

## **Rotorcraft Performance, Controls, and Aerodynamics: A Multidisciplinary Approach**

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### **ABSTRACT:**

Helicopter design includes several disciplines with often-conflicting requirements. A formal system design framework is developed in this research where the designer coordinates with disciplinary experts to find an overall optimized design while simultaneously optimizing disciplinary objectives. The overall system objective function chosen in the preliminary design is minimum production cost for a light turbine-training helicopter. Several disciplinary objectives including specific fuel consumption for propulsion, empty weight for weights group, and figure of merit for aerodynamics group are optimized. In addition to disciplinary optimization, several analyses are performed including vehicle engineering, dynamic analysis, stability and control, transmission design, and noise analysis. The design loop starts from the conceptual stage where the initial sizing of the helicopter is done based on mission requirements. The initial sizing information is then passed to disciplinary experts for preliminary design. The design loop is iterated several times using multidisciplinary design techniques like All At Once (AAO) and Collaborative Optimization (CO) approaches. A light training helicopter is proposed that satisfies all the mission requirements, is optimized for several disciplines and has minimum production cost. Merits, demerits, requirements and limitation of the proposed methodology are discussed.

### **INTRODUCTION**

The multidisciplinary nature of helicopter makes it hard for the preliminary designer to estimate the actual cost of the aircraft in the early design stage. There has been a lot of emphasis on bringing more and more design information early in the design stage [1, 2, 3, 4]. In this research, a variety of disciplinary design analyses are performed at the preliminary helicopter design stage where the design cycle is repeated in an iterative fashion using Multidisciplinary Design Optimization (MDO) to ensure an overall optimized design. All At Once (AAO) and Collaborative Optimization (CO) techniques developed by Kroo, Sobieski, Braun et al [5, 6, 7] are used. These methods help integrate various design disciplines while removing their interdependency. AAO approach solves the problem by removing disciplinary optimizers and introducing a multi-objective criterion for the system level optimizer. CO allows simultaneous use of disciplinary optimizers thus ensuring that not only an overall optimized design is obtained, but also the design is best from disciplinary point of view.

A light turbine-training helicopter is used as baseline for analysis. The requirements come from the Request For Proposal (RFP) from AHS 2006 student design competition. The helicopter is expected to lift two 90 kg people, 20 kg of miscellaneous equipment, and enough fuel to Hover Out of Ground Effect (HOGE) for 2 hours, into HOGE at 6,000 ft on an ISA + 20°C. The winning design team at Georgia Tech made use of a variety of software packages and codes for different disciplines to perform the analyses. The idea is to perform the required mission with minimum cost. A variety of software packages and codes for different disciplines are integrated in this research to perform analyses.

In a traditional design approaches, due to strong dependency of disciplines on each other, it is not possible to run several analyses in parallel and therefore the design process is slowed down significantly. Infact, in several cases, by the end of the design, it is not possible to complete even one design loop involving all analyses simultaneously. This process does not guarantee overall system cost minimization.

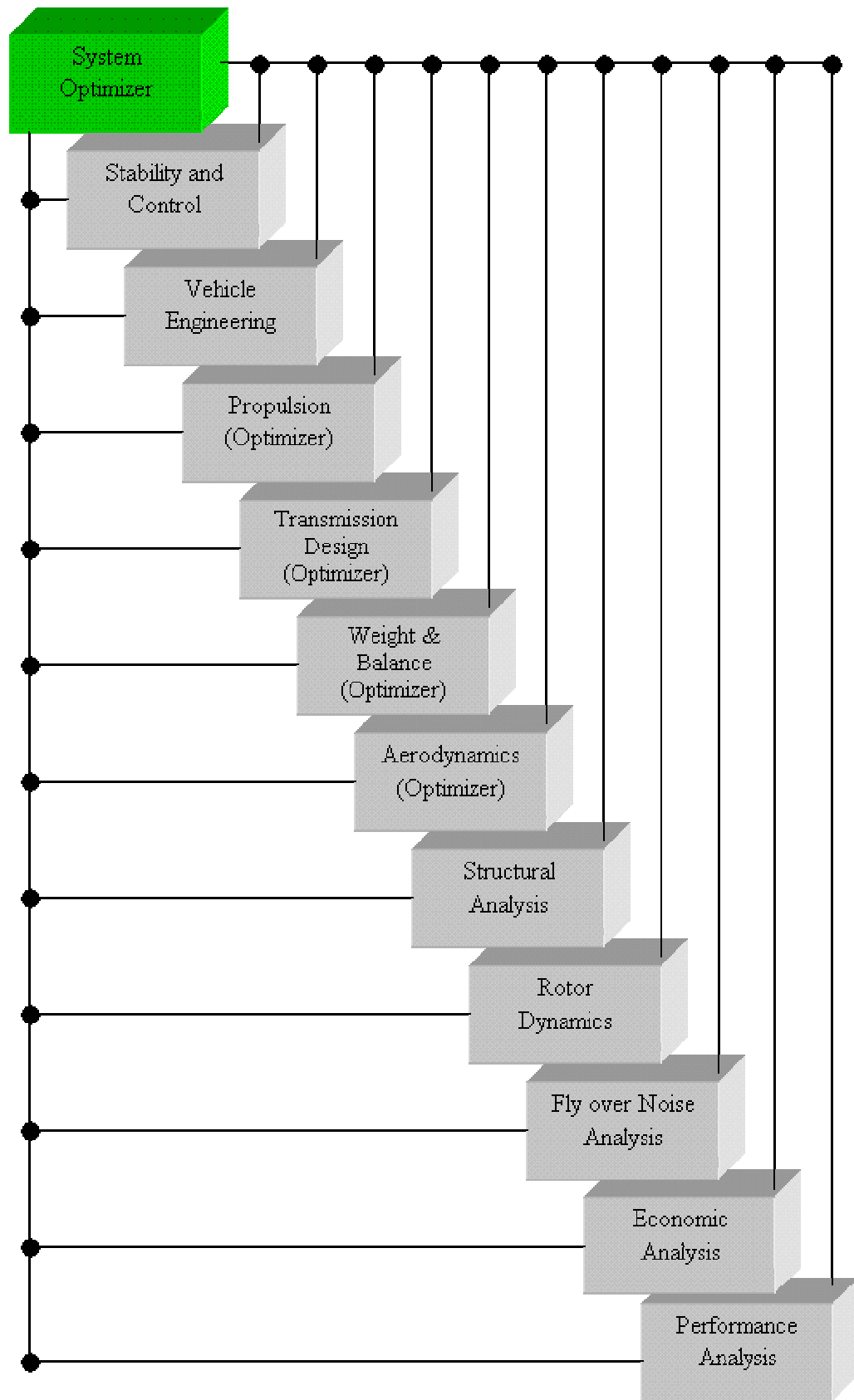


Figure 1: Multidisciplinary design environment

In this research, a platform is developed where all the disciplinary codes, software and analyses are integrated and several design loops are performed. The overall system design criterion is chosen to be the minimum production cost. All the disciplinary and the system level design constraints are satisfied. Optimized results obtained from AAO and CO approaches are compared. These methods, when fully converged, ensure an overall optimized design with several disciplines involved. A data repository is created where design information is stored iteratively. As the design matures, new information is obtained from disciplines and subsequent analyses are performed. A parallel design helps reduce the design time from several months to a few hours. The entire design process is automated in this research. Analyses performed in parallel are shown in Figure 1. There are no feedback or feed forward loops between different disciplines and all the disciplinary optimizers are retained. The weight optimizer minimizes the empty weight of the helicopter, the propulsion optimizer minimizes the fuel consumption and emission, and the aerodynamics optimizer maximizes the hover Figure of Merit. All the other disciplines are of analysis type.

The initial problem setup is time consuming and tedious but after the problem is setup and software packages are integrated, information flow becomes very efficient. ModelCenter is used as a platform for information transfer and system level optimization. Individual

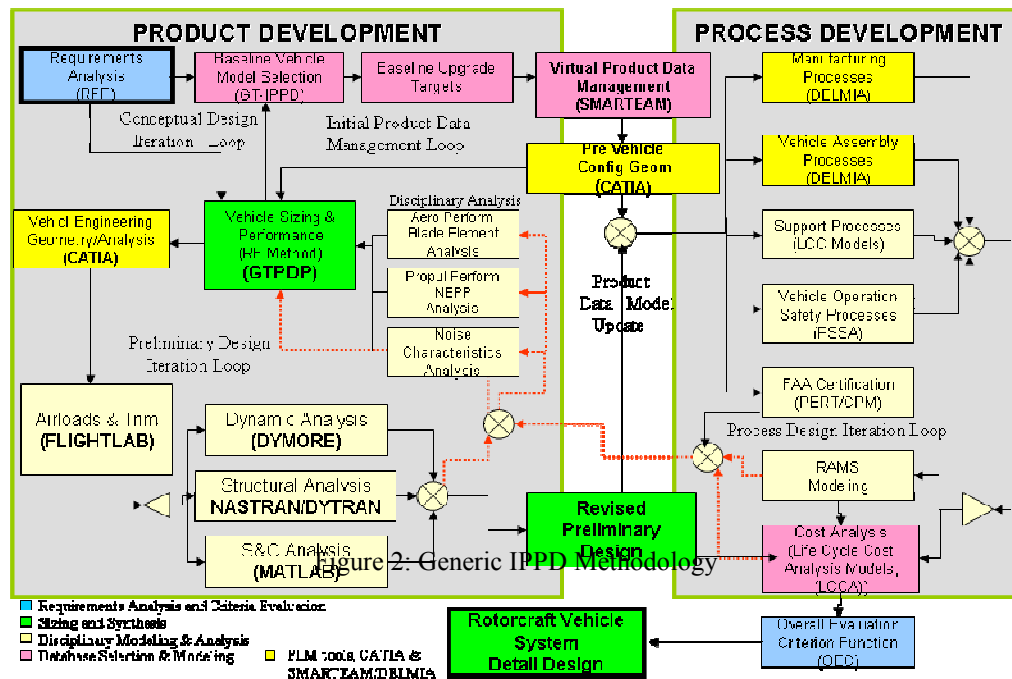
wrappers are written for data transfer between ModelCenter and disciplinary codes. These codes include commercial software, legacy codes and customized in house programs. Data is transferred in batch mode for rapid analysis.

