Conceptual Airplane Design Systems

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1 INTRODUCTION

The initial airplane conceptual design phase sets the overall size and configuration of the vehicle and thus drives most of the cost of the airplane development project. Many airplane conceptual design systems and tools have been developed over the years, but none is fully integrated and each requires extensive training to use. When starting a clean sheet airplane design, it is assumed that the design requirements are known at the onset of the design process. Often design requirements change during the design process, which leads to redesign work, or even starting over again. Changing requirements and methods used can lead to a design that eventually does not meet the initial requirements.

Integrated conceptual design systems that are user-friendly, computationally fast, and rigorous in their modeling of all major constraints, objectives, and considerations are, thus, extremely important in airplane design.

This chapter will provide a historical overview of available airplane conceptual design systems. Brief descriptions of selected existing, commercially available, conceptual airplane design systems are included together with an outline of early-stage conceptual design based on key equations that can be easily programmed.

2 AIRPLANE DESIGN SYSTEMS

Many companies and universities have developed conceptual/preliminary airplane design systems. A comprehensive list of paper and article abstracts written on these tools and background are listed in Appendix D of Anemaat (2007). Most references deal with small subsets of design systems, such as geometry representation or concentration on computational fluid dynamics (CFD) and/or finite element analysis (FEA). Besides conventional conceptual design systems as described in the next section, there are also the so-called knowledge-based design systems, which often use specialized computer languages to capture design knowledge. These systems are still in their infancy. Section 4 describes several of these systems.

3 DESIGN SYSTEMS: HISTORY

An overview of commercially available airplane design systems and/or university-developed systems (not necessarily still fully operational) is provided in the following sections. Selected commercially available software programs are described in more detail based on information provided by their developers.

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3.1 CDS

Raymer (1979) describes the design system developed at Rockwell International. Configuration Development System (CDS) contains a configuration development system that is fully 3D. An aircraft is described as a collection of components, such as wings, engines, and fuselages each consisting of three-dimensional cross sections. An interface to an aerodynamics module has been developed.

3.2 Paper airplane

In the early 1980s, the Flight Transportation Laboratory of MIT (Elias, 1983) started the development of Paper Airplane. The program uses symbolic manipulation (nonnumeric computation) to handle objects such as design variables and design functions. The advantage of this is that there is no distinction between input and output parameters. When one parameter is unknown, Paper Airplane will deduce one parameter from the known parameters. No further documentation beyond 1983 has been found on this system.

3.3 ACSYNT: aircraft synthesis

This code was developed by the ACSYNT Institute, a joint venture between NASA Ames and Virginia Polytechnic Institute (Jayaram and Myklebust, 1992). The code is still in use by quite a few companies and universities. It has evolved from a UNIX-based system to a PC-Windows-based system and contains a detailed geometry module.

3.4 ADAS: aircraft design and analysis system

This system has been developed at the Delft University of Technology (Bil, 1988) and is written in Fortran. The geometry was defined in MEDUSA, a solid modeling CAD system originally and later used as AutoCAD. ADAS is no longer operational. Many methods are still valid today. The tool requires programming experience and good deal of CAD experience.

3.5 RDS

This program (Raymer, 1993) developed by Daniel Raymer is MS-DOS based and contains a geometry engine. Optimization methods are included. No detailed stability and control is included. It contains a basic sizing code, similar to Roskam methods (Roskam, 1989). It is available as a commercial product. It is also available as a student version through the American Institute of Aeronautics and Astronautics (AIAA).

RDS is over 30 000 lines of source code dedicated to the development, analysis, and optimization of new aerospace vehicle concepts. RDS features a 3D CAD module for design layout and has analysis modules for aerodynamics, weights, propulsion, and cost. Also included are aircraft sizing, mission analysis, and complete performance analysis including takeoff, landing, rate of climb, P_s, f_s, turn rate, and acceleration. RDS provides graphical output for drag polars, L/D ratio, thrust curves, flight envelope, range parameter, and so on. The Professional version of RDS has automatic and numerous other features to support the daily work of the design professional.

RDS follows the design and analysis methods of Raymer (2006). These methods are distilled from the classical and time-proven techniques commonly used in industry design groups for early visibility into design drivers and options. RDS automates these methods to permit a tremendous quantity of calculation including trade studies and optimization in the very early stages of design.

The RDS-Design Layout Module (DLM) is an original, built-in CAD program developed especially for the conceptual design of new aircraft and spacecraft. While perhaps not as graphically powerful as a commercial CAD program, RDS-DLM is uniquely suited to aircraft conceptual design. RDS-DLM has dozens of airplane-specific design capabilities to rapidly create and modify a design. Design capabilities include wings, tails, fuselages, nacelles, seats, canopies, and virtually any other airplane components. RDS allows interactive assembly of the aircraft in any view, "flying" the parts into position with the mouse. RDS-DLM uses the aircraft industry Society of Allied Weight Engineers (SAWE) Group Weight Statement component categories to identify the design of various parts and to automatically pass the geometric data to the RDS analysis modules.

RDS analysis is calculated on the basis of inputs entered by the user in a number of spreadsheet-like arrays. Column and row labels prompt for the required inputs, which can be stored, edited, and printed. "Fudge factor" inputs are provided to permit adjusting analysis results based upon actual aircraft data or projections for advanced technologies. Figure 1 shows the RDS program flowchart.

The RDS aerodynamics module estimates parasite drag (subsonic and supersonic), drag due to lift, lift curve slope, and maximum lift from a user-defined input matrix. Analysis methods are based upon classical techniques, as defined in (Raymer, 2006). Subsonic parasite drag is estimated by the component buildup method. Supersonic wave drag is determined by the equivalent Sears-Haack technique. Transonic

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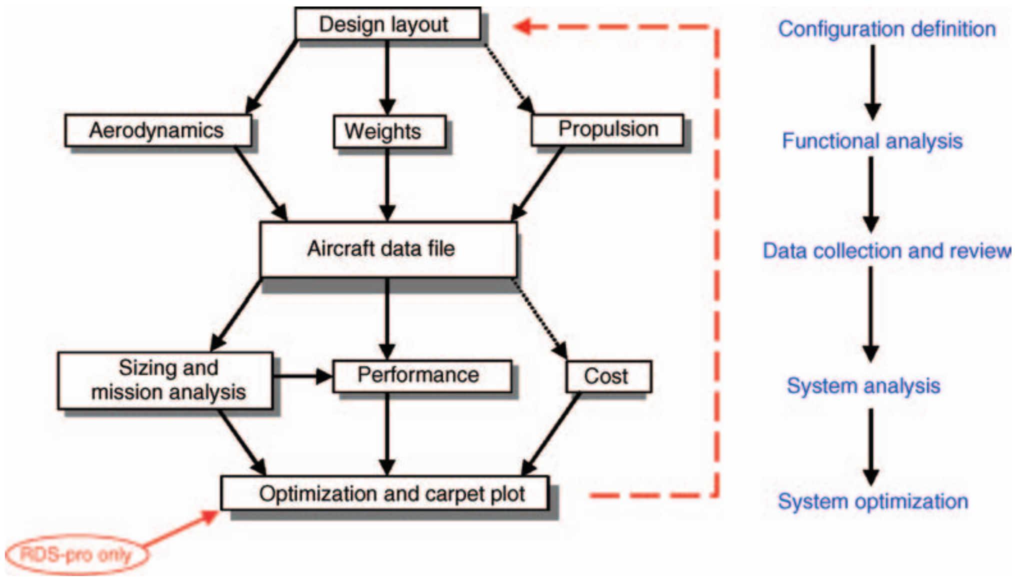

Figure 1. RDS program flowchart. Image courtesy of Conceptual Research Corporation.

drag is determined by empirical fairing between M_{dd} (the drag divergence Mach number, corresponding to the point on the C_D vs. M curve where $dC_D/dM = 0.05$) and supersonic wave drag. Drag due to lift is calculated by the leading-edge suction method using C_L-alpha (lift curve slope) calculated with DATCOM methods. Maximum lift is calculated using DATCOM methods, as are longitudinal stability and control.

Weights and balance are estimated statistically from inputs defined in a spreadsheet-like matrix, after selection of aircraft type (fighter, transport/bomber, or general aviation). Results are presented in standard weight report format, including structures group weight (fuselage, wing, etc.), propulsion group, equipment group, and useful load group. Correction factors permit estimation of the weight impact of nonstandard materials and other emerging technologies. Factors can also be used to calibrate the RDS weight equations to some known design. Center of gravity is determined from input component locations and is summed for empty weight, zero-fuel weight, and takeoff gross weight.

Propulsion analysis includes installation analysis for jet engine thrust and specific fuel consumption, and propeller thrust and specific fuel consumption for piston-prop engines. Jet engine installation analysis takes an uninstalled engine file and applies appropriate corrections such as differences between reference and actual inlet pressure recovery, actual bleed coefficient, and installed inlet drag. Defaults are provided for many values, such as the MIL-E-5008B reference pressure recovery schedule.

Propeller analysis calculates thrust and specific fuel consumption from inputs such as horsepower and brake-specific fuel consumption as functions of altitude, propeller efficiency as a function of advance ratio (J), and static thrust coefficient ratio as a function of power coefficient. Tip mach and blockage effects are included.

Cost analysis uses the statistical DAPCA IV model (RAND Corporation Development and Procurement Cost of Aircraft, Version IV) for development and procurement costs. Life cycle cost and airline economic costs are calculated by yearly accumulation of costs based upon user inputs, adjusted for the inflation rate. Net present value and internal rate of return on investment can also be calculated for airliners.

