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Automatic Generation of 3D-CAD Models to Bridge the Gap between Aircraft Preliminary Sizing and Geometric Design

J. Abulawi, K. Seeckt, M. Pommers, D. Scholz
Hamburg University of Applied Sciences
Department of Automotive and Aeronautical Engineering
Berliner Tor 9, 20099 Hamburg, Germany

Abstract

This paper presents an extension to the Aircraft Preliminary Sizing Tool PreSTo which has been developed at the HAW Hamburg. The extension is called "PreSTo-Vis"; it bridges the gap between the mathematical sizing process and three-dimensional (3D) geometrical aircraft design. The core of this add-on to PreSTo is a universal aircraft surface model which was created using an advanced parametric associative design method in the 3D computer-aided design (CAD) system CATIA V5. A Microsoft Excel-based Visual Basic project automatically reads the output spreadsheets of the preliminary sizing process, processes these data and reconfigures the 3D CAD model to visualize the concept geometry of the new aircraft. Thus the design engineer has the chance to gain a three-dimensional impression of the calculated aircraft dimensions, and he obtains a parametric surface model in a native CAD format suitable for further geometric refinement and analysis.

1 Introduction

The design process of a new aircraft can be split up into the several phases. Once the need for a new aircraft design has been established by strategic planning and market analysis, the process starts with an early configuration phase where the suitability and feasibility of basic aircraft concepts is explored. It provides the input for the subsequent phase which Torenbeek refers to as conceptual design [1]. In this concept phase, the aircraft architecture is further refined and developed until a sufficient level of detail is reached to initiate the following definition phase where individual system elements are defined. The concluding development phase establishes the final aircraft design in terms of structure, systems and manufacturing processes [2]. Its main milestones are the beginning of final assembly and the first flight, and the phase ends with the entry into service.

In the feasibility phase, the initial idea is explored until a basic concept of the aircraft is established. For this purpose, a preliminary sizing process is required which provides the basic input for the exploration of aircraft architecture concepts. In the preliminary sizing process, the design engineer collects and uses the top-level aircraft requirements (TLARs) posed to the aircraft design to develop an initial layout of the notional aircraft. This comprises the selection of an overall aircraft configuration (tail-aft, canard, etc.), the type of propulsion system (jet/propeller) and also includes determining first assumptions for the size, mass and performance characteristics of the new aircraft design.

During the following conceptual and the detailed design phases the actual aircraft design is repeatedly analyzed, modified and further determined in an increasing level of detail. In the early design stages, however, the design engineer is forced to make initial assumptions for necessary aircraft parameters that will not be determined until subsequent design steps have been accomplished. Consequently, the overall aircraft design process is highly iterative. This iterative nature of aircraft design makes it advisable and mandatory in modern engineering work to simplify and expedite such design loops in order to minimize the aircraft design lead time. For this purpose various types of computer software are applied to reduce the amount of manual work and to minimize sources of error.

This paper addresses the application and improvement of software support to the preliminary sizing process and the early geometric exploration of configuration concepts. It discusses suitable stages in the aircraft concept design process for the application of freely available tools to support decision-making for aircraft configuration and dimensioning. In the main part, this paper presents a new module for the Aircraft Preliminary Sizing Tool PreSTo which bridges the gap between the definition of aircraft parameters and geometric CAD modeling.

2 Current aircraft design software

Among the software currently in use for aircraft design and aeronautical engineering education are the programs CEASIOM and PrADO. CEASIOM (Computerised Environment for Aircraft Synthesis and Integrated Optimisation Methods) [3] is a Matlab-based suite of several programs for the investigation and simulation of the aerodynamic, flight mechanical and aeroelastic properties of aircraft. The individual programs share one common parametric aircraft model, which allows for first analyses and assessments of the aircraft properties in an early stage of the aircraft design process. This marks a shortcut to previous time-consuming and expensive iteration loops at higher detail levels.

The Preliminary Aircraft Design and Optimization program PrADO [4] is a comprehensive program that comprises all major disciplines of aircraft design from geometric description of the aircraft via structural analysis to flight mission simulation and estimation of the aircraft direct operating costs. This broad range of investigations and the high fidelity of the tool allow for extensive and sophisticated analysis results of a notional new aircraft already during conceptual design.