The design team estimated the average vehicle cost, based on the production of 3000 units, to be \$203,541.85 per unit. This estimate was based on sequential disciplinary analyses. The results obtained from MDO environment with parallel execution show a reduction in the average unit cost to \$178,175.69. This is a 12.46% reduction in cost while all the constraints and RFP mission requirements are satisfied. This study demonstrates an automated framework for preliminary helicopter design. The framework ensures that detailed disciplinary analyses are performed in an automated manner in parallel at the initial design stage while at the same time overall disciplinary and system level optimized results are obtained. The platform also allows the designer to add further detailed disciplinary analyses so that the overall fidelity of the system can be improved.

### DESIGN METHODOLOGY

The generic Integrated Product and Process Development (IPPD) methodology shown in Figure 2 allows the engineers and program managers to decompose the product and process design iterations [8,

## GIT Rotorcraft IPPD PD & PLM Methodology



9, 10, 11]. The product development cycle of IPPD methodology is further divided into the conceptual and preliminary design loops. In this research, disciplinary analyses are identified, linked with each other through a common platform, and preliminary design loop iteration is performed in an automated fashion. This approach provides an opportunity to perform system optimization using MDO techniques.

Several requirements exist for a framework to provide an easy to use and robust MDO environment. Key attributes for the MDO environment, as listed by Sobieski [12], are computer speed, computer agility, task decomposition, sensitivity analysis, human interface and data transmission. The framework requirements for MDO application development have been outlined in the work of Salsas and Townsend [13] as architectural design, problem formulation, problem execution, and access to information.

Sobieski [12] indicates that among several tools that specialize in process integration and exploration, ModelCenter from Phoenix Integration Inc. among some others focus on product modeling and ease of tools and process integration across distributed and heterogeneous computing environments. ModelCenter is used in this research because of its flexibility to incorporate several existing commercial packages e.g. Excel, Matlab, MathCad, CATIA etc. ModelCenter also facilitates the use of wrappers to integrate in-house legacy codes.

Two MDO approaches, i.e. All At Once (AAO) and Collaborative Optimization (CO) are used in this research to resolve the conflicting objective functions of different disciplines and the system level optimizer. AAO approach dictates that all the local design variables and constraints are moved to the system level. The local disciplinary optimizers are eliminated. The problem is reduced to a single level scheme with just one system optimizer. AAO approach with the capability of parallel execution of disciplines is depicted in Figure 3. With this approach, the disciplines become independent of each other. This approach facilitates the information flow from the repository to the respective disciplines and back to the repository in an automated fashion.

When the feedback loops are removed, compatibility constraints are added to the system level optimizer. The generic system level problem is defined as follows.

$$\text{Objective Function: } \overline{\text{Minimize } F}$$

$$\text{Subject To: } \overline{g}, \overline{g}_A, \overline{g}_B$$

$$\text{Variables: } \overline{X}, \overline{X}_A, \overline{X}_B$$

Where

$\overline{F}$  = Overall Evaluation Criterion (OEC)

$\overline{g}$  = System level constraints

$\overline{g}_A, \overline{g}_B$  = Compatibility constraints

$$\overline{g}_A = \left\| \overline{B}' - \overline{B} \right\|^2 - \varepsilon \leq 0$$

$$\overline{g}_B = \left\| \overline{A}' - \overline{A} \right\|^2 - \varepsilon \leq 0$$

$\overline{X}$  = System level variables

$\overline{X}_A, \overline{X}_B$  = Disciplinary variables

Where

$\overline{A}, \overline{B}$  = Actual output vectors from disciplines A and B

$\overline{A}', \overline{B}'$  = Intermediate variables

The intermediate variables are copies of true outputs from disciplinary analyses. These variables are additional independent variables and are treated just like design variables that the optimizer has to deal with. The compatibility constraints ensure that the difference between the disciplinary outputs and outputs from system level result in the same values. This approach eliminates iterations between disciplines. There is no optimization conflict between disciplines. However the system level optimizer can become very large for a problem with several disciplines and several variables. AAO also removes the control of local variables by local experts or local optimizers. The expert codes are

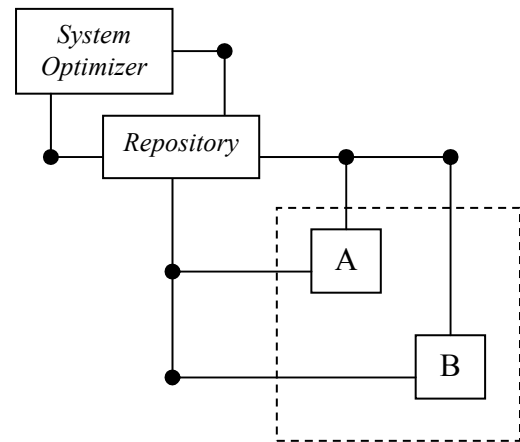


Figure 3: AAO Approach with a Central Data Repository

reduced to simple analysis only mode, making them servants to the system level optimizer. No problem solving occurs at the local level. Some of these issues are addressed by the CO approach.

Collaborative Optimization is a design architecture developed by Sobieski et al [14, 15, 16, 17, 18, 19, 20], specifically created for large-scale distributed analysis applications. In this approach, a problem is decomposed into user-defined number of subspace optimization problems that are driven towards interdisciplinary compatibility and the appropriate solution by a system level coordination process [16]. The fundamental concept behind the development of Collaborative Optimization architecture is the belief that disciplinary experts should be able to contribute to the design process while not having to fully address local changes imposed by other groups of the system. To facilitate this decentralized design approach, a problem is decomposed into sub-problems along domain specific boundaries. Through subspace optimization, each group is given control over its own set of local design variables and is charged with satisfying its own domain specific constraints. Communication requirements are minimal because knowledge of other group's constraints or local design variables is not required. The objective of each sub-problem is to reach agreement with the other groups on values of the interdisciplinary variables. A system level optimizer is employed to orchestrate this interdisciplinary compatibility process while optimizing the overall objective. To avoid the conflict between disciplinary objectives, collaborative optimization replaces the objective functions of each disciplinary optimization. The new objective function attempts to minimize a newly defined error function, known as J term. These J terms measure the relative error between the output variables of the disciplinary tools and

corresponding target values. These target values are set by the system level optimizer, which is configured to optimize a system level objective function under the constraint that the J terms in each discipline are kept within a certain tolerance. Each disciplinary tool is allowed to vary all of its usual inputs and local variables to minimize its own objective function. This allows for the disciplinary experts to focus on their domain specific issues while maintaining interdisciplinary compatibility. Collaborative Optimization in a Design Structure Matrix (DSM) format is shown in Figure 4. A generic Collaborative Optimization problem is given as follows.

System Level Problem:

Objective Function: *Minimize*  $f$   
 Constraints:  $\overline{J}_A, \overline{J}_B, \overline{J}_C \leq 0$   
 Variables:  $\overline{X}, \overline{A}, \overline{B}, \overline{C}$

Disciplinary Problem A:

Objective Function: *Minimize*  
 $J_A = \left\| \overline{B}' - \overline{B}_A \right\|^2 + \left\| \overline{C}' - \overline{C}_A \right\|^2 + \left\| \overline{A}' - \overline{A} \right\|^2$   
 Subject To:  $g_A \leq 0$   
 By Changing:  $\overline{X}_A, \overline{B}_A, \overline{C}_A$

Similar problems are defined for disciplines B and C. This decomposition strategy allows for the use of existing disciplinary analyses without major modification and is also well suited to parallel execution across a network of heterogeneous computers.

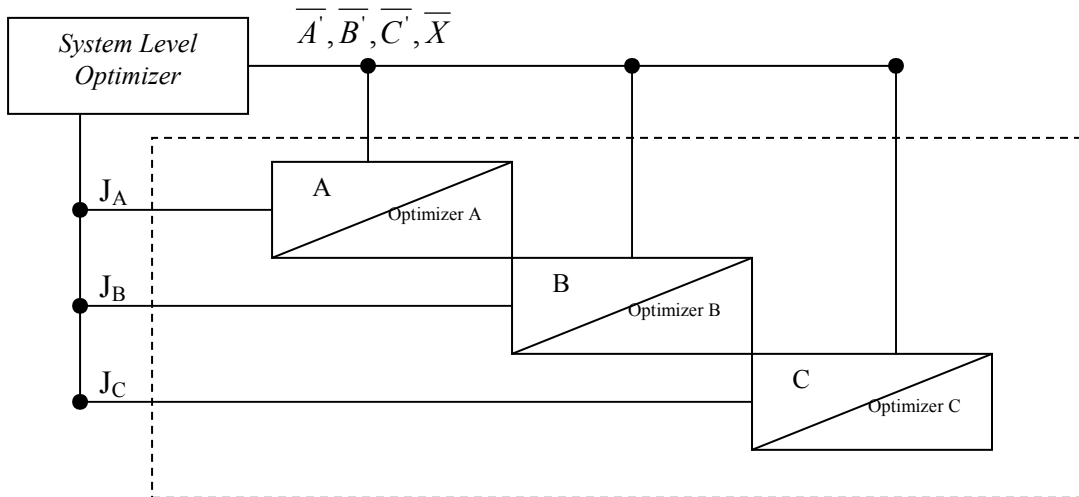


Figure 4: Collaborative Optimization Design Architecture

A complex system like rotorcraft design is composed of several levels of problems. Each system is divided into further subsystems. Several models including in-house codes, commercial software, legacy codes and programs are integrated in this research using ModelCenter as the common platform.

