



# Lessons Learned During Solutions of Multidisciplinary Design Optimization Problems

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# **Lessons Learned During Solutions of Multidisciplinary Design Optimization Problems**

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## **Abstract**

Optimization research at NASA Glenn Research Center has addressed the design of structures, aircraft and airbreathing propulsion engines. During solution of the multidisciplinary problems several issues were encountered. This paper lists four issues and discusses the strategies adapted for their resolution. (a) The optimization process can lead to an inefficient local solution. This deficiency was encountered during design of an engine component. The limitation was overcome through an augmentation of animation into optimization. (b) Optimum solutions obtained were infeasible for aircraft and air-breathing propulsion engine problems. Alleviation of this deficiency required a cascading of multiple algorithms. (c) Profile optimization of a beam produced an irregular shape. Engineering intuition restored the regular shape for the beam. (d) The solution obtained for a cylindrical shell by a sub-problem strategy converged to a design that can be difficult to manufacture. Resolution of this issue remains a challenge. The issues and resolutions are illustrated through six problems: (1) design of an engine component, (2) synthesis of a subsonic aircraft, (3) operation optimization of a supersonic engine, (4) design of a wave-rotor-topping device, (5) profile optimization of a cantilever beam, and (6) design of a cylindrical shell. The combined effort of designers and researchers can bring the optimization method from academia to industry.

## **I. Introduction**

Optimization research at NASA Glenn Research Center has addressed the structural design of airbreathing propulsion engines and Space Station components, aircraft synthesis, as well as performance improvement of the engines. The accumulated multidisciplinary design activity is collected under a testbed entitled COMETBOARDS (ref. 1). Several issues were encountered while generating solutions to the multidisciplinary problems. This paper lists four issues and presents the strategies that were employed for their resolutions. (a) The optimization process produced a local inefficient design for a rear divergent flap of a downstream mixing nozzle. An augmentation of animation improved the design. (b) Solutions obtained for aircraft and engine problems, using single optimization algorithm, encountered infeasibility even though the values of the merit function were in the vicinity of the correct solutions. The infeasibility was eliminated through a cascading of multiple algorithms. (c) The shape optimization of a beam produced an irregular shape. The regular shape could be restored through engineering intuition. (d) For a cylindrical shell, the

subproblem solution strategy converged to local design that could be difficult to manufacture. Resolution of this issue is a challenge. This paper expounds upon the lessons learned in solving multidisciplinary problems with little emphasis on the algorithm or analysis method. The paper is divided into five subsequent sections. An outline to the testbed COMETBOARDS is given in section II. A description of the illustrative examples is given in section III. The next section describes the four issues: the local solution and animation, infeasibility and the cascade strategy, irregular design and intuition, and substructure solution and manufacturability. Discussions and conclusions are given in sections V and VI.

## **II. COMETBOARDS Testbed**

The design optimization testbed COMETBOARDS can evaluate the performance of different optimization algorithms and analysis methods while solving a problem. It is a research testbed but not a commercial code. The acronym COMETBOARDS stands for “COMparative Evaluation TestBed of Optimization and Analysis Routines for the Design of Structures.” The scope of the testbed has been expanded to include the design of structures, the synthesis of aircraft, the operation optimization of airbreathing propulsion engines. COMETBOARDS has three different analysis methods and one dozen optimization algorithms. It has a modular organization with a soft coupling feature, which allows quick integration of new or user-supplied analyzers and optimizers without any change to the source code. The COMETBOARDS code reads information from data files; formulates design as a sequence of subproblems, and generates the optimum solution. COMETBOARDS can be used to solve a large problem, definable through multiple disciplines, each of which can be further broken down into subproblems. Alternatively, it can improve an existing system by optimizing a small portion of a large problem. Other unique features of COMETBOARDS include design variable formulation, constraint formulation, subproblem strategy, global scaling technique, analysis approximation through neural network and linear regression method, use of sequential or parallel computational platforms, and so forth. The special features and unique strengths of COMETBOARDS assist convergence and reduce the amount of CPU time required to solve difficult optimization problems of the aerospace industry. COMETBOARDS has been successfully used to solve the structural design of the International Space Station components, the design of the nozzle components of an airbreathing engine, and airframe and engine synthesis for subsonic and supersonic aircraft, mixed flow turbofan engine, wave-rotor-topped engine, and so forth. The modular organization of COMETBOARDS is depicted in Figure 1. Brief descriptions of some of its modules follow.

**Scaling and constraint formulation:** A multidisciplinary design problem can have a distorted design space because its variables and constraints can vary over a wide range. For example, an engine thrust design variable, which is measured in kilopounds, is immensely different from its bypass ratio, which is a small number. Likewise, the landing velocity of an aircraft measured in knots and landing or takeoff field lengths measured in units of thousands of feet differ both in magnitude and in units of measure. This module provides a scheme to reduce the distortion by scaling the design variables, the objective function, and the constraints such that their relative magnitudes during optimization calculations are around unity. The constraints are reformulated to alleviate redundancy without affecting the problem definition. Constraint formulation alleviates redundancy and reduces their number (ref. 2). The cascade algorithm employs more than one optimizer to solve a complex design problem when individual mathematical programming methods experience difficulty (ref. 3).

The module “Analyzers—Structure, Aircraft, Engine—Neural networks and Regression approximations” houses three different types of analysis methods. For structural analysis the methods available are: COSMIC NASTRAN (ref. 4), MSC/NASTRAN (ref. 5), MHOST (ref. 6), Analyze/Danalyze codes (ref. 7), and IFM/Analyzers (ref. 8). Aircraft analysis can use the FLOPS code (ref. 9). The NEPP code (ref. 10) is employed for airbreathing propulsion engine cycle analysis. Neural network (ref. 11) and regression techniques (ref. 12) can be employed for analysis approximation. A problem can utilize any one of three analyzers: (1) an original analyzer, for example FLOPS code, or one of the two derived analyzers based on (2) a neural network or (3) a regression approximation.

The module “Engine operations” in Figure 1 refers to the performance optimization of airbreathing propulsion engines for multiple operation points (ref. 13). “Aircraft synthesis” refers to the airframe and engine integration for subsonic and supersonic aircraft (ref. 3).

The module “Structural design—Subproblem strategy and Parallel computational environment” refers to design of structures through regular optimization or a subproblem strategy. This strategy is available in sequential and parallel computational environments (ref. 14). “Multiple disciplines” refers to the solution of a problem, which is defined through different disciplines. COMETBOARDS can accommodate several disciplines each of which can be further divided into subproblems. Subproblem strategy is an attempt to alleviate convergence difficulties that can be encountered during the solution of a large optimization problem. In this strategy the large problem is replaced by a sequence of overlapping modest subproblems. The solution to the large problem is obtained by repeating the solution to the set of subproblems until convergence is achieved.