Missions are interactively created by selecting mission element types (takeoff, cruise, combat, etc.) and then entering the required data such as cruise range in a matrix format. Then, the aircraft can be sized to that mission, resulting in the sized design takeoff weight and the fuel weight to perform the mission. The aircraft may be sized assuming either a rubber engine (an engine model based on existing engines that can be or a fixed size engine. It is also possible to analyze the as-drawn aircraft for range and loiter.

Performance calculations include takeoff, landing, rate of climb, P_s, f_s, turn rate, and acceleration. RDS also graphs the aircraft flight envelope, rate of climb, P_s contours, f_s contours, and specific range parameter.

Graphs are plotted with a sophisticated curve fit routine, and text, lines, circles, and boxes can be added. Finished RDS graphs can be captured as bit-maps for rapid production of technical reports and briefing charts. In RDS-Pro, the data defining RDS graphs can be output in an ASCII format readable by most spreadsheets and commercial graphing programs. Figure 2 shows typical aerodynamic results in RDS.

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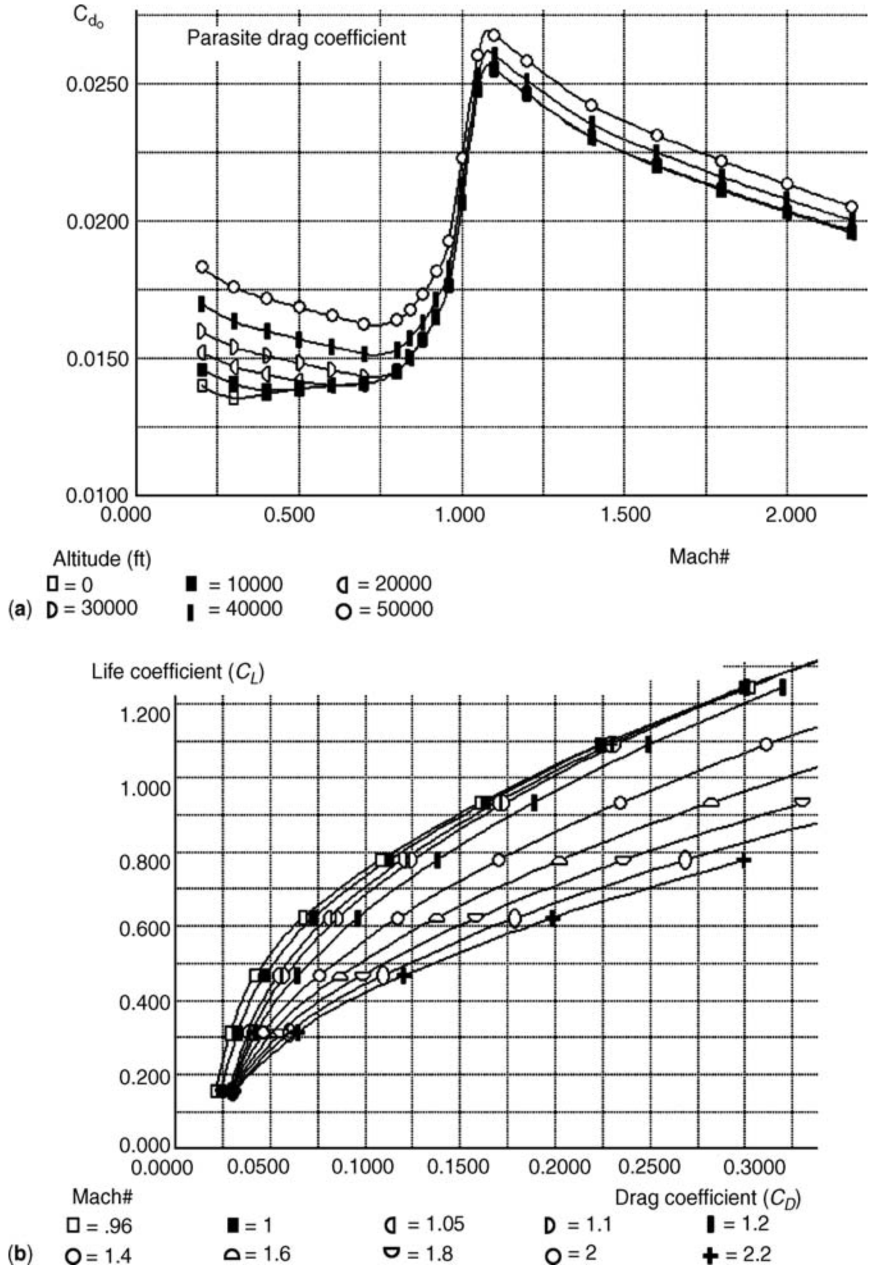

Figure 2. Typical RDS aerodynamic output. Image courtesy of Conceptual Research Corporation.

3.6 Advanced aircraft analysis: first generation

In 1988, at the University of Kansas under the guidance of Professor Jan Roskam, several graduate students started automating (Roskam, Malaek and Anemaat, 1990) the methods in (Roskam, 1989, 1996; Roskam and Lan, 1997). The result of this development was the first version of Advanced Aircraft Analysis (AAA). This software ran on Apollo DN-series workstations (UNIX-based), was programmed in Pascal, and used Apollo proprietary graphics routines. The language Pascal was chosen since Apollo tools were mostly written in Pascal and the original user interface tools on the Apollo workstation were written in Pascal (using Apollo GPR graphics primitives) and were originally donated by General Dynamics to the University of Kansas.

A prototype system was installed at the University of Kansas and was used only for class instruction. This first generation of AAA contained the following modules:

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1. Weight Sizing
2. Class I Drag
3. Performance Sizing
4. Performance Analysis
5. Class I Weight and Balance
6. Control
7. Dynamics
8. 2D Geometry
9. High Lift

AAA allows the design to be based on a hierarchy of modeling methods, recognizing the need for quick estimates very early in conceptual design followed by higher accuracy of modeling later. In Class I methods, only a minimal amount of input generation is required. With Class II methods, more detailed and refined estimates of the airplane can be made but more input information is required.

The first generation of AAA contained a simple user interface, with input and output sections and a toolbar with a calculate and print button. The symbols used for the input and output parameters were text based, without subscripts, superscripts, or Greek symbols. For instance $c_{l_{\alpha_{rw}}}$ was presented as c_l_a_rw. This made it harder to learn the system. Plotting and simple database functions to store and retrieve files were also part of this AAA.

3.7 Advanced aircraft analysis: second generation

In 1991, Design, Analysis and Research Corporation (DARcorporation) of Lawrence, Kansas, acquired the rights for AAA and continued developing AAA as a commercial venture. The same year, DARcorporation released Version 1.0 of AAA running on Apollo Domain and 400-series computers.

The program was developed to provide a powerful framework to support the nonunique process of aircraft conceptual/preliminary design. The system allows design engineers to rapidly evolve an aircraft configuration from weight sizing to detailed performance calculations, while working within regulatory constraints. The program is designed to reduce the preliminary design phase cost and to bring advanced design methods to small businesses and universities. The objective was to create a user-friendly computer program that allows designers (not discipline specialists) to rapidly assess the performance, structural weight breakdown, stability, and control characteristics of arbitrary new airplane configurations.

AAA requires only a minimum of specialist knowledge. It is also used for teaching, so novice users are expected to be able to quickly get up to speed. It contains a help system that familiarizes the user with the theoretical and methodological background of the various software modules.

During 1991 and 1992, AAA was ported to the X-Windows system for all graphics and user interface using the programming language C and Pascal.

From 1991 to 1995, AAA was ported to additional computer systems and environments, modules were added. The user interface was still primitive and was based on the first-generation AAA.

The second-generation AAA software contained 13 modules, a database, and help section.

In most of the analytical modules, the user has the option to use Class I or Class II methods.

3.8 Advanced aircraft analysis: AAA third generation

The AAA software has been under development for many years. AAA makes extensive use of the object-oriented technology. The focus is on methods such as weights, aerodynamics, geometry, cost, stability and control, dynamics, propulsion, structures, and loads. These are the main modules of the software. It is up to the user (designer) to decide which modules to use and in what order. The program does not force the user into a certain design path. The object-oriented structure is primarily method driven. Each module has a path that leads to a calculation (i.e., the method). The software uses windows, toolbars, and dialog boxes to communicate with the user. When one of the application buttons at the top of the main window is selected, the corresponding application window is displayed (see Figure 3).

The application window contains menu button selections that allow the user to select a calculation to be performed. The software uses a flowchart method for the user interface as shown in Figure 3. This allows the user to see the path selected in reaching a certain location. The software consists of calculation modules as described in Table 1.

The input/output window opens after selecting the type of calculation to be performed. The input/output window contains numeric data necessary to perform a calculation. For some calculations, information about the airplane configuration and airplane certification type are required so that the correct calculation method can be used. Before the input/output window is displayed, the program will display a dialog box allowing the user to specify configuration choices. For example, the program will ask the user to define empennage surfaces before the input/output window for longitudinal stability calculations is displayed.