## ROTORCRAFT MDO MODELS AND ANALYSES

Light Turbine Training Helicopter (LTTH) is chosen for the application of the IPPD methodology using MDO tools. Detailed disciplinary tools, analyses, software packages, and programs are identified and integrated using a common platform. The integration of disciplines using a common platform enables the transfer of design information from one discipline to another in an efficient manner. A centralized database is created where all the latest information from all the disciplines is stored. The dynamic platform enables the application of optimization techniques at the system level. LTTH baseline information comes from the 23<sup>rd</sup> annual student design competition 2006 Request For Proposal (RFP) [21] published by the American Helicopter Society (AHS). The goal is to develop a two-place single turbine engine, training helicopter that is affordable. The mission requirements and some of the system level constraints are also defined in the RFP. This includes the capability to lift two 90kg people, 20kg of miscellaneous equipment, and enough fuel to Hover Out of Ground Effect (HOGE) for 2 hours, into HOGE at 6,000 ft on an International Standard Atmosphere (ISA) + 20°C day. The winning LTTH design team at Georgia Tech further refined these requirements and new details are added. Based on the RFP, a mission profile is generated as shown in Figure 5.

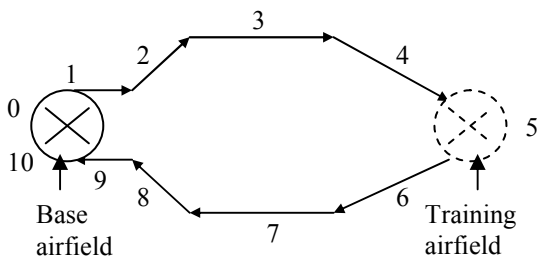


Figure 5: Mission Profile for LTTH design

The LTTH design team developed a conceptual baseline vehicle using the performance requirements stipulated in the RFP. This was followed by preliminary design, which provides more detailed analysis in multiple disciplines to identify the necessary baseline vehicle

modifications. Disciplinary analyses include aerodynamic performance optimization, structural design, analysis, and material selection, CAD modeling, helicopter stability and control analysis, dynamic analysis, propulsion system design, helicopter training industry research and cost analysis. The goal of the proposed design can be summarized as reducing the cost while improving product quality and value [22].

Important disciplines involved in the preliminary design loop of IPPD methodology shown in Figure 2 are identified in this research. All possible tools, analysis packages, commercial software, legacy codes and in house programs are utilized and integrated using a common platform i.e. ModelCenter. Individual optimization problems are defined for propulsion, economics, weight and balance and aerodynamics groups. Details of the analyses used in each discipline are discussed in the following section. All the disciplines integrated in this research are shown in Design Structure Matrix (DSM) format in Figure 1.

## Performance Analysis

Prouty [23] remarks that the results obtained from performance analysis can be used in design tradeoff studies. Before the analysis can be done, it is important to collect the individual items of information that are required. These include the performance of the individual rotors, the installed engine performance, the power loss in transmission and accessories, the vertical drag in hover, the tail rotor fin interference, and the parasite drag in forward flight. Johnson [24] indicates that calculation of helicopter performance is largely a matter of determining the power required and power available over a range of flight conditions. Two methods that are used for performance analysis are the Fuel Ration ( $R_F$ ) method and the Georgia Tech Preliminary Design Program (GTPDP), which is based on regression of historical data.

One of the methods used to size VTOL concept in this research is the extended  $R_F$  method for advanced VTOL aircraft. It is a graphical technique for the parametric analysis of aircraft for a given design specification, and provides a preliminary design tool for the investigation of the interrelated effects of significant design parameters on the gross weight of the aircraft. The method is based on a graphical simultaneous solution of equations expressing the weight and performance characteristics of an aircraft, which enforces the compatibility of the resulting gross weight solution with both weight and performance predictions [25, 26]. One of the biggest limitations of  $R_F$  method is that it only allows the designer to minimize the gross weight. Also only a few variables are involved in the analysis. More

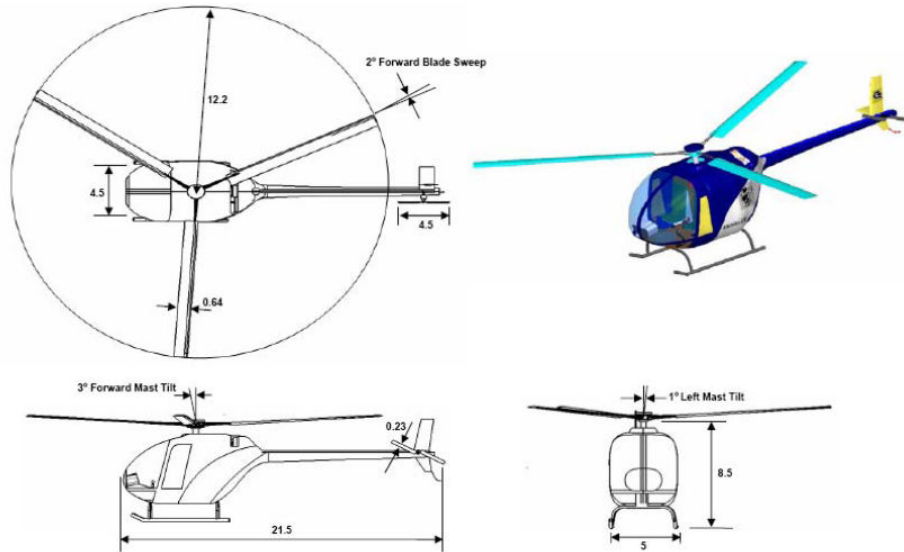


Figure 6: Three-view drawing of baseline vehicle

comprehensive preliminary design tools like HESCOMP and GTPDP are available for initial sizing. GTPDP is utilized iteratively in the design loop in this research.

GTPDP is a preliminary performance analysis program in nature based on an energy approach and has been written to yield results quickly and inexpensively [27]. Yet, the results are of sufficient accuracy that sound understanding of a helicopter behavior can be obtained and valid comparison can be made. Some of the important outputs obtained from GTPDP are as follows

- Power available verses altitude and temperature
- Power required verses airspeed
- Hover ceiling verses weight and temperature
- Vertical rate of climb (ROC) verses weight
- Power coefficient ( $C_p$ ) verses thrust coefficient ( $C_T$ ) for hover Out of Ground Effect (HOGE) and Hover In Ground Effect (HIGE)
- Power coefficient ( $C_P$ ) verses advance ratio ( $\mu$ ) and Thrust coefficient ( $C_T$ ) verses advance ratio ( $\mu$ )
- Figure of Merit (F.M) verses Gross Weight (GW)

The mission profile analysis is also performed in GTPDP. GTPDP is simple and quick preliminary helicopter design code but the calculations are approximate and it uses simple approaches and equations. So more detailed disciplinary analyses are required for a complete and optimized preliminary design of the helicopter. The initial outputs obtained from the baseline vehicle analysis in GTPDP are used as inputs for the other disciplinary analyses. Besides the

initial analysis, GTPDP is also used in the system design iteration to get approximate mission performance output. GTPDP is integrated with ModelCenter, so information can be transferred from GTPDP to other disciplines. COM/API is used in conjunction with wrapper file that communicates and helps transfer inputs and outputs back and forth between GTPDP and ModelCenter.

### Vehicle Engineering

Besides developing graphical models of vehicle components, a design package is used for several other analyses including weight and moment estimates. A state of the art design package, CATIA V5 is used for the CAD design of vehicle in this study. LTTH design team developed several detailed models of components of the baseline helicopter. These components are then integrated using assembly function. Isometric and three view baseline vehicle drawings developed by the design team are shown in Figure 6. Some of the components of the assembly are transformed into parametric models. These models are then linked with ModelCenter. With the help of these parametric models, the vehicle geometry can be updated as design values change. Some of the important components that are parameterized are the main rotor, tail rotor, vertical tail and horizontal tail. Because of the link between CATIA and ModelCenter, it is possible to dynamically change geometric information from ModelCenter and promptly update drawings. Therefore as the design changes during iterations in the system level optimization process, the CAD model gets updated automatically. Some of the data that is extracted from the models include the

moment of inertias, surface areas, volumes, and masses of individual components. CATIA built-in functions are used to calculate these parameters. The mass and volume information is passed to the weights group and the surface area information goes to the aerodynamics analysis. The moment of inertia information is passed to the rotor dynamics group and is eventually used for calculating rotor frequencies and stiffness matrices. All this information flow is facilitated through a centralized repository. Like all other disciplines, the information obtained from vehicle engineering group also goes to the system level optimizer and is stored in a data file. This information is then passed on to respective disciplines as needed. In addition to the numerical information, CATIA model can also be used for generating a mesh, which can be used for CFD analysis in aerodynamics discipline or FEM analysis in the structures discipline.