However, these programs, as well as available commercial aircraft design programs such as RDS [5], AAA [6] and Pacelab APD [7] among others, require an initial design of the new aircraft already as their input. Thus, prior to the application of these programs the design engineer or student already has to possess information on the geometry and configuration of the planned aircraft. The focus of these programs is to analyze and refine initial design concepts rather than to assist the designer in conceiving them.

The Aircraft Preliminary Sizing Tool PreSTo developed at the Hamburg University of Applied Sciences (HAW Hamburg) follows a different approach. PreSTo starts at the very beginning of the aircraft design process (see Figure 1). The tool already supports the user in developing an initial aircraft design based on the main requirements for the aircraft which are defined in the top-level aircraft requirements (TLARs) posed to the aircraft. These are:

- the aircraft design mission described by the required payload, range and cruise Mach number
- the landing field length,
- the take-off field length, and
- the minimum climb gradients after take-off (2nd segment) and after a missed approach.

Based on these five requirements an aircraft design point in terms of wing loading and thrust-to-weight ratio (for jet aircraft) or power-to-mass ratio (for propeller aircraft) is determined using a method developed at NASA [8]. From this aircraft design point the notional new aircraft is dimensioned – beginning as a point mass, followed by sizing of the individual main aircraft components (fuselage, wings and high-lift system, tailplane, etc.). Throughout this process, the user is assisted with suggestions for not yet defined aircraft parameters based on information from statistics, aircraft design literature (e.g. Torenbeek [1] and Roskam [9]) and aircraft design lecture notes [10].

PreSTo is implemented in a Microsoft Excel workbook. Each worksheet of this file covers a distinct design step. For each aircraft configuration determined with PreSTo, all design geometric parameters are saved in a separate file. From there, they can be reloaded into PreSTo or exported to CEASIOM and PrADO for further investigation. More information on PreSTo is given in [11] and on the PreSTo website [12].