The preliminary design process used in AAA consists of a number of interdependent design steps. These steps begin

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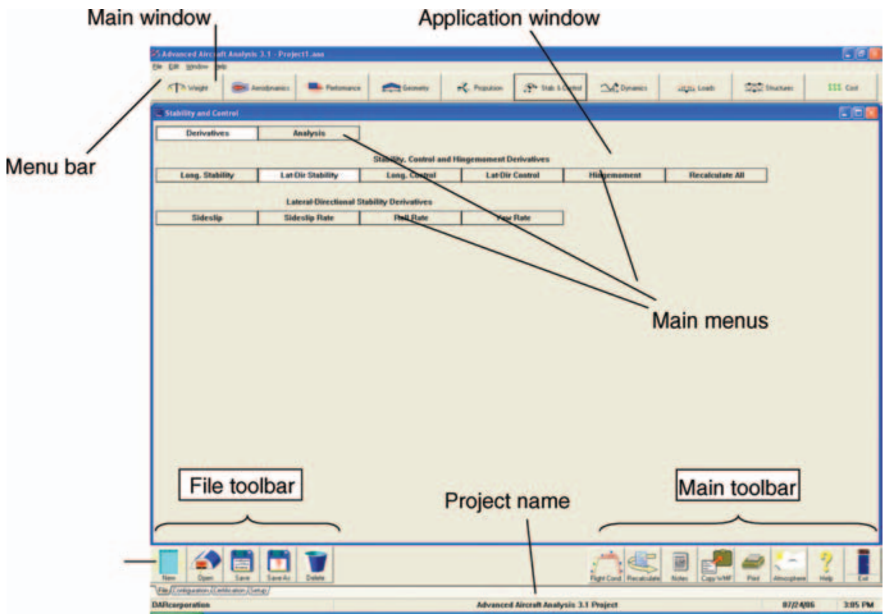

Figure 3. The AAA main window.

with constraints and requirements in the form of a mission specification, and end with a preliminary design that meets all the specifications of the mission requirement. Class I and Class II design and analysis methods consist of several steps. An example of Class I and Class II design steps is presented in Figure 4.

3.8.1 *Preliminary design steps used in AAA*

A preliminary airplane design follows the design steps forward from one step to the next. If a design is found to be unacceptable at any point in the process, it can return to any previous step (iteration). The software can also be used to analyze existing airplanes. In this case, it is possible to enter the design process at any point to perform analysis calculations.

These steps are as follows:

- Mission specification
- Preliminary sizing and sensitivity analysis
- Preliminary configuration layout and propulsion system integration
- Class I analysis, configuration design, and configuration comparison
- Class II analysis and configuration refinement

3.8.2 *Mission specification*

The mission specification usually includes the following parameters:

- Payload and type of payload
- Range and/or loiter requirements
- Cruise speed and altitude
- Field length for takeoff and for landing
- Fuel reserves
- Climb requirements
- Maneuvering requirements
- Certification base (FAR, JAR, VLA, LSA, MIL, or AS specs)

Depending on the customer, further performance requirements may be specified. Preliminary design always starts with a mission specification.

3.8.3 *Preliminary sizing and sensitivity studies*

At this stage, the following parameters are determined:

- Gross takeoff weight, W_{TO}
- Empty weight, W_{E}
- Mission fuel weight, W_{F}
- Maximum required takeoff thrust, T_{TO}, or takeoff power, P_{TO}
- Wing area, S, wing aspect ratio, A, wing taper ratio, and sweep angle
- Maximum required clean lift coefficient, $C_{L_{\max}}$
- Maximum required takeoff lift coefficient, $C_{L_{\max_{\mathrm{TO}}}}$
- Maximum required landing lift coefficient, $C_{L_{\max_L}}$
- Airfoil type and thickness
- Flap type and flap size

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Table 1. Application modules of the AAA Program.

Application	Calculation modules
Weight	• Class I takeoff weight and fuel calculation • Class I and Class II weight and balance analysis and center of gravity calculation for current loading
Aerodynamics	• Class I wing and high lift device design • Class I lifting surface and airplane lift calculation • Class I and Class II drag polar calculation • Lift, drag, and moment distributions over a lifting surface • Airplane aerodynamic center calculation • Power effects on airplane lift and pitching moment • Ground effects of airplane lift and pitching moment • Dynamic Pressure Ratio
Performance	• Class I performance sizing • Class II performance analysis
Geometry	• Class I wing, fuselage, and empennage layout • Aero-Pack Interface • Lateral tip-over analysis • Scale
Propulsion	• Class I installed thrust/power calculation • Inlet/nozzle sizing
Stability and Control	• Longitudinal and lateral- directional stability and control derivatives, including thrust/power • Control surface and trim tab hinge moment derivatives • Class I stability and control empennage sizing • Class II longitudinal and lateral-directional trim, including stick force and pedal force calculations
Dynamics	• Open loop dynamics analysis • Automatic control system analysis
Loads	• Velocity–load factor (*V*–*n*) diagram generation • Structural component internal load estimation
Structures	• Material property tables • Class I component structural sizing
Cost	• Airplane program cost estimation

Sensitivity studies can also be performed at this step in the design process. These studies determine how maximum takeoff weight varies with several performance and/or weight parameters. Figure 5 shows the Class I sizing process implemented in AAA. At present, decisions are still made by the user. So, if requirements are not met, the user is still required to change input parameters manually.

3.8.4 *Class I configuration design and configuration comparison*

Class I methods (see Roskam, 1989) require a relatively small amount of engineering person hours to comprehend and to use. These methods have limited accuracy but can quickly eliminate bad configuration ideas or arrangements. Using these methods, it is possible for the designer to compare a number of preliminary design ideas and determine which are worthy of more detailed design studies.

Figure 6 shows the process flow employed in sizing for stability using volume coefficients and Class I weight and balance. At this point, more detail on geometry is required, such as taper ratios, sweep angles, and aspect ratios.

3.8.5 *Class II analysis and configuration refinement*

Class II methods require significantly more engineering person hours than Class I methods. However, analysis accuracy is significantly improved using Class II methods. These methods are used in the stage of the preliminary design where only a limited number of design concepts are evaluated. Class II design analysis methods are used in conjunction with more refined design/analysis steps taken in preliminary airplane design. The design steps that are part of Class I and Class II design and analysis are highly interdependent and follow a unique path for every airplane design. The design process modeling concentrates on gathering the analysis methods necessary to perform the different design steps.

Most of the design steps in Figure 5 are implemented in the current version of the Advanced Aircraft Analysis software.

3.9 AirplanePDQ by DaVinci Technologies, LLC

AirplanePDQ (DaVinci Technologies, 2009a) is a conceptual design tool for light-sport aircraft, ultralight aircraft, experimental aircraft, and general aviation aircraft. It takes a graphics-oriented approach specifically designed to be intuitive and easy to use by amateur airplane designers. AirplanePDQ includes a computer-aided design/drawing package for producing airplane drawings and tools for analyzing aircraft performance, handling, and stability and control. Initial airplane sizing is done rapidly using a wizard-based approach. The designer specifies a few basic performance requirements, chooses from among several aircraft configuration options (high wing or low wing, tricycle gear or tail-dragger, etc.) and then the wizard performs sizing

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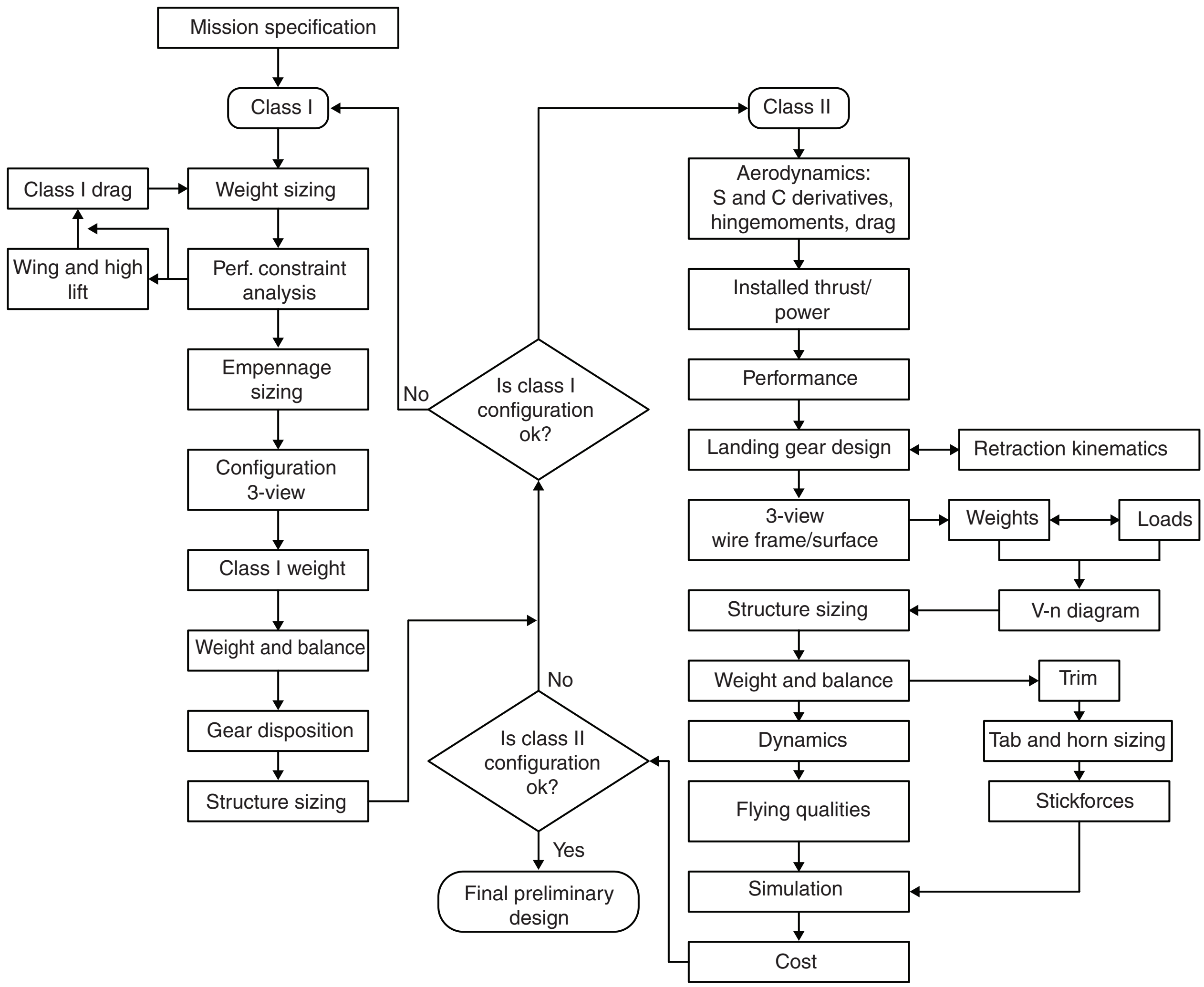

Figure 4. AAA preliminary design process detailed steps.

calculations and generates an initial three-view drawing of the aircraft based on the designer's inputs. Once the initial drawing has been generated, the designer can quickly modify the design by clicking and dragging with the mouse to guide the CAD engine in altering the drawing to meet his or her needs. As changes are made to the drawing, the software automatically updates the design information and performance analysis. The analysis tools then indicate the degree to which the design is meeting the performance goals and if further changes to the design are needed for safety, handling qualities, or performance reasons. The analysis tools not only generate detailed performance estimates but also guide the designer in sizing and adjusting the configuration of the aircraft to help ensure that the design is safe and practical.