### **Stability and Control and Trim Analysis**

A variety of analysis tools including the Georgia Tech Unified Simulation Tool (GUST), FlightLab and Matlab trim analysis code and linear control root locus plots are investigated for stability and control discipline in this research. GUST, used at Georgia Tech for UAV research and development, has been designed to take input parameters from rotor dynamics, aerodynamics, gear dynamics, and flight controls with sensors – enabling it to monitor flight characteristics and perform missions using trajectories in real life scenario [28, 29, 30]. GUST is an instrumental tool in the pilot development process. FlightLab on the other hand is an industry standard program. The Georgia Tech AHS design team used FlightLab for trim analysis and established linear models around trimmed flight conditions for the LTTH. For integration with preliminary design loop, Matlab based trim analysis and root locus analysis are performed. An in-house trim analysis code is designed. A linear version of the nonlinear model is generated around each trim point after the parameter sweep is accomplished to study root locus plots. Using the reduced order linear model, the local behavior of the vehicle at a given flight condition is also observed. Closed form expressions are used for trim to quickly obtain responses. The simplified trim analysis is appropriate for trim estimates when extreme flight conditions e.g. stall or compressibility effects are not considered. However, an aircraft design that is not trimmed for the required flight condition is of very little or no value. Therefore it is critical that a detailed trim analysis is performed to ensure a fully trimmed aircraft. For that purpose, a detailed and complete trim analysis is performed offline after the final optimized aircraft configuration is achieved. This is in addition to the simplified trim analysis performed in system iterations.

An in house BEM00225 code [31] is used for this purpose. BEM00225 is a blade element rotor model, customized for calculation of power required and forces of various configurations of rotor in various flight conditions. It is capable of trimming at most of the flight conditions including hover and forward flight at any specified atmospheric condition. The model assumes rigid blade with flapping hinge offset and flapping springs. Pitt and Peters [32] first harmonic inflow is assumed. The detailed trim analysis using all the nonlinear equations ensures a complete and comprehensive helicopter system.

In this research, air loads and trim analysis solutions are investigated for various flight modes and helicopter configurations and integrated with ModelCenter. Since trim analysis and stability and control analysis do not pose optimization problems, they are used as constraints in the overall system level optimization problem. The constraints in trim analysis are the limits on the control inputs. A rotorcraft that can perform all the required maneuvers with less required control input has the capability to perform more aggressive maneuvers. So one helicopter design iteration is compared with another in terms of the required control input. These comparisons are done repeatedly in the system level iterations. The constraints from the root locus analysis are defined in terms of handling qualities defined in Aeronautical Design Standards (ADS 33) [33]. Stability and control links with ModelCenter include the trim analysis, calculation of stability derivatives and damping parameters.

### **Aerodynamic Analysis**

As long as all the performance requirements are met, attaining the best possible aerodynamic shape is one of the objectives of the design of all flying bodies. A combination of preliminary and detailed analyses is performed in this research. The results obtained from low fidelity analysis help accelerate the system level iterations. The high fidelity results obtained from CFD are introduced from time to time to get better results. Simple Blade Element Theory (BET) is used for rotor in hover and climb for quick analysis. A FPDA (Flat Plate Drag Area) code is used for calculating component drag. Blade element theory is used to calculate the forces of the blade due to its rotation through air, and hence the forces and performance of the entire rotor. Blade element theory combined with Landgrebe wake model [34] is also used to evaluate the rotor hover performance. The blade element code with Landgrebe wake model is integrated with ModelCenter and is used in conjunction with simplified closed form expression of Blade element momentum theory model for forward flight. Since aerodynamics is very closely related to



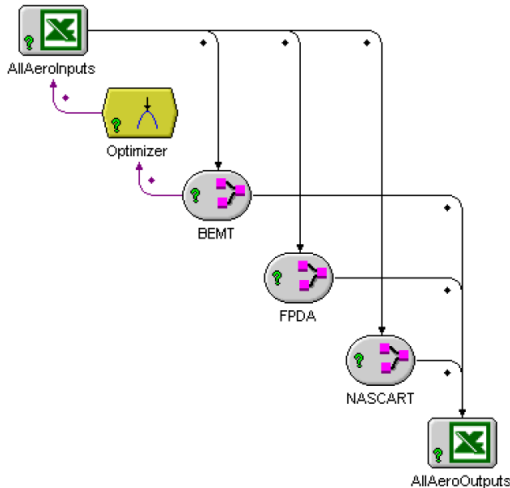


Figure 7: Summary of Aerodynamic Analyses

performance, most of the optimization criteria e.g. minimize power requirement, etc. are defined in the performance discipline or system level problem. However, since MDO allows the use of sub level disciplinary optimizers, an optimization problem is also introduced in aerodynamics discipline. In hover case, Figure of Merit is maximized by changing the variables that directly affect hover performance and keeping the remaining variables fixed at the baseline value. The optimization problem is given as follows:

Objective Function: *Maximize Figure of Merit*

Variables:

$$\begin{aligned} -12 &\leq \text{Twist angle} &\leq -5 \\ 2 &\leq \text{No. of blades} &\leq 4 \\ 1\% &\leq \text{Root cutout} &\leq 15\% \end{aligned}$$

The results obtained from the aerodynamics optimization problem are shown in Table 4.

A simplified code originally created in Boeing Aircraft Company, is used to calculate the approximate flat plate drag areas of individual helicopter components [35]. The profile drag is calculated for fuselage, wing, empennage including the horizontal and vertical tails, nacelle, rotor pylon, fairings for transmission, engine components, Auxiliary Power Unit (APU) etc. The airframe drag is calculated to address the forward speed requirements. A drag buildup method is used to estimate the equivalent flat plate drag area of the vehicle. The Fortran based drag estimation code is integrated with ModelCenter. A summary of Aerodynamic analysis integration is shown in DSM format in ModelCenter environment in Figure 7.

## Propulsion Analysis

One of the main requirements from RFP is to design a new turbine engine for light training helicopter. Historical light turbine engines are compared on the basis of engine weight, specific fuel consumption, compressor pressure ratios, and mass flow rate. This comparison gives an approximate idea of the size, weight and compression ratio of the new engine to be designed. These values are used as starting point for the design. Various analysis packages available commercially and non-commercially for turbine engine design are explored. These include the NASA Engine Performance Program (NEPP), On-Design (ONX) and Off-Design (OFFX) from Aircraft Engine Design AEDsys [36, 37] and Gas Turb 10. Gas Turb 10 is a sophisticated program available for on-design and off-design cycle analysis for turboshaft engines. It provides a wide variety of predefined engine configurations, thus allowing an immediate start of calculations. Parametric studies, Monte Carlo simulations and cycle optimization tasks are completed using this program. Since this program has a module for calculating turboshaft engine cycle parameters, and it produces results that are compatible with those obtained from NEPP, it is chosen for integration with ModelCenter. However, ModelCenter requires a COM/API for integration of any software with graphical interface. A faster way to integrate Gas Turb 10 with ModelCenter is to create Response Surface Equations (RSE) and use those to iteratively run the program in conjunction with other programs from a single platform. The design team also generated detailed CAD drawings of the proposed engine. The weight of the engine is estimated by specifying material properties. An optimization problem is defined in the propulsion group to minimize the SFC by changing the size of the engine and keeping the engine cycle parameters constant. Allison 250-C 20 engine is use for Gas Turb 10 calibration. The optimization problem is defined as follows.

Objective Function: *Minimize SFC*

Constraints:

$$\begin{aligned} x1 &\leq \text{Mass Flow Rate} &\leq x2 \\ y1 &\leq \text{Pressure Ratio} &\leq y2 \end{aligned}$$

Variables:

*Mass Flow Rate*  
*Pressure Ratio*

Sequential Quadratic Programming (SQP) is used to perform the optimization. The results are discussed in the results section.

## **Rotor Dynamics Analysis**

Rotor dynamic analysis is performed to obtain rotor feathering, flapping and lead lag frequencies. These frequencies are compared with rotor natural frequencies to establish that as the design changes, the rotor and the fuselage does not suffer with resonance. The vibratory characteristics are evaluated in this research using a flexible multi body analysis code called DYMORE developed by Bauchau et al [1]. The blades are modeled by beam elements. The natural frequencies of the rotor system are determined using a quasi-static case in which the velocity schedule in DYMORE is set to have each individual fraction of rotor speed occurring at a specific time. Since LTTH baseline has 3 bladed rotor, the important frequencies considered are the forcing functions that occur at 1P, 2P, 4P, and the multiples of 3P, where P is the per revolution frequency. A fan plot is generated for visual confirmation that no frequencies overlap for any design iteration. A Matlab script is developed to link DYMORE with ModelCenter. Important variables identified in Matlab include the main rotor radius, tip speed, and hinge offset. It is the designer's responsibility to ensure that there is good separation of natural frequencies.

## **Transmission Design**

For LTTH design, a simplified split torque transmission design is selected using requirements analysis methodology. Bellocchio et al [38] argue that split torque transmission design demonstrates several key advantages over a more conventional planetary gearbox design. The general configuration of split torque transmission follows the design presented by Hanson [39]. The Hanson transmission provides an optimized integration of hub configuration selected for LTTH design and its propulsion sources by minimizing the design complexity and increasing the structural integrity of the overall drive system. The Hanson transmission design utilizes a combination of only four main gears to achieve the required gear reduction between the engine and the rotor system and its reduction in parts directly translates to savings in both overall weight and cost. Bellocchio performed ModelCenter analyses to capture the behavior of the planetary drive. A link is provided to these analyses from the system level optimization problem. The weight estimation and shafting elements are integrated in ModelCenter. The planetary drive models integrated in ModelCenter includes the weight estimation spreadsheet and individual shaft sizing spreadsheets. The weight estimation spreadsheet calculates speed, torque, power, and power losses for each gear and shaft of the drive system. This spreadsheet also provides the total gearbox weight based on the solid rotor volume method, and total drive

system weight estimation based on the Boeing-Vertol and Research Technology Laboratory (RTL) weight equations.