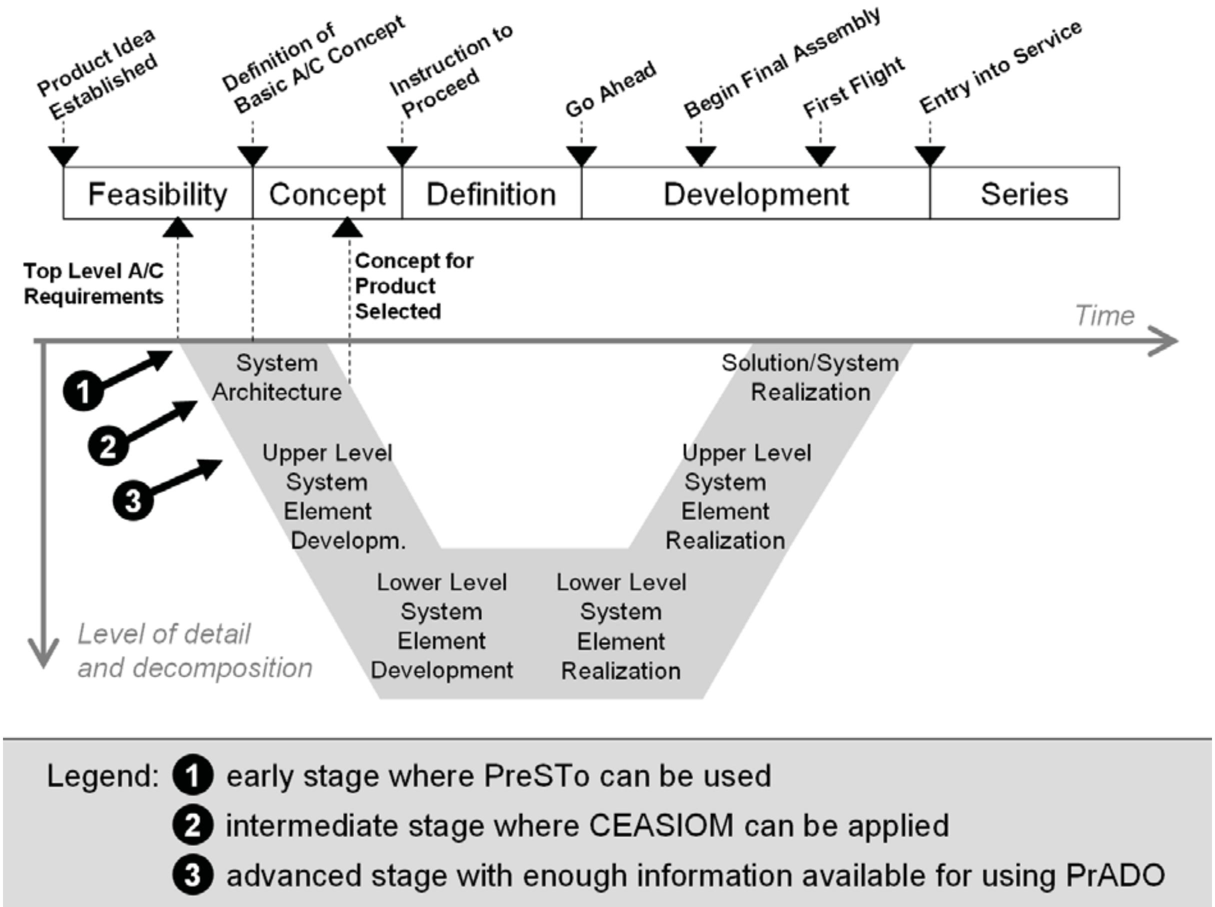

Figure 1: Application of PreSTo, CEASIOM and PrADO in concept development[1]

3 The role of Geometric Modeling and Visualization

In the early design phase, the TLARs must be translated into a suitable aircraft architecture. Each of the main configuration items must be roughly dimensioned to ensure that the main functions of the aircraft can be fulfilled. The geometric parameters and the resulting mechanical properties defined in this process are strongly interrelated through complex constraints and dependencies. As multiple solutions to this set of relations exist, it is crucial to assess the suitability of the determined geometric parameters at a very early stage, before further time-consuming detailed design processes are accomplished.

[1] The depicted development phases and milestones correspond to the Airbus business process "Develop new Aircraft" [13], and the Vee model corresponds to that published by the INCOSE [14].

Experienced designers may possess the skill to judge the suitability of geometric parameters by comparing the numeric values to those of previous design projects. However, a visualization of the resulting aircraft geometry does help them to avoid errors in this early concept assessment. Inexperienced designers and students fully depend on the visual impression of a graphical presentation to assess the plausibility of their design results. Many aircraft design tools provide such feedback with simple two-dimensional plots of the aircraft silhouette. With three-dimensional design being the state of the art, it is desirable to support the intuitive process of judging an aircraft design with a proper 3D surface model.

For a long time, the generation of aircraft concept models was too complex a task to be performed in early stages of aircraft design where configurations are varied and explored in multiple iterations. Available CAD systems did not permit the automatic generation of the required models and their functionalities for reconfiguring and redimensioning existing models were limited. Consequently, geometric modeling was considered a bottleneck in the early stage of multi-disciplinary aircraft design optimization [15]. To overcome this problem, specialized tools for modeling aircraft configurations were developed like the surface modeler SUMO [16]. The focus of this tool is the rapid generation of aircraft surface models and associated surface and volume meshes. Such models provide the basis for aerodynamic, aeroelastic and structural analysis, e.g. with finite element analyses (FEM) and computational fluid dynamics analyses (CFD).

However, designers do not only wish to view the resulting geometry and perform numeric analyses. Quite often, they need to explore the geometry of an aircraft concept with the functions offered by a sophisticated CAD system. Additionally, they may want to modify the topology or certain dimensions of the geometric model without having to go through all steps of the preliminary sizing process. SUMO supports the export of the surface model, but it can only output the neutral 3D geometry format IGES (Initial Graphics Exchange Specifications). As this format is a non-parametric, history-free representation of the resulting geometry, it is impossible to modify the geometry when it is imported to the CAD system CATIA V5, which is currently the most widely used CAD system in the aircraft industry.

CATIA V5 however, permits the creation of adaptive parametric-associative CAD models which can be reconfigured and redimensioned within certain limits determined by the design intent of the initial model [17]. Furthermore, this CAD system has an integrated application programming interface for design automation [18]. For this reason, PreSTo-Vis was developed to exploit the functionality of CATIA V5 and bridge the gap between parameter-based preliminary sizing and geometric design.

The tedious task of manual CAD modeling is thus avoided, and the initial aircraft geometry is defined by the parameters which are the output of the preliminary sizing process. In this respect, PreSTo-Vis agrees with the suggestions of Rodriguez and Sturdza who favor the parametric geometry generation from a set of key aircraft design parameters [19]. The concept of PreSTo-Vis agrees with the approach presented by Ledermann as it uses the sophistication of native CAD geometry to provide a “common knowledge based parametric-associative geometry” [20]. However, PreSTo-Vis extends this scope by automatically reading and processing the design parameters determined and supplied by PreSTo. It thus offers an uninterrupted tool chain from top-level aircraft requirements to a modifiable aircraft geometry in the desired native 3D-CAD format as shown in Figure 2.

