NEW APPROACHES TO HSCT MULTIDISCIPLINARY DESIGN AND OPTIMIZATION

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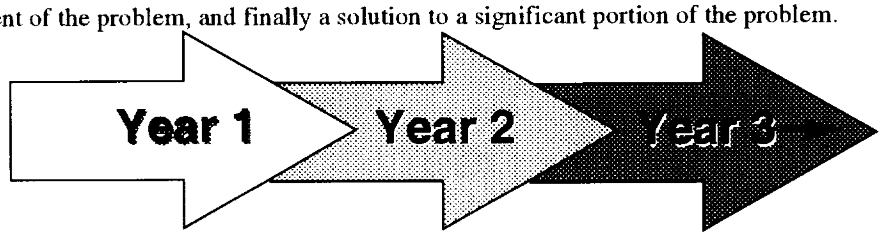
PROJECT OVERVIEW

The successful development of a capable and economically viable high speed civil transport (HSCT) is perhaps one of the most challenging tasks in aeronautics for the next two decades. At its heart it is fundamentally the design of a complex engineered system that has significant societal, environmental and political impacts. As such it presents a formidable challenge to all areas of aeronautics, and it is therefore a particularly appropriate subject for research in mulitdisciplinary design and optimization (MDO). In fact, it is starkly clear that without the availability of powerful and versatile multidisciplinary design, analysis and optimization methods, the design, construction and operation of an HSCT simply cannot be achieved. The present research project is focused on the development and evaluation of MDO methods that, while broader and more general in scope, are particularly appropriate to the HSCT design problem. The research aims to not only develop the basic methods but also to apply them to relevant examples from the NASA HSCT R&D effort. As shown in Figure 1 below the research involves a three year effort aimed first at the HSCT MDO problem description, next the development of the problem, and finally a solution to a significant portion of the problem.



Problem Description	Problem Development	Problem Solution
• AFW MDO Structure	• Design Framework	• Analysis & RSE Integration
• DSPT Research	• DSP Palette	• IMAGE Architecture
• Computing Requirements	• Analysis Tools	• Design Exploration

Figure 1. Three Year Task Schedule

The Year 1 effort focused on identification of a specific (and academically "tractable") portion of the broader HSCT design problem. The initial attention was on the HSCT wing design including both the product and process development aspects, but the focus has shifted towards the multidisciplinary effort to handle the aeroelastic design of the wing and more specifically the case of an "active aeroelastic wing" (referred to as AAW or AFW for "active flexible wing"). Year 1 effort was also spent on adaptation and development of basic decision support methods to the problem and on the development of computing requirements for a practical system. The Year 2 effort involved the further development of the wing design framework, the development of specific classes of decision support problems (DSP palettes), and the identification and development of specific analysis tools. The present Year 3 effort involves incorporation of robust design simulation methods involving the use of response surface equations (RSE's) to bring high-fidelity, discipline-specific analysis and modelling methods forward into conceptual design studies from their more traditional places in subsystem level preliminary design efforts. These methods and tools are now being tested and evaluated in sample MDO studies using the IMAGE design computing architecture.

YEAR 3 OBJECTIVES AND RESULTS

Research under the subject grant is being carried out in a jointly coordinated effort within three laboratories in the School of Aerospace Engineering and the George Woodruff School of Mechanical Engineering (see Figure 2 and titles above). The objectives and results for Year 3 (interim) of the research program are summarized the table below. The "Objectives" and "Expected Significance" are taken directly from the Year 3 Proposal presented in October 1995, and "Results" summarize what has been accomplished for the funded portion of this past year. A discussion of these results is provided in the following sections. A listing of papers, presentations and reports that acknowledge grant support, either in part or in whole, and that were prepared during the entire contract period is provided in an attachment.

Objectives	Expected Significance	Results
1. Complete Development of IDES, including the identified high performance computing environment.	1. Provides significant improvement in the support provided to designers of advanced aerospace vehicles.	1. A step by step approach based on the response surface method, decision support techniques, and a computing infrastructure (IMAGE) has resulted in the described simulation environment.
2. Demonstrate the IDES addressing the design of a HSCT wing using advanced technologies and their impact on the overall economic viability	2. Provides demonstration of IDES capabilities and a test case for other IDES users.	2. Initial demonstration problem completed and documented: HSCT system level synthesis with cost as the key objective and wing aerodynamic and structural technologies modeled.
3. Identify additional New Approaches for incorporation into IDES. Include an integrated aero-structures-control HSCT wing demonstration in IDES and address the tradeoffs between product and process enhancements.	3. Provides for continuous improvement to IDES through its open architecture.	3. Continuous improvement translates to new technologies: initial methodology to design for Active Aeroelastic Wing Technology developed, encompassing multidisciplinary interactions (aero-structure-controls).

1. DEMONSTRATION OF NEW APPROACHES: INTEGRATING THE RESEARCH

Research in Years 1 and 2 focused on specific method development for MDO applications. Three key results include the following. Implementation of the multilevel wing optimization strategy developed in the first year effort resulted in a tool for multidisciplinary wing design, documented in Dr. Röhl's Ph.D. Thesis [Rohl (95)], which was used for optimal wing jig shape and aeroelastic tailoring studies in consideration of buckling constraints. A *robust concept exploration method* has been developed by Dr. Chen and documented in her Ph.D. dissertation [Chen (95)]. Finally, a unique computing infrastructure for design has taken shape through the work of Dr. Hale [Hale (96c)]. However, the final objective of Georgia Tech's efforts towards "New Approaches to MDO" was not the production of useful, but disparate, tools. Instead, the driving motivation is *system synthesis* through the intelligent integration of these MDO tools. Year 3 results described below highlight this emphasis. Such synthesis is especially important for the evaluation of new technologies, such as the Active Aeroelastic Wing concept under development by Rockwell International, a partner with Georgia Tech for the past three years.

Integration of the tools and techniques developed was guided by NASA Langley's MDO research and Technology Program Strategic Plan for MDO, which identified the three generic elements of MDO: data management, design-oriented analysis, and design space search. We have cast the elements in the setting of *system sythesis*, since this is ultimately where important objectives (especially cost) are realized. Consistent with our previous research under this grant, the HSCT provides the specific testbed for demonstrating the integration of the three MDO elements for the purpose of making intelligent design decisions, using the proper objectives at each point in the design timeline. The aeroelastic analysis and design of the HSCT wing is the subsystem which provides the impetus for developing better design oriented analysis. The result of these Year 3 integration activities are described next.

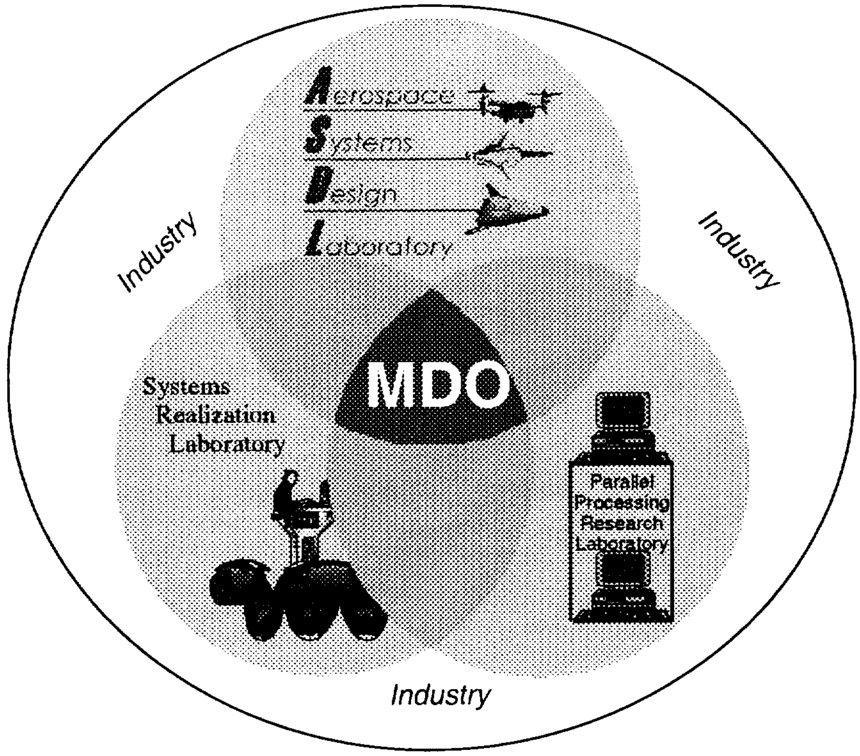


Figure 2. Coordinated University/Government/Industry Team

2. DEMONSTRATION OF NEW APPROACHES: SYSTEM SYNTHESIS OF THE HSCT, WITH AN AERO-STRUCTURE-CONTROL APPLICATION

One portion of the research under New Approaches attempts to tackle the design-oriented analysis dilemma by *combining* the empirical and idealized analysis approaches in order to provide the desired relationship between design variables and the key aircraft quantities required for synthesis. To do so, two complimentary statistical techniques, the Design of Experiments (DOE) and Response Surface Methodology (RSM), are used for the purpose of forming expressions for the relationships based on complex analyses. These expressions are called Response Surface Equations (RSEs). DeLaurentis [96a] describes the use of statistical techniques for aerodynamic *modeling* and system *optimization*. Mavris [96a] presents the use of RSEs in the realm of aircraft economic viability assessments.