Substructure strategy, a key module of COMETBOARDS, is further illustrated through the design of a cargo-bay support of the International Space Station. The support structure is fabricated out of four plates, a cluster of plates referred to as a box, and five beams, as shown in Figure 2. For the purpose of design, the support system was divided into four active and one passive substructures. The first substructure was the closed box (FGHKIJ) consisting of five plates. Its finite element model was obtained by discretizing it into 72 (QUAD4 ) shell elements. The second substructure was a trapezoidal plate (FHEC), and its finite element model had 37 shell elements. The third and fourth substructures were triangular plates (GHE and GHD) with 12 finite elements each. The fifth substructure contained the five connecting beams BD, BG, AD, AG, and AF. The beam designs were not changed. These passive variables did not participate in the design calculations but were retained during reanalysis. Two independent finite analysis codes LE\_HOST and MSC/NASTRAN were used to verify the finite element model of the support structure. The finite element model with a total of 133 QUAD4 shell and 20 beam elements was considered adequate for design optimization because both analyzers produced an acceptable level of accuracy for stress, displacement, and frequency. The substructures were clustered next to obtain a set of subproblems. A subproblem contains a substructure along with some or all of its neighboring substructures. The four substructures were clustered to obtain the following four subproblems:

Subproblem 1: substructures 3 and 4

Subproblem 3: substructures 1 and 2

Subproblem 2: substructures 1 and 4

Subproblem 4: substructures 2 and 3

Notice the coupling between subproblems: substructure 1 is common to subproblems 2 and 3. Likewise, substructure 2 is common to subproblems 3 and 4, and so forth. Adequate coupling between substructures is required for convergence. Inappropriate coupling can increase the amount of computation and/or encounter convergence difficulties. At this time substructure coupling is decided intuitively. However, it may be possible to automate substructure coupling through the

gradient scheme developed in reference 15. The COMETBOARDS testbed can optimize a system that can be defined in terms of 100 optimization subproblems (ref. 14).

In the module “Problem formulation and solution,” information is read from data files, the design is cast as a sequence of optimization subproblems, and the solution is obtained.

The COMETBOARDS testbed is written in the Fortran 77 language except for the neural network algorithm, which is written in the C++ language. The testbed is available in the Unix operating system in workstations and Cray computers.

## **II.1 Optimization Algorithms in COMETBOARDS**

One dozen mathematical programming algorithms are available in COMETBOARDS. A list of the algorithms in no particular order follows.

- (1) Method of feasible direction (FD) (ref. 16)
- (2) Modified feasible direction method (mFD) (ref. 17)
- (3) Reduced gradient method (RG) (ref. 18)
- (4) Generalized reduced gradient method (GRG) (ref. 19)
- (5) Sequence of unconstrained minimization technique (SUMT) (ref. 20)
- (6) Sequential linear programming (SLP) (ref. 16)
- (7) Sequential quadratic programming method (SQP) (ref. 21)
- (8) IMSL optimization routine (IMSL) (ref. 22)
- (9) NPSOL package of NAG library (NLPQ) (ref. 23)
- (10) Sixteen different versions of optimality criteria methods (OC) (ref. 24)
- (11) A genetic algorithm (GENMO) (ref. 25)
- (12) Fully utilized design algorithm (FUD) (ref. 15)

Different algorithms employ different strategies to calculate the search direction and the step length. The comparative performance of the algorithms in solving a set of 45 problems is reported in reference 26. The performance of six algorithms in solving a set of medium and large structural problems is depicted in a bar chart in Figures 3(a) and 3(b), respectively. Examples with design variables in the range of 20 to 39 with about 200 behavior constraints are referred to as medium problems, see Figure 3(a). Examples with more than 40 independent design variables and several hundred constraints are referred to as large problems, see Figure 3(b). The success rate of different optimization algorithms for 10 large structural problems is also depicted in a Venn diagram in Figure 3(c). Cascade solutions for the problem are given in a table (see insert 3(e)). The success of an algorithm is represented by unity, which is the normalized value of the merit function, see Figures 3(a) and 3(b). A normalized value of less than unity (an infeasible solution) or greater than unity (an overdesign condition) represents underperformance. Most optimizers available in the testbed solved at least one-third of the examples, but none of the optimizers could successfully solve all the problems. Every structural problem could be solved by at least one of the six different optimization algorithms. However, even the most robust optimizer encountered difficulty in generating optimum solutions for aircraft and engine problems.

## **III. Illustrative Examples**

For the purpose of illustration, we have selected six problems:

- Problem 1—Structural design of an engine component.
- Problem 2—Synthesis of a subsonic aircraft.
- Problem 3—Operation optimization of a supersonic engine.

Problem 4—Design of a wave-rotor-topping device.

Problem 5—Profile optimization of a cantilever beam.

Problem 6—Design of a cylindrical shell.

Augmentation of animation into optimization is illustrated through Problem 1. Problems 2, 3, and 4 illustrate the cascade strategy. Problem 5 addresses shape optimization. The subproblem solution strategy is illustrated through problem 6. Brief definitions of the problems follow.

### **III.1 Problem 1: Structural Design of an Engine Component**

A mixed-flow turbofan engine exhaust nozzle referred to as a “downstream mixing nozzle” for a High Speed Civil Transport aircraft to operate at a cruise speed of Mach 2.4 and in a range of 5000 nautical miles is shown in Figure 4(a). It is fabricated out of rear and forward divergent flaps, rear and forward sidewalls, bulkheads, duct extensions, six disk supports, and other components. The design complexity of the nozzle is increased with flight Mach number, pressure ratio, temperature gradient, dynamic response, and degradation of material properties at elevated temperature. The flap is made of Rene 125 material with a Young’s modulus of 30.4 million psi, a Poisson ratio of 0.3, a density of 0.308 lb/in.<sup>3</sup> and an allowable strength of 117 ksi. The flap shown in Figure 4(b) has a length of 96 in. and a width of 72 in. It is supported by two variable-depth edge beams with a maximum depth of 14 in. A grid with a spacing of 12 in. by 12 in. and a depth of 2 in. stiffens the flap. MHOST and MSC/NASTRAN analyzers were used for the static as well as the dynamic analyses of the flap. A finite element model with 5593 degrees of freedom and 946 QUAD4 elements was used for analysis because both methods produced acceptable values for stress, deformation, and frequency. For this problem, the thickness of the edge beams, stiffeners, and skin panel were considered as the design variables. The flap was designed for minimum weight for von Mises stress, local buckling, displacement, and frequency constraints. The problem had 946 stress and 946 instability constraints, as well as four displacements and one-frequency constraints.

### **III.2 Problem 2: Synthesis of a Subsonic Aircraft**

The system synthesis capability of COMETBOARDS is illustrated through a subsonic aircraft to operate at Mach 0.85 cruise speed. Solution of this problem required a soft coupling of COMETBOARDS to NASA Langley’s aircraft analysis code FLOPS. The FLOPS analyzer encompasses several disciplines: weight estimation, aerodynamic analysis, engine cycle analysis, propulsion data interpolation, mission performance, airfield length requirement, noise footprint calculation, and cost estimation (refs. 27, 28, and 29). The objective of the synthesis problem was to determine an optimum airframe-engine design combination for a set of active design variables under specified engine and aircraft behavior parameters to minimize a composite merit function that could be generated as a linear combination of weight, mission fuel, lift-to-drag ratio, and NO<sub>x</sub> emission. The design variables considered were engine thrust, wing area, engine design point turbine entry temperature, overall pressure ratio, bypass ratio, and fan pressure ratio. Constraints were imposed on mixed approach climb thrust, second segment climb thrust, landing approach velocity, takeoff field length, jet velocity, and compressor discharge temperature. For the subsonic aircraft model, the gross takeoff weight was considered as the merit function.

