PreSTo Wing Module Optimization for the Double Trapezoidal Wing

Karunanidhi Ramachandran and Dieter Scholz

Abstract This paper explains the Aircraft Preliminary Sizing Tool (PreSTo) developed at the Hamburg University of Applied Sciences. From the different modules of PreSTo, PreSTo wing, and its sweep angle have been taken as the key feature to explain further. In order to figure out the necessary values for the double trapezoidal wing a loop has been created between the kink chord, inner taper ratio, inboard leading edge sweep angle, and inboard 25 % chord sweep angle. By the end of the loop all the major chords, sweep angles, and taper ratios are calculated and a 2D representation of the wing is given. PreSTo will interact with the user by giving suggestions and during certain parameter conflicts; it can give warning to the user concerning his previous made design choices. Values of wing parameters generated in the wing module are finally stored into PreSTo central database. OpenVSP Connect retrieves values from PreSTo central database and visualizes the aircraft and its wing in 3D with NASA's tool Open Vehicle Sketch Pad (OpenVSP).

Keywords Wing module · Optimization · Trapezoidal wing · Presto · Open vehicle sketch pad (open VSAP)

Abbreviations

A	Aspect ratio
AAA	Advanced Aircraft Analysis
ACSYNT	Aircraft Synthesis
AERO	Aircraft Design and Systems Group
APD	Aircraft Preliminary Design
c	Chord (index: t = tip, r = root, k = kink)

K. Ramachandran (✉) · D. Scholz
Aircraft Design and System Group (AERO), Hamburg University of Applied Sciences,
Berlinor Tor 11, 20099 Hamburg, Germany
e-mail: chandran.ramk@gmail.com

D. Scholz
e-mail: info@profscholz.de

CATIA V5	Computer-Aided Three-Dimensional Interactive Application Version 5
CAPDA	Computer Aided Preliminary Design of Aircraft
CEASIOM	Computerized Environment for Aircraft Synthesis and Integrated Optimization Methods
d_f	Fuselage diameter
FLOPS	Flight Optimization System
GUI	Graphical User Interface
HAW Hamburg	Hamburg University of Applied Sciences
MAC	Mean Aerodynamic Chord
OPerA	Optimization in Preliminary Aircraft Design
OpenVSP	Open Vehicle Sketch Pad
PrADO	Preliminary Aircraft Design and Optimization Program
PreSTo	Aircraft Preliminary Sizing Tool
RDS	Raymer Design System
SAS	Simple Aircraft Sizing
y_k	Distance between kink chord and fuselage centerline

1 Introduction

The aircraft design process has its own different phases. In each phase, we need to deal with all of the main parts of the aircraft like wing, fuselage, and empennage. Where the basic needs of the aircraft figured out by the strategic planning and market analysis group and the design engineers will continue their work later on. The whole design process has an iterative character. Every change will cause an alteration of some other value [1].

Design engineers at different aircraft industries are using their own kinds of preliminary design software. Such software is not openly available and shrouded in secret. There are also many private research groups and Universities with their own design tools. Commercial aircraft design tools which are available online for use are RDS, AAA, APD, and CEASIOM [2–5]. Daniel Raymer developed RDS Integrated Aircraft Design and Analysis based on his book "Aircraft Design: A Conceptual Approach." Jan Roskam created the software tool AAA (Advanced Aircraft Analysis) based on his book "Airplane Design." Pacelab GmbH in Berlin developed APD (Aircraft Preliminary Design). The CEASIOM (Computerized Environment for Aircraft Synthesis and Integrated Optimization Methods) developed by SimSAC is an aircraft design software openly available. CFS Engineering provides support for the tool.

Aircraft design tools that are made by universities and research organizations are PrADO, CAPDA, FLOPS, and ACSYNT. CAPDA (Computer Aided Preliminary Design of Aircraft) was developed at Technical University Berlin as a tool for the analysis and Conceptual Design of commercial aircraft [6]. PRADO (Preliminary Aircraft Design and Optimization) program was developed for many years as a

modular Aircraft Design tool at Technical University Braunschweig [7]. FLOPS (Flight Optimization System) is a multidisciplinary tool (with nine modules) for designing and evaluating advanced aircraft concepts. It was developed by NASA [8]. ACSYNT (Aircraft Synthesis) started as an initiative of Ames research center to improve the conceptual design process. It is now Joint Sponsored Research Agreement by Ames Research Center, NASA, and Virginia Tech [9].