Even with the availability of improved disciplinary information, designers are still faced with how to best manage and make decisions upon this information. The lack of a solid formulation for a design space search and the inability to conduct searches by tailoring the computing design process are deficiencies which contribute to decision making difficulties. In more general terms, there has been a lack of viable distribution schemes for implementing large-scale problems within computing frameworks. A design-oriented computing infrastructure addresses these problems through a joint process and information modeling scheme that supports evolutionary design activities. One such infrastructure has been created and is used in the current research effort. This scheme is suited for small design tasks as well as large, proprietary, distributed analysis efforts. This computing infrastructure is based on a well defined and tested system for seeking solutions: the Decision Support Problem Technique described in [Mistree (93)] . The application problem discussed below will demonstrate how a design problem can be managed and areas of good solutions can be found based on potentially conflicting goals and constraints.

What is to follow will describe a synthesis simulation environment which is well suited for the introduction, modeling, and evaluation of *innovative* technologies. These technologies motivate the need to search for ways to include complex, interdisciplinary analysis in system level optimization and for improved design decision making through an understanding of the relationship between fundamental design variables and system objectives. The status of method development at this point in the Year 3 effort is discussed first followed by a highly detailed example problem involving the disciplines of aerodynamics, structures, and controls. The example completed through a search for good wing planform designs for an HSCT considering static and dynamic aeroelastic constraints as well as system level performance constraints.

Design Oriented Analysis Via Approximation Functions

As more and more problems that were traditionally solved in isolation are approached from a multidisciplinary point of view, design-oriented analysis has become increasingly important. One such problem is the aeroelastic design of supersonic transport wings with system level objectives. Numerous techniques have been developed and demonstrated which focus on the wing design aspect. It is the efficient integration and use of this "sub-problem" in a system synthesis environment that has not received significant attention. Under New Approaches research, analysis techniques usually associated with design stages where key geometric variables have been fixed, such as the use of Finite Element Models (FEM), are utilized in a design space consisting of these important geometric parameters. This is accomplished through the combined use of DOE/RSM and parametric analysis tools. *It soon becomes apparent that the most critical parametric tool required is an automated FE grid generator* [Rohl (95)]. Once the capability to rapidly model and analyze different wing planforms is obtained, an approximation function for the structural weight of an aeroelastically optimized wing can be constructed. Thus, the specific problem of integrating system and discipline level design environments is addressed, and cost, performance, and manufacturing trades can be made (representing the primary thrust of the so called Integrated Product and Process Development (IPPD) philosophy).

Often the relationship between some quantity of interest (a response) and predictors (input variables) is either too complex to determine or unknown. In these cases, an empirical approach is necessary to determine the behavior and this provides the basis for the Response Surface Methodology (RSM). RSM is comprised of a group of statistical techniques for empirical model building and exploitation. By careful design and analysis of experiments, it seeks to relate a response, or output variable, to the levels of a number of predictors. The Design of Experiments, as the name suggests, originates from the experimental fields where empirical relations were sought due to the unavailability of analytical models. In the application of the current research, the "experiments" are actually "simulations", but the goal is the same: construct an empirical model where an analytical model is unavailable or impractical. Clearly, this model building approach can assist in the formation of design-oriented analysis.

The implementation of RSM results in Response Surface Equations. RSEs are regression equations which seek to represent analysis of a phenomenon in the form of equation(s) consisting of the factors (or design variables) which are known to be functionally related to the phenomena. Since synthesis codes rely on increasingly outdated databases and more sophisticated disciplinary codes often are too cumbersome to be embedded in a design optimization loop, RSEs bridge the gap between what is needed and what is available. Further, DOE/RSM is just one of several methods available for function approximation and model building. Fuzzy Logic and Neural Networks are two recent, promising techniques in this area.

DOE provides an organized way of obtaining data for the regression analysis and a technique for avoiding the "curse of dimensionality". The DOE is used to determine a table of input variables and combinations of their levels which can be analyzed to yield a response value. This also encompasses other procedures such as Analysis of Variance. Full-factorial designs are used to construct model equations which account for all possible combinations of variable settings. Fractional factorial DOEs are used to produce results similar to full factorial designs, but require less information and consequently fewer analyses. This is accomplished by reducing the scope of the model to only account for effects of interest.

A generalized RSE is shown in EQ (1) where main, quadratic, and second order interactions effects are shown.

$$R = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum_{i<j}^{k} b_{ij} x_i x_j \qquad (1)$$

where,

b_i are regression coefficients for the first degree terms,
b_{ii} are coefficients for the pure quadratic terms,
b_{ij} are the coefficients for the cross-product terms

A trade-off exists when exercising fractional factorial designs. The number of simulations (experiments) required grows as the increasing degree to which interaction and/or high order effects are desired to be estimated. Since generally only a fraction of the full factorial number of cases can realistically be executed, estimates of high order effects and interactions are often not possible. They are said to be confounded, or indistinguishable, from each other in terms of their effect on the response. This aspect of fractional factorial designs is described by their *resolution*. Resolution III implies that main effects are entirely confounded with second order interactions. Thus, one must assume these interactions to be zero or negligible in order to estimate the main effects. Resolution IV indicates that all main effects can be estimated, though second order interactions are confounded with other such interactions. Resolution V means that both main effects and second order interactions are can be estimated. However, for Resolution V designs, third order interactions would be confounded with second order effects, and hence they would not be distinguishable [DeLaurentis (96a)]. In our HSCT wing structural weight example presented, a second degree polynomial model of the selected responses in k-variables is assumed to exist as in eq. (1).

Design Decision Making in Wing Design

The aeroelastic wing design method used in conjunction with the DOE/RSM is described in detail in DeLaurentis [96b]. The framework centers on a finite-element based structural optimization of a wing box under aerodynamic loads that is subject to stress and flutter constraints. The wing is represented by a varying complexity spar and rib model and utilizes multiple shape functions for distribution of design parameters. A initial wing box finite element model generator that uses system level geometric, mission, and weight information to create a complete mesh of the wing structure has been completed [Rohl (95)]. A maneuver load program, called Integrated Structure/Maneuver Design (ISMD), provides for the computation of static external loads [ISMD-Rockwell (95)]. The key objective of the wing design procedure here is a balance between the desire for a parametric procedure and a desire for increased analysis accuracy. A method for achieving this balance will be demonstrated in the simulation experiment below.

The MDO methodologies developed in the present work are coordinated in an MDO *infrastructure and integration* project which has become to be known as DREAMS (Developing Robust Engineering Analysis Models and Specifications) [Hale (96a)]. This work resulted in the development of an *open* computing infrastructure that facilitates the design of complex engineering systems. This infrastructure is called IMAGE (Intelligent Multidisciplinary Aircraft Generation Environment). IMAGE is considered open for two reasons [Hale (96b)]. First, the infrastructure permits *freedom* for a designer to model both processes and information as required at a particular point in a design's timeline. This is accomplished through an information model which incorporates schema evolution. Schema evolution is a general term used to describe an information model that captures time-dependent product and process characteristics at varying degrees of accuracy *and* fidelity. As a result, product descriptions can be modified as fidelity increases. In the case of a wing design, an initial product description is based on parametric components. During finite element analysis, a more detailed model is required that includes node and member definitions. Both of these representations can coexist-exist in the information model. Moreover, specific instances (e.g. values) can be accumulated for decision-making and optimization.

IMAGE facilitates a necessary paradigm shift in early conceptual solution algorithms. Ultimately design processes culminate in decision-making. These are represented by discrete milestones in a design's life-cycle. At each milestone, a designer desires to know as much about a problem before further restricting a design. Before eliminating alternatives or reducing product families, potential technologies or applications should be explored. This can be accomplished by applying various solution techniques. An example that illustrates the benefits of applying alternate solution strategies follows.

Traditionally, decisions have been based on optimality criteria imposed locally on a limited design representation. As designs progress, either local or system level changes may cause an optimal target to shift, rendering the design infeasible. The ideas behind optimal solutions are depicted in Figure 3. Initially, a system may optimally satisfy problem constraints and customer requirements, represented by peaks in the solution space shown in Figure 3. A particular problem solution is represented by a ball in the figure. A problem shift will cause the system to deviate from an optimal solution, thus rendering the initial solution to be sub-optimal or even infeasible.