## **Weight and Balance**

Traditionally, weights are estimated in the initial design stage both by extensive expensive and by good judgment about existing and future engineering trends. Multiple linear regressions are used to derive equations for each aircraft component from weights data on previous aircraft. Prouty [23] lists a set of regression equations for preliminary design weight estimates based on work done by Shinn et al [40, 41]. These equations are used in this research to determine the initial system weight estimates of fuselage, landing gear, nacelle, engine installation, propulsion subsystems, fuel systems, drive systems, cockpit control, instruments, hydraulics, electrical, avionics, furnishing and equipments, air conditioning and anti icing, and manufacturing variations.

Another approach to calculate weights is to use the vehicle-engineering package. In this study, CATIA is used to calculate certain component weights. The CATIA link with ModelCenter allows the designer to dynamically change the part designs parametrically from ModelCenter by changing the variables as they get updated from one system level iteration to another.

Few component weights are also obtained from the preliminary design tool. In the case of LTTH, the preliminary design tool used is GTPDP. The weights obtained from GTPDP are compared with the weight estimates of Prouty and those obtained from CATIA. These results match well. The component weight estimates and their influences on the lateral and longitudinal centers of gravity are determined. The CATIA model is used to determine the CG for each component based on the reference line i.e. Station line (STA), Water Line (WL), and Butt Line (BL).

The vehicle engineering components that are directly linked with ModelCenter include the main rotor, tail rotor, and horizontal and vertical tails. The weights are calculated in ModelCenter as design variables are changed iteratively. Since the link between CATIA and ModelCenter is dynamic, the model geometries are updated as the system level optimizer changes the design variables. The weights of individual components are calculated and then stored in one file where all the weights are added up.

An optimization problem is also defined in the weights discipline. One of the important system design requirements is to achieve the required performance

with minimum weight. Since the objective function posed by weights discipline is of concern to all other disciplines, it affects the system level optimization. The objective function of the weights group is to minimize the overall empty weight of the aircraft. The constraints come from RFP where the minimum Hover Out of Ground Effect (HOGE) requirement is 2 hours. The fuel flow rate information is obtained from performance discipline. Mathematically, the optimization problem, independent of all the other disciplines is posed as follows:

Objective Function: *Minimize Empty Weight*

Constraints: *Weight of Fuel (Gallons)  $\geq X$*

Variables: *Radius<sub>Main Rotor</sub>*  
*Chord<sub>Main Rotor</sub>*  
*Radius<sub>Tail Rotor</sub>*  
*Number of Blades*  
*Engine RPM*  
*V<sub>TIP Main Rotor</sub>*  
*Radius<sub>Tail Rotor</sub>*

Where  $X = \text{Fuel Flow Rate} \times \text{No. of hours of operation required}$

The results of the optimization problem are discussed in the results section. The optimized results obtained from weights sub system are then passed on to the system level problem where the system level optimizer integrates all the other sub systems and changes the variables iteratively to achieve the optimized system level objective function.

### Economic Analysis

Economic analysis is of significant importance in this study because of the fact that the total cost of the vehicle is used as the Overall Evaluation Criterion (OEC) for the system level optimizer. All the other disciplines work not only to maximize their own individual criteria but also minimize the overall cost of the system. Therefore minimum cost is of interest to every discipline. The cost analysis packages used in this research include the GTPDP cost mode [27], Bell cost model [42] and Price H model. Preliminary cost estimates obtained using GTPDP are group weights based on historical data. More detailed development, recurring production, and operating and support cost analyses are performed using PC based Bell cost model. A multilevel parametric approach is utilized in the model to estimate development and recurring production cost for helicopters. Inputs for this approach use information available at a project's preliminary stage. Operating and support cost is predicted by companion model that utilizes the outputs from recurring production cost model. The model predicts the

cost of each aircraft subsystem by dividing it into three separate categories: sub-contractor, labor, and materials. A weight-cost factor is calculated for the baseline design by the LTH design team to identify the real cost drivers. The five areas identified as the most influential are the power plant, fuselage, flight controls, drive system, and rotor. These subsystems with their sub-contractors, labor, and material categories allocated by percentage for the baseline vehicle are shown in Figure 8. This figure demonstrates the strong influence of material selection for the fuselage, flight controls, drive system, and rotor; accounting for over 50% of the total vehicle production cost. The total average cost for LTH baseline design is \$200,576. This cost includes both direct and indirect operating costs. The baseline cost is used as a starting reference for the objective function of system level design loop. Direct and indirect costs are also calculated using Bell cost model. The design team used Price H model to calculate the new engine cost.

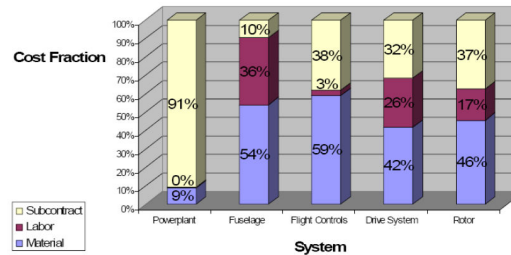


Figure 8: Cost structure for major cost driving systems

The PC based Bell cost model is Excel based code. This facilitates easy integration with ModelCenter because external wrapper is not required for this purpose. Instead; built-in ModelCenter API is used to send data back and forth between Excel and ModelCenter. A link to Price H model is also provided for future expandability. The economics optimization problem is given as follows:

Objective Function: *Minimize Avg. Prod. Cost*

Constraints: *Production units  $\geq 3,000$*

*Production rate  $\geq 300/\text{yr}$*

Variables:

*Number of blades (MR)*

*Number of blades (TR)*

*Empty Weight*

*Fuel Consumption*

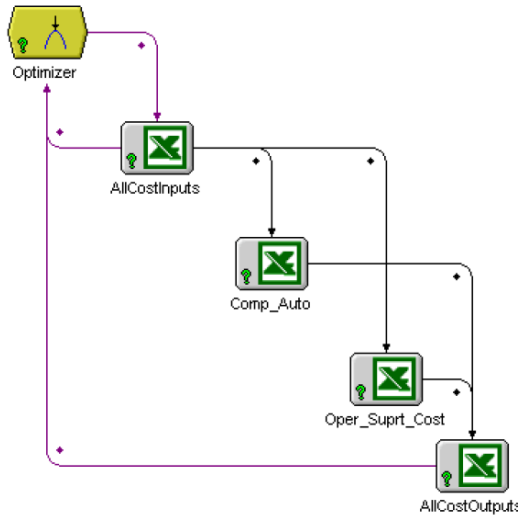


Figure 9: Economic analysis integrated in ModelCenter

### Miscellaneous Analyses

There are numerous other studies that can be performed at the preliminary design stage. These not only include further improvement of the fidelity of the current analyses but also the introduction of new analyses that will make the design more diverse. A few other disciplines and analyses are explored as part of this research. These include the noise analysis and structural analysis. The noise analysis is performed using GTPDP where flyover noise is estimated using regression of historical data. For the purpose of fatigue stress calculations, a variety of software packages are explored including DYMORE. Stiffness matrices and stress distribution are calculated using Variable Asymptotic Beam Section (VABS) code [43]. DYMORE can also be used for trimming the aircraft. This can be used for sanity check for the trim process done in Matlab. Besides DYMORE, links are also provided in this research through ModelCenter for Finite Element structure analysis using MSC software NASTRAN and PATRAN, which are useful for future expandability.

All the important and available disciplinary analysis packages, in-house codes, and commercial software are integrated using a common platform i.e. ModelCenter. A centralized repository is generated where all the design variables and analysis outputs are stored. The repository is continually updated with new design information as soon as analysis results are obtained from any discipline.

## RESULTS AND DISCUSSIONS

The application of MDO techniques in the preliminary rotorcraft design stage involves identification of all the

disciplines involved, their key variables, disciplinary constraints, objective functions, and optimum results. The goal is to design a rotorcraft starting from a baseline in minimum amount of time, at minimum cost while satisfying disciplinary and system constraints.

Four different MDO problems are solved in this study. Before performing the AAO and CO analyses, which are computationally expensive, it is prudent to verify the new design environment against known design. This provides a level of confidence in the program design environment and reveals any inconsistencies within the integration process. The baseline LTTH is used to verify the analyses that are used. Analyses performed with the new framework are discussed in problem 1. There is no optimization involved in any of the disciplines. The disciplines are reduced to simple analysis modes. This ensures that the results obtained match with those obtained from AHS design team and hence prove the framework developed, integration, and connectivity of analyses are correct. In problem 2, individual disciplinary optimizers are included but no system level optimization is performed. So individual disciplines are optimized but overall system may not be optimal. In problem 3, AAO approach is employed. Problem 3 has two parts. In the first part, there is a single system level objective function, i.e. cost, that is of interest to every discipline but there are no disciplinary optimizers. In the second part, an Overall Evaluation Criterion (OEC) is defined that makes it a Multi-Objective optimization problem. The OEC is a composite of all the objective functions of individual disciplines that have optimizers. Finally, in problem 4, Collaborative Optimization is performed at the system level; as well as individual disciplinary optimizations are performed at the disciplinary levels. The individual disciplinary objective functions are modified from those of Problem 2 to ensure that there is no conflict between optimizers. The results of all the problems are compared. Some of the important baseline variables are shown in Table 1.