AirplanePDQ is specifically designed for use by amateur airplane designers. The target market includes homebuilders, aviation enthusiasts, flight simmers, and students; but AirplanePDQ also includes many advanced features that equally make it of interest to professional designers and engineers. AirplanePDQ is appropriate for light-sport aircraft, ultralight aircraft, experimental aircraft, and light general aviation aircraft. It supports virtually all known aircraft configurations and can be used to design piston-powered, jet-powered, and turboprop aircraft as well as sailplanes. Figures 7 and 8 show typical screenshots.

3.9.1 *Sizing methodology*

AirplanePDQ Airplane Sizing Wizard (DaVinci Technologies, 2009b) calculates the approximate sizes and positions of each major aircraft component based on the requirements you specify. These calculations are performed using a combination of "rules of thumb," statistical estimation based on previous designs, and straightforward analytical formulas.

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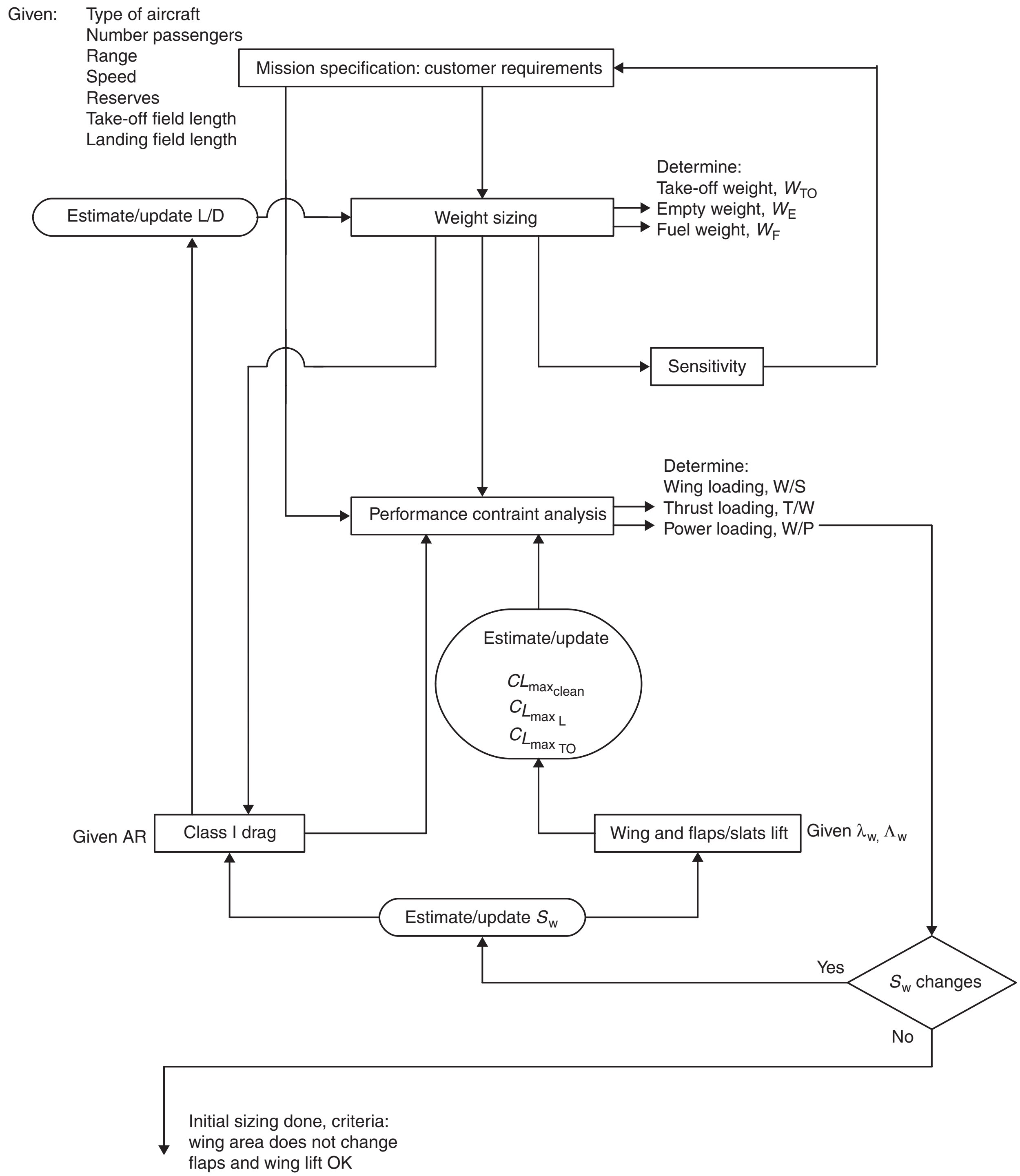

Figure 5. AAA: Class I sizing flowchart.

The first sizing task performed is initial estimation of the aircraft gross weight, power, fuel capacity, and wing area. These estimates must be done iteratively because all four of these quantities are interdependent. The process is started by guessing an initial fuel capacity. The aircraft useful load is then calculated from:

$$(\text{Useful load}) = (\text{number of passengers})^*(\text{average passenger weight}) + (\text{cargo weight}) + (\text{fuel weight}) \quad (1)$$

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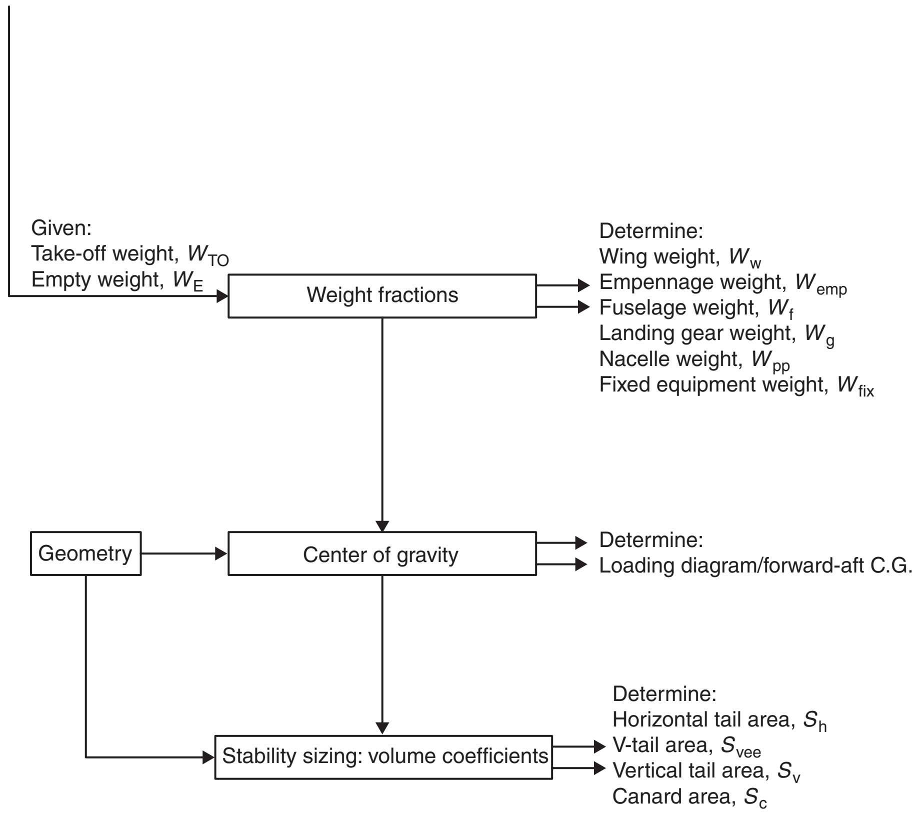

Figure 6. AAA: Class I weights and stability sizing flowchart.