Tools developed at the Hamburg University of Applied Sciences follow a different approach. SAS (Simple Aircraft Sizing) is only the first step in the tool chain of preliminary aircraft design. SAS allows manual analysis of basic preliminary sizing parameters; OPerA (Optimization in Preliminary Aircraft Design) allows optimizing conceptual design parameters and PreSTo (Aircraft Preliminary Sizing Tool) offers a modular, manual, interactive, and more detailed approach of every conceptual design step. The complexity and the features increase gradually from SAS to PreSTo. The tool chain follows in this way:

SAS => OPerA => PreSTo => Further Tool Evaluation and Display Tools

2 Simple Aircraft Sizing (SAS)

The philosophy of SAS is to support the aircraft designer converting certain mission requirements into important aircraft parameters. The program is set up as a spreadsheet in Excel. An advantage using a spreadsheet over the use of programming languages is its efficient integration of input, calculation, and output. Excel is easy to understand and does not need an expert to operate. It is easy to store and compatible with most of the operating systems and computers.

SAS consists of well-proven equations and calculation sequences from the lecture of Prof. Scholz. From basic input parameters to aircraft design like payload and range, landing, and take-off field length the outputs like required thrust and wing area are calculated, complemented by maximum take-off mass, fuel mass, and other mass parameters. On the way to these results aerodynamic and other parameters like Oswald factor, maximum glide ration, zero-lift drag coefficient, minimum drag lift coefficient, specific fuel consumption are calculated, to name only a few [10].

3 OPerA—Optimization in Preliminary Aircraft Design

The main aim of OPerA was to apply formal optimization to aircraft preliminary design and preliminary aircraft cabin design. Aircraft basic parameters like aspect ratio, maximum lift coefficients are the engineer's choice. Especially for inexperienced aircraft designers it is difficult to choose all required parameters in the best way. The challenge is to find that combination of design parameters which is an optimum for the design. However, this optimum combination of design parameters found by formal optimization is only a starting point to a further detailed design

described by more parameters in PreSTo. Adding PreSTo to OPerA means to combine formal optimization with a subsequent interactive and experienced-driven aircraft design environment [11].

OPerA goes way beyond Preliminary Sizing. It deals with many more parameters and offers many features only found in Conceptual Design. It includes drag and mass estimations, derivation of main geometrical parameters, a specific fuel consumption model, direct operating cost (DOC) calculation and even evaluation of Added Values. Nevertheless, it stays a simple tool, although allowing a complete Aircraft Design analysis. OPerA is limited to conventional aircraft configurations, but includes innovative concepts and cabin parameters that are normally not part of conceptual design. OPerA requires only Microsoft Excel 2007 and makes use also of Excel's built-in optimizer know as the Solver [12].

4   Overview of PreSTo

PreSTo is still under development, but progressing. PreSTo is a modular and interactive tool that requires manual input. It stretches from preliminary sizing to conceptual design. It will ultimately contain a module for each step of classical Aircraft Design:

- Sizing (PreSTo-Sizing)
- Cabin and Fuselage Layout (PreSTo-Cabin)
- Wing Layout
- Design for High Lift
- Empennage Layout
- Landing Gear Layout
- Mass and CG Estimation
- Drag Estimation
- DOC Calculation
- Results, Interfaces to other Tools, 3D Visualization (OpenVSP-Connect).

Each module has its own Excel file. The idea is to open in a first step the desired aircraft project contained in an Excel file by means of a Graphical User Interface (GUI). This file also stores the database describing the project. Figure 1 shows the central GUI of PreSTo. When the aircraft project is opened, parameters are set in Excel. Once the user interactively generated new values for further design parameters, the values are written back into the database with help of the graphical user interface. The only file necessary to store the project is the database file (with the GUI, Fig. 1). When future developments of PreSTo come with improved modules, these updated modules will be available on the Internet for download. The aim is to keep all existing databases compatible with new versions of the modules [13].
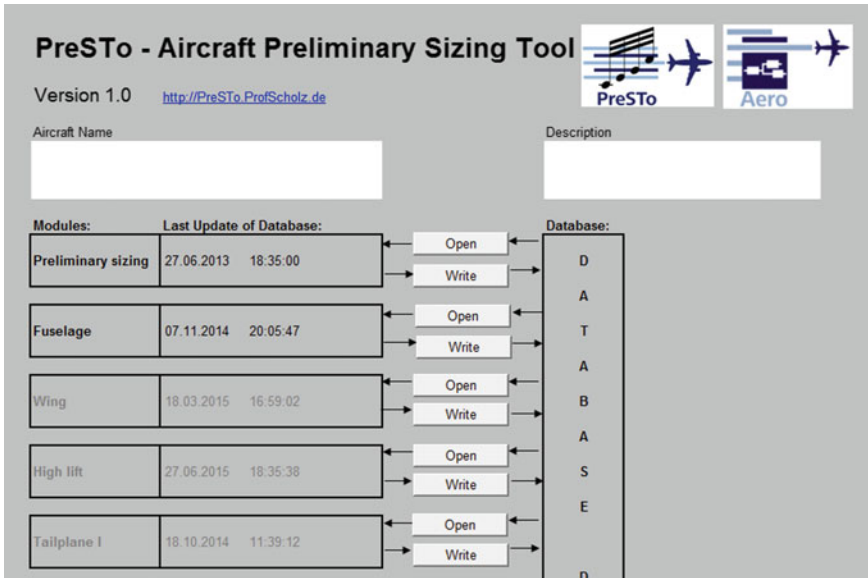
Fig. 1 Graphical User Interface (GUI)