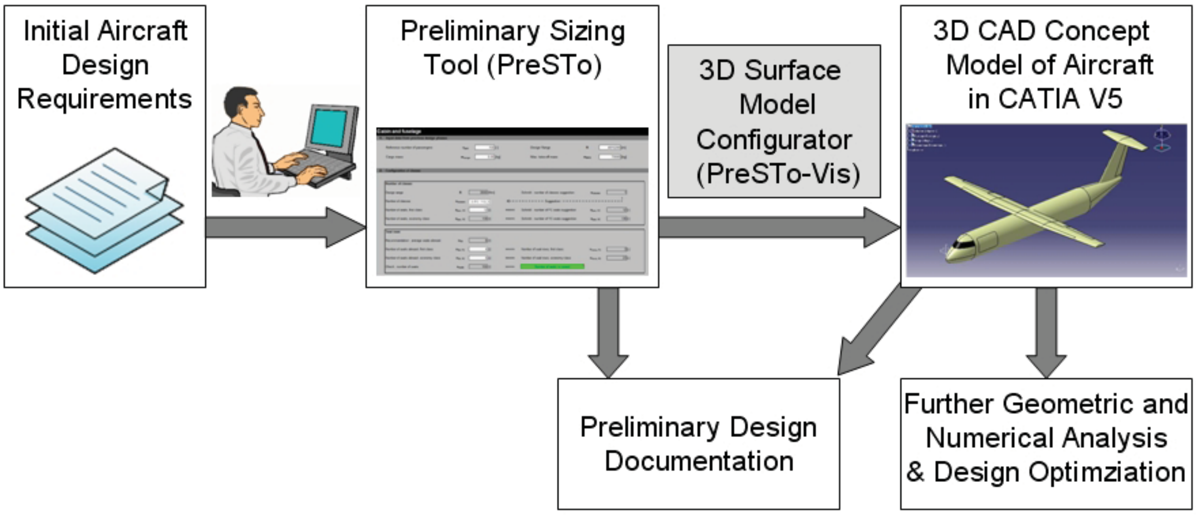

Figure 2: Extension of the preliminary aircraft sizing tool chain by PreSTo-Vis

In contrast to other parametric aircraft design solutions (e.g. [21]; [22]), PreSTo-Vis was developed as an optional extension to the preliminary design tool. The preliminary sizing process with PreSTo requires only an Excel license. However, users with access to CATIA V5 can use PreSTo-Vis to visualize their aircraft configuration in a 3D CAD model. PreSTo-Vis either uses design parameters determined with PreSTo and saved in a separate file or it prompts the user to input the desired parameter values. If the user wishes to change the aircraft geometry PreSTo-Vis can also read design parameters from the CATIA model, save them in the aircraft configuration file. From there, they can be read into PreSTo where the preliminary design calculations can be repeated with the modified data.

4 The Functionality of PreSTo-Vis

PreSTo-Vis was initially developed by Pommers [23] as an Excel-based Visual Basic project and has been further extended by aeronautical engineering students of HAW Hamburg. Its source code can be embedded in the PreSTo workbook or saved in a separate workbook. The currently available version was developed in Microsoft Excel 2003 and accesses the CATIA V5 application via Active-X components. Consequently the program can automatically read the output data provided in PreSTo and process the data to reconfigure an existing aircraft surface model in CATIA V5. The universal parametric aircraft model was developed by Pommers [23] using a strongly cascading adapter technology with associative multi-model links which was originally developed for automotive concept design [24]. The systematic structure of the CAD model and the strict adherence to naming and modeling conventions as well as predefined programming rules permitted the subsequent refinement and extension of the CAD model and the associated VBA source code by other students in successive design projects.

The structure of the CAD model is depicted in Figure 3. Thanks to the adapter technology, the CAD model can be refined and improved without having to adjust the source code of PreSTo-Vis. As PreSTo is continuously extended and improved, future adaptations of the PreSTo-Vis source code are easily implemented to hand over new design parameters to corresponding new CAD model parameters. The main adapter of the CAD model acts as a universal interface between the individual surface models of the aircraft components and the design parameters determined in the preliminary sizing process.