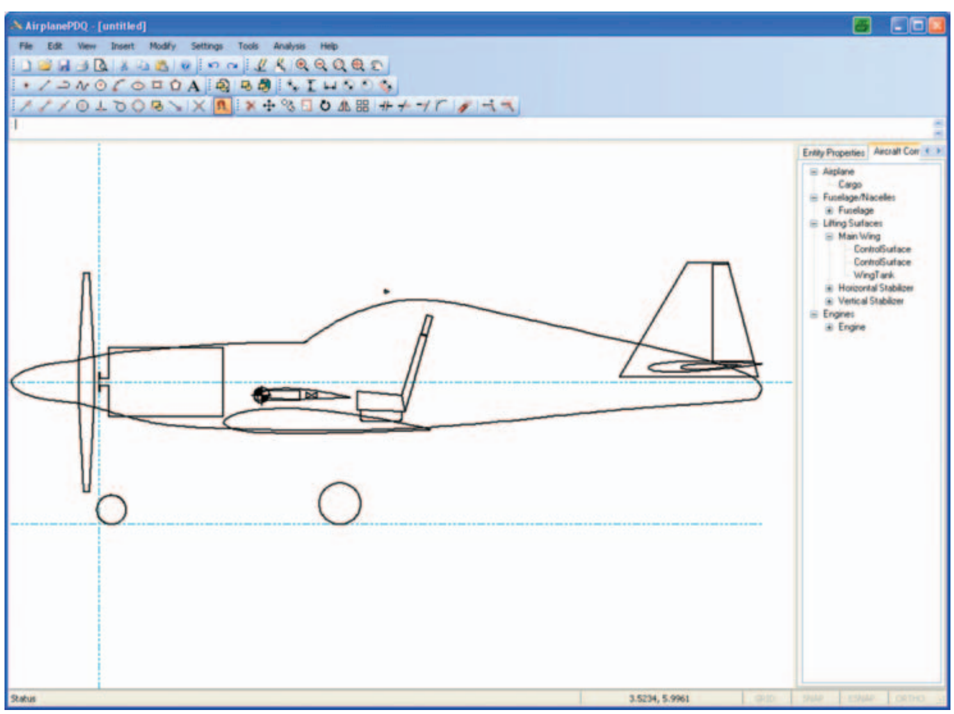

Figure 7. AirplanePDQ airplane sideview. Image courtesy of DaVinci Technologies.

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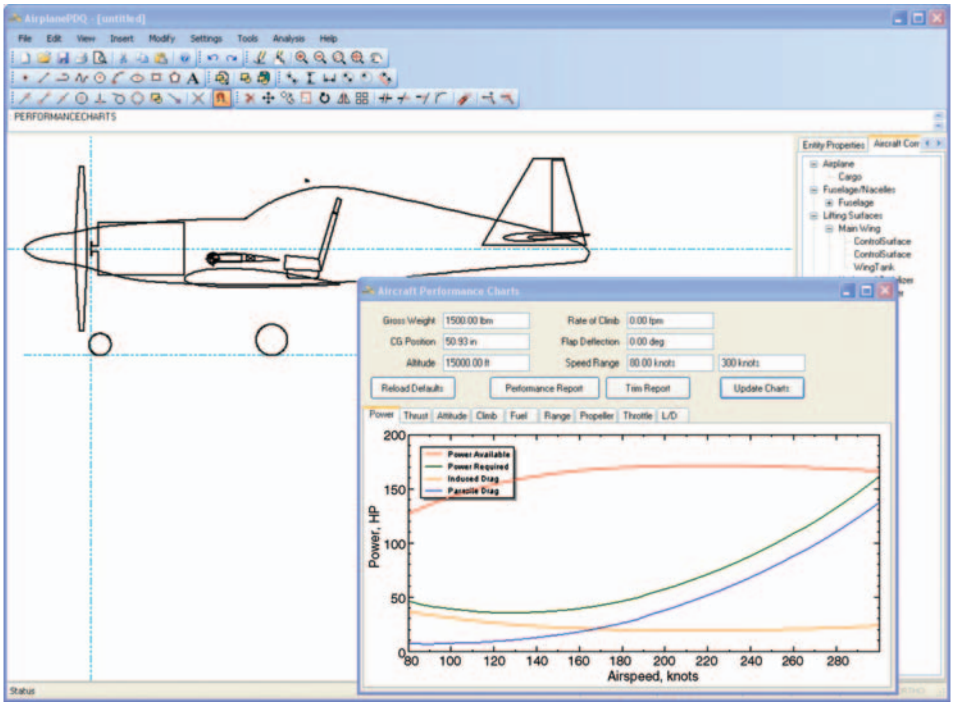

Figure 8. AirplanePDQ airplane sideview with airplane performance data. Image courtesy of DaVinci Technologies.

Given this initial useful load, the gross weight of the aircraft can be estimated through comparison with other existing aircraft. The gross weight can be estimated from the useful load using the expression (with gross weight and useful load in lbs) based on a statistical curve fit:

$$\text{Gross weight} = 7.48 \times \text{useful load} \circ 0.854 \tag{2}$$

With this estimate of the aircraft gross weight, we can then calculate the wing area necessary for the design to achieve the desired stall speed. The lift of the aircraft wing can be written:

$$L = \frac{1}{2}\rho V^2 S C_L \tag{3}$$

where L is the lift force, ρ is the air density, V is the airspeed, S is the wing area, and C_L is the wing lift coefficient. This equation can be used to calculate the required wing area by rearranging the terms and noting that the required lift is the gross weight. The equation becomes

$$S = \frac{L}{\frac{1}{2}\rho V_{\text{Stall}}^2 C_{L,\max}} \tag{4}$$

Here, V_{stall} is the desired stall speed that was entered in the sizing wizard and $C_{L\max}$ is a measure of how much lift a wing is capable of producing before it stalls. A typical high aspect-ratio wing without flaps has a $C_{L,\max}$ in the range 1.2–1.5 and with plain flaps as used on most light aircraft $C_{L,\max}$ will be in the range 1.6–2.0. For initial sizing purposes, a $C_{L,\max}$ of 2.0 is assumed.

The next step is to calculate the required thrust and power needed to meet the specified cruise speed and rate of climb requirements. To do this, an estimate of the airplane's drag is first needed. Drag is typically broken down into at least two components, the induced drag and the parasite drag. The induced drag is the drag that results from the production of the lift by the wings. The parasite drag includes the skin friction of the air passing over the surface of the aircraft as well as other types of drag that are lumped in with the skin friction. The initial drag estimate is calculated based on comparisons with other existing aircraft.

A statistical curve fit is constructed through the data and defines a parasite drag coefficient estimate in the form (where velocity is in statute miles h^{-1}):

$$C_{D\text{p}} = 20.27 V_{\text{cruise}}^{-1.258} \tag{5}$$

To get the total drag estimate, the induced drag contribution is added and can be calculated from

$$C_{D\text{i}} = \frac{C_L^2}{\pi e A R} \tag{6}$$

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where the cruise lift coefficient is calculated from

$$C_{L\text{cruise}} = \frac{GW}{\frac{1}{2}\rho S V_{\text{cruise}}^2} \tag{7}$$

The total drag coefficient at cruise is then

$$C_D = C_{D\text{p}} + C_{D\text{i}} \tag{8}$$

and the drag force is

$$D = \frac{1}{2}\rho V_{\text{cruise}}^2 S C_D \tag{9}$$

To maintain a straight and level flight, the thrust available from the engine/propeller combination must equal or exceed this drag force. The power necessary to generate this amount of thrust can be calculated from

$$P = \frac{TV}{\eta} \tag{10}$$

where P is the power, T is the thrust, V is the airspeed, and η is the propeller efficiency. An average propeller efficiency of 85% is used for the sizing calculations.

Since the cruise speed should be achieved at 75% of the maximum rated power at the sea level, the required engine power to meet the cruise requirement is

$$P_{\text{cruise}} = \frac{T_{\text{cruise}} V_{\text{cruise}}}{0.75\eta} \tag{11}$$

In addition to the cruise requirement, a rate of climb requirement can be specified and engine power required to meet that requirement can be calculated. To calculate the maximum rate of climb, we must first estimate the airspeed for the best rate of climb and the corresponding lift and drag coefficients. For a propeller-driven airplane, the induced drag coefficient at the speed for best rate of climb can be shown to be

$$C_{D\text{i}} = 3C_{D\text{p}} \tag{12}$$

that is one third of the parasite drag coefficient. Consequently, at the best rate of climb speed the total drag coefficient is

$$C_D = 4C_{D\text{p}} \tag{13}$$

Given the induced drag coefficient, the lift coefficient at the best rate of climb speed can be calculated as

$$C_L = \sqrt{\pi e AR\, 3C_{\text{D}_P}} \tag{14}$$

It then follows that the speed for the best rate of climb is approximately

$$V = \sqrt{\frac{GW}{\frac{1}{2}\rho C_L S}} \tag{15}$$

With the best rate of climb speed and the drag coefficient in hand, the required thrust to obtain the desired best rate of climb is calculated from

$$T_{\text{best ROC}} = \frac{1}{2}\rho V_{\text{best ROC}}^2 S C_D + GW \frac{\text{ROC}}{V_{\text{best ROC}}} \tag{16}$$

and the power required is

$$P_{\text{ROC}} = \frac{T_{\text{best ROC}} V_{\text{best ROC}}}{\eta} \tag{17}$$

The engine power required from the combined cruise speed and rate of climb requirements are then just the greater of P_{cruise} and P_{ROC}.

Once the engine power is known, the characteristics of a hypothetical engine (often called a rubber engine) of that power can be calculated on the basis of characteristics of other aircraft engines of similar power ratings.

If a particular engine model is selected instead of the "Custom Engine" option, then the characteristics of that engine are retrieved from the engine database.

With the engine SFC (specific fuel consumption) information, the aircraft gross weight, the cruise lift, and drag coefficients available, the final parameter necessary for the gross weight sizing can be calculated. This is the fuel weight needed to meet the range requirement, which can be calculated from what is known as the Breguet range equation:

$$\text{Fuel weight} = GW\left(1 - \mathrm{e}^{-\frac{\text{RangeSFC}}{\eta}\frac{C_L}{C_D}}\right) \tag{18}$$

This fuel weight will most likely be somewhat different from the initial guess of the fuel weight made earlier. Consequently, there is a need to iterate through these calculations. At the end of each iteration, the fuel weight at the end of these calculations is compared with the fuel weight from the previous iteration to test for convergence to a solution. At the end of the process, converged values for a gross weight estimate, engine power estimate, and wing area estimate are obtained.