5 PreSTo Wing Design

The wing section of an aircraft is a fundamental part of aircraft design. Initial input of parameter required to begin with the PreSTo wing optimization. Written VBA codes imports parameters from the database of PreSTo. When users click the 'Open' button in the GUI for the wing module, the VBA program opens the wing module and inserts the basic parameter into this module. These basic parameters are from the previous modules, which are stored in the database. Typically, users have defined a certain range and number of passengers and other fundamental parameters in the very beginning. Based on these fundamental parameters inserted by the user the fuselage length, fuselage diameter, the lift coefficient in cruise, a first fuel estimation, and other parameters are set. The wing module that now follows consists of several worksheets with only one being visible for the end user. The other worksheets contain plane data, graphs, airfoil data, and constants [13]. Several wing parameters are calculated as detailed in the Sects. 5.1 and 5.2.

5.1 Sweep Angle

Wing sweep reduces the negative effects on the wing from transonic and supersonic flow. Wing sweep also improves roll stability of the aircraft. A double trapezoidal wing has two different sweep angles—a sweep angle for the inner wing and a sweep

angle for the outer wing. Wing sweep may be forward or aft, but in most of the cases, it is aft swept and defined with respect of the 25 % chord line. Two sweep angle suggestions are given in PreSTo based on Howe [14] and Raymer [15] to the user. The different sweep angles give freedom to the user to choose, because both authors' suggestions come from experience and are free to be adapted. The inner wing sweep is calculated as follows:

$$\tan = (\varphi_i) = \frac{x}{y_k - d_f/2} \tag{1}$$

This inner sweep calculation is for the 25 % chord line. 'X' is found from the taper ratio of the inner wing. This states the increase toward the wing root.

$$\frac{3}{4}c_r = \frac{3}{4}c_k + x$$

$$\Leftrightarrow \frac{3}{4}(c_r - c_k) = x \quad \text{with } \lambda_i = \frac{c_k}{c_r} \rightarrow x = \frac{3}{4}c_k\left(\frac{1}{\lambda_i} - 1\right)$$

Leads to the final formula (2),

$$\varphi_{i,25} = \arctan\left(\frac{\frac{3}{4}c_k\left(\frac{1}{\lambda_i} - 1\right)}{y_k - \frac{d_f}{2}}\right) \tag{2}$$

Inner taper ratio

The overall taper ratio is depicted with suggestions from Howe [14] or Torenbeek [1]. The outer taper ratio depends on the overall taper ratio and the inner taper ratio (3)

$$\lambda_o = \frac{\lambda}{\lambda_i} \tag{3}$$

The inner taper ratio is the ratio of the kink chord to the root chord according to Eq. (4), but can also be geometrically derived to be dependent on the kink chord and wing sweep according Eq. (5).

$$\lambda_i = \frac{c_k}{c_r} \tag{4}$$

$$\lambda_i = \frac{c_k}{c_k + \left(y_k - \frac{d_f}{2}\right)\tan\left(\varphi_{0,i}\right)} \tag{5}$$

Equation (6) considered in case of different inboard trailing edge sweep,

$$\lambda_i = \frac{c_k}{c_k + \left(y_k - \frac{d_f}{2}\right)\left[\tan\left(\varphi_{0,i}\right) - \tan\left(\varphi_{100,i}\right)\right]} \tag{6}$$

Kink chord

The intersection of the two trapeziums is called the "kink." The area of double trapezoidal wing calculated according to Eq. (7).

$$S = 2\left[c_r\frac{d_f}{2} + \frac{(c_r + c_k)\left(y_k - d_f/2\right)}{2} + \frac{(c_k + c_t)(b/2 - y_k)}{2}\right] \tag{7}$$