### **III.3 Problem 3: Operation Optimization of a Supersonic Engine**

The operation optimization of airbreathing propulsion supersonic engine required a soft coupling of the analyzer NEPP, the NASA Engine Performance Program, to the optimization testbed COMETBOARDS. The engine-cycle NEPP code can configure and analyze almost any

type of gas turbine engine that can be generated through the interconnection of a set of standard physical components such as propellers, inlets, combustors, compressors, turbines, heat exchangers, flow splitters, nozzles, and others. An engine can be designed for different types of hydrocarbon jet fuels, cryogenic fuel, and slurries. For their thermodynamic analysis, built-in curve fits generated from empirical results have been incorporated into the NEPP code. A description of the NEPP code with typical input files for a set of engine configurations can be found in references 30 and 31.

The engine operation optimization problem, with its associated design variables (such as the engine shaft speed, the wave-rotor speed, the flow area, the geometrical parameters of the ducts, etc.) and constraints (imposed on pressure ratios, surge margins, temperature limits, and entrance Mach number, etc.) was cast as a sequence of nonlinear optimization subproblems with thrust as the merit function. Engine operation design became a sequence of interdependent problems, or one optimization subproblem for each operating point. The optimization process typically adjusted a few engine parameters. The difficulty in the engine problem did not lie with the number of active design variables, but it was associated with its multiple operating-point character, constraint validity ranges, and the iterative nature of engine cycle analysis. The most reliable individual optimization algorithm available in COMETBOARDS could not produce a satisfactory feasible optimum solution for this engine problem because of the large number of operation points in the flight envelope, the diversity of the constraint types, and the overall distortion of the design space. However, COMETBOARDS' unique features—which included a cascade strategy, variable and constraint formulations, and scaling devised especially for difficult multidisciplinary applications—successfully optimized the performance of subsonic and supersonic engine concepts. Even when started from different design points, the combined COMETBOARDS and NEPP codes converged to about the same global optimum solution. This reliable and robust design tool eliminated manual intervention in the design of the airbreathing propulsion engines and eased the cycle analysis procedures.

Engine design is illustrated through a supersonic Mixed-Flow Turbofan Engine (MFTF) problem. It was configured with 15 components and was designed for a flight envelope with 122 operating points. The design required the solution of a sequence of 122 optimization subproblems. The objective was to maximize the net thrust of the supersonic engine at each operating point, accounting for an installation drag. Each subproblem had 3 independent design variables and 22 behavior constraints.

### **III.4 Problem 4: Design of a Wave-Rotor-Topping Device**

A high bypass-ratio subsonic wave-rotor topped turbofan engine is made of 16 components that are mounted on two shafts with 21 flow stations. It was modeled with standard components that include an inlet and a splitter, then branching off to a compressor, a duct, and a nozzle. The main flow proceeded through a fan, a duct, a high-pressure compressor, a duct, a high-pressure turbine, a low-pressure turbine, a duct, and a nozzle. The components mounted on the first shaft included the fan, the compressor along the secondary flow branch, the low-pressure turbine, and a load. The second shaft carried the high-pressure compressor along the main flow, the high-pressure turbine and a load. The four-port wave-rotor (with burner inlet and exhaust, compressor inlet, and turbine exhaust), was located between the high-pressure compressor and the high-pressure turbine. The engine operating condition was specified by a 47-mission flight envelope, with altitude in the range (sea level to 40 000 ft) and speed between (0.0 to 0.85) Mach. To examine the benefits that accrue from the wave-rotor device, the engine was optimized considering several of its baseline variables and constraints, not explicitly associated with the wave-rotor, as passive. The design

objective was to maximize the net engine thrust at each of the 47 operating points. It had two design variables: heat added to the wave-rotor and the wave-rotor speed. Its 16 behavior constraints included the corrected speed ratio for the compressor and the fan, the unmixed wave-rotor temperature, the surge margin on the compressor, and the fan pressure ratio for the turbine.

### **III.5 Problem 5: Cantilever Beam**

Calculation of an optimum profile or depth along the length is illustrated considering the cantilever beam shown in Figure 5. The beam is made of aluminum with a Young's modulus  $E = 10 \times 10^6$  psi, a Poisson's ratio  $\nu = 0.3$ , and a weight density  $\rho = 0.1$  lb/in.<sup>3</sup> It is 240 in. long and 6 in. deep. The beam weight was the merit function and stress and displacement were its behavior constraints. For the purpose of analysis, the beam was modeled with six 20-node-hexahedral elements of the IFM/Analyzers code (ref. 32). The finite element model with 160 displacement degrees-of-freedom was used for the analysis model because it adequately predicted the stress and displacement responses of the beam. The profile optimization problem had nine depth design variables, and its nine constraints included eight stress and one displacement limitations.

### **III.6 Problem 6: Cylindrical Shell**

A cylindrical shell with rigid diagrams under two line loads is shown in Figure 6. It is made of steel with a Young's modulus  $E = 30 \times 10^6$  psi, a Poisson's ratio  $\nu = 0.3$ , and a weight density  $\rho = 0.289$  lb/in.<sup>3</sup>. It has a radius of 100 in. and length of 200 in. Because of symmetry, only one-eighth of the structure was considered for design. A finite element model with 100 QUAD4 elements of the MHOST analyzer was considered adequate to predict its response. Its design was cast as an optimization problem with weight as the objective function and constraints were imposed on stress and displacement. The thickness of the cylinder along its length and circumference were considered as design variables through a profiled depth link factor to provide a heavier design under the load. The one-eighth shell model was divided into four substructures along its length. The substructures were clustered to obtain three and four subproblems for sequential and parallel computations, respectively. An additional fourth subproblem was required to avoid convergence difficulty in parallel calculations.

## **IV. Issues in Multidisciplinary Design Optimization**

The four issues: (a) local solution and animation, (b) infeasibility and cascade strategy, (c) irregular design and intuition, and (d) substructure solution and manufacturability are addressed in this section.

### **IV. (a) Local Solution and Animation**

The design of the flap or Problem 1, which is depicted in Figure 4(b), was obtained using three optimization algorithms. All three methods produced the same optimum weight of 1448.2 lb. At the optimum, the frequency at 40 Hz and displacement at 1 in. were the active constraints. Stress and local instability were passive constraints. Its animation at the 40 Hz frequency was examined, and one frame is depicted in Figure 4(c). The animation exhibited a local frequency condition. The edge beams vibrated with significant amplitude, while the response of the rest of the structure was insignificant. In other words, only a small part of the structure carried a major portion of the load. In this design, the edge-beams became more failure prone than other parts of the structure.

The configuration of the flap was modified through an examination of the animation of a series of designs. The final modified configuration was obtained by increasing the depth of a single edge stiffener to 6 in. from its original 3-in. depth. This configuration was optimized. The increase in the material for this stiffener was compensated for by a reduction in the thickness of the edge beam by 58 percent between the two configurations. The dynamic animation of the flap and the von Mises stress distribution are shown in Figures 4(d) and 4(e), respectively. The structure vibrated in a breathing type of mode, or the entire flap responded as a single unit. The optimum design also displayed a full stress condition for a major portion of the flap as shown in Figure 4(e). The optimum weight at 1204.7 lb. was 20 percent lighter than the original configuration. Animation-assisted optimization reduced the weight and improved the overall design of the flap.