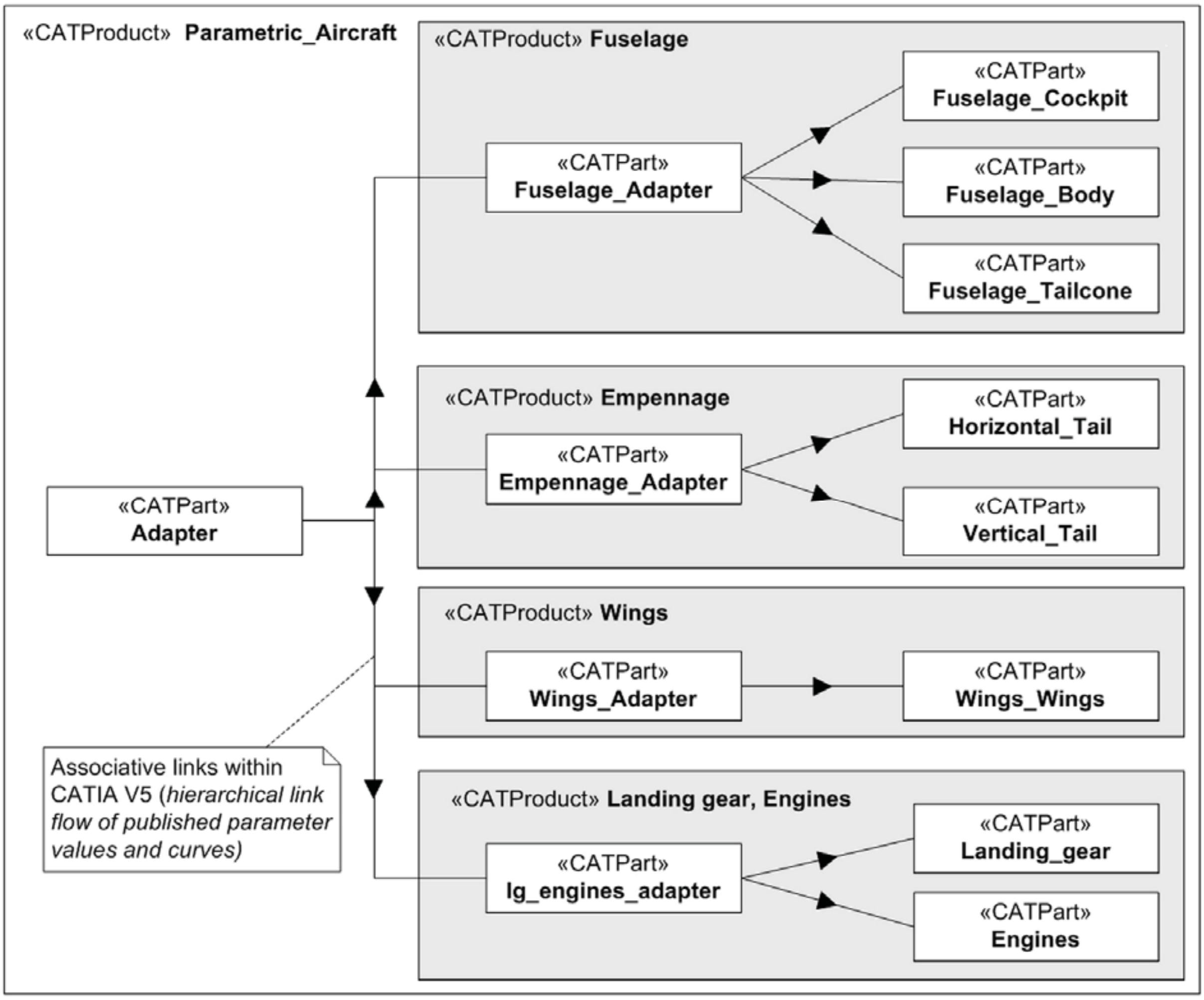

Figure 3: Cascading adapter structure of the parametric aircraft model

To give the designer a realistic impression of the newly defined aircraft concept geometry, information on cockpit, fuselage and wing design can be processed by PreSTo to generate new control points, splines and free-form surfaces to replace existing geometry in the parametric aircraft model. In the current version of PreSTo-Vis, this method is used to recreate the wing profile according to individual profile selections in PreSTo. The aircraft design engineer who uses PreSTo-Vis immediately obtains a three-dimensional presentation of the aircraft concept determined in the preliminary sizing process. Figure 4 gives an overview of the flow of activities in PreSTo-Vis.