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3.9.2 *Aircraft component sizing in airplanePDQ*

After the aircraft gross weight and wing area have been calculated, the sizes of the various major components can be calculated. The first step in this process is sizing of the cabin based on the desired seating arrangements. This is accomplished by laying out the seats in rows with allowance for space between and around the seats. The external fuselage width and height are derived by adding a fuselage structural allowance of 2 in. to the cabin dimensions. A combination of techniques is used to calculate the fuselage length. First, a historical average based on gross weight is calculated from an expression of the form:

$$L_{\mathrm{F}} = A(GW)^{b} \tag{19}$$

The coefficients used for A and b depend on the aircraft configuration. The second consideration is the fuselage fineness ratio. The fuselage fineness ratio is calculated from

$$\text{fineness ratio} = \frac{L_{\mathrm{f}}}{\max\left(W_{\mathrm{f}}, H_{\mathrm{f}}\right)} \tag{20}$$

The length of the fuselage calculated from the historical average above is constrained so that the fineness ratio will be greater than or equal to a certain value that depends on the aircraft wing configuration.

The lifting surfaces and control surfaces are sized next. A reference wing area is calculated previously to meet the stall speed requirement, and this reference area is used to determine the sizes of the various lifting surfaces. For a canard configuration, the canard is sized at 25% of the reference area and the main wing is sized at 75%. For a monoplane or flying wing layout, the main wing is sized at the reference area. For a biplane layout, each of the planes in the biplane is sized at 50% of the reference area.

The horizontal and vertical stabilizers, if present, are sized based on the wing areas using a "volume coefficient" technique. The vertical and horizontal stabilizer volume coefficients are defined, respectively, as

$$c_{\mathrm{VT}} \equiv \frac{L_{\mathrm{VT}} S_{\mathrm{VT}}}{b_{\mathrm{W}} S_{\mathrm{W}}} \tag{21a}$$

$$c_{\mathrm{HT}} \equiv \frac{L_{\mathrm{HT}} S_{\mathrm{HT}}}{\bar{c}_{\mathrm{W}} S_{\mathrm{W}}} \tag{21b}$$

where L_{VT} and L_{HT} are the vertical and horizontal stabilizer moment arms to the aircraft CG, S_{VT} and S_{HT} are the vertical and horizontal stabilizer areas, respectively, b_{W} is the main wing span, $\bar{c}_{\mathrm{W}}$ is the main wing average chord, and S_{W} is the main wing area. These two equations can be manipulated to solve for the stabilizer areas, and default values are used for the volume coefficients to calculate the required areas.

3.9.3 *Aircraft layout in airplanePDQ*

Layout of the design, once the sizing is complete, is a process of placing the individual components and wrapping a fuselage around them. If the configuration has an engine in the nose, then that engine is placed first at the reference point (0,0,0). The cabin is placed immediately aft of the engine or in the nose if no engine is up front. The vertical location of the cabin is adjusted to ensure visibility over the nose. If the design has a rear engine, it is placed immediately aft of the cabin. The fuselage is essentially wrapped around these major interior components with a length as calculated above. The lifting surfaces (except for tail surfaces) are placed at specific percentages of the fuselage length aft of the aircraft nose. For example, for a monoplane tractor layout the main wing is placed at 27% of the fuselage length. The vertical placement of the lifting surfaces depends on the configuration option selected on the Airplane Sizing Wizard. The wings are placed at the bottom of the fuselage, at the top of the fuselage, or at the midpoint of the fuselage. The reference point on the wing for placement purposes is the root 1/4 chord point. Tail surfaces are generally placed so that the trailing edge of the tail surface is at the aft end of the fuselage.

The overview of the RDS, AAA, and AirplanePDQ systems above serves to highlight the modeling methods used, information flow, user interfaces, and data sources used in the conceptual/preliminary design phases. It should be noted, however, that when statistical data are used for the estimation of various important parameters, any new design will be limited to configurations similar to previous ones (with, maybe, some correction factors to account for technology developments). If a drastically new configuration is to be developed, for which no statistical data are available in the form of characteristics of similar other aircraft, care must be taken to bring into the early design stages methods of analysis that will capture the inherent behavior of the new configuration in all its aspects. A good airplane design system will, thus, allow interfacing and data exchange with outside analysis modeling packages in areas such as CFD, structural finite element modeling, advanced engine design codes, and so on.

3.10 Aircraft design software by optimal aircraft design

A relative newcomer to the market is ADS by OAD. ADS (Optimal Aircraft Design SPRL, 2009) is developed for the

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design of light aircraft. The software consists of

- Analysis Module
- Statistical Analysis Module
- Design Module
- Optimization Module
- 3D Module
- Balance and Stability
- Digitizer Module
- Airplane Database
- Airfoil Database
- Useful Tools Module

A series of screenshots are shown in Figures 9 and 10.

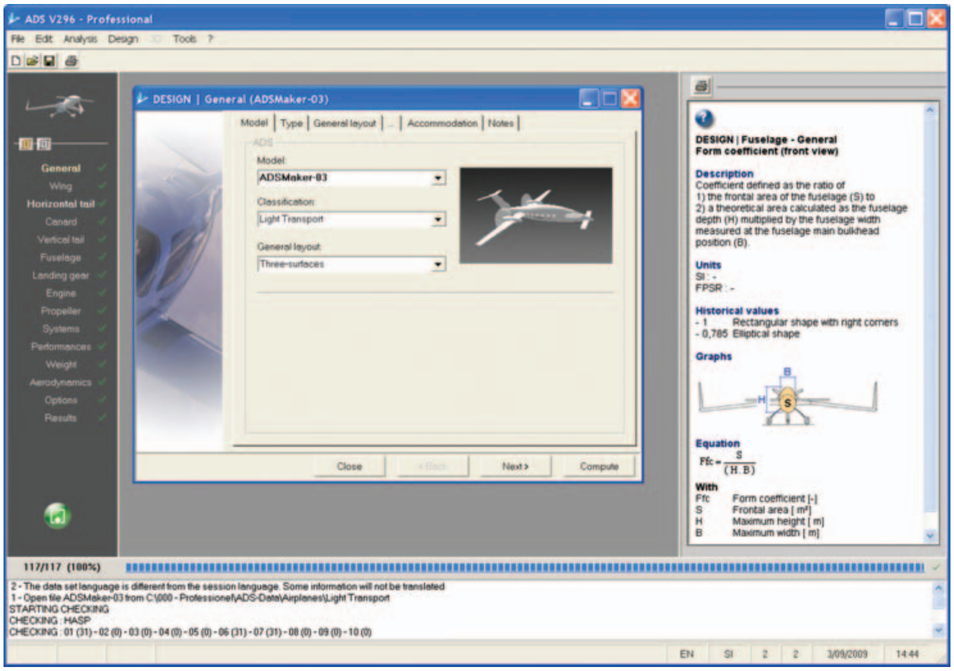

Figure 9. ADS typical input screen. Image courtesy of Optimal Aircraft Design.

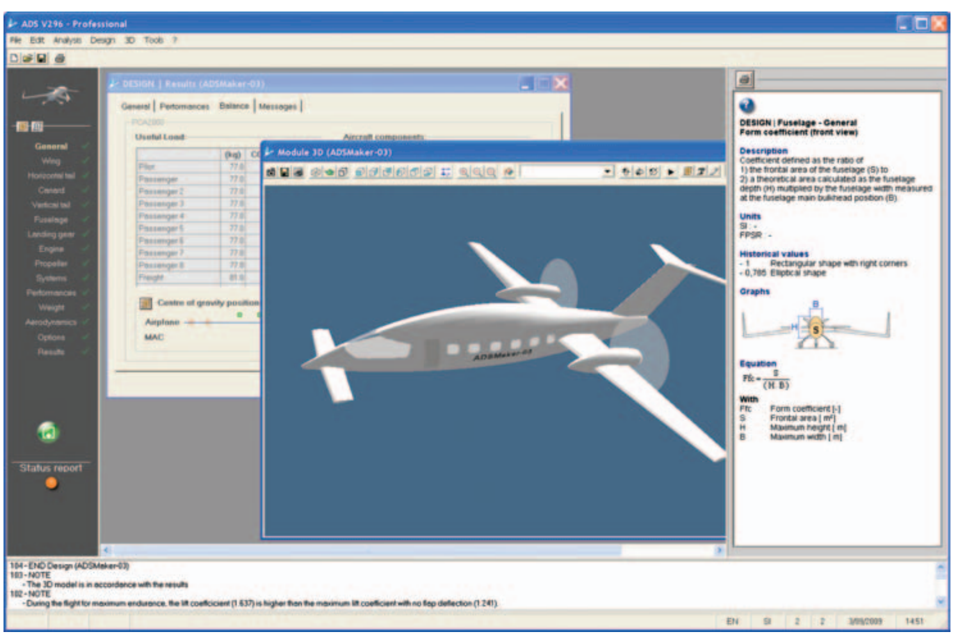

Figure 10. ADS typical results screen. Image courtesy of Optimal Aircraft Design.

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The design process in ADS is divided into three levels:

- The first level is called the design with "given objectives."
- The second level is called the design with "given means."
- The third level is called the design with "given geometry."

In Level 1 design, the user starts with a set of specifications and uses this as input data. He will evaluate only First-order parameters that will significantly affect the results. The results of Level 1 design will allow the user to define an aircraft configuration that will meet the design specifications. Statistical methods are used to evaluate the design. both the preliminary geometry and the thrust are generated.

In Level 2 design, the user moves to a more detailed approach. The Level 1 design parameters are verified by extensive algorithms. Weight estimations are conducted and different flight conditions are explored. The stability of the airplane is also checked. A 3D model is generated that enables the results of the design process to be verified.