#### **IV. (b) Infeasibility and Cascade Strategy**

Individual optimization algorithms encountered difficulty in generating solutions to aircraft and engine problems. A useful strategy that combined the strength of more than one optimizer was conceived. This cascade strategy, using a number of optimization algorithms, one followed by another in a specified sequence, was found to be superior to the component optimizers, see Figure 3(d). The cascade algorithm was employed to solve the 10 large structural problems referenced in Section II.1. The success rate of the cascade strategy and the individual algorithms is shown in Figures 3(c) and 3(e). The cascade strategy solved all 10 problems.

Cascade solutions to the subsonic aircraft, the supersonic mixed-flow turbofan engine, and the subsonic wave-rotor-topped engine are shown in Figure 7. The subsonic aircraft system design problem was solved using a three-optimizer cascade algorithm: optimizer 1, followed by optimizer 2 and optimizer 1 again. The cascade solution, along with solutions obtained from individual algorithms, is depicted in Figure 7 and Table I.

Optimizer 1, when used alone, converged to a heavy infeasible solution at 202 005 lb for the aircraft weight see Figure 7(a). Likewise, optimizer 2 alone also produced a heavy design at 202 854 lb, see Figure 7(b). Optimizer 1 required a takeoff field length of 6282 ft against an available 6000-ft runway. Optimizer 2 overestimated the excess fuel requirement at 8150 gal against a desired amount of 5000 gallons. The convergence rate of the two algorithms differed producing solutions that were 1 percent and 2 percent overweight, respectively, for the two algorithms, see Figures 7(a) and 7(b). The two solutions, although close to the optimum, were not attractive to industry because they violated the safety margins. A cascade algorithm created from the same two optimizers (optimizer 1 - optimizer 2 - optimizer 1) successfully solved the problem with a feasible optimum solution at 199 818 lb for the aircraft weight, see Figure 7(c).

Solution of the mixed-flow supersonic and wave-rotor-topped subsonic engines also required the cascade strategy. A two-optimizer cascade, (optimizer 3 followed by optimizer 2) successfully solved the supersonic engine problem, see Figure 7(d). The solution to the wave-rotor-enhanced subsonic engine, see Figure 7(e), required a three-optimizer cascade algorithm: optimizer 1 followed by optimizer 2 and optimizer 1 again.

Aircraft (FLOPS) and engine (NEPP) analyzers are nonlinear codes that incorporate multiple disciplines. The analysis assumptions, dependent on altitude, Mach number, and engine power setting, can be challenged. The Newton-Raphson iterations during “engine-balancing” may not converge, leading to an engine “stall condition” with zero thrust, or to the NEPP code producing a NaN (not a number) for some constraints. A single optimization algorithm can terminate abruptly, or hit a constraint boundary without any improvement to the merit function. To overcome the difficulties in aircraft and engine analysis codes we employed two competing approximators: linear

regression and neural network methods. Even then, the cascade algorithm was required because individual algorithms encountered difficulty (ref. 13). The nature of engine and aircraft problems required the strength of multiple algorithms or the cascade strategy even with the analysis approximators, which however, was not expected.

#### **IV.(c) Irregular Design and Intuition**

The profile optimization of the cantilever beam, or Problem 5, was attempted with uniform upper and lower bounds for the design variables at 0.5 in. and 15 in., respectively, see Table II. The optimization problem was solved using optimizer 4. The solution obtained is shown in Figure 5 and Table II. The optimum weight was 1697.5 lb, and the root stress was the only active constraint. An odd-shaped profile shown in Figure 5 was obtained. The profile was peculiar because the free end, corresponding to a zero stress condition, had a depth of 5.14 in. instead of an anticipated lower bound depth of 0.5 in. The optimum solution most likely challenged linear structural analysis assumptions, and the optimization iterations encountered difficulties. The situation did not improve when a different optimization algorithm or a cascade strategy was employed. The problem was solved successfully with manual intervention. Instead of uniform upper or lower bounds and a single optimization algorithm, the design was cast as a sequence of subproblems. Upper and lower bounds and initial design—through engineering intuition—were progressively changed for the subproblems. This procedure produced a converged solution that is shown in Figure 5. It had the same minimum weight of 1697.5 lb, which was identical to the odd-shaped design. Its root stress and tip displacement were the active constraints. For this problem, optimization algorithms converged to two distinct local solutions with equal minimum weight. Industry will be more inclined to accept the monotonically profiled beam than the odd-shaped design.

The flap design and beam profile calculations represent typical problems of the aerospace industry. Neither problem could be solved satisfactorily without manual intervention. The difficulties encountered to some extent justify the reluctance of the aerospace industry to accept advanced optimization methods, abandoning their time-tested design rules. Neither mathematical programming algorithms nor the traditional design rules could produce optimum hardware configurations that could be manufactured. Their combination, however, was a winner.

#### **IV.(d) Subproblem Solution and Manufacturability**

A nonmanufacturable solution obtained in the subproblem strategy is illustrated considering the design of a cylindrical shell problem, or Problem 6. Solution to the problem was obtained using:

- (1) Regular optimization, where the entire structure was considered as a single problem.
- (2) Subproblem solution, wherein four overlapping substructures were used.

The optimum profiles for the cylindrical shell obtained using regular and subproblem strategies are depicted in Figure 6. The two optimum weights obtained were 1161.95 lb and 1154.1 lb for regular and subproblem strategies, respectively. The difference of 0.676 percent in the solutions could be considered negligible especially for the problem complexity. The depth differed substantially between the two solutions. At the crown, the optimum depths of 1.322 in. and 2.471 in. obtained by the two methods varied by 53 percent. At the optimum, the regular optimization and the subproblem strategy produced a different number of active constraints. The subproblem strategy produced only active stress constraints, whereas both stress and displacement constraints were active for the regular optimization. The profile obtained using regular optimization was more uniform than that generated through subproblem optimization. To verify the existence of two different designs (one obtained from the subproblem strategy and the other from the regular optimization), we

resolved the regular optimization case by setting the initial design equal to the optimum solution that was generated from the subproblem strategy. The solution converged to the initial design, confirming the existence of the two local solutions with about the same minimum weight. For this problem the attractiveness of subproblem strategy has been challenged because the design thus obtained is more difficult to manufacture compared to the regular solution. The authors are not aware of a scheme to alleviate this limitation of the subproblem solution strategy.

## **V. Discussions**

Discussion is given for multiple design solutions and the convergence of algorithms.

### **V.1. Multiple Design Solutions**

More than one optimum solution can be obtained for engineering design problems. For example, different solutions were obtained for the nozzle flap, beam profile, cylindrical shell, subsonic aircraft, and engine problems. The values of merit function changed little between the different solutions. The intermediate designs, however, could become nonmanufacturable or their safety could be questioned. These limitations were alleviated through animation and engineering intuition. The utilization of animation improved the design of the nozzle flap, and manipulation of the design bounds promoted the manufacturability of the beam.

Philosophically, we can arrange design methods into a spectrum. Experience occupies the bottom strata. Optimization methods belong to the upper spectrum. Popular design rules occupy the central spectrum. Design improved as we moved from the lower to upper spectrum methods but complexity increased. The design optimization method is in existence for about half a century, yet its full potential has yet to be exploited by industry. The situation can be improved by merging design optimization with the engineering knowledge contained in the broad spectrum methods. This goal can be achieved when proponents of the optimization method and industrial designers work in tandem.