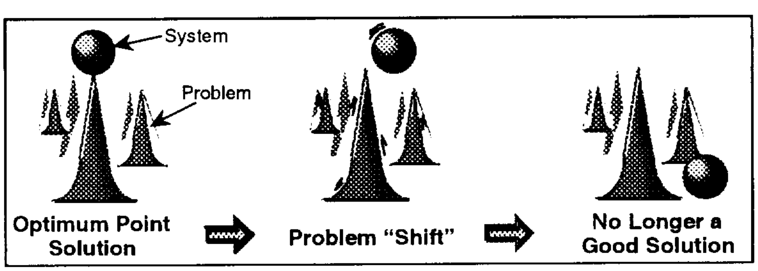


Figure 3. An Optimal Solution

To utilize alternative solution techniques, a paradigm shift must occur whereby design freedom is left open in earlier design stages. This can be accomplished through the use of a satisficing solution. A satisficing solution is one that provides a region of solutions that minimizes the deviation between customer and manufacturer requirements and design constraints, bounds, and goals. The template used to describe this type of formulation is referred top as a Compromise Decision Support Problem.[Mistree (9x); Bras (91)] As a result, a designer can base decisions about a design on regions of plausible design derivatives/alternatives that exist at that point in design time. A pictorial aid for the notion of satisficing solutions is presented in Figure 4. Optimal peaks are replaced by satisficing mesas, leading to robust design solution regions. Early in the design process, a designer bases decisions on a region of acceptable design solutions. As the region evolves throughout design processes, particular design decisions remain valid and lie within the region of candidate solutions (a mesa).

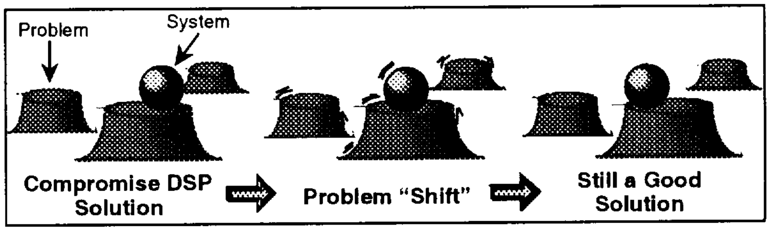


Figure 4. Satisficing Solution Used Early in Design

The methods employed during the determination of satisficing solutions lend themselves to the more recent use of approximation techniques. Using these techniques, continuos representations of particular analyses are created (to a know degree of accuracy) and are used in place of the original analysis tools. Using these approximations permits rapid concept exploration during conceptual design as well as the incorporation of probabilistic methods [DeLaurentis (96a)]. In addition, a designer has the capability to make design decisions based on downstream information brought into earlier design stages.

These two models, satisficing and optimal, are encountered as Support Problems are used in design processes. As shown in Figure 5, satisficing solutions are used early in design processes since less is known about designs. Represented by a fading timeline, the need and use of satisficing solutions diminishes as a design progresses. As designs are refined, more is known about a design and a designer begins to look for solutions that approach optimal type solutions, as seen in Figure 6. At this point, traditional optimization methods as well as newer global sensitivity approaches may be used to aid in problem solution.

Figure 5. Satisficing Solution Used Early in Design

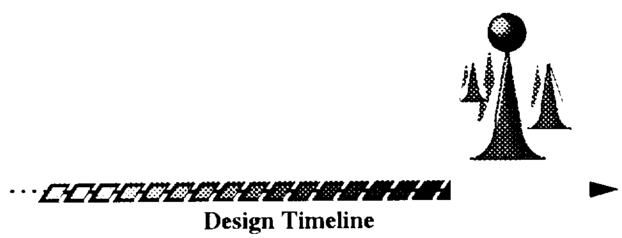


Figure 6. Optimal Solution Used Later in Design

Simulation Exercise: Synthesis with Aeroelastic Wing Design

The complex problem of finding good designs for a flexible HSCT wing based on the combined (and generally conflicting) objectives of minimum cost and maximum performance will be exercised in this demonstration of the developed simulation environment. The solution of this problem requires the combined analysis capabilities from the aerodynamics, structures, and controls disciplines. In addition, the simulation is multi-leveled, with objectives calculated at the system level through sizing and synthesis but with most of the design parameters distributed in subsystem level disciplines. The contributing analyses introduced through response equations allow a designer to perform tradeoffs in terms of the size of the design space searched and complexity of the tools used. A hierarchical system decomposition summarizing the problem is illustrated in Figure 7.

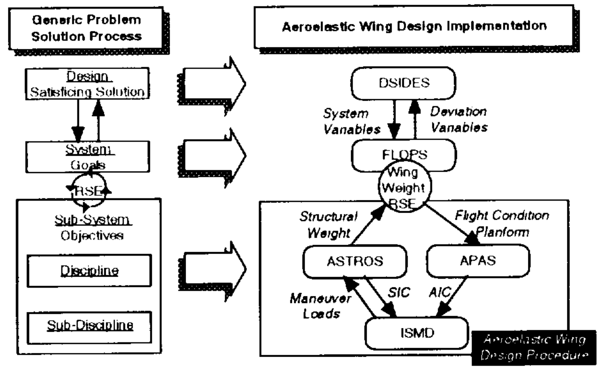


Figure 7. Hierarchical System Decomposition

Wing Design Level

The objective at this level is to use FEM-based analysis to construct an RSE which relates geometric wing design parameters to wing structural weight. A detailed description and exposition of the FEM model used and the analysis procedure is contained in DeLaurentis (96b). With the aid of Figure 8 and the paragraphs below this procedure is described. First, a DOE is selected to define a series of wing planforms which form the design space. These planforms become inputs to the aerodynamic-structures-loads analysis shown in Figure 8. The mesh generation procedure developed translates the aerodynamic grid (to which the air and inertia loads are applied) into an "equivalent" structural grid (FEM nodal mesh). The structural grid is used by the Automated STRuctural Optimization System (ASTROS), developed at Wright Laboratory, for weight distribution among the modeled spars, ribs, and spar caps to satisfy strength and flutter constraints given the applied net loads (air and inertia loads combined) due to maneuver . The structural and aerodynamic interactions are represented through structural influence coefficients (SICs) and aerodynamic influence coefficients (AICs). AICs relate aerodynamic loads to changes in local panel angles of attack while SICs relate normal deflections of the panels with application of a unit load.

The ISMD code uses the SICs (from ASTROS) and AICs to calculate trim control surface settings and the resulting net loads on the model. These net loads must later be transformed into the structural grid. For this study, an expected worst case static loading condition is assumed to be a 2.5-g symmetric pull-up at a Mach number of .9 and altitude of 30,000 ft. This maneuver is used to generate the trimmed static loads in ISMD. The output of the ASTROS/ISMD iteration is the converged wing structural weight for that particular planform and loading condition (see Figure 8). This procedure is based on the method outlined in Miller (94).

In the ASTROS optimization, mass is redistributed in an attempt to reduce structural weight while satisfying strength and flutter constraints. The flutter condition of Mach 3.12 at an altitude of 60,000 ft. is also investigated in the optimization for each case. An assumption inherent to the use of an RSE approach is that since flutter is met for all data points in the DOE, then flutter will be met for all points within design space. At minimum, this assumption should be checked on any configurations which result from the design space search. Structural optimization information (e.g. converged element thickness' for each case of the DOE) is not carried through to the RSE but can be retained separately if desired.

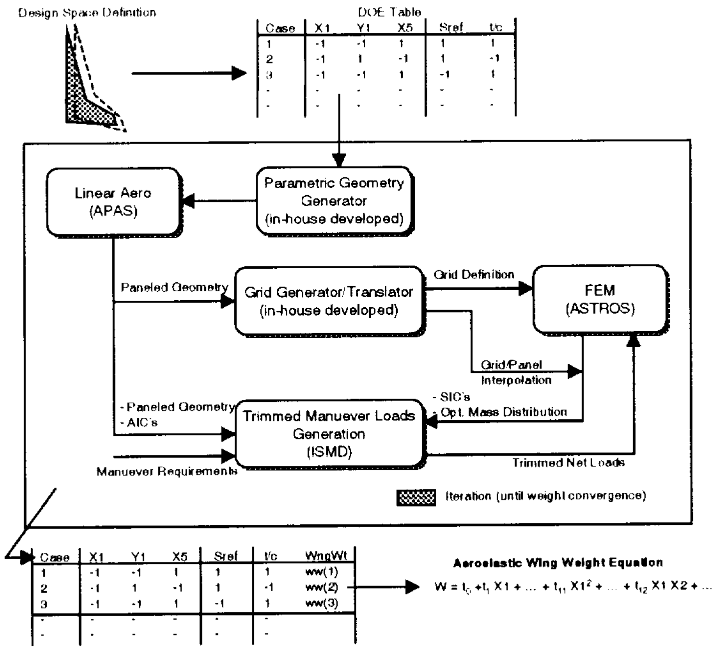


Figure 8. Aeroelastic Wing Design Procedure [DeLaurentis(96b)]

A five-variable, face-centered design tested at three levels is chosen for the DOE. It is a Resolution V design, meaning both main effects and second order interactions are accounted for and are not confounded with each other. This results in 27 distinct simulations which need to be performed. The variables and their selected ranges for the DOE are shown in Table 1. These variables correspond to the definitions shown in Figure 3, and the variables *X1*, *Y1*, and *X5* are normalized by the wing semispan and defined from an origin at the wing root leading edge. Additional variables are defined in Figure 9, some of which will be used in the system design problem.

