PURCH) and the mean of direct operating cost (DOC) meet their targets in the three scenarios when economics is the first priority (Scenarios 2, 4, and 5); they do not make their targets otherwise. Mean maximum lift to drag ratio (LDMAX) exhibits poor performance except in Scenario 7; in Scenario 7, LDMAX achieves its target of 17 only because it is at the first priority level. The mean of maximum cruise speed (VCRMX) achieves its target in 6 out of 8 cases. During the overall trade-off study (Scenario 1) and the performance trade-off study (Scenario 3), VCRMX does not reach its goal of 200 kts. The mean of maximum range (RANGE) reaches its target in 5 out of 8 cases. During the economic studies, Scenarios 2-5, RANGE meets its target, but when other performance factors are ranked above RANGE, Scenarios 6 and 7, RANGE does not achieve its goal nearly as well.

Based on these observations, the top-level design specifications are classified into one of two categories: those which can be fixed and those which should remain unfixed but with a narrower range. Based on the trends in Figures 5 and 6, the ranged set of top-level design specifications for the family of GAA is:

- Tail length to diameter ratio (ELODT) = [3.75]
- Sweep angle (SW) = [6°]
- Engine activity factor (AF) = [85-92]
- Cruise speed (CSPD) = [Mach 0.24 - Mach 0.34]
- Aspect ratio (AR) = [7 - 8.8]
- Wing loading (WL) = [20 lb/ft^2 - 25 lb/ft^2]
- Propeller diameter (DPROP) = [5.5 ft - 5.96 ft]
- Seat width (WS) = [14 in - 20 in]

For further verification, we compare the results obtained from using the RCEM with the baseline aircraft found by solving the GAA compromise DSP separately for the 2, 4, and 6 seater aircraft. These comparisons are discussed in the next section.

4. COMPARISON OF THE ROBUST DESIGN RESULTS AGAINST THE BASELINE MODELS

Up to this point, we have been designing all three aircraft in our family of GAA simultaneously using the RCEM, and we developed a ranged set of top-level design specifications which is "common and good" for the 2, 4, *and* 6 seater GAA. An obvious question arises, namely, *what losses are incurred by finding a "common and good" ranged set of top-level design specifications for the family of GAA?* To examine the extent to which system performance is scarified when designing all three aircraft simultaneously using the RCEM, we must first determine the appropriate baseline models for comparison. The baseline models for the 2, 4, and 6 seater GAA are found by solving the GAA compromise DSP, see Appendix, using the second order response surface models for a fixed number of passengers. For example, the 6 seater baseline model is obtained by evaluating the response surface models for 6 people and solving the compromise DSP using the target values for the 6 seater aircraft given in Table 2. In order to compare results, the deviation function, Z, is an Archimedean formulation in which the deviations of the goals are equally weighted at the same priority level.

Three different starting points (the upper and lower bounds of the design variables along with the midpoints) are considered for consistency when solving the compromise DSP to find the baseline models. The corresponding system responses of the baseline models are listed in Table 4 along with the system responses for the solutions found by using the RCEM, specifically Scenario 1 from Section 3.2, Table 3. Observations regarding this data are as follows.

- In general, the empty weight, direct operating cost, maximum lift to drag ratio, and maximum speed characteristics for the baseline models and the RCEM solutions are equivalent.
- The RCEM solutions have slightly lower purchase prices and slightly higher maximum cruise speeds; however, the baseline models perform better than the RCEM solutions. The baseline models have slightly higher maximum lift to drag ratios and longer flight ranges and require less fuel.
- Although the target value of 2500 nautical miles is not met by either family of aircraft, the baseline models can fly 100 - 150 nm farther (with less fuel) than the solutions found using the RCEM. This is a substantial loss that occurs when using the RCEM to design all three aircraft simultaneously in this example problem.
- The final deviation function values of the individual baseline models are much better than the deviation function values for the RCEM solutions. For the 2 seater GAA for instance, the deviation function of the baseline model is approximately 5 times better than the 2 seater GAA found using the RCEM.