### **V.2. Convergence of Optimization Algorithms**

Consider the convergence of the subsonic aircraft weight by two different algorithms, shown in Figures 7(a) and 7(b). Convergence was monotonic by both methods even though the rate differed, as expected. A similar trend was observed for the engine problems. Convergence at times oscillated about a mean solution until the maximum iteration limit was reached. Redundancy of the active constraints, their continuity and convexity may have created this situation. Engineering design problems may not satisfy some of the basic requirements that form the foundation of mathematical programming methods. For example, the stress and displacement constraints of structural problems are by nature redundant (ref. 2). The specified range of the constraints of engine and aircraft problems are susceptible to violation during optimization calculations. Optimum solution to multidisciplinary problems of the industry have to be obtained utilizing available analysis and optimization capabilities. The cascade strategy was found successful in generating reliable solutions for structures, aircraft, and engine problems. The cascade strategy was required even when neural network and regression approximators were used to approximate constraints and merit functions of the engineering design problems—this however was not expected.

## VI. Conclusions

An animation-assisted optimization successfully solved the flap design problem. Cascading of multiple algorithms solved aircraft and engine problems. The beam profile problem was solved through an incorporation of engineering intuition. Generating a regular manufacturable design using a subproblem optimization scheme still remains a challenge. Bringing optimization methods to their rightful industrial environment from the academic plane requires the combined effort of designers and optimization researchers.

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TABLE I: Solution to the subsonic aircraft design problem using a cascade strategy

	Cascade solution (Optimizer 1–2–3) Optimum design <sup>a</sup>	Optimizer 1 solution (as percent of cascade solution) Infeasible and heavy	Optimizer 2 solution (as percent of cascade solution) Feasible but heavy
Weight, lb	199 818.00	1.01	1.02
Design variables			
Wing aspect ratio (from 5 to 12)	8.33	0.94	1.19
Engine thrust, lb (from 20 000 to 70 000 lb)	31 228.21	.94	.99
Wing area, ft <sup>2</sup> (from 1000 to 3000 ft <sup>2</sup> )	1 936.05	1.04	1.00
Quarter-chord sweep angle of the wing, deg (from 0° to 45°)	11.63	.93	2.32
Wing thickness to chord ratio (from 0.05 to 0.15)	.09	.89	1.22
Engine design point turbine entry temperature, °R	3 014.29	.93	.94
Overall pressure ratio (from 10 to 40)	39.12	.83	.86
Bypass ratio (from 0.1 to 15.0)	5.65	.61	.68
Fan pressure ratio (from 1.1 to 3.5)	1.83	1.16	1.14
Constraints			
Approach velocity, kn (not to exceed 125 kn)	118.75	0.98	1.0
Takeoff field length, ft (not to exceed 6000 ft)	6 000.00	<sup>a</sup> 6 282.00	<sup>a</sup> 6 000.00
Landing field length, ft (not to exceed 6000 ft)	5 460.00	.98	1.0
Mixed approach thrust, lb (normalized with respect to 100 000 lb)	97 000.00	1.02	1.0
Second segment climb, lb (thrust normalized with respect to 100 000 lb)	93 000.00	1.03	.98
Compressor discharge temperature, °R	1 416.20	.93	.95
Excess fuel, gal (normalized with respect to 5000 gal)	5 000.00	<sup>a</sup> 2 150.00	<sup>a</sup> 8 150.00

<sup>a</sup>Actual values.

TABLE II: Intermediate and final solutions for the beam profile

Intermediate solution [Only the stress constraint at the root was active.]					Final solution [Tip displacement and root stress were the active constraints.]				
Design variable	Lower bound	Initial design	Upper bound	Optimum design	Design variable	Lower bound	Initial design	Upper bound	Optimum design
1	0.5	10.0	15.0	14.68	1	10.0	12.0	13.0	11.72
2				2.98	2	9.0	8.0	12.0	9.00
3				5.04	3	6.0	7.0	10.0	6.22
4				6.27	4	5.0	6.0	9.0	6.17
5				5.41	5	4.0	5.0	8.0	5.02
6				.50	6	3.0	4.0	7.0	3.67
7				2.49	7	2.0	3.0	6.0	2.00
8				2.67	8	1.0	2.0	5.0	1.32
9				5.14	9	.5	1.0	4.0	.50