Table 1: Results obtained from baseline analysis

|   |            |
|---|------------|
| Main rotor radius                       | 12.2 ft    |
| Main rotor tip speed                    | 650 ft/sec |
| Main rotor chord                        | 0.64 ft    |
| Main rotor twist angle                  | -10 deg    |
| Main rotor effective hinge offset       | 0.07       |
| Main rotor vertical distance from C.G   | 6.64 ft    |
| Main rotor lateral offset from C.G      | 0 ft       |
| Main rotor longitudinal offset from C.G | 0.33 ft    |
| Pre cone angle                          | 2.75 deg   |
| No. of main rotor blades                | 3          |
| Figure of Merit                         | 0.68       |
| Tail rotor radius                       | 2.25 ft    |
| Tail rotor twist angle                  | 0 deg      |

|                              |                      |
|------------------------------|----------------------|
| Tail rotor pre cone angle    | 1.5 deg              |
| Tail rotor blade chord       | 0.23 ft              |
| Engine takeoff Horsepower    | 184 HP               |
| Engine max continuous power  | 160 HP               |
| Vehicle empty weight         | 800 lbs              |
| Vehicle gross weight         | 1454 lbs             |
| Vehicle flat plate drag area | 7.29 ft <sup>2</sup> |
| Flyover noise                | 90.6 dB              |
| Tail boom length             | 17 ft                |
| Average unit production cost | \$203,541            |
| Direct operating cost        | \$93.48              |

The values listed in Table 1 are only a representative few of the outputs obtained from various analyses. All the outputs are stored in a repository. This repository is useful especially in problems 2, 3 and 4 where optimizers are used. The detailed design information is stored in the repository as a function of iterations.

In problem 2, individual optimization problems are defined for propulsion, economics, weight and balance, and aerodynamics disciplines. Disciplinary design variables are identified, constraints are determined, and objective functions are specified. The optimization problems are discussed earlier in their respective sections.

### Propulsion Optimization Results

The propulsion optimization process photographically sizes the engine. The internal engine cycle parameters are fixed to the calibration engine using Gas Turn 10. This optimization routine finds the optimal engine size that provides the minimum fuel consumption. Two optimization problems are performed in this process. In the first problem, the horsepower is not used as one of the constraints. This causes the optimizer to change the variables or reduce the size of the engine to a degree that it becomes infeasible for the LTTH application. The horsepower output turns out to be 166.8 HP. Although the Maximum Continuous Power (MCP) of the baseline design is less than that value as shown in Table 1, the takeoff power is greater, and therefore this design does not satisfy the RFP requirements. In the second problem, the shaft horsepower is used as one of the constraints. This ensures that the engine produces at least the takeoff power required for the application. Given the horsepower constraint, optimal fuel consumption is obtained and the engine is sized for that application. The optimization results and the engine sizes for the two problems are compared in Table 2.

Table 2: Propulsion Optimization Results

| <i>Variable</i>   | <i>Without<br/>Horsepower<br/>constraint</i> | <i>With<br/>horsepower<br/>constraint</i> |
|-------------------|--|---|
| Airflow (lbs/sec) | 1  | 1.13                                      |
| Pressure Ratio    | 7.47   | 7.46                                      |
| Shaft Horsepower  | 166.83                                       | 184                                       |
| SFC               | 0.45   | 0.451                                     |
| TIP (Psi)         | 82.7   | 82.62                                     |

The optimization problem with horsepower constraint takes more iterations to converge to the final solution than the problem without the constraint. The horsepower constraint remains active at the end of the iteration process. The SFC value does not change significantly as the constraint is added. This is due to the fact that the optimizer photographically increases the size of the engine by increasing the mass flow rate and slightly decreasing the compressor pressure ratio. It is also important to note that propulsion optimization is performed independent of other disciplinary constraints or RFP requirements. Therefore the overall picture is not captured in this analysis. Although the SFC, power and engine size results are favorable, they do not reflect the real impact on the overall system design.

### Weight and Balance Optimization Results

The primary objective function of the weights optimization as discussed earlier is to minimize the empty weight of the aircraft. The weights optimizer impacts some of the important design variables of the helicopter. The fuel quantity constraint of the problem defined earlier is determined from the RFP, where one of the requirements is to Hover Out of Ground Effect (HOGE) for 2 hours. It is observed from the initial baseline performance analysis results that the fuel burn rate is approximately 8.6 gallons/hour. Therefore it is required to carry at least 20 gallons of fuel including the start, warm up, taxi, land, idle and reserve requirements as shown below.

$$\begin{aligned}
 \text{Fuel Quantity Required} &= \text{Fuel burn rate (gal/hr)} \times \text{No.} \\
 &\text{of hours of operation} + \text{Reserve} \\
 &= 8.6 \text{ (gal/hr)} \times 2 \text{ (hrs)} + \text{Reserve } (\sim 2.8\text{gal}) = 20 \\
 &\text{gallons}
 \end{aligned}$$

The results obtained from weights optimization problem are listed in Table 3.

Table 3: Weights Optimization Results

| <i>Variable</i>             | <i>Optimization Results</i> |
|-----------------------------|-----------------------------|
| Vehicle empty weight + fuel | 855.23 lbs                  |
| Fuel Quantity               | 20 gallons                  |
| Main rotor radius           | 7 ft                        |
| Main rotor tip speed        | 600 ft/sec                  |
| No. of blades               | 2                           |
| Main rotor chord            | 0.32 ft                     |
| Tail rotor radius           | 2.25 ft                     |

The results listed in Table 3 are optimum from weights discipline viewpoint but they are exclusive of all the other disciplines. In other words, performance or any other disciplinary constraints are not considered in this particular problem. With these results, the weights groups seem to do very well by reducing the empty weight by 6.43% but the information about other disciplines is not available and therefore it can not be identified how they will perform or whether their disciplinary constraints will be satisfied under the variable conditions identified by the weights group. For this reason, it is important to consider all the disciplines simultaneously in a system optimization problem as discussed in the AAO and CO sections.

### Aerodynamics Optimization Results

The aerodynamics optimization problem chosen in this study is related to the 2-hour hover requirement from RFP. It is not only desirable to hover, but is also advantageous to hover with minimum power consumption or maximum efficiency. Figure of Merit (F.M) is a good way of determining the hover efficiency of a rotor as indicated by Prouty [23]. The optimization results are shown in Table 4.

Table 4: Results of Hover Optimization Problem

| <i>Variables</i> | <i>Optimization Results</i> |
|------------------|-----------------------------|
| Figure of Merit  | 0.872                       |
| Twist angle      | -9.72 deg                   |
| Number of blades | 2                           |
| Root cutout      | 13.23%                      |
| Solidity         | 0.01                        |

It can be observed from Table 4 that maximum Figure of Merit is obtained from increasing the solidity. It is observed that most of the helicopters in the light category have the main rotor solidity less than 10% [44]. Only a few very large helicopters have higher solidity values. The figure of merit value is increased by approximately 20% by changing the design variables listed in aerodynamics optimization problem. However the value of Figure of Merit obtained in the overall system level optimization problem is more reliable than the individual disciplinary optimization results

especially when they are performed independent of other disciplines.

### Economics Optimization Results

Most of the performance design variables affect the economics discipline in an indirect manner. For example; changing the chord of the main rotor blade may not directly affect the cost of the vehicle but it affects the weight of the system, which has a direct impact on the cost. Therefore there are only a few system design variables involved in the economic analysis that also affect other disciplines. The important design variables include the number of main rotor blades, number of tail rotor blades, fuel consumption and vehicle empty weight. Vehicle average production cost per unit is used as the optimization criterion. The constraints are defined in the RFP where the requirement is to produce atleast 300 units per year for ten consecutive years. This translates to a total of 30,000 units. The optimization results are listed in Table 5.

Table 5: Economics Optimization Results

| <i>Variables</i>                 | <i>Optimization Results</i> |
|----------------------------------|-----------------------------|
| Average Production cost per unit | \$178,175                   |
| Production Units                 | 3,000                       |
| Production Rate                  | 300/yr                      |
| Number of main rotor blades      | 2                           |
| Number of tail rotor blades      | 2                           |
| Vehicle empty weight + fuel      | 789.85lbs                   |
| Fuel consumption                 | 8.63 gal/HP-hr              |

The rest of the disciplines, i.e. stability and control, rotor dynamics, noise analysis and performance analysis are simple analyses without optimizations. The overall cost obtained using this technique is \$178,175. This is approximately 12.46% lower than the unit production cost figure of \$200,576 reported by the AHS design team [28]. The results obtained by AHS design team are without any optimization. All the disciplines are of analysis type as discussed in problem 1. The use of disciplinary optimization problem 2 shows a decrease in the overall cost of the system, while disciplinary constraints are satisfied and the respective objective functions are optimized. To optimize the overall system level problem it is necessary to understand the impact of all disciplines on one another. This is only possible when the information is passed between different disciplines and an overall optimization problem is solved. All At Once approach and Collaborative optimization techniques are explored for the overall optimization problem.

## All At Once Approach (AAO)

Two separate AAO problems are solved in this study. One has a single objective function where the overall average production cost of the system is minimized. The second problem is a multi-Objective problem where a composite objective function or an Overall Evaluation Criterion (OEC) is selected for solving the problem. These problems are defined mathematically as follows.

### Single Objective Optimization Problem

A single objective function that is of interest to all the disciplines and the system designer is the minimum cost. The economic constraints are the production units and the production rate. In addition, two more constraints are added to the system level. These constraints are obtained directly from RFP requirements. The fuel capacity constraint is discussed in the earlier section. The payload constraint comes from the requirement of being able to carry two 90kg people, 20kg of miscellaneous items and 2 hours worth of fuel. The total payload is calculated as follows.

Payload (lbs) = Two people + miscellaneous items + Two hours of fuel

Payload (lbs) =  $2 \times 198.4$  (90kg) + 44.1 (20kg) +  $20 \times 5.65$  (20 gals  $\times$  5.65lb/gal)  $\approx$  554 lbs

The payload constraint affects the performance discipline where the performance is calculated based on 554 lbs payload requirement. The fuel constraint affects the weight discipline. All the local variables from individual disciplinary optimization problems and analyses are passed on to the system level optimizer. The system level optimizer becomes much larger than individual disciplinary optimizers. This significantly slows down the optimization process. However as overall system level optimized design is obtained. The AAO single objective mathematical problem is shown as follows.