Based on these observations, *overall* system performance is only slightly sacrificed by designing the family of GAA simultaneously using the RCEM; however, individual aircraft performance may suffer significantly. The family of designs found using the RCEM are more robust since there is considerably less deviation between the system performance responses for the family of aircraft than for the baseline models taken as a whole. This is as expected because we used robust design principles to minimize the effects of noise, i.e., the number of passengers, on the system and develop a ranged set of top-level design specifications which is "common and good" for all three aircraft.

Table 4 -- System Responses of the Robust Design Solutions and Baseline Models

Run #	Goal	*Baseline Solutions* Achieved Value			*RCEM Solutions* Achieved Value		
		2 Seater	4 Seater	6 Seater	2 Seater	4 Seater	6 Seater
1. upper bounds	fuel wt, lb	442.8	400.1	349.1	483.9	460.4	441.6
	empty wt, lb	1892.1	1931.7	1983.0	1847.7	1870.5	1889.8
	DOC, $	60.0	60.0	61.6	59.2	60.0	60.4
	purchase, $	42418.8	42972.6	43952.1	41767.0	42116.0	42518.0
	max. lift/drag	15.9	15.3	15.5	15.4	15.2	15.2
	max. speed, kts	197.6	193.1	191.6	199.4	197.5	197.6
	max. range, nm	2473.2	2473.3	2367.4	2318.3	2281.0	2261.9
	DEV FCN	0.0178	0.0245	0.0334	0.0788	0.0747	0.0685
2. mid-points	fuel wt, lb	450.1	401.9	350.0	487.2	464.0	445.5
	empty wt, lb	1885.4	1929.9	1982.0	1845.5	1868.0	1887.0
	DOC, $	60.0	61.2	61.6	58.1	59.0	59.3
	purchase, $	42310.2	43046.0	43830.9	41665.0	42006.0	42401.0
	max. lift/drag	16.0	15.5	15.4	15.5	15.3	15.3
	max. speed, kts	198.6	194.2	190.5	199.4	197.5	197.6
	max. range, nm	2492.2	2432.8	2439.1	2370.0	2331.7	2311.5
	DEV FCN	0.0148	0.0278	0.0304	0.0766	0.0725	0.0657
3. lower bounds	fuel wt, lb	449.7	400.2	350.1	477.9	454.4	435.6
	empty wt, lb	1885.5	1931.4	1983.5	1854.4	1877.2	1896.5
	DOC, $	60.2	60.2	61.4	59.1	60.0	60.4
	purchase, $	42322.1	42940.8	43956.8	41806.0	42154.0	42556.0
	max. lift/drag	16.0	15.2	15.6	15.4	15.2	15.2
	max. speed, kts	198.5	192.7	192.1	198.6	196.7	196.8
	max. range, nm	2494.9	2496.4	2359.0	2340.8	2301.7	2280.8
	DEV FCN	0.0151	0.0240	0.0319	0.0757	0.0715	0.0654

5. CLOSING REMARKS

The work in this paper represents an initial step toward developing a foundation for designing families of products. In the situation where a family of products can be designed around common noise factors, the RCEM provides a suitable starting point for *developing a ranged set of top-level design specifications for a family of products*. Although not shown in this paper, the RCEM could be used to design a family of products around variable control factors as well.

In the GAA example problem in Section 3, we have demonstrated how to *design a family of products around a common noise factor as efficiently as a single product* through the incorporation of robust design principles in the RCEM in the early stages of the design process. Implementation of robust design in our example is facilitated through the use of second order response surface models which allow us to approximate system performance means and standard deviations for modeling the robust design objectives of "bringing the mean on target" and "minimizing the deviation". By specifying a ranged set of top-level design specifications which are good for a variety of design scenarios, we have created a robust and flexible family of designs which can be quickly adapted to meet changing customer demands. Thus, *the RCEM enables us to improve system flexibility and provides a means for designing families of products.*

Future work includes additional validation and verification of the RCEM as well as development of alternate robust design methods. Current areas of investigation for utilization of the RCEM include integrated product and process design (Peplinski, et al., 1996) and the design of an advanced short take-off and vertical landing lift engine (Koch, et al., 1996). Alternate robust design methods we are investigating include the development and implementation of design capability indices (Chen, et al., 1996) which can be used to measure the capability of a family of designs to satisfy a *ranged* set of design requirements.