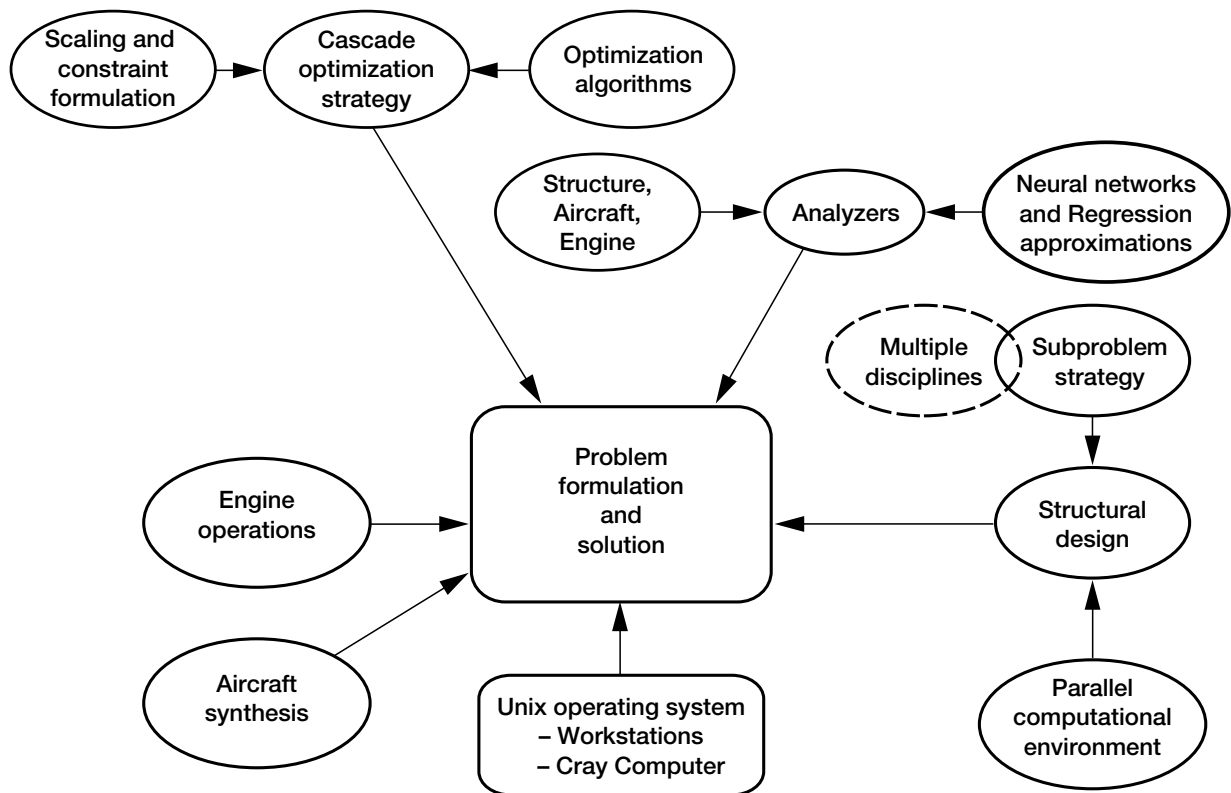
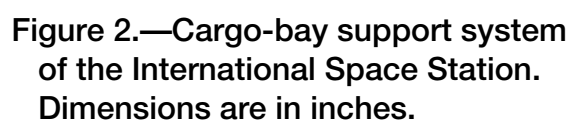
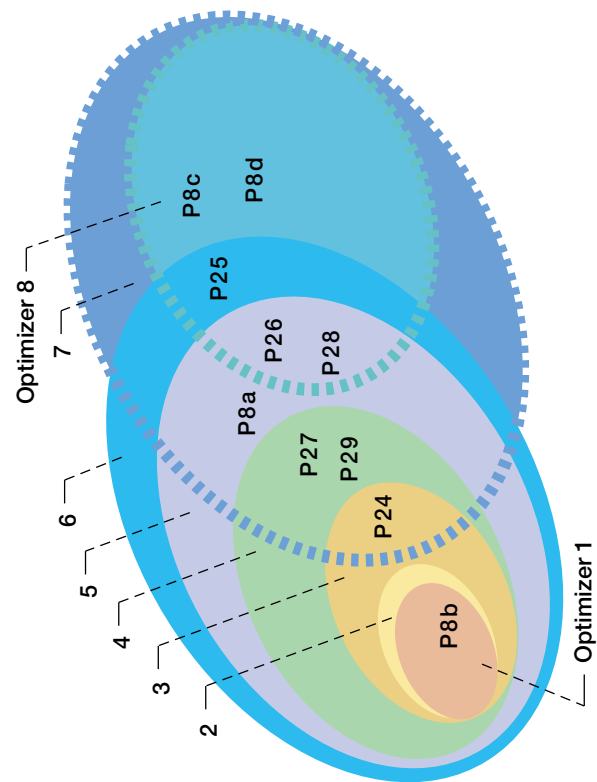
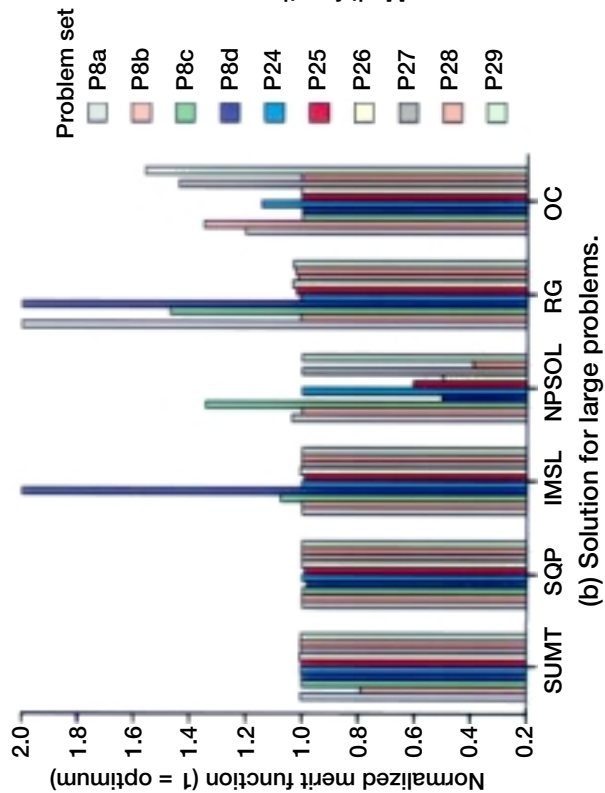
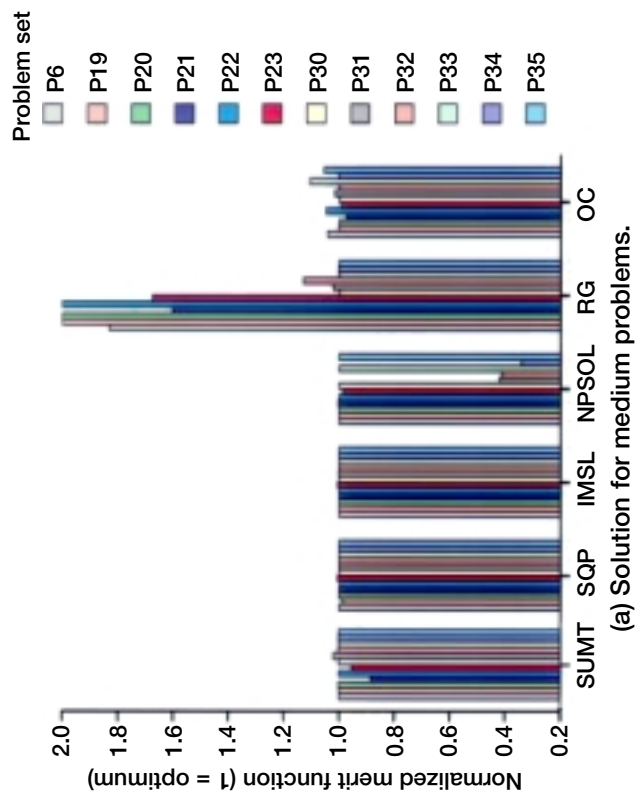


Figure 1.—Organization of the multidisciplinary design optimization testbed COMETBOARDS.





(e) Success rate of algorithms.

Algorithm	Success out of 10 problems
Cascade	10
Optimizer 1	1
---	1
2	2
---	4
3	7
---	8
4	9
---	5
5	6
---	7
6	8
---	9
7	10
---	1
8	2
---	3
9	4
---	5
10	6

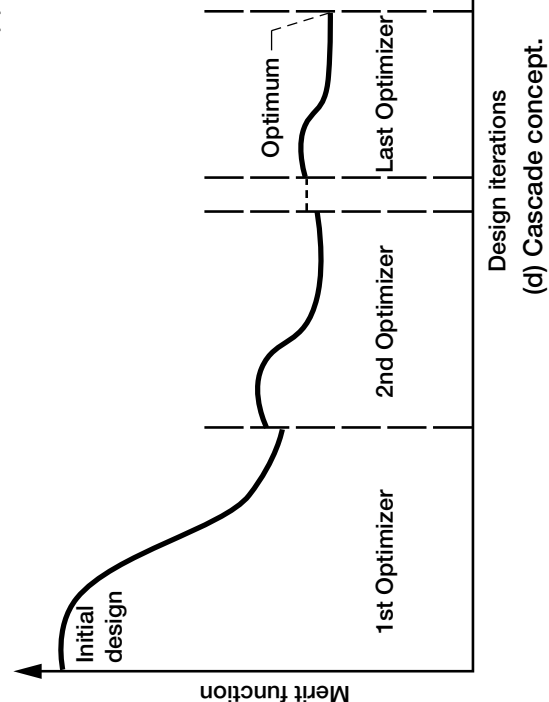


Figure 3.—Comparative evaluation of optimization algorithms.