In Level 3 design, the user can perform various sensitivity trade studies. The impact of changing or varying different design parameters on the performance can be evaluated. The performance characteristics in different flight conditions can also be analyzed in this phase.

The resulting airplane design parameters are plotted along with similar airplanes. If there is a big discrepancy, the user can then go back and change the design.

4 KNOWLEDGE-BASED DESIGN SYSTEMS

Several knowledge-based design systems are being developed and researched at universities and research institutes. An overview of selected such systems is presented in the following sections.

4.1 Delft university of technology

The Systems Engineering and Aircraft Design Group of the Delft University of Technology developed a distributed computational design system concept called *Design and Engineering Engine* (DEE, Figure 11). This is a multidisciplinary collection of design and analysis tools, able to automatically interface and exchange data and information, to support *what-if* studies and multidisciplinary design optimization through the automation of noncreative and repetitive design activities. The main components of the DEE architecture are addressed below.

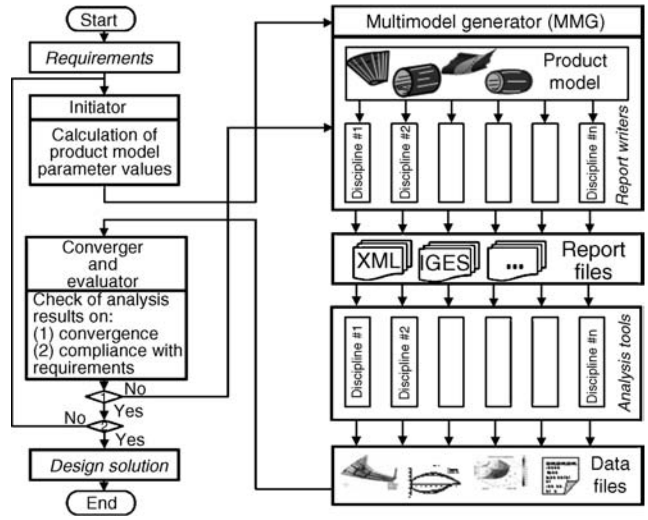

Figure 11. Design and Engineering Engine paradigm. Image courtesy of Delft University of Technology.

The multimodel generator (MMG) is a true knowledge-based engineering (KBE) application that provides a parametric modeling environment for the geometry generation of conventional and novel aircraft configurations and feeds the various DEE analysis tools with the related and dedicated aircraft abstractions. The MMG uses High Level Primitives: parametric objects that can be can be adjusted and assembled, also in batch mode, to form a wide range of aircraft configurations and variants. It also uses Capability Modules: software components able to process the geometry of the High Level Primitives into discipline-specific knowledge to be exported to the various DEE analysis tools (Anemaat, 2007; Raymer, 1979; Elias, 1983; Jayaram and Myklebust, 1992; Bil, 1988; Raymer, 1993; Roskam, 1989; Raymer, 2006; Roskam, Malaek and Anemaat, 1990; Roskam, 1996; Roskam and Lan, 1997; Olson, 1997; DaVinci Technologies, 2009a and 2009b; Optimal Aircraft Design SPRL, 2009; La Rocca and van Tooren, 2007, 2009). The MMG was initially developed in the ICAD system and is under migration to the next-generation KBE system GDL.

The initiator generates a first feasible solution to initiate a what-if study or multidisciplinary optimization. The Initiator can be just an editor to set initial parameter values or a set of sizing tools, for example, those based on aircraft design handbook methods. Modules available are, for example, fuselage sizing based on payload requirements, trapezoidal wing planform sizing based on mission requirements, aerodynamic load estimation, and airframe mass and stiffness estimations (Schut and van Tooren, 2007).

The analysis tools are selected according to the design case at hand and can be developed in-house or commercial off the shelf. When required, first surrogate models can be

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built using the MMG in combination with a design of experiments module and the analysis tools. The tools operate on data and models fed by the MMG and/or exchanged between each other by means of appositely developed interfaces. One of the most relevant analysis tools is the in-house-developed flight mechanics model (FMM), which is a generic flight mechanics toolbox able to analyze the dynamic behavior and performance of a complete vehicle (either fixed wing or rotary wing) early in the conceptual/preliminary design phase. The FMM integrates submodels from various disciplines, such as aerodynamics, structures, and propulsion, into one single aircraft model. The submodels can be either physics-based or empirical, depending on the application. Several functions are built in the FMM toolbox including a trim routine to calculate the aircraft attitude and control deflections under a certain flight condition, a linearization routine to derive linear aircraft models for designing autopilots, an automated handling qualities and mission analysis, and an analysis method to assess engine failures and aircraft responses to atmospheric disturbances. All the vehicle models can be generated automatically, which enables the FMM toolbox to be integrated in the DEE (Voskuijl, La Rocca and Dircken, 2008).

The converger and evaluator checks the convergence of the various analysis results, allows the designer to select the parameters for the what-if study or MDO, evaluates the performance/characteristics of the design (what-if study) or the objectives/constraints set by the designer (MDO), and selects the parameter values for the next design to be analyzed (MDO). Both commercial optimizers and in-house tools are used.

The communication framework consists of wrapper agents for all DEE components. The agents communicate via web connections and take care of the execution of the DEE components, data and information exchange, and data storage. DEE components can be distributed over different computer networks and be running on machines with different operating systems (Berends and van Tooren, 2007). Necessary condition for any tool to join the DEE federation is the capability to operate in batch mode and provide remote accessibility.

The capabilities of the DEE (as a whole or components) have been demonstrated in several research studies. These include the European project MOB, where the multidisciplinary design and optimization of a blended wing body freighter have been achieved across a distributed, transnational computational design framework (Morris *et al.*, 2004), and TAILORMATE, a collaboration project with Airbus, where the redesign of a large passenger aircraft vertical tail was performed in full automation (Schut and van Tooren, 2007; Cerulli *et al.*, 2006).

In another recent research study, the DEE framework has been used to design a system of flight control surfaces for a Prandtl Plane, a novel aircraft configuration featuring a box-wing configuration for minimum induced drag. The parametric aircraft model, a first-order aerodynamic panel method, and the flight mechanics toolbox have been used to determine the number, location, and minimum size of the various control surfaces required for adequate control authority while satisfying a set of handling quality requirements.

4.2 NASA langley research center

A general description of work performed at NASA (Wood and Bauer, 2002; Gloudemans, 2006; Carty and Davies, 2004; Rhodes, 1999; Dahl, Hill and Chemaly, 2006) is given. TechnoSoft also works closely with NASA Langley on software development using Adaptive Modeling Language (AML). At present, work is focused on Vehicle Sketch Pad (VSP, Gloudemans, 2006) that has similar features as AMRaven regarding geometry representation. Most of the design processes used by NASA Langley are based on ACSYNT (Jayaram and Myklebust, 1992) and Model Center (Carty and Davies, 2004) and are not specifically designed for knowledge capture.

The Intelligent Synthesis Environment (ISE), as it was initially formulated (Rhodes, 1999), was a $100 million per year effort that was to span 20+ years in NASA, and it was to develop advanced simulation throughout the life cycle of a mission or program. This program began the formulation phase and some momentum was developed over about a 2-year period and then was abruptly eliminated. It was never funded at the level that was initially planned.[1] The major supporter for the activity was administrator Daniel Goldin within NASA and when he left NASA the program died.

There were several efforts that started with that program at NASA Langley that received quite a bit of attention. ISE is the activity that first used Model Center at NASA Langley. ISE enhanced the CAPRI interface for different CAD systems and several other small activities but no real product. The planning phase occurred in 1998–2000 and was eliminated in 2001.

4.3 Technosoft AMRaven

AMRaven, Adaptive Modeling Rapid Air Vehicle Engineering Environment, has been developed in AML by TechnoSoft, Inc. in collaboration with the US-AFRL, NASA and major aerospace companies.

A detailed description of the AMRaven environment is given in (Dahl, Hill and Chemaly, 2006). AMRaven is an

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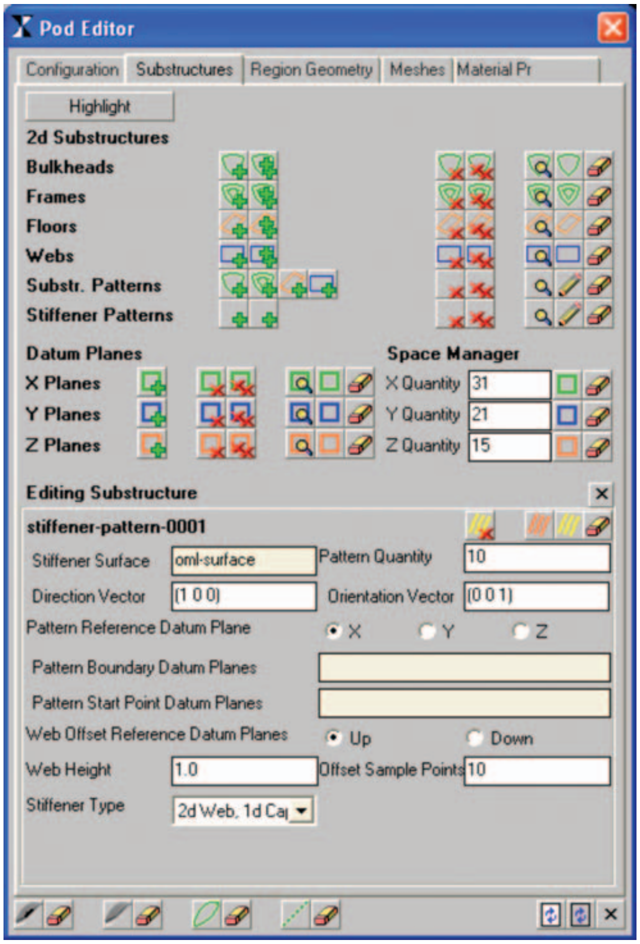

Figure 12. AMRaven Pod editor user interface. Image courtesy of TechnoSoft.

environment enabling integrated design and analysis of air vehicles and is built on the AML object-oriented framework. It has a fully automated modeling environment to couple aerodynamic and structural analysis. It contains a feature-based design environment incorporating custom airplane components such as pods, wings, control surfaces, spars, ribs, and bulkheads.