As PreSTo-Vis creates native CAD geometry in CATIA V5, the designer can refine and edit the created 3D aircraft model. All analysis functions of CATIA V5 can be used, e.g. to determine wing surface area and local centers of gravity from individual components. If required, the surface geometry can be exported to neutral standard geometry representations like STEP AP 214, 3DXML or JT.

To document the preliminary sizing activities, PreSTo-Vis automatically creates a three-view drawing of the aircraft which conforms to engineering drawing standards. This drawing is saved as a separate drawing file in native CAD format for further editing and future reference and in PDF format for universal access and long-term archival. If desired, an image of the drawing can be embedded in an Excel spreadsheet together with the preliminary sizing data.

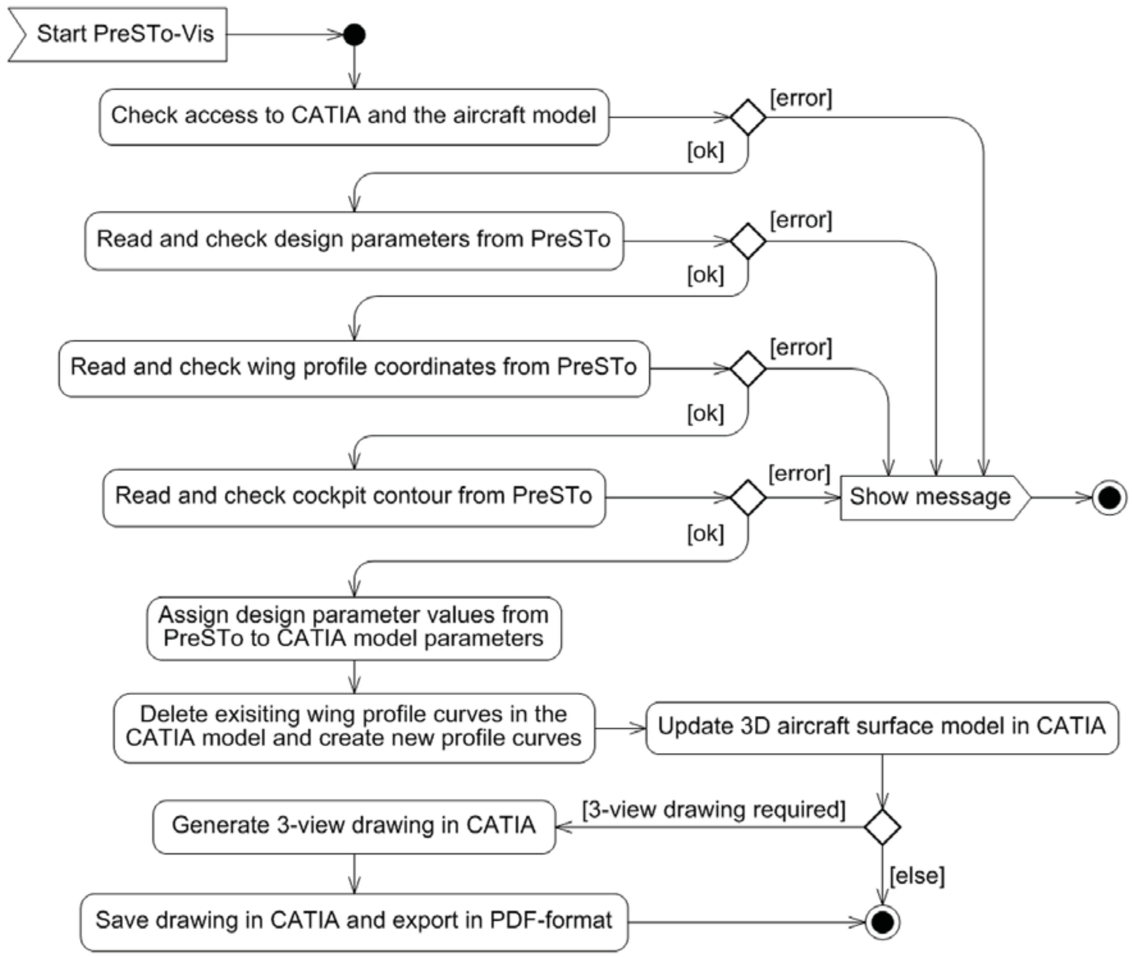

Figure 4: Activity diagram of PreSTo-Vis

5 Example: Application of PreSTo and PreSTo-Vis

In the practical example described below, the preliminary sizing process is performed with the main aircraft requirements of the Fairchild-Dornier 728. This aircraft was initially conceived as a regional passenger jet to compete with the Embraer 170 and the Bombardier CRJ700. Due to economic reasons it was never taken into service. For this paper, it was taken as an example because TLAR data is publicly available and the results of the preliminary sizing with PreSTo can be compared to the prototype of the aircraft which was actually built and rolled out in March 2002 [25].

