APPLICATION OF THE AIRCRAFT PRELIMINARY SIZING TOOL PRESTO TO KEROSENE AND LIQUID HYDROGEN FUELED REGIONAL FREIGHTER AIRCRAFT

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Abstract

This paper introduces the structure and application of the Aircraft Preliminary Sizing Tool PreSTo. PreSTo has been developed by the Hamburg University of Applied Sciences and is based on the aircraft design lecture of Prof. Dr. Dieter Scholz. PreSTo supports the user in designing an aircraft based on user-defined requirements. It is especially used for educational purposes, and many students have been involved in the development of the tool. The design steps currently incorporated into PreSTo are preliminary sizing, fuselage, wing, tailplane and landing gear design. Jets as well as propeller driven aircraft can be investigated. It is shown how to use the tool for the quick initial design of kerosene- and liquid hydrogen-fueled regional freighter aircraft. The reference aircraft for this study was chosen to be the ATR 72 full freighter version. The obtained results are of good accuracy.

1. INTROCUTION

1.1. The aircraft design process

The aim of an aircraft design process is to deliver a geometrical description of a notional new aircraft. Moreover, the designer must be able to make predictions concerning the operation of that aircraft in terms of its flight performance and operating costs among others. For aircraft design education this means that the students have to get to know the process and process steps on the way to the desired knowledge about the new aircraft. At the Hamburg University of Applied Sciences (HAW Hamburg) the aircraft design lecture is given by Prof. Dr. Dieter Scholz [1], [2]. The focus of the lecture lies on the design of civil transport aircraft. The design process used is geared to methodologies presented in Corning [3], Loftin [4] and Roskam [5]. It is depicted in Figure 1.

The aircraft design process is split up into 16 steps. It starts with the determination of the requirements posed to the new aircraft and trade-off studies with existing aircraft to establish a target market niche. It follows a preliminary sizing of the aircraft that determines an aircraft design point in terms of wing loading m_{MTO}/S_W and thrust-to-weight ratio $T_{TO}/(m_{MTO} \cdot g)$ or power-to-weight ratio $P_{TO}/(m_{MTO} \cdot g)$ in case of propeller aircraft. Subsequent to the preliminary sizing where the aircraft was still treated as a point mass the aircraft fuselage is shaped as the first aircraft component as it is the only part of the aircraft that can be designed independently of the following ones. The maximum number of passengers is used in combination with comfort standards and certification requirements to obtain a fuselage cross section and cabin layout. The next design step is the sizing and shaping of the wing according to the cruise Mach number and based on handbook methods and recommendations. The following design steps comprise the sizing of the high-lift devices and tails

in different levels of accuracy ranging from quick handbook methods to the application of the stability and control data compendium Datcom published by the US Air Force Flight Dynamics Laboratory [6]. The final design steps are the calculation of the flight performance and stability and control characteristics of the now determined aircraft and an assessment of the economic efficiency in terms of the aircraft's direct operating costs. Of course, these last design steps may lead to necessary changes of the previous design steps in case the earlier assumptions cannot be met. When finally all requirements are met the fuselage cross section, cabin layout, three-view drawing and table of the aircraft's parameters and operational characteristics are prepared.

In aeronautical engineering education aircraft design lends itself very much for student projects. The students may apply the presented process for re-designs of existing aircraft or notional new ones and learn about the reasons why current aircraft look the way they do [7], [8]. Another possibility for student projects is to use individual steps of the process of the aircraft design lecture and further handbook data and program them into an aircraft design tool [9], [10], [11], [12], [13], [14], [15], [16]. Especially for these educational purposes the Aircraft Preliminary Sizing Tool PreSTo was created at HAW Hamburg.