Equation (7) written as follows,

$$S = \frac{d_f}{2}(c_r - c_k) + y_k(c_r - c_t) + \frac{b}{2}(c_k + c_t) \tag{8}$$

By taking c_k out in common, Eq. (9) modified in terms of taper ratios,

$$S = \frac{d_f}{2}c_k\left(\frac{c_r}{c_k} - 1\right) + y_k c_k\left(\frac{c_r}{c_k} - \frac{c_t}{c_k}\right) + \frac{b}{2}c_k\left(1 + \frac{c_t}{c_k}\right) \tag{9}$$

Substituting, $\lambda_i = \frac{c_k}{c_r}$, $\lambda_o = \frac{c_t}{c_k}$
c_k can be found with the formula (10):

$$c_k = \frac{s}{\frac{d_f}{2}\left(\frac{1}{\lambda_i} - 1\right) + y_k\left(\frac{1}{\lambda_i} - \lambda_o\right) + \frac{b}{2}(1 + \lambda_o)} \tag{10}$$

The kink chord is dependent on the inner taper ratio only. The outer taper ratio is calculated from the overall taper ratio. The other values are present already.
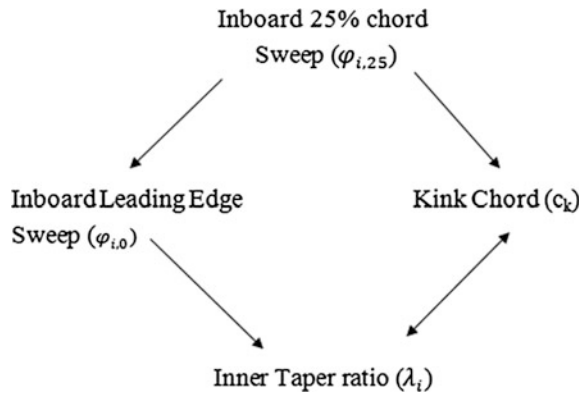
Inboard sweep
The inboard sweep is calculated via Eq. (11).

$$\varphi_{i,25} = \arctan\left(\frac{\frac{3}{4}c_k\left(\frac{1}{\lambda_i} - 1\right)}{y_k - \frac{d_f}{2}}\right) \tag{11}$$

Only inboard taper ration is required in the above formula. It is calculated from the Eq. (5). Sweep angle at different percentage of chord given in Eq. (12) [16].

$$\tan(\varphi_n) = \tan(\varphi_m) - \frac{4}{A}\left[\frac{n - m}{100} \cdot \frac{1 - \lambda}{1 + \lambda}\right] \tag{12}$$

**Fig. 2** Loop created for optimization of Taper ratio

Equations (5), (10), (11), and (12) will form the loop to find all the necessary values. The kink ratio $\eta_k = y_k/(b/2)$ is a percentage of semi span where the kink chord is located. It follows from statistics. With these two values the iteration process starts and values for inner and outer taper ratios, inner sweeps, and all chords are given. In essence, following values are dependent in the loop (Fig. 2). In the loop, double arrow between kink chord and inner tapper ratio indicates that both are sharing the same unknowns.

The settings in the Excel solver can be manually changed or automatically when incorporated in the VBA code during startup. When the PreSTo workbook is opened, the settings will automatically be configured to allow for iterations with a maximum of 100 or a maximum discrepancy of 0.001 [17].

5.2 Wing Geometry Results

The basic wing geometry of the double trapezoidal wing is drawn using inner, kink, and outer chord, inner and outer sweep angle, and inner and outer taper ratio. The resultant wing diagram is shown in Fig. 3. The red dot indicates the Aerodynamic Center (AC) located on the Mean Aerodynamic Chord (MAC), and the pink line shows the kink chord.

Fig. 3 Wing geometric results
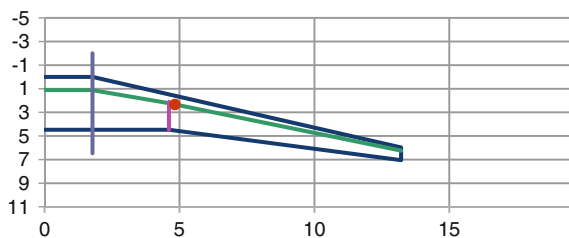
6 OpenVSP Connect

OpenVSP Connect is primarily intended as an interface tool between any aircraft design tool and Open Vehicle Sketch Pad (OpenVSP) from NASA [18]. OpenVSP Connect needs OpenVSP for the display of the aircraft. In the order of 50 core parameters of the aircraft are used to calculate the many input parameters required by OpenVSP to sketch a passenger aircraft. For each of the core parameter, a proposed value is given in the user interface and automatically applied as long as the user does not specify his/her own value. This is a fundamental principle of the program. The user will always get assistance from the PreSTo. This too proposes values to fill the required fields. The program works in "automatic mode" by using all proposed or default values. Based on the minimum of just two input values "cruise Mach number" and "number of passengers" an aircraft can be sketched automatically [19].