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APPENDIX

The GAA compromise DSP for our example problem is included in this appendix. For a full description of the compromise DSP and its solution algorithm, refer to (Mistree, et al., 1993). For each of the key words of the compromise DSP (Given, Find, Satisfy, and Minimize), we present the formulation for the GAA example problem. Not included, however, are the second order response surface models which we used. They can be found in (Simpson, 1995) and are not included here because of their length.

Given:
- Response Surface Models based on simulations of GASP
- Mission Profile (altitude, range, etc.)
- Low wing position, retractable landing gear, 3 blades

Find:
- cruise speed, CSPD
- aspect ratio, AR
- propeller diameter, DPROP
- sweep angle, SW
- wing loading, WL
- engine activity factor, AF
- tail length to diameter ratio, ELODT
- seat width, WS

Satisfy:

System Constraints
- takeoff noise ≤ 75 dbA
- propeller tip speed ≤ 850 ft/sec
- direct operating cost ≤ 80 $/hr
- ride roughness factor ≤ 2.0 nmu
- empty weight ≤ 2200 lbs
- fuel weight ≤ 500 lbs

System Goals for bringing mean on target:
- minimize mean of
  - fuel weight: $WFUEL\_AVG(\mathbf{X})/400 + d_1^- - d_1^+ = 1.0$
  - empty weight: $WEMP\_AVG(\mathbf{X})/1950 + d_2^- - d_2^+ = 1.0$
  - operating cost: $DOC\_AVG(\mathbf{X})/60 + d_3^- - d_3^+ = 1.0$
  - purchase price: $PUR\_AVG(\mathbf{X})/42000 + d_4^- - d_4^+ = 1.0$
- maximize mean of
  - max. lift/drag: $LDMAX\_AVG(\mathbf{X})/17 + d_5^- - d_5^+ = 1.0$
  - max. speed: $VCRMX\_AVG(\mathbf{X})/200 + d_6^- - d_6^+ = 1.0$
  - max. range: $RANGE\_AVG(\mathbf{X})/2500 + d_7^- - d_7^+ = 1.0$

System Goals for minimizing std. deviation:
- fuel weight: $3{*}WFUEL\_DEV(\mathbf{X})/50 + d_8^- - d_8^+ = 1.0$
- empty weight: $3{*}WEMP\_DEV(\mathbf{X})/50 + d_9^- - d_9^+ = 1.0$
- operating cost: $3{*}DOC\_DEV(\mathbf{X})/5 + d_{10}^- - d_{10}^+ = 1.0$
- purch. price: $3{*}PUR\_DEV(\mathbf{X})/1000 + d_{11}^- - d_{11}^+ = 1.0$
- max. lift/drag: $3{*}LDMAX\_DEV(\mathbf{X})/1 + d_{12}^- - d_{12}^+ = 1.0$
- max. speed: $3{*}VCRMX\_DEV(\mathbf{X})/10 + d_{13}^- - d_{13}^+ = 1.0$
- max. range: $3{*}RANGE\_DEV(\mathbf{X})/225 + d_{14}^- - d_{14}^+ = 1.0$

Minimize

The sum of the deviation variables associated with the mean and std. deviation of each response, see Table 3:
- fuel weight: d_1^+ and d_8^+
- empty weight: d_2^+ and d_9^+
- direct operating cost: d_3^+ and d_{10}^+
- purchase price: d_4^+ and d_{11}^+
- maximum lift to drag ratio: d_5^- and d_{12}^+
- maximum cruise speed: d_6^- and d_{13}^+
- maximum range: d_7^- and d_{14}^+