Table 1. Design Variables and Ranges

Description	***Variable Name***	***Minimum Value***	***Maximum Value***
Kink X-location	X1	1.54	1.69
Kink Y-location	Y1	0.44	0.58
Root Chord	X5	2.19	2.36
Wing Reference Area (ft^2)	Sref	8500	9500
In-Outboard Thickness (%)	t/c	2.5	3.3

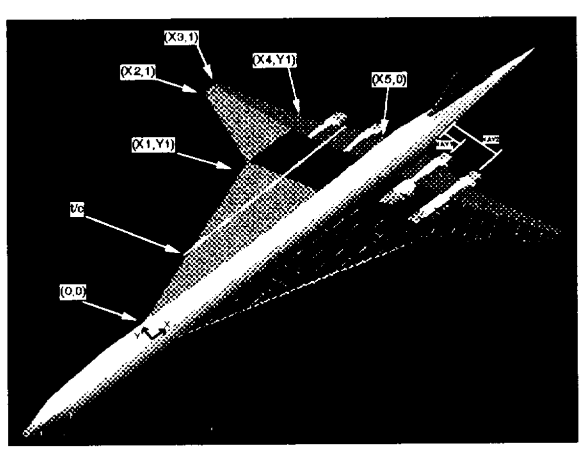


Figure 9. Design Variable Definitions

It seems clear that five wing design variables and one flutter condition may not be detailed enough for a design problem in an industrial setting. We agree. However, a fundamental goal of this Year 3 effort is to establish a "Proof of Concept" and demonstrate the feasibility of the concept on a manageable complexity level. If the demonstration is successful, more detailed contributing analyses (e.g. doubling the number of FEM nodes, adding flutter cases, etc.) should only add time to the RSE construction process, not necessarily difficulty. A key fact to remember is that even a DOE/RSM scheme can be impractical if the number of design parameters and/or the analysis execution times are unreasonably high.

Returning to the problem at hand, each of the different cases (i.e. planform shapes) from the DOE is executed according to the procedure in Figure 8. At this point in this study, only one ASTROS/ISMD iteration is performed since it was felt that the coarseness of the structural model did not warrant any further convergence tolerance. The resulting responses are collected and an RSE for wing weight as a function of planform variables is formed. This RSE is then used to replace the estimate used in the synthesis code FLOPS (FLight OPtimization System, NASA Langley), whose wing weight prediction is based on historical data of mostly dissimilar wing shapes.

The second order polynomial wing weight RSE based on the variables in Table 1 is depicted in Figure 10(a) in the form of a prediction profile with the design variables at their midpoint settings. The "-1" and "1" limits represent the normalized minimum and maximum settings given in Table I. The center value on the ordinate is the half-model, structural wing weight based on the current settings of the five design variables. A first check of the validity of the equation involves examining the trends. For example, increasing *X1* and decreasing *Y1* together lead to a outboard shift of the wing area distribution (see Figure 9 and Figure 10 (b)). Thus, an increase in weight is expected and indeed is borne out in the profile for those variables in Figure 10 (b). An important attribute of the DOE/RSM approach used here is that a *direct, quantifiable link between weight prediction and fundamental design variables of interests (and their interactions) is obtained.* This can be invaluable in conducting sensitivity analysis and/or finding feasible regions of good designs.

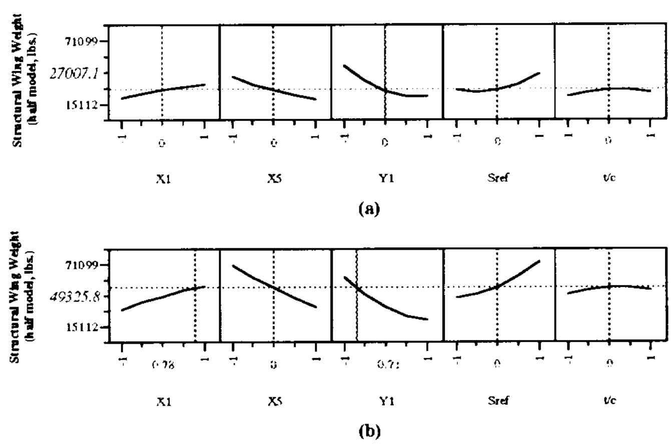


Figure 10. RSE for FEM Supersonic Transport Wing Weight Equation: (a) Prediction Profile for Midpoint Settings; (b) Example of Increasing Weight as Kink Locations Moves Inboard

A series of measures can be investigated which pertain to the quality of the regression. The most common is the R-Square value. The R-square value is the square of the correlation between the actual and predicted responses. Thus, an R-square value of one implies that all the fit errors are zero (i.e. a perfect fit). The R-Square value for the RSE in Figure 10 is .9900, a satisfactory result.

System Synthesis Level

With the structural wing weight RSE in hand, attention turns toward its role in the sizing and synthesis code FLOPS. Aircraft sizing algorithms, including FLOPS', center around a fuel balance. A vehicle is "defined" by the specification of drag polars at multiple flight conditions as well as engine performance in the form of thrust and fuel flow tables. This vehicle is then "flown" along a designated mission through climb, cruise, descent, etc. If, at the end of the mission, the fuel available (determined from volume considerations) is equal within some tolerance to the fuel required (fuel used to fly the mission plus reserve fuel), the aircraft is said to be sized. If not, an iteration takes place by increasing/decreasing the fuel available as appropriate and re-flying the mission. Once converged, the main outputs include gross weight, fuel weight, and values for any number of performance constraints.

Multidisciplinary analysis takes place in the sizing code through the interaction of the disciplinary RSEs. Aerodynamic RSEs for a supersonic transport were generated and incorporated into FLOPS [DeLaurentis (96a)]. In that application, the response was the components of vehicle drag as a function of geometry (see Figure 3) and flight condition for a supersonic transport. In a similar manner, for the problem studied in this presently, the wing structural weight RSE generated is integrated into FLOPS to replace the existing prediction method. These equations are presently used concurrently during the sizing and synthesis process and are based on the same set of design variables and ranges.

Ultimately, however, the key attribute of the supersonic transport wing weight RSE, when embedded in the synthesis code, is that it provides a formulation that shows the correct trends as a function of geometric characteristics and based on sophisticated analysis

Design Level

Once the RSE's have been implemented in the new FLOPS tool, the system synthesis procedure is modeled in IMAGE. The aeroelastic wing design problem is cast as a Compromise Decision Support Problem. Here a satisficing solution is sought that minimizes the deviation among takeoff gross weight, fuel weight, and required yield per revenue passenger mile from their respective goals. A satisficing solution is particularly important at this point in the design cycle because the location of a *region of particularly good designs* is desired. The objective is to find a robust design and not a single design candidate.

The Compromise DSP Template is shown in Figure 11. This Template is entered into IMAGE using a Graphical User Interface (GUI). During the solution of this Compromise DSP, the FLOPS tool containing the wing weight RSE will be executed in order to determine the design variable states for constraint, goal, and deviation function calculations. The template depicts the *conflicting* system goals: minimize takeoff gross weight (TOGW), ticket price (required average yield per revenue passenger mile, $/RPM), and takeoff flyover noise. Constraints are both explicit (Takeoff Field Length, TOFL, Landing Field Length, LFL, and Approach Speed, Vapp) and implicit (flutter, strength, etc.). Using IMAGE, FLOPS can be linked directly to the System Support Problem defining the Palette for the Compromise DSP. If FLOPS were separated into its disciplinary modules, each module could be linked to functionally independent System Support Problems. Thus, the modular aspects of using IMAGE are easy to utilize.

System design variables for this exercise include a set of parameters normalized by the wing semispan which uniquely define a cranked planform, such as the one envisioned for an HSCT. These are defined in Figure 9. Note that several of these variables are common to the wing weight RSE. As DSIDES varies the system level variables, the wing weight is recalculated during aircraft sizing in FLOPS via the response equation. RSEs based on these same planform variables which predict vehicle aerodynamics were formed [DeLaurentis (96a)] and are also embedded in FLOPS in this exercise.