Objective Function: *Total Avg. Production Cost*

Constraints: *Payload  $\geq$  554 lbs*  
*Fuel capacity  $\geq$  20 Gallons*  
*Production Units  $\geq$  30,000*  
*Production Rate  $\geq$  300/yr*

Variables:

Aerodynamics:

*Rotor twist angle*  
*No. of main rotor blades*  
*No. of tail rotor blades*  
*Root cutout*  
*Main rotor radius*  
*Rotor tip speed*

Economics:

*Main rotor chord*

*Production Units*  
*Production rate*  
*Flight hours per year*

Weights:

*Area of horiz. stabilizer*  
*Area ratio of horiz. stab.*  
*Area of vert. stabilizer*  
*Area ratio of vert. stab.*  
*Tail rotor radius*

Performance:

*Tail rotor chord*  
*Tail rotor tip speed*

Stability and Control:

*Main rotor vertical offset*  
*Main rotor lateral offset*  
*Main rotor long. offset*  
*Per cone angle*  
*Length of tail boom*  
*Tail rotor twist angle*  
*Tail rotor pre cone angle*  
*Tail rotor long. offset*  
*Tail rotor vertical offset*  
*Tail rotor lateral offset*  
*Tail rotor root cutout*  
*Tail rotor collective angle*  
*Horz. stabilizer long. offset*  
*Horz. stabilizer vert. offset*

Transmission:

*Life of transmission*

It is important to note that most of the variables defined in the single objective function problem are shared by more than one discipline.

### Multiple Objective Optimization Problem

A composite OEC is defined that as objective functions of all individual disciplines that pose optimization problems as discussed in problem 2. The OEC is stated as follows. The system level objective in the multi optimization problem is to minimize the OEC.

$$OEC : \frac{\text{Average Production Cost} \times SFC \times \text{Empty Weight}}{F.M}$$

In this study, equal weights are given to all components of OEC. This is done to ensure that the results obtained from the multi objective AAO optimization problem can be compared with those of the single objective optimization problems and individual disciplinary optimization problems discussed in problem 2. The system optimizer convergence history of single and multi objective optimization problems are shown in Figures 10 and 11 respectively.

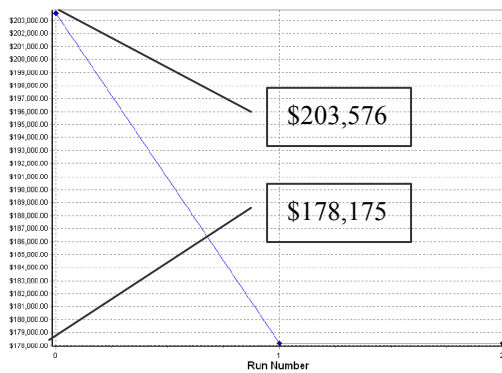


Figure 10: Convergence history of AAO single objective approach

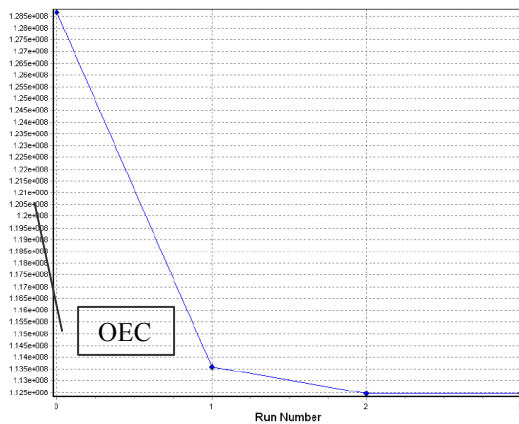


Figure 11: Convergence history of AAO with multi-objective approach

The multi objective optimization problem takes more system iterations to find the overall optimized design. The optimization takes 1.5 to 2 clock hours for each system level iteration on Pentium 4, 2.8 GHz, 512 MB Ram machine. It takes approximately 8-10 clock hours to perform all the disciplinary analyses iteratively and perform the system level optimization. Sequential Quadratic Programming (SQP) is used for system optimization. AAO results are shown in Table 6.

Table 6: Results of AAO problem

| Variable            | Single Objective | Multiple Objective |
|---------------------|------------------|--------------------|
| Avg. Prod Cost      | \$178,175        | \$178,175          |
| F.M                 | 0.722            | 0.725              |
| Empty wt. (lbs)     | 799              | 799                |
| SFC (lb/hr-hr)      | 0.452            | 0.452              |
| Payload (lbs)       | 554              | 554                |
| Fuel Capacity (gal) | 20               | 20                 |
| Production units    | 5,000            | 5,000              |
| Production rate     | 500              | 500                |
| Main rotor twist    | -8°              | -8°                |
| No. of rotor blades | 3                | 2                  |

|                         |        |        |
|-------------------------|--------|--------|
| Main rotor radius (ft)  | 12.2   | 10     |
| Main rotor tip speed    | 650    | 650    |
| Main rotor chord        | 0.64   | 0.673  |
| No. of tail rotor blade | 2      | 2      |
| Flight hours per year   | 500    | 500    |
| Tail rotor radius (ft)  | 2.25   | 1.5    |
| Tail rotor chord (ft)   | 0.23   | 0.23   |
| Tail rotor tip speed    | 700    | 700    |
| Length of tail boom     | 17     | 17     |
| Xmsn Life (hr)          | 10,000 | 10,000 |

The overall unit production cost of the vehicle in the single and multi objective problems is \$178,175. This is 11.17% reduction in cost compared to problem 1, the AHS design, where no optimization is performed and disciplines are treated as simple analyses. This is also a 12.5% reduction in cost compared to problem 2 in which all the disciplines are optimized independent of each other. Although the average production cost figure is the same for single and multi-objective problems, however unlike single objective problem, other OEC components i.e. SFC, empty weight, and F.M are also optimized in the multi objective optimization problem. Use of OEC guarantees that optimized results of individual components of OEC are obtained. Optimized results for these components of OEC are shown in Table 6. The Figure of Merit is improved by 0.4% compared to baseline and single objective optimization problem. No improvement is observed in SFC or empty weight. These results indicate that SFC and empty weight are already at or close to their optimized values at the starting point of the optimization when all the disciplines and their constraints are taken into account. The optimized values, objective functions, constraints, and important variables are compared between problems 1, 2, and 3 with the results obtained from CO in the following section.

The biggest advantage of AAO approach is that there are no optimization conflicts between disciplines. Only one optimizer is used at the single level. But this makes the system level optimizer very large and slows down the process. The local disciplinary variables are removed from the disciplines where the disciplinary optimization can be performed. In other words, the expert codes, or codes with optimizers are reduced to simple analysis only modes. In addition, not all the disciplinary constraints are completely satisfied. In the fourth problem in this study, Collaborative Optimization (CO) is applied for system level optimization.



## Collaborative Optimization (CO)

It is desirable to keep disciplinary expert in control over disciplinary variables and not make them ‘slaves’ of the system level optimizer. CO allows the system designer to leave local variables and constraints at the local level, and keep much of the creative control in hands of the disciplinary experts. CO also removes the objective function conflicts. A set of variables is defined for CO problem. The variables are arranged in sets and expressed in matrix format. System level design variables are denoted by  $\overline{SYS}$ . There are a few hundred variables at the system level. A select few are shown as following.

$$\overline{SYS} = \begin{bmatrix} Radius_{MR} \\ RotorSpeed_{MR} \\ Chord_{MR} \\ NoOfBlades_{TR} \\ Pr econeAngle_{MR} \\ TwistAngle_{MR} \\ Life_{Transmission} \end{bmatrix}$$

Similarly disciplinary outputs are defined in matrices. These are referred to as  $\overline{Discipline}$  where various disciplines considered in this study include stability and control, propulsion, transmission, weights, aerodynamics, economics and performance. The disciplinary design variables are also defined in terms of sets and are represented as matrices. These are given by  $\overline{X}_{Discipline}$ . In the CO environment, the local disciplinary and system level constraints do not change. At every step of the system level optimization, the local optimizers must produce a feasible design. All the local and system level constraints must be satisfied. Four new sub problems are defined in the four disciplines where the optimizers are located, as defined in problem 2. A sample new problem for propulsion optimization group is shown as follows.

Minimize:

$$J_p = \left\| \overline{S \& C} - \overline{S \& C}_p \right\|^2 + \left\| \overline{Trans} - \overline{Trans}_p \right\|^2 + \left\| \overline{Weights} - \overline{Weights}_p \right\|^2 + \left\| \overline{Aero} - \overline{Aero}_p \right\|^2 + \left\| \overline{DYN} - \overline{DYN}_p \right\|^2 + \left\| \overline{Econ} - \overline{Econ}_p \right\|^2 + \left\| \overline{Perf} - \overline{Perf}_p \right\|^2 + \left\| \overline{P} - \overline{P} \right\|^2$$

$$\text{Constraints: } g_p \leq 0$$

$$\text{Variables: } \overline{X_p, S \& C_p, Trans_p, Weights_p, Aero_p, DYN_p, Econ_p, Perf_p}$$

Where

$J_p$  = New scalar composite objective function

$\overline{Discipline}$  = System level target for local optimizers

$\overline{Discipline}_p$  = Local versions of disciplinary variables, or interaction variables of other disciplines that affect propulsion discipline. There are mirror versions of targets and are treated like variables here

$\overline{P}$  = True output of the analysis

$g_p$  = Local constraints

$\overline{X}_p$  = Local variables of propulsion discipline

The true outputs from the propulsion analysis are function of local variables, system variables, and variables from other disciplines that affect propulsion. Similar disciplinary CO problems are defined for economics, weights, and aerodynamics disciplines. The system level CO problem is given as follows.