5.1 Determination of geometric parameters with PreSTo

As main aircraft requirements, the following data are used:

- Design range: 2550 km
- Number of passengers: 75
- Cruise Mach number: 0.81
- Landing field length: 1420 m
- Take-off field length: 1463 m
- Climb gradients after take-off and missed approach acc. to CS-25 and FAR Part 25.

These requirements as well as the selection of a twin-engine jet propulsion system lead to an aircraft design point of 0.324 thrust-to-weight ratio and 469 kg/m² wing loading. This aircraft design point as basis for the subsequent sizing of the aircraft leads to an initial mass estimation of the aircraft of 33 t maximum take-off mass and a required wing area of about 71 m². As the first aircraft component, the fuselage is sized based on a cabin floor plan (see Figure 5).

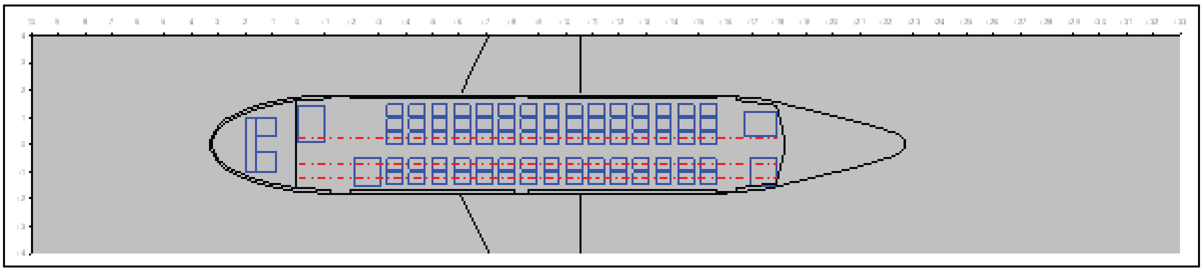

Figure 5: PreSTo cabin floor plan of Fairchild-Dornier 728 re-design

Subsequently, the other main aircraft components (wing, high-lift system and tailplane) are dimensioned in PreSTo. Similar to Figure 5, the results of the component dimensioning processes are visualized in PreSTo as sketches. The geometric aircraft parameters determined with PreSTo are very close to the actual dimensions of the reference aircraft FD 728.

The nose section geometry is defined in a separate PreSTo sheet which guides the designer through the process of selecting suitable profile curves. The results of the each preliminary sizing step can be saved in a separate Excel worksheet which provides the data to PreSTo-Vis which reconfigures the three-dimensional surface model in CATIA V5 to visualize the aircraft design.

5.2 PreSTo-Vis

Prior to starting PreSTo-Vis, the generic parametric aircraft model is opened in CATIA V5. In the Excel application, PreSTo-Vis is started. It checks the accessibility of the CAD model and reads the output parameters of PreSTo including the wing airfoil coordinates. Then, PreSTo-Vis calls CATIA and assigns the values of the design parameters to the corresponding CAD-model parameters and recreates the wing airfoil curvature. The CAD-model is then automatically updated and available for further analysis and modification in CATIA V5. Figure 6 shows the resulting configuration of the re-designed FD 728 in CATIA V5 on the left and the PDF-version of the automatically generated three-view drawing on the right.