1.2. PreSTo

This section describes PreSTo's general structure and introduces shortly the individual worksheets. Pictures of some exemplary results are shown in Section 2 where PreSTo's application to regional freighter aircraft is presented. Figure 4 gives an impression of PreSTo's user interface.
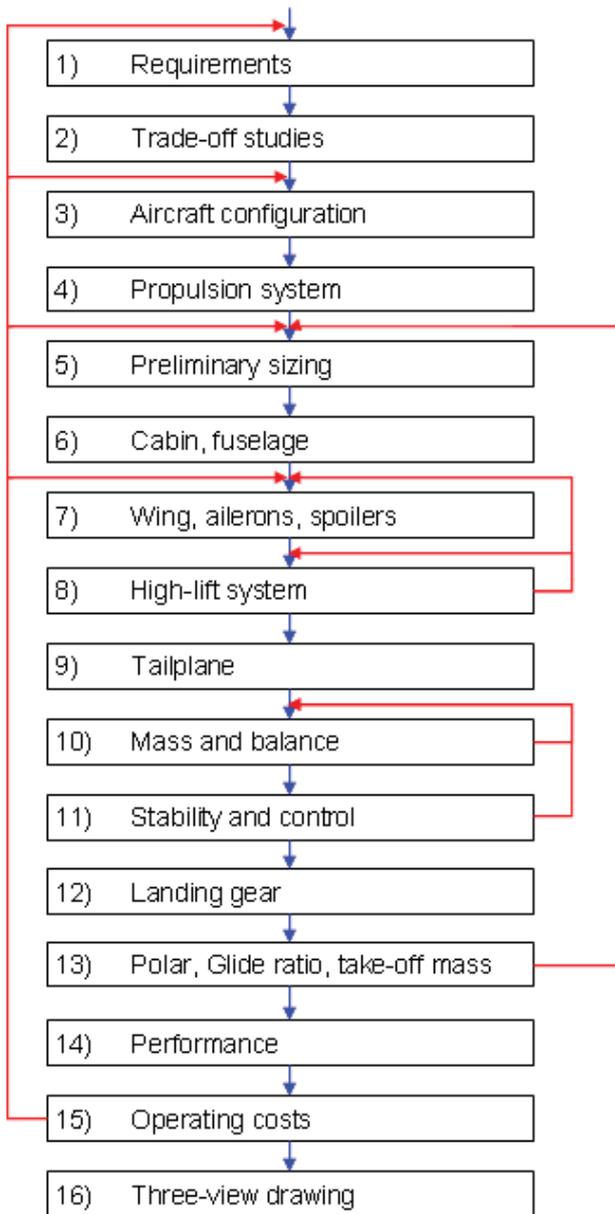
FIG 1.   Aircraft design process

1.2.1.   General

PreSTo consists of a set of Microsoft Excel worksheets of which each one treats one particular design step. This modular structure widely simplifies its application and allows for its further extension e.g. by student projects. At the time of writing this article, the following design steps have already been implemented into PreSTo or are in preparation:

- Preliminary sizing,
- Fuselage,
- Wing,
- High-lift devices,
- Tailplane (1st order),
- Landing gear (1st order),
- Tailplane (2nd order).

Statistic sheets provide the user with data on real aircraft during input data selection or estimation as decision support, and additional sheets offer links to the more in-

depth aircraft design programs:

- PrADO (Preliminary Aircraft Design and Optimization program), an in-depth and comprehensive aircraft analysis and design tool of the TU Braunschweig [17],
- CEASIOM (Computerised Environment for Aircraft Synthesis and Integrated Optimisation Methods), a Matlab application suite for the analysis of an aircraft's stability and control characteristics very early in the aircraft conceptual design phase [18].

Furthermore, a connection between PreSTo and the CAD software CATIA V5 was created. This allows for the visualization of the PreSTo result by adapting a parametric-associative CATIA V5 aircraft model.

As already mentioned, PreSTo is especially used for aircraft design education. A simplified version is available for download from http://FE.ProfScholz.de. This version has been successfully in use for almost ten years and can also be run in the spreadsheet Calc of the OpenOffice.org software suite.

1.2.2.   Preliminary sizing

The methodology applied for the preliminary sizing is based on the method described by Loftin in the NASA Reference Publication 1060 from 1980 [4]. In this method the five main requirements

- Landing field length,
- Take-off field length,
- Climb gradient after take-off (2nd segment),
- Missed approach climb gradient and
- Cruise flight (payload, cruise Mach number)

are solved simultaneously by means of one matching chart and determine the aircraft design point (see Figure 2).
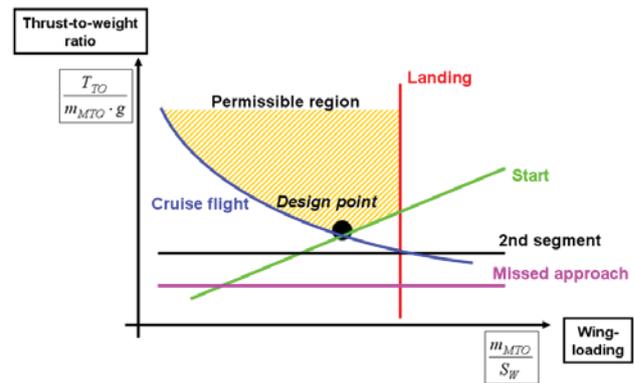
FIG 2