Objective Function: Minimize OEC

$$\text{Constraints: } \overline{g} \leq 0$$

$$\overline{J}_{Discipline} \leq 0$$

$$\overline{g}_{Discipline} \leq 0$$

$$\text{Variables: } \overline{X}, \overline{Discipline}$$

Where  $\overline{g}_{Discipline}$  are compatibility constraints and are only used for the disciplines that do not have local optimizers. This technique is better suited for gradient-based methods. SQP is used for system and disciplinary optimizers. Duplicate answers for each variable are created. The target of the disciplinary optimizers and system compatibility constraints is to be able to converge all these duplicate variables to the same answers at the end of every system level iteration. This method takes more iterations and is therefore much slower than AAO approach. The CO design environment developed in ModelCenter is shown in Figure 12. The links between various disciplines and the

system repository indicate the information flow. The magenta dashed lines indicate the transfer of  $J_s$  from disciplines with optimizers to the system level optimizers. These  $J$  terms are used as constraints at the system level problem.

Copies of disciplinary variables are also stored in the repository. Some of the design variables are shared by more than one discipline. The compatibility constraints and disciplinary objective functions ensure that these variables converge to common values at the end of every system level iteration. A total of approximately 500 variables are tracked in the combined system and disciplinary optimization problems. The optimization results obtained from CO are shown in Table 7.

|  |        |        |
|--|--------|--------|
| Fuel Capacity (gal)                              | 20     | 20     |
| Production units                                 | 5,000  | 5,000  |
| Production rate (units/yr)                       | 500    | 500    |
| Main rotor twist (deg)                           | -8°    | -8°    |
| No. of rotor blades                              | 3      | 2      |
| Main rotor radius (ft)                           | 12.2   | 10     |
| Main rotor cutout                                | 0.07   | 0.07   |
| Main rotor tip speed (ft/s)                      | 650    | 650    |
| Main rotor chord (ft)                            | 0.64   | 0.673  |
| No. of tail rotor blade                          | 2      | 2      |
| Flight hours per year                            | 300    | 500    |
| Tail rotor radius (ft)                           | 2.25   | 1.5    |
| Area of horizontal stabilizer (ft <sup>2</sup> ) | 0.743  | 0.743  |
| Area of vertical stabilizer                      | 2.62   | 2.62   |
| Tail rotor chord (ft)                            | 0.23   | 0.23   |
| Tail rotor tip speed (ft/s)                      | 700    | 700    |
| Tail rotor twist angle (°)                       | 0      | 0      |
| Tail rotor pre cone (°)                          | 1.5    | 1.5    |
| Tail rotor vertical offset                       | 3.7    | 3.7    |
| Tail rotor lateral offset                        | 0.8    | 0.8    |
| Length of tail boom (ft)                         | 17     | 17     |
| Transmission Life (hr)                           | 10,000 | 10,000 |

Table 7: Results of CO problem

| Variable        | Single Objective | Multiple Objective |
|-----------------|------------------|--------------------|
| Avg. Prod Cost  | \$178,393        | \$178,175          |
| F.M             | 0.722            | 0.725              |
| Empty wt. (lbs) | 799              | 799                |
| SFC (lb/hr-hr)  | 0.452            | 0.452              |
| Payload (lbs)   | 554              | 554                |

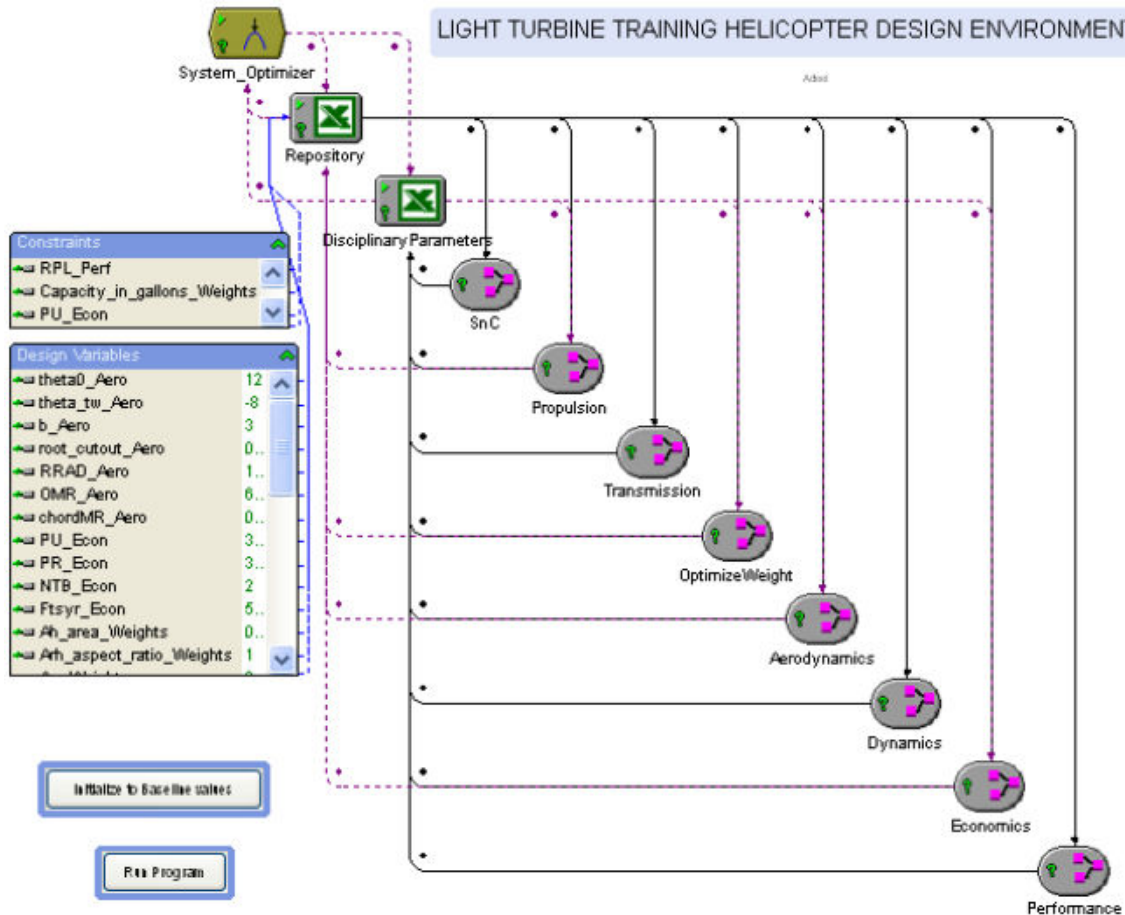


Figure 12: MDO design environment developed and implemented in ModelCenter

There are some issues involved with the implementation of CO. The setup time required for CO is very large. New variables and constraints are introduced at the system level. These variables are copies of individual design variables of various disciplines. New objective functions i.e.  $J_s$  are created for disciplinary problems. Compatibility constraints are introduced in the system level optimization problem for disciplines that do not have local optimizers. CO also creates duplicate answers corresponding to all the disciplines. The objective of local optimizers and compatibility constraints is to ensure that the duplicate copies of all the disciplinary variables converge to the same values at the end of each system optimization loop. Each system level iteration is a combination of sub problems including the convergence of individual optimizers and that of the system level optimizer. This process makes the optimization problem extremely large. The estimated computation time for CO, with approximately 500 system variables from all the disciplines, local variables of those disciplines, and system level and local constraints, amount to several thousand clock hours. The total number of function calls required is also greater than that of AAO approach. This makes the implementation of CO infeasible for very large problems. To accelerate the optimization process, optimized results from AAO problem are used as starting values for CO problem. This reduces the optimization time per loop from several thousand hours to a few hours. The results obtained from AAO are very similar to those of the CO problem while the time required to perform the analysis is significantly shorter.

## CONCLUSIONS

Key components involved in the rotorcraft preliminary design process are identified in this study. Design tools available both at the conceptual and preliminary design stages are determined. Capabilities and limitation of these design tools are identified. These design tools include commercially available software, legacy codes, and in house programs. Design variables that are of interest to more than one discipline are linked via a repository. The architecture enables the transfer of information between different tools in an integrated manner. According to IPPD methodology, the detailed mission analysis is performed at the conceptual stage of the design. The suggested design methodology allows the integration of various disciplines in a plug and play fashion. The framework allows the designer to visualize the effects of change of important design variables simultaneously at all the disciplines involved. Objectives and constraints of various disciplines are identified. Few optimization techniques that facilitate this architecture are applied in this study. These include individual disciplinary optimization, All At Once

approach, and Collaborative Optimization. A light turbine training helicopter is chosen for the proof of concept. Different optimization problems are compared and their results are analyzed. It is observed that system optimization problem requires significant more execution time than individual design analyses. However the overall design time is reduced from several months to a few hours with the aid of the integrated and automated design architecture. Although the setup time is significant, an overall optimized design is obtained. It is observed that by making little changes in the design variables, all the disciplinary constraints are satisfied, and a helicopter with minimum cost is designed. In summary, following improvements are observed in the preliminary rotorcraft design with the use of MDO techniques.

- The design process is automated
- Disciplinary inter-dependency is removed which facilitates parallel execution of analyses
- Current and updated information is available to all the disciplines at all times during the design process
- The overall time required to design a rotorcraft is significantly reduced
- Disciplinary and system optimization is possible using MDO techniques

## FUTURE WORK

The architecture developed in this research has a lot of potential for future expansion. Use of distributed computing architecture can make improvements in both AAO and CO approaches. ModelCenter can be used to integrate analyses that are located on different computing platforms at remote geographic locations. With the use of several parallel computing machines, the design time can be reduced if the information transfer rate is not compromised. New disciplinary analysis tools can be integrated and the overall fidelity of the system can be improved.

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