7 Summary and Future Steps

In this report, main task was designing a double trapezoidal wing. Various extra parameters used to get the required double trapezoidal plan form. There is a dependency between taper ratio, kink chord, root chord, tip chord, and sweep. With the use of an Excel solver, loop created and implemented in order to find the suitable values for designing the trapezoidal wing. Besides these suitable values, the end users still have the choice to use another number of preferences. OpenVSP connect is one of the important features of PreSTo. OpenVSP connect helps to visualize the 3D view of the complete aircraft and the separate modules.

PreSTo is still under development phase. Most of the modules are already finished and some of it has to be updated with the latest design options (Extra features). In future, possibilities for connecting some complicated analysis software's (CFD, MATLAB…, etc) with PreSTo will be studied.

References

1. E. Torenbeek, *Synthesis of Subsonic Airplane Design*. Delft University Press, 1982.
2. D. P. Raymer, "Conceptual Design Modeling in the RDS-Professional Aircraft Design Software," *49th AIAA Aerosp. Sci. Meet. Incl. New Horizons Forum Aerosp. Expo.*, pp. 1–11, 2011.
3. W. a. J. Anemaat and J. Roskam, "Advanced Aircraft Analysis," *DARcorporation*, no. 785, 2014.
4. PACE, "Pacelab Aircraft Priliminary Design (APD)," 2011. [Online]. Available: https://www.pace.de/products/preliminary-design/pacelab-apd.html. [Accessed: 20-Sep-2015].

5. SimSAC, "CEASIOM (Computerized Environment for Aircraft Synthesis and Integrated Optimization Methods)," 2015. [Online]. Available: http://www.ceasiom.com/index.php. [Accessed: 27-Dec-2015].

6. M. Schmid, "CAPDA-Computer Aided Preliminary Design of Aircraft," 2009. [Online]. Available: https://www.luftbau.tu-berlin.de/menue/forschung/abgeschlossene_projekte/visual_capda/. [Accessed: 04-Sep-2015].

7. Wolfgang Heinze, "PrADO—Preliminary Aircraft Design and Optimization," 2008. [Online]. Available: https://www.tu-braunschweig.de/ifl/simulationswerkzeuge. [Accessed: 20-Dec-2015].

8. T. M. Lavelle and B. P. Curlett, "Graphical user interface for the NASA FLOPS aircraft performance and sizing code," 1994.

9. NASA, "ACSYNT—Aircraft Synthesis," 1997. [Online]. Available: https://www.nasa.gov/ames/spinoff/aircraft_design_software/#.VoSQkvkrLIU. [Accessed: 22-Dec-2015].

10. Dieter Scholz, "SAS-Simple Aircraft Sizing," 2008. [Online]. Available: http://fe.profscholz.de/. [Accessed: 19-Dec-2015].

11. Dieter Scholz, "OPerA—Optimization in Preliminary Aircraft Design," 2011. [Online]. Available: http://opera.profscholz.de/. [Accessed: 10-Dec-2015].

12. M. F. Nita, "Contributions to Aircraft Preliminary Design and Optimization," 2013.

13. AERO, "Aircraft Design and Systems Group," 2015. [Online]. Available: http://aero.profscholz.de/. [Accessed: 20-Dec-2015].

14. D. Howe, *Aircraft conceptual design synthesis*. Professional Engineering Publishing Limited, 2000.

15. D. P.Raymer, *Aircraft Design: A Conceptual Approach*. American Institute of Aeronautics and Astrinautics, Inc., 1992.

16. Dieter Scholz, *Aircraft Design Lecture Notes*. Hamburg: HAW Hamburg, 2012.

17. Ozgrid, "Excel Training," 2014. [Online]. Available: http://www.ozgrid.com/forum/showthread.php?t=187310. [Accessed: 25-Dec-2015].

18. J. R. Gloudemans, "OpenVSP," 2012. [Online]. Available: http://www.openvsp.org/.

19. Dieter Scholz, "OpenVSP Connect," 2013. [Online]. Available: http://openvsp.profscholz.de/. [Accessed: 19-Dec-2015].