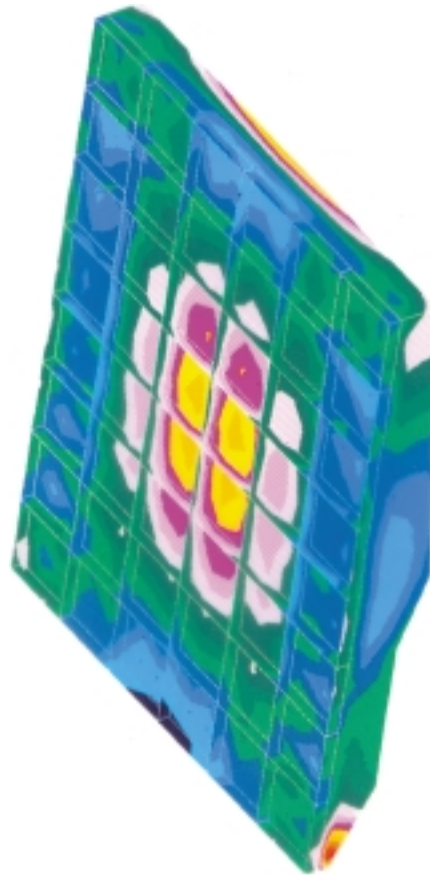
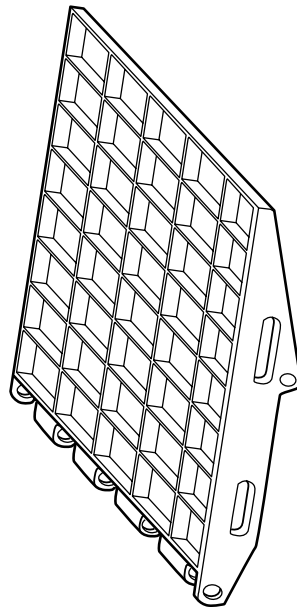
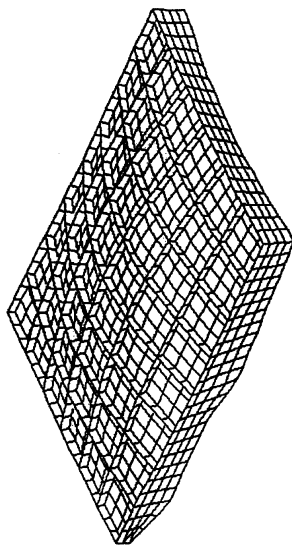
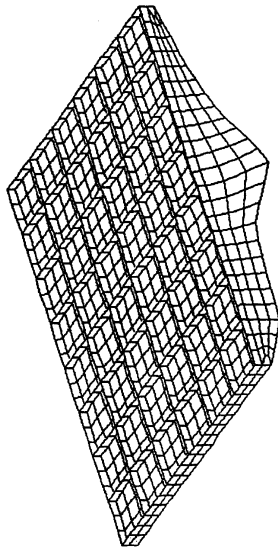
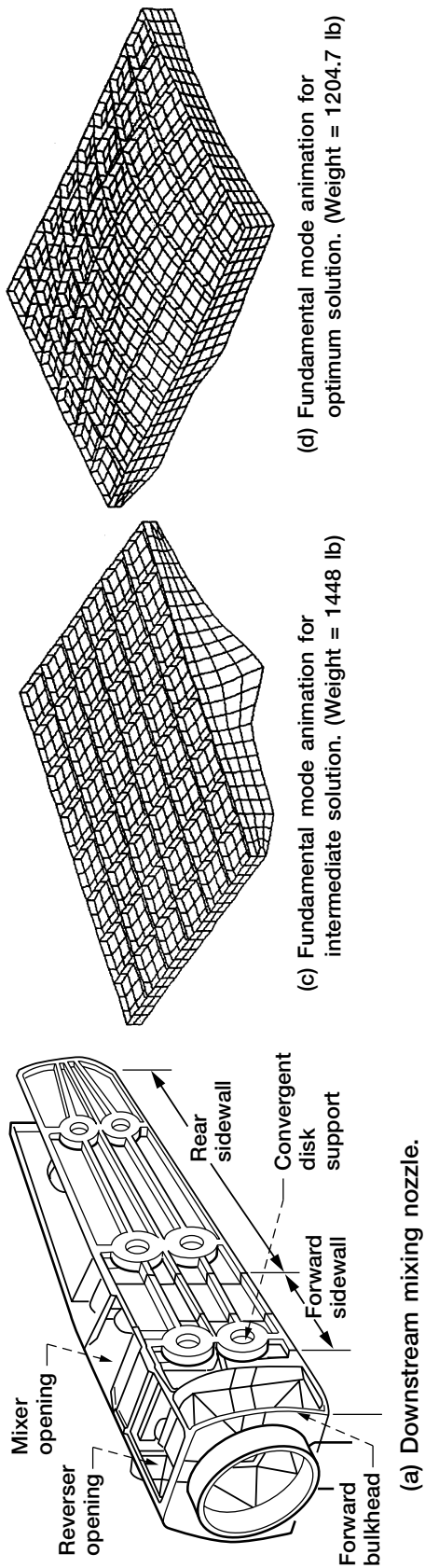


Figure 4.—Design of a rear divergent flap of a downstream mixing nozzle.

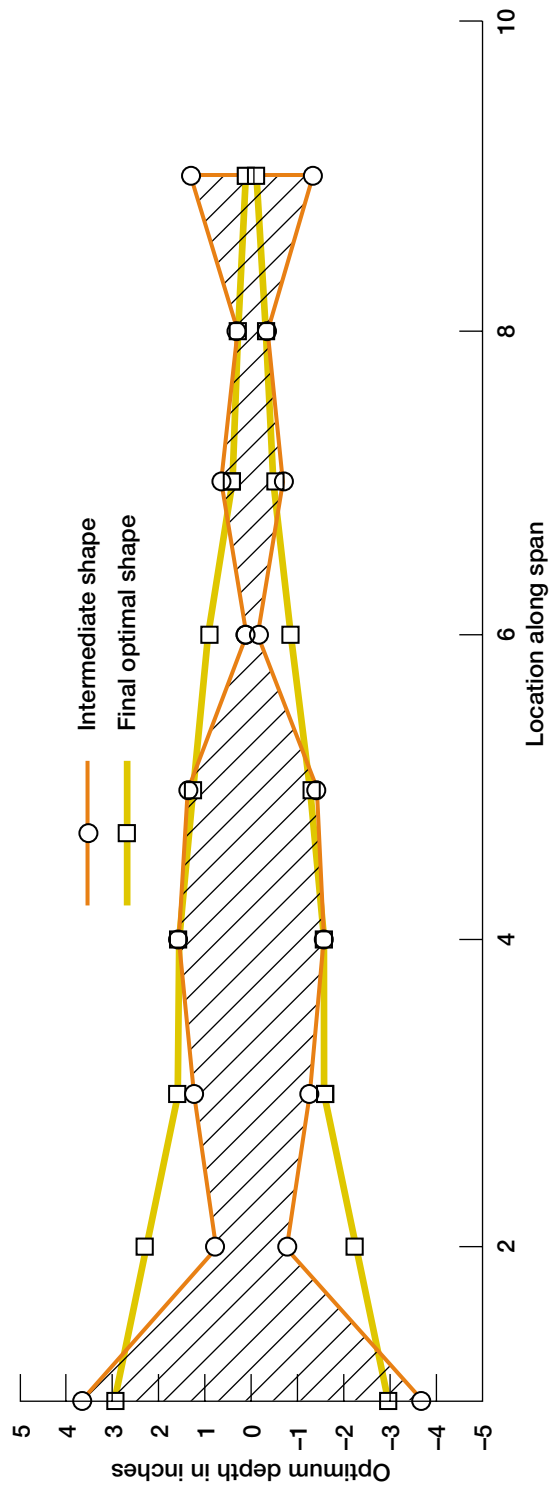
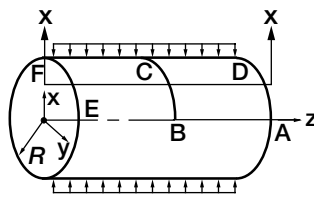
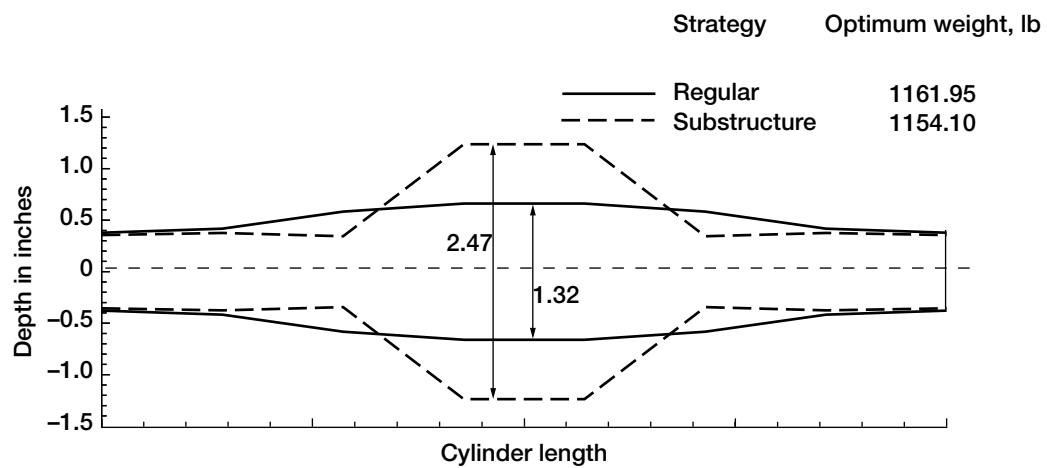