Given:

- FLOPS v5.7
- Response surface equations for Aero/Structures/Control Module in FLOPS
- # passengers NPT = 300
- Mission profile (altitude, range, reserve fuel, etc.)
- Generic HSCT baseline configuration
- Overall design requirements including constraints, C(**X**), and goals, G(**X**)

Find:

- The system variables, **X**
  - Leading edge kink, X1
  - Leading edge tip, X2
  - Trailing edge tip, X3
  - Trailing edge kink, X4
  - Root chord, X5
  - Kink locations, Y1
  - Position of wing on fuselage, XWING
  - Thrust-weight ratio, TW
  - Wing area, SREF
- The values of the deviation variables associated with goals, G(**X**):
  - Takeoff gross weight, TOGW(**X**): d1-, d1+
  - Flyover noise, FNOISE(**X**): d2-, d2+
  - $/RPM, DRPM(**X**): d3-, d3+

Satisfy:

- The system constraints, C(**X**), *as determined by FLOPS*
  - takeoff field length Š upper bound
    TOFL(**X**) Š 11,000 ft
  - landing field length Š upper bound
    LFL(**X**) Š 11,000 ft
  - approach velocity Š upper bound
    VAPP(**X**) Š 155 kts
  - lower bound Š second segment climb gradient
    SCLBG(**X**) ` 0
  - lower bound Š missed approach climb gradient
    ACLBG(**X**) ` 0
- The system goals, G(**X**), *as determined by FLOPS*
  - Minimize takeoff gross weight, TOGW(**X**):
    $TOGW(X)/825,000 + d1^- - d1^+ = 1.0$
  - Minimize flyover noise, FNOISE(**X**):
    $FNOISE(X)/104.0 + d2^- - d2^+ = 1.0$
  - Minimize $/RPM, DRPM(**X**):
    $DRPM(X)/0.11 + d3^- - d3^+ = 1.0$
- The bounds on the system variables

Minimize:

- A deviation function associated with:
  - Takeoff gross weight, TOGW(**X**), $d1^+$
  - Flyover noise, FNOISE(**X**), $d2^+$
  - $/RPM, DRPM(**X**), $d3^+$

  Z = {f1(d1+), f2(d2+), f3(d3+)}

Figure 11. Compromise DSP Template for Wing Design

Given the DSP and associated assumptions, the DSIDES code is used to *find* the values of the system design variables which *minimize* the deviations of the goals from their respective targets while *satisfying* the imposed constraints.

Simulation Results

The Aeroelastic Wing Design Problem is solved using IMAGE, the modular architecture for design decision-making. Recall that the wing weight RSE has been integrated into FLOPS. In turn, FLOPS is made into an agent for integration into the overall architecture. IMAGE will utilize FLOPS as a tool which is used to determine responses to the system variables (e.g. namelist variables are changed the new aircraft is sized).

IMAGE calls DSIDES as the toolkit used to solve the Compromise Decision Support Problem that is shown in Figure 11. DSIDES uses an Adaptive Linear Programming (ALP) algorithm to determine the perturbations in system variables. These perturbed variables are input into FLOPS and then FLOPS is executed to determine the values of the variables associated with the goals. The nonlinear goals and constraints are calculated by IMAGE and given back to DSIDES so that the solution process can continue.

A screenshot of this problem implemented in IMAGE is shown in Figure 12. This shows the Palette Network used to define the problem. This particular network is not complex because the problem solution only requires the execution of FLOPS. FLOPS is executed on an RS6000/320H and IMAGE is running on a Sparc 1000. An object editor is shown where problem variables, goals, constraints, etc. are entered into the database by a designer. Finally, an interface is shown that depicts the system variable history as DSIDES determines a satisficing solution.

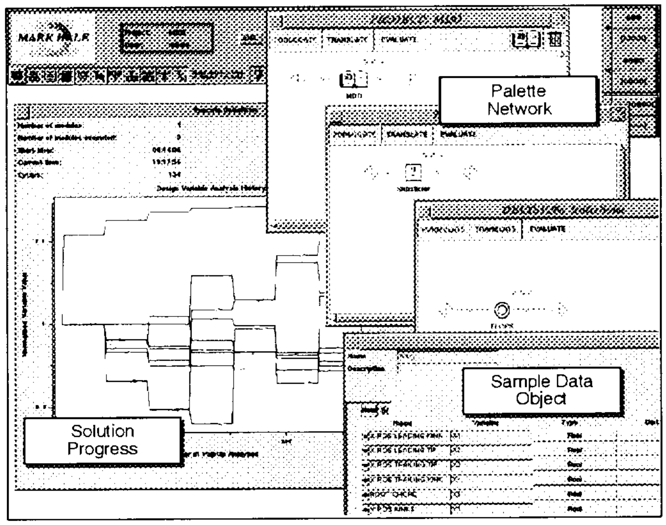


Figure 12. Screenshot of IMAGE During Execution

The Compromise DSP from Figure 11 is entered into IMAGE via a Graphical User Interface. For this analysis, the deviation function chosen is an Archimedean which can be compared to traditional synthesis studies. A Preemptive Formulation is currently being studied and will be discussed later. In the Archimedean Function, deviation variables are weighted relative to each other. Goals are set for each of the deviation variables representing Takeoff Gross Weight (TOGW), Required Yield per Revenue Passenger Mile ($/RPM) and Flyover Noise (FNOISE). The deviation function was taken to be an equal weighting of each of these three variables and is as follows in Eq. (2):

$$Z = 0.33\ TOGW^{+} + 0.33\ FNOISE^{+} + 0.33\ \$/RPM^{+} \tag{2}$$

Each of the deviation variables will be minimized and their goals will hopefully be simultaneously achieved. This formulation parallels the use of an overall evaluation criteria as a solution objective function.

An Archimedean Solution has been found using IMAGE. The results of this solution are in Table 2. Discretized wing parameters are normalized with respect to wing semi-span and system goals are normalized with respect to their targets. The $/RPM goal was not achieved in this solution. DSIDES did however find a solution that minimizes the deviation function. During the solution process, it was found that the bounds on the Thrust-Weight Ratio are too small to affect the solution and should be increased in further studies. The baseline and final planform shapes are compared in Figure 13.

Table 2. Design Space Search Results

	Baseline	Archimedean Solution
System Variables		
Leading Edge Kink (X1)	1.62	1.54
Leading Edge Tip (X2)	2.23	2.10
Trailing Edge Tip (X3)	2.49	2.40
Trailing Edge Kink (X4)	2.28	2.20
Root Chord (X5)	2.35	2.19
Kink Y Positions (Y1)	0.51	0.55
Wing Position (XWING)	0.29	0.29
Thrust-Weight Ratio (TW)	0.31	0.32
Wing Area (SREF)	8500.0 ft^2	8583.1 ft^2
Goals		
Takeoff Weight (TOGW)	1.114	0.98
Required Yield / RPM ($/RPM)	1.344	1.23
Flyover Noise (FNOISE)	0.970	0.95
# FLOPS Calls	-	171
Solution Time	-	25 Hours

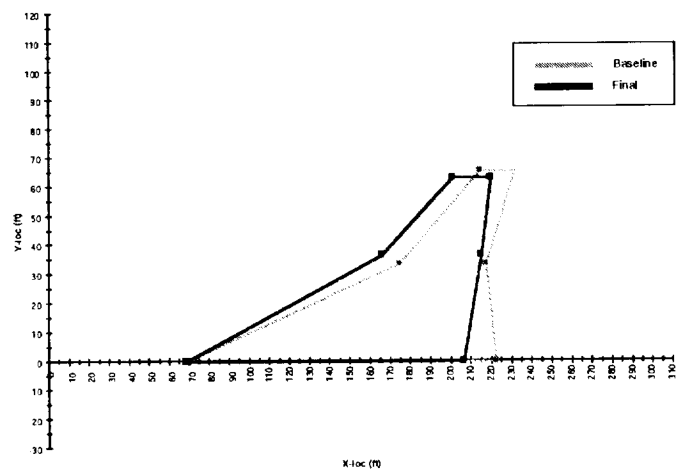


Figure 13. Planform Comparison: Baseline vs. DSP Solution

Each FLOPS execution took approximately 8 minutes on an RS6000/320H. Because of calculation time and that accuracy is not necessary required during early conceptual design, solution tolerance was set at 10%. IMAGE requires less than 30 seconds per FLOPS execution for data handling and solution calculations through DSIDES.

IMAGE was found to be an easy way to configure and link this design problem. FLOPS was made into an agent and integrated into the system in less than a day and the actual wing design problem was configured in the same amount of time. With IMAGE, alternative deviation functions can be entered (this will be discussed in the next section) and solved using IMAGE. Variable history during solution is stored within IMAGE so that results similar to those discussed here can easily be generated.

Finally, in addition to verifying the statistical accuracy of the RSE, it is of interest to examine how well the equation predicts the response for a point outside the DOE database. This was done by running the wing design procedure of Figure 8 using the Archimedean solution design variable results from Table 2. The percent error of the RSE prediction in relation to the ASTROS/ISMD appears acceptable, though it certainly warrants an examination of more data points for a more definite confirmation. The comparison is shown in Table 3.

Table 3. RSE Error at Solution Point

	ASTROS/ ISMD	RSE	RSE % Error
Wing Structural Weight	34,448 lbs.	37,776 lbs.	-9.66 %

3. A PARALLEL STUDY FOR WING DESIGN DATA STRUCTURES

During the course of implementing this design scenario in IMAGE, the need to have a well defined data model became evident. In addition, research has shown that advances in the aircraft technologies have resulted in an increase in the amount of data required to define a design during the conceptual stages [Hall (96a)]. A conceptual design dictates a close multidisciplinary effort requiring large amounts of data exchange. In order to optimize the design process, it is crucial that a top-down data management design structure be in place in the early phases of the design. This structure will provide consistency in data format and allow ease of data exchange between the various disciplines involved in the design process. In the conceptual design phase, consideration must be given to the changing structure of the of the database as the product design evolves. Current database design approaches are typically limited to the detailed design phase where the data organization is fixed.

The complexity of an HSCT design problem dictates a close multidisciplinary effort requiring large amounts of data exchange. This problem is illustrated in Figure 14. Moreover, with the enormous development costs associated with such a design, corporate teaming is essential. It is critical to the success of the HSCT and future aircraft design that a new approach be taken toward the management and exchange of information. A top-down data management design structure should be developed and implemented in the early stages in order to optimize the design process.

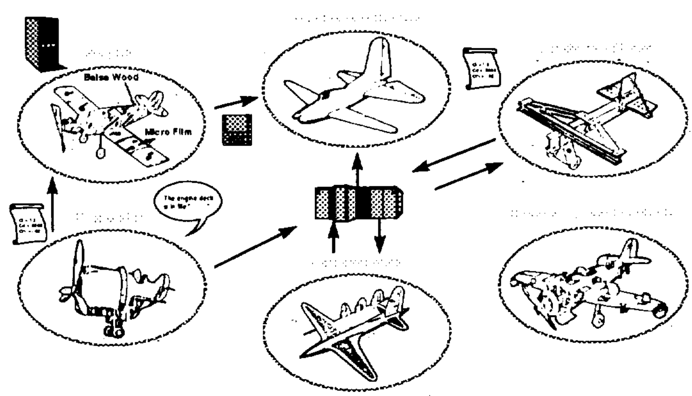


Figure 14. The data management problem

The data modeling problem is experienced for both design process and product models. Hall has investigated the use of IDEF0 structures for representing a design. These are shown in Figure 15 and Figure 16. The use of these diagrams can be extended to the use of design Palettes as was done for the AFW problem. A graphical interface was given in Figure 12.

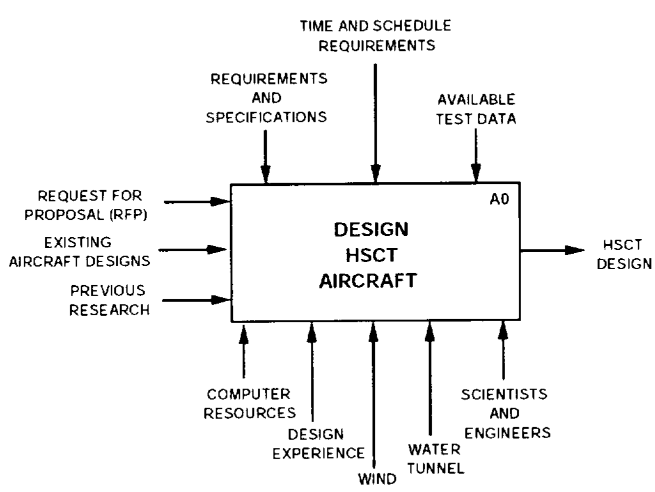


Figure 15. IDEF0 - Level 0

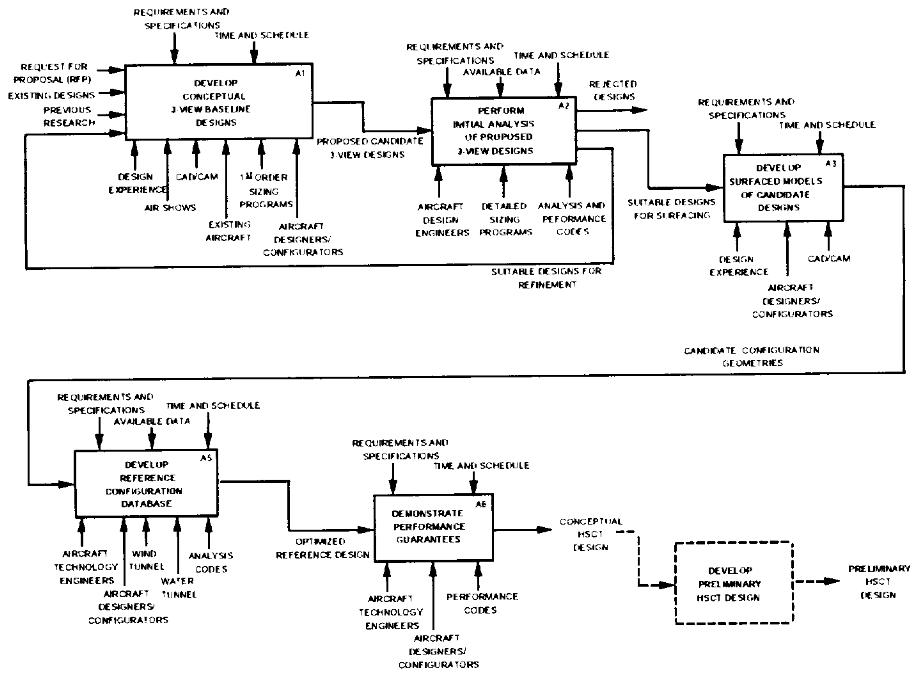


Figure 16. IDEF0 Diagram - Level 1.

A data model is also required for the product information. Figure 17 shows the IDEF1X model for typical aircraft components. In this example, an aircraft configuration is made up of the components engine, fuselage, gear, inlet, nozzle, canard, horizontal, vertical, and wing. This type of data model is also utilized within the IMAGE architecture.

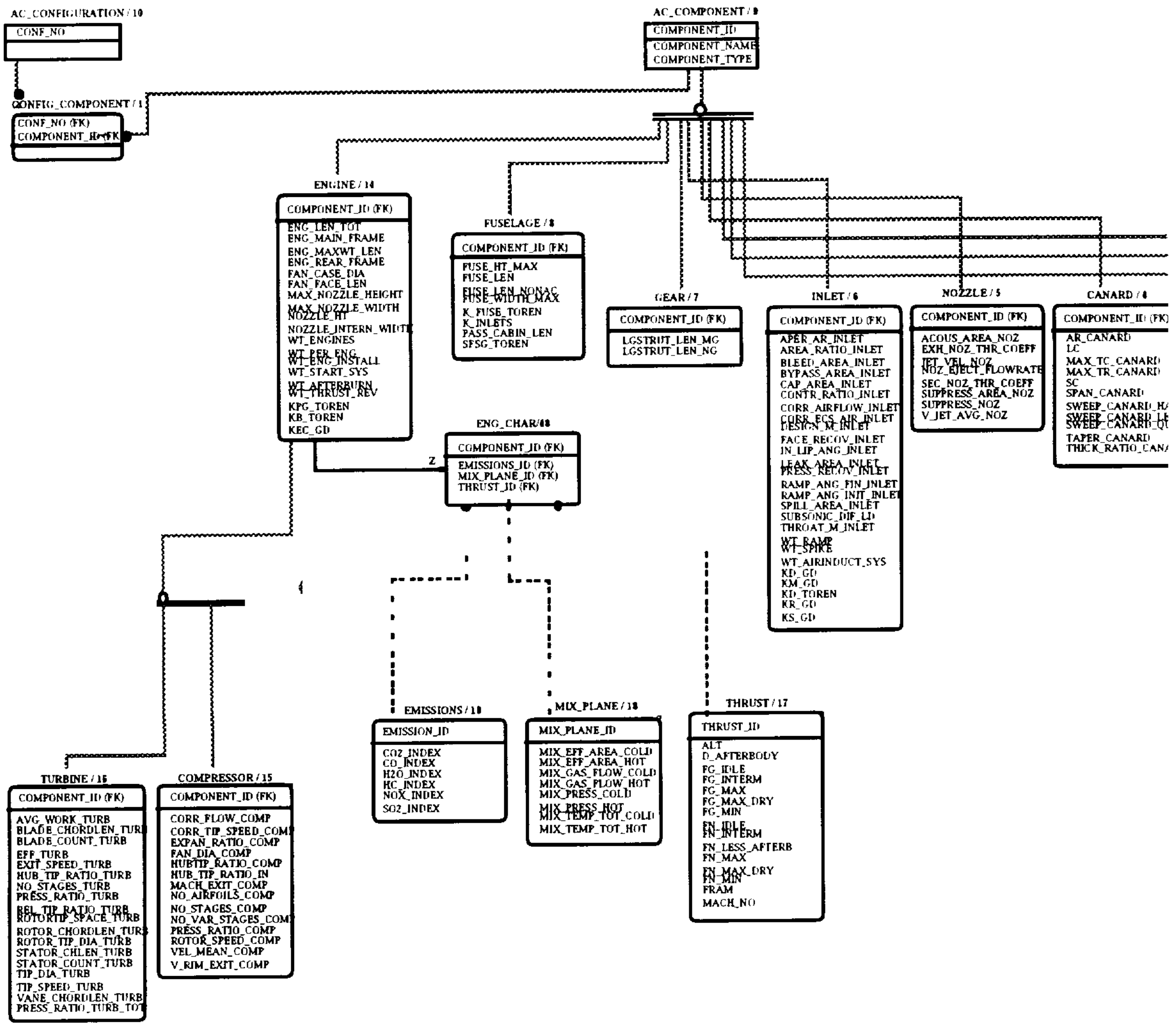


Figure 17. IDEF1X diagram of aircraft components.