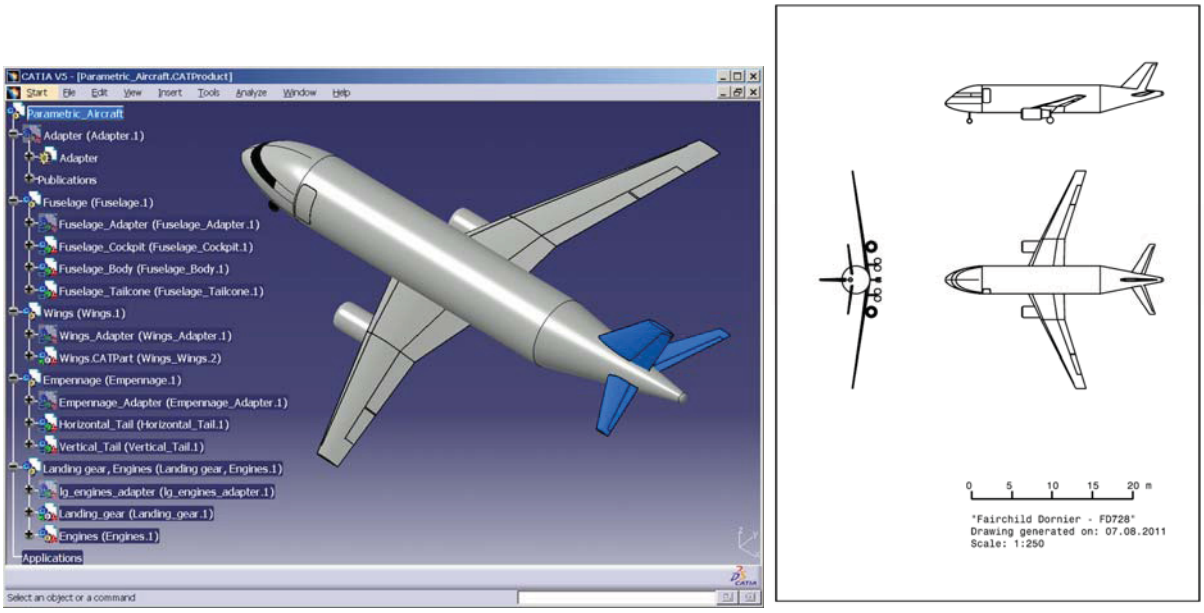

Figure 6: CATIA-model of the FD 728 redesign and the associated three-view drawing

6 Summary and Future Steps

The particular advantage of the aircraft preliminary sizing tool PreSTo is its applicability in the very early stage of aircraft design, immediately after determination of the TLARs. In the past, three-dimensional geometric presentations of aircraft configurations specified with PreSTo could only be obtained by transferring PreSTo results to other preliminary design tools like PrADO and CEASIOM or by importing the data to the aircraft surface modeler SUMO. The newly developed add-on PreSTo-Vis closes the existing gap between the numeric design parameters obtained in the preliminary sizing process and the computer-aided design process for further geometric analysis and variation. PreSTo-Vis automatically reads and processes design parameters and geometric configuration data supplied in Excel worksheets and reconfigures an existing sophisticated parametric aircraft surface model in the 3D-CAD system CATIA V5. To permit a roundtrip, it can read design parameters from the CATIA V5 model to reconfigure preliminary sizing data which can then be reassessed with PreSTo.

The functionality of PreSTo and PreSTo-Vis are continuously being extended to improve the level of detail of the preliminary sizing process and obtain a more realistic aircraft model. Among the design details to be specified in future versions of PreSTo and then used to reconfigure the parametric CAD model are wingtip devices, dorsal fin, engine attachment and landing gear. It is planned to explore the possibility of using the CATIA surface model to generate surface and volume meshes required for numeric analysis of the aircraft geometry. The modular design of PreSTo-Vis and the cascading adapter structure of the parametric aircraft model strongly support further extensions. Even now, PreSTo-Vis is a valuable extension of PreSTo offering immediate access to a realistic three-dimensional representation of aircraft concepts to be explored in the early stage of aircraft development.

Abbreviations

3DXML	Three-dimensional product representation in extended markup language
AAA	Advanced Aircraft Analysis
APD	Aircraft Preliminary Design
CATIA V5	Computer Aided Three-Dimensional Interactive Application Version 5

CEASIOM	Computerised Environment for Aircraft Synthesis and Integrated Optimisation Methods
CRJ	Canadair Regional Jet
FD	Fairchild-Dornier
HAW Hamburg	Hamburg University of Applied Sciences
JT	Jupiter Tessellation
PDF	Portable Document Format
PrADO	Preliminary Aircraft Design and Optimisation programme
PreSTo	Aircraft Preliminary Sizing Tool
PreSTo-Vis	PreSTo-Visualization Add-On
RDS	Raymer Design System
STEP AP 214	Standard for the Exchange of Product model data, Automation Protocol 214
SUMO	Surface Modeler
TLAR	Top-Level Aircraft Requirement

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