Figure 5.—Profile optimization of a cantilever beam for stress and displacement constraints.



(a) Cylindrical shell.



(b) Optimum profile along cylinder length.

Figure 6.—Substructure optimization of a cylindrical shell.

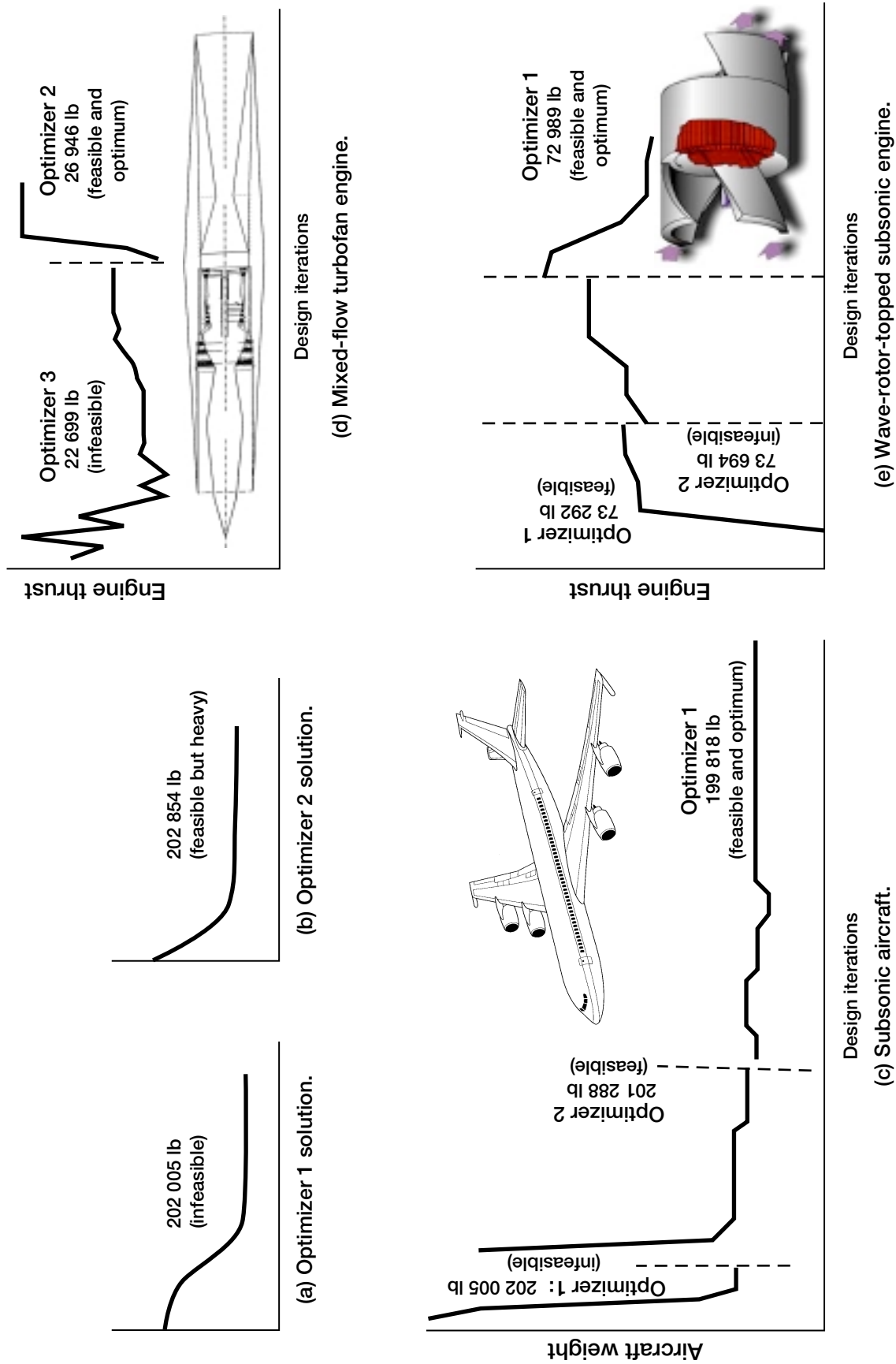


Figure 7.—Cascade solutions for aircraft and engine problems.

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13. ABSTRACT (Maximum 200 words)  Optimization research at NASA Glenn Research Center has addressed the design of structures, aircraft and airbreathing propulsion engines. During solution of the multidisciplinary problems several issues were encountered. This paper lists four issues and discusses the strategies adapted for their resolution. (a) The optimization process can lead to an inefficient local solution. This deficiency was encountered during design of an engine component. The limitation was overcome through an augmentation of animation into optimization. (b) Optimum solutions obtained were infeasible for aircraft and air-breathing propulsion engine problems. Alleviation of this deficiency required a cascading of multiple algorithms. (c) Profile optimization of a beam produced an irregular shape. Engineering intuition restored the regular shape for the beam. (d) The solution obtained for a cylindrical shell by a subproblem strategy converged to a design that can be difficult to manufacture. Resolution of this issue remains a challenge. The issues and resolutions are illustrated through six problems: (1) design of an engine component, (2) synthesis of a subsonic aircraft, (3) operation optimization of a supersonic engine, (4) design of a wave-rotor-topping device, (5) profile optimization of a cantilever beam, and (6) design of a cylindrical shell. The combined effort of designers and researchers can bring the optimization method from academia to industry.				
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