4. RESEARCH PARTICIPANTS (3 YEAR SUMMARY)

The New Approaches to Multidisciplinary Design and Optimization is a three year ongoing effort. The tasks can be coarsely broken into those shown in **Error! Reference source not found.**. A number of student have participated in this contract, with a number of Doctoral Degrees granted (see Figure 18). This project also required much industrial contribution as shown in Figure 18.

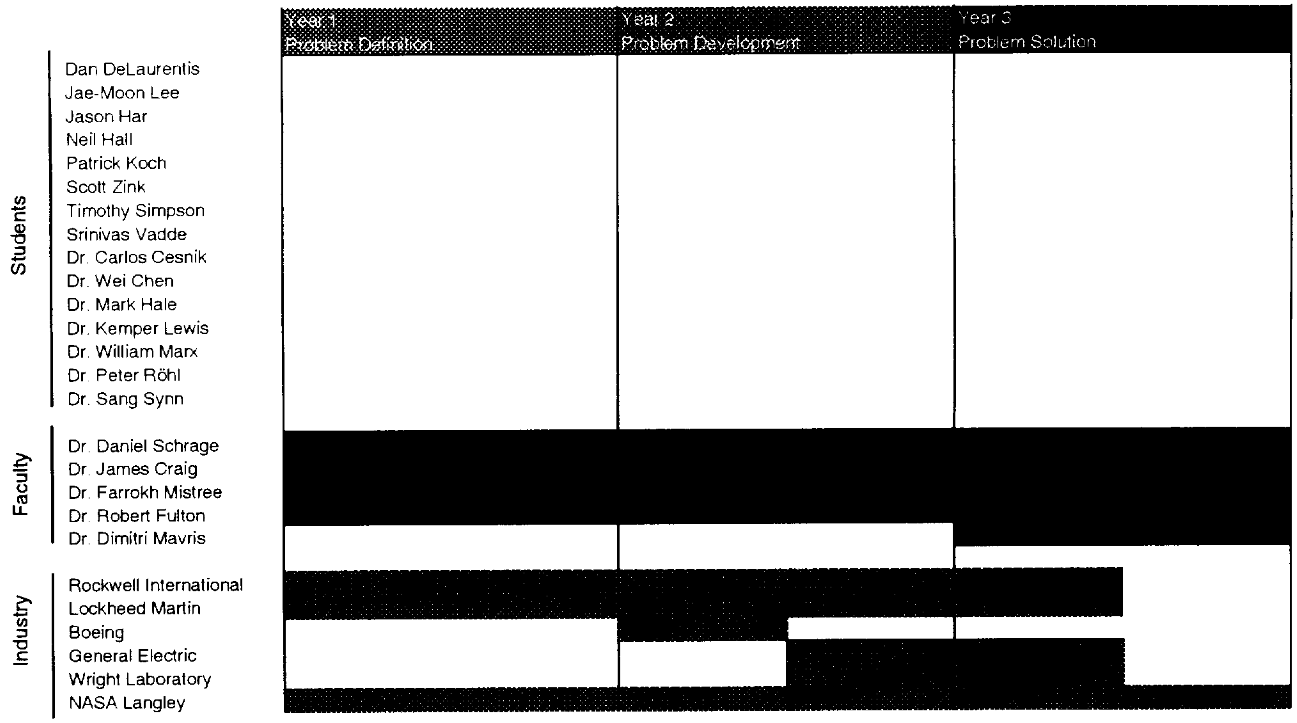


Figure 18. Three Year Involvement

NEW APPROACHES TO HSCT MULTIDISCIPLINARY DESIGN AND OPTIMIZATION

Year 3 Presentations, Publications and Workshops
Grant NGT 51102L

December 31, 1996

The following workshops and publications (referencing support from the Grant 51102L) were accomplished under the third year's research effort:

Bras, B. A. and F. Mistree, "Designing Design Processes in Decision-Based Concurrent Engineering," SAE Transactions Journal of Materials & Manufacturing, vol. 100, no. , pp. 451-458, Warrendale, PA, SAE International, 1991.

Chen, W., A Robust Concept Exploration Method for Configuring Complex Systems, Ph.D. Dissertation, School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA, 1995.

DeLaurentis (96a), D.A., Mavris, D.N., "An IPPD Approach to the Preliminary Design Optimization of an HSCT using Design of Experiments", 20th ICAS Congress, Sorrento, Italy, September 1996.

DeLaurentis (96b), D. A., C. E. S. Cesnik, J.-M. Lee, D. N. Mavirs and D. P. Schrage, "A New Approach to Integrated Wing Design in Conceptual Synthesis and Optimization," Sixth AIAA / NASA / USAF / ISSMO Symposium on Multidisciplinary Analysis and Optimization, Bellevue, WA, September 4-6, 1996. AIAA-96-4174.

Hale (96a), M. A., J. I. Craig, F. Mistree and D. P. Schrage, "DREAMS & IMAGE: A Model and Computer Implementation for Concurrent, Life-Cycle Design of Complex Systems," Concurrent Engineering: Research and Applications, vol. 4, no. 2, pp. 171-186, June 1996.

Hale (96b), M. A. and J. I. Craig, "Techniques for Integrating Computer Programs into Design Architectures," Sixth AIAA / NASA / USAF / ISSMO Symposium on Multidisciplinary Analysis and Optimization, Bellevue, WA, September 4-6, 1996. AIAA-96-4166.

Hale (96c), M. A., "An Open Computing Infrastructure that Facilitates Integrated Product and Process Development from a Decision-Based Perspective," Doctoral Dissertation, Georgia Institute of Technology, School of Aerospace Engineering, July, 1996.

Hall (96a), Neil S. and Fulton, Robert E., "An Investigation of a Relational Database Approach to a Multidisciplinary Conceptual Design for the HSCT", 1996 ASME Design Engineering Technical Conferences and Computers in Engineering Conference, Irvine, California, August 18-22, 1996, Paper Number 96-DETC/EIM-1425.

Hall (96b), Neil S. and Fulton, Robert E., "Impact of Data Modeling and Database Implementation Methods on the Optimization of Conceptual Aircraft Design", Research Paper, School of Mechanical Engineering, Georgia Institute of Technology, 1996.

Integrated Structures/Maneuver Design Program, Rockwell International, North American Aircraft, 1995.

Mavris, D.N., Bandte, O., and Schrage, D.P., "Economic Uncertainty Assessment of an HSCT Using a Combined Design of Experiments/Monte Carlo Simulation Approach", 17th Annual Conference of the International Society of Parametric Analysts, San Diego, CA, May 1995.

Miller, G.D., "An Active Flexible Wing Multidisciplinary Design Optimization Method", AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Panama City, FL, 7-9 September 1994.

Mistree, F., Hughes, O.F., and B.A. Bras, *The Compromise Decision Support Problem and the Adaptive Linear Programming Algorithm*, E. Kamat, M.P., Structural Optimization: Staus and Promise, Wahcington DC, (pp. 247-286), AIAA, 1993.

Röhl, P.J., "A Multilevel Decomposition Procedure for the Preliminary Wing Design of a High Speed Civil Transport Aircraft," Ph.D. Thesis, School of Aerospace Engineering, Georgia Institute of Technology, June 1995.

Synn, Sang Y. and Fulton, Robert E., "Prediction of Parallel Computing Performance", Research Paper, Parallel Processing Lab, School of Mechanical Engineering, Georgia Institute of Technology, 1996.

Workshops Supported by NASA Grant NGT 51102L:

HSCT External Advisory Board Meeting and Workshop, Georgia Institute of Technology, Atlanta, GA, May 1996.

Year 2 Presentations, Publications and Workshops
Grant NGT 51102L

October 16, 1995

The following workshops and publications (referencing support from the Grant 51102L) were accomplished under the second year's research effort:

Chen, W., Allen, J.K., Mavris, D.N., Mistree, F., Tsui, K-L, 1995b, "Integration of Response Surface Method with the Compromise Decision Support Problem in Developing a General Robust Design Procedure," *Advances in Design Automation* (Azarm, S., et al. Eds.), New York: ASME, 1995, pp. 485-492. ASME DE-Vol. 82-2.

Chen, W., Allen, J.K., Mavris, D.N., Mistree, F., 1995c, "Robust Concept Exploration for Developing the Top-Level Specifications of Complex Systems," *Engineering Optimization*., (in press).

Chen, W., 1995a, A Robust Concept Exploration Method for Configuring Complex Systems, Ph.D. Dissertation, School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA.

Hale, M. A., 1994a, "Preliminary Agent Technologies with CATIA," presented at the CATIA Operators Exchange Meeting, Dallas, October 9-13.

Hale, M. A., 1994b, "IMAGE: A Design Integration Framework Applied to the High Speed Civil Transport," HM301: First University/Industry Symposium on High Speed Civil Transport Vehicles, North Carolina A&T State University, December 4-6.

Hale, M.A., 1995a, "A Computing Infrastructure that Facilitates Integrated Product and Process Development from a Decision-Based Perspective," Ph.D. Thesis Proposal, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA, January.

Hale, M. A. and Craig, J. I., 1995b, "Use of Agents to Implement and Integrated Computing Environment," *Computing in Aerospace 10*, AIAA, San Antonio, TX, March 28-30, Preprint: AIAA-95-1001.

Hale, M. A., Craig, J. I., Mistree, F., Schrage, D. P. , 1995c, "Implementing an IPPD Environment from a Decision-Based Design Perspective," ICASE/LaRC Workshop on Multidisciplinary Design Optimization, Hampton, VA, March 13-16.

Hale, M. A., Craig, J. I., Mistree, F. and Schrage, D.P., 1995d, "On the Development of a Computing Infrastructure that Facilitates IPPD from a Decision-Based Design Perspective," 1st AIAA Aircraft Engineering, Technology, and Operations Congress, Anaheim, CA. Preprint AIAA-95-3880.

Hall, N., and Fulton, R.E., "A Relational Database Application to Multidisciplinary Conceptual Design for HSCT," (Submitted for the publication).

Lewis, K., Lucas, T. and Mistree, F., 1994, "A Decision-Based Approach for Developing A Ranged Top-Level Aircraft Specification: A Conceptual Exposition," AIAA/NASA/USAF/ ISSMO Symposium on Multidisciplinary Analysis and Optimization, Panama City, Florida, 465-481. Paper No. AIAA-94-4304-CP.

Lewis, K. and Mistree, F., 1995a, "On Developing a Taxonomy for Multidisciplinary Design Optimization: A Decision-Based Perspective," First World Congress of Structural and Multidisciplinary Optimization, Goslar, Germany. Paper number 118.

Lewis, K. and Mistree, F., 1995b, "Designing Top-Level Specifications: A Decision-Based Approach to a Multiobjective, Highly Constrained Problem," 36th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, New Orleans, LA. pp. 2393-2405.

Lucas, T., 1995a, Formulation and Solution of Hierarchical Decision Support Problems, M.S. Thesis, School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA.

Lucas, T., Vadde, S., Chen, W., Allen, J.K. and Mistree, F., "Utilization of Fuzzy Compromise DSPs for Hierarchical Design Problems", 1994, AIAA/ASME/ASCE/AHS/ACS 35th Structures, Structural Dynamics and Materials Conference, Hilton Head, South Carolina, pp. 1753-1763. Paper No. AIAA-94-1543-CP.

Mistree, F., Lewis, K. and Stonis, L., 1994, "Selection in the Conceptual design of Aircraft," AIAA/NASA/USAF/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Panama City, Florida, 1153-1166. Paper No. AIAA-94-4382-CP.

Röhl, P.J., Mavris, D.N., and Schrage, D.P., 1994, "A Multilevel Decomposition Procedure for the Preliminary Wing Design of High-Speed Civil Transport Aircraft," First Industry/Academy Symposium on Research for Future Supersonic and Hypersonic Vehicles, Greensboro, NC, December.

Röhl, P.J., Schrage, D.P. and Mavris, D.N., 1995a, "Combined Aerodynamic and Structural Optimization of a High-Speed Civil Transport Wing," 36th AIAA Structures, Dynamics, and Materials Conference, New Orleans, LA, April, Preprint AIAA 95-1222.

Röhl, P.J., 1995b "A Multilevel Decomposition Procedure for the Preliminary Wing Design of a High Speed Civil Transport Aircraft," Ph.D. Thesis, School of Aerospace Engineering, Georgia Institute of Technology, June 1995.

Röhl, P.J., Mavris, D.N., and Schrage, D.P., 1995b, "Preliminary HSCT Wing Design Through Multilevel Decomposition," 1st AIAA Aircraft Engineering, Technology, and Operations Congress, Los Angeles, CA, September 19-21, AIAA 95-3944.

Simpson, T.W., 1995a, Development of a Design Process for Realizing Open engineering Systems, M.S. Thesis, School of Mechanical Engineering, Georgia Institute of Technology, August 1995.

Simpson, T.W.,Bauer, M.D., Allen, J.K. and Mistree, F., 1995b, "Implementation of DFA in Conceptual and Embodiment Design using Decision Support Problems," *ASME Advances in DesignAutomation* (Azarm, S., et al. Eds.), New York: ASME, pp. 485-492. ASME DE-Vol. 82-2.

Synn, S.Y. and Fulton, R.E., 1994a, "The Concurrent Element Level Processing for Nonlinear Dynamic Analysis on a Massively Parallel Computer", Third National Symposium on Large-Scale Structural Analysis for High-Performance Computers and Workstations, Norfolk, VA, November 8-11, (also in *Journal of Computer Systems in Engineering*).

Synn, S.Y. and Fulton, R.E., 1994b, "The Prediction of Parallel Skyline Solver and its Implementation for Large Scale Structural Analysis," Third National Symposium on Large-Scale Structural Analysis for High-Performance Computers and Workstations, Norfolk, VA, November 8-11, (Also, in *Journal of Computer Systems in Engineering*).

Synn, S.Y., 1995a, "Practical Domain Decomposition Approaches for Parallel Finite Element Analysis," Ph.D. Thesis, School of Mechanical Engineering, Georgia Institute of Technology, January 1995.

Synn, S.Y. and Fulton, R.E., 1995b, "Practical Strategy for Soncurrent Substructure Analysis," *Journal of Computers & Structures*, Vol.54, No.5.

Synn, S.Y., Schwan, K., and Fulton, R.E., 1995c, "Analysis of Large Scale Heterogeneous Structures on Massively Parallel Computers," *Journal of Concurrency: Practice and Exercise* (Submitted for the publication in the *Journal of Concurrency, Practice/Experience*).

Vadde, S., 1995, *Modeling Multiple Objectives and Multilevel Decisions in Concurrent Design of Engineering Systems*, M.S. Thesis, School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA.

Vadde, S., Allen, J.K., Lucas, T. and Mistree, F., 1994, "On Modeling Design Evolution along a Design Time-Line," AIAA/NASA/USAF/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Panama City, Florida, 1474-1482. Paper No. AIAA-94-4313-CP.

Workshops Supported by NASA Grant NGT 51102L:

HSCT External Advisory Board Meeting and Workshop, Georgia Institute of Technology, Atlanta, GA, May 1995.

Year 1 Presentations, Publications and Workshops
Grant NGT 51102L

October, 1994

The following workshops and publications (referencing support from the Grant 51102L) were accomplished under the second year's research effort:

Hale, M. and J. Craig, "Preliminary Development of Agent Technologies for a Design Integration Framework," AIAA-94-4297, 5th AIAA/NASA/USAF/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Panama City, FL, September, 1994.

Hall, N., and R. Fulton, "A Relational Database Approach to a Multidisciplinary Conceptual Design for the HSCT," Georgia Institute of Technology, September, 1994.

Lewis, K., T. Lucas and F. Mistree, "A Decision-Based Approach for Developing Ranged Top-Level Aircraft Specifications: A Conceptual Exposition," AIAA-94-4304, 5th AIAA/NASA/USAF/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Panama City, FL, September, 1994.

Lucas, T., S. Vadde, W. Chen, J. Allen, and F. Mistree, "Utilization of Fuzzy Compromise DSPs for Hierarchical Design Problems," AIAA-94-1543, AIAA/ASME/ASCE/AHS/ACS 35th Structures, Structural Dynamics and Materials Conference, Hilton Head, SC, April, 1994.

Marx, W., D. Schrage and D. Mavris, "Integrated Product Development for the Wing Structural Design of the High Speed Civil Transport," AIAA-94-4253, 5th AIAA/ NASA/USAF/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Panama City, FL, September, 1994.

Marx, W., D. Schrage and D. Mavris, "Integrated Design and Manufacturing for the High Speed Civil Transport," ICAS-94-10.8.3, 19th ICAS Congress/AIAA Aircraft Systems Conference, Anaheim, CA, September, 1994.

Mistree, F., K. Lewis and L. Stonis, "Selection in the Conceptual Design of Aircraft," AIAA-94-4382, 5th AIAA/NASA/USAF/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Panama City, FL, September, 1994.

Röhl, P., D. Schrage and D. Mavris, "A Multilevel Wing Design Procedure Centered on the ASTROS Structural Optimization System," AIAA-94-4411, 5th AIAA/NASA/USAF/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Panama City, FL, September, 1994.

Vadde, S., J. Allen, and F. Mistree, "On Modeling Design Evolution Along a Design Time-Line," AIAA-94-4313, 5th AIAA/NASA/USAF/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Panama City, FL, September, 1994.

Workshops Supported by NASA Grant NGT 51102L:

HSCT External Advisory Board Meeting and Workshop, Georgia Institute of Technology, Atlanta, GA, December 1993.

HSCT External Advisory Board Meeting and Workshop, Georgia Institute of Technology, Atlanta, GA, May 1994.