AMRaven contains a full 3D modeling environment with a graphical user interface as shown in Figure 12. Primitives, surfaces, solids, and Boolean operators are supported. Fuselage and wing outer mold lines (OML) can be created in this environment, as well as internal structure (see Figure 13). (*Note*: Figure 13 does not show a finalized substructure but is provided for illustration of the AMRaven capabilities.)

AMRaven contains a modular architecture (geometry, structural analysis, meshing module, and aerodynamics module) and is object oriented. All models are composed of a hierarchy of objects representing various aspects of the design.

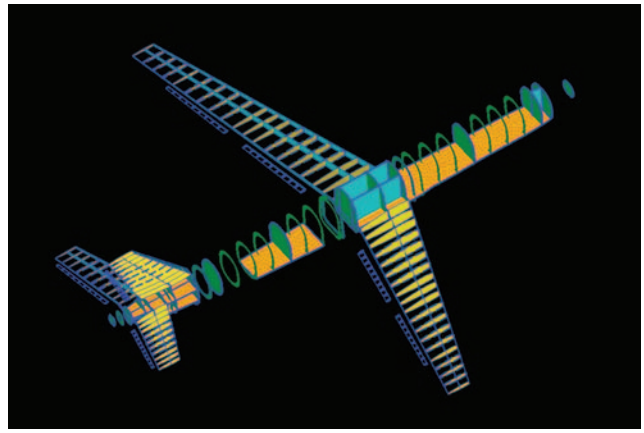

Figure 13. AMRaven airliner substructure. Image courtesy of TechnoSoft.

A major limitation of AMRaven is that the initial configuration must be known and is not coupled to a mission-based design.

4.4 Pacelab APD by PACE

Pacelab APD (PACE, 2009) is a recently launched conceptual and preliminary aircraft design tool by Berlin-based engineering software provider PACE addressing the needs of aircraft analysts, conceptual design engineers, aircraft integrators, and subsystem domain experts (see Figure 14). Pacelab APD builds on the company's knowledge-based engineering platform Pacelab Suite, which combines a consistent object-oriented data model and knowledge-based working techniques of capturing, formalizing, and applying engineering knowledge.

Pacelab APD's parametric data model fully supports physical units and multidimensional data tables to model engine, aerodynamic, and performance data. Product data and methods derived from legacy tools can be integrated and will be represented and used in exactly the same way as natively defined ones.

The setup of the product data model is supported by a user-extensible aircraft library and an interactive aircraft configurator. The aircraft library provides calibrated models of the most common commercial aircraft, from wide-body jetliners to single-engine turboprops, while the aircraft configurator guides users through the installation and positioning of predefined components such as wings, tail surfaces, engines, or undercarriages (see Figure 15). The aircraft configurator can also be extended with user-specific items.

A unique characteristic of Pacelab APD is that the input and output parameters of a calculation can be swapped freely,

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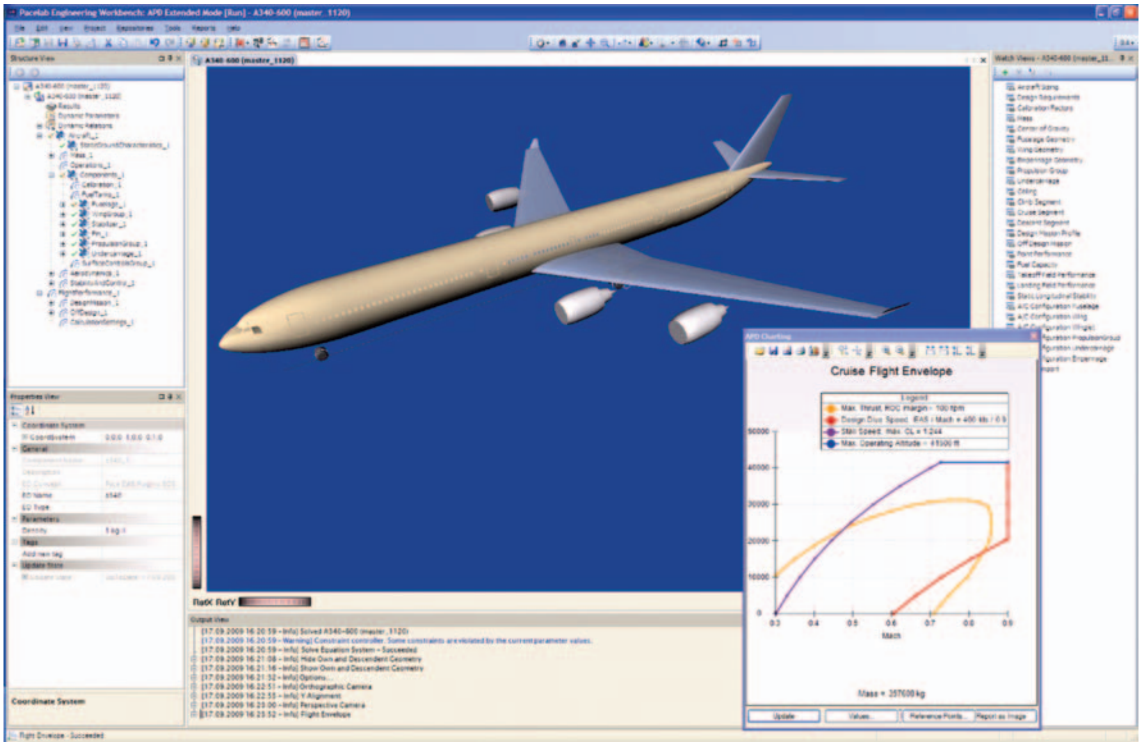

Figure 14. Pacelab APD application window. Image courtesy of PACE.

thus reversing the direction of the calculation. A simple example of parameter reversion is the calculation of the wing aspect ratio as a function of the span, or vice versa; both can be selected directly from the user interface and require no manual adjustment of the data model. For this purpose, Pacelab APD provides predefined "calculation cases," which consist of sets of interdependent parameters representing typical design scenarios.

By default, Pacelab APD uses calculation methods from the public domain (Torenbeek, 1982; Raymer, 2006), which can be easily substituted with proprietary higher fidelity methods. For flight performance analysis, the software relies on first-principles calculations with the Pacelab performance kernel, which drives the company's established performance software solutions for airline analysts (Pacelab Mission) and airline operations (Pacelab SCAP and Pacelab CI OPS).

Pacelab APD supports local and global optimization use cases with robust gradient methods and genetic algorithms (e.g., NLPQLP, Frontline, and so on). Any output parameter can be subject to optimization, with the influencing input parameters automatically detected and available as degrees of freedom. In addition, *n*-dimensional trade studies help to investigate the behavior of output parameters when a set of related input parameters is varied. Violations of user-defined constraints are automatically highlighted in the display of results, which can be tabular or depicted in 2D/3D graphics.

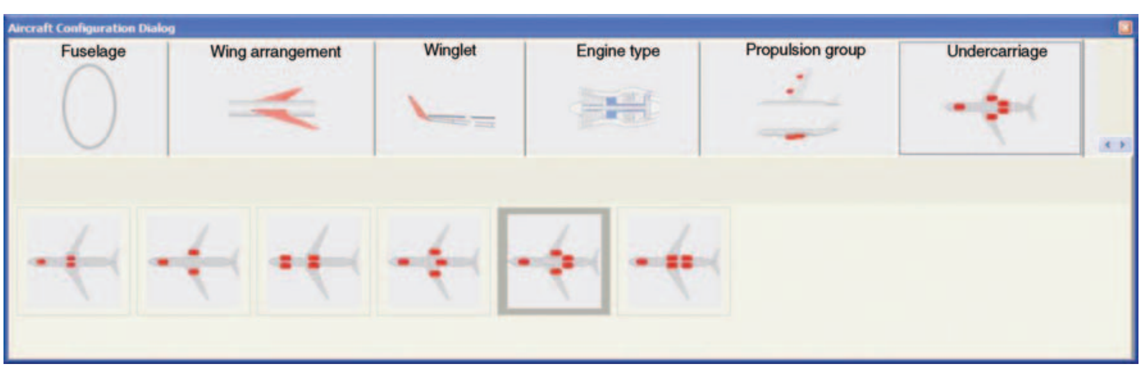

Figure 15. Pacelab APD aircraft configurator. Image courtesy of PACE.

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Pacelab APD offers preconfigured reports covering typical aspects such as mass breakdown and field and mission performance. All reports can be freely adapted or extended by the user. In addition, Pacelab APD comes with a library of aircraft performance charts including Cruise SFC, Cruise Flight Envelope, and High Speed Drag Polar. The charts are dynamic and update automatically when parameter values change. External reference data may be imported to graphically match known results.

Intended for user extension, many of Pacelab APD's core entities (component models, analysis methods, reports, etc.) can be supplemented or customized through its standard interfaces. These also allow the integration of external analysis and simulation tools or highly specialized functionality, for example, for systems architecture design or structural analysis.

5 CONCLUSIONS

A detailed description of commercially available airplane conceptual design tools is given. With the development of new computer programming languages to capture design knowledge, new tools will be developed based on legacy design tools such as RDS, AAA, and OAD and complete newly developed tools.

NOTE

1 Ronnie E. Gillian, NASA Langley, private communication, March 15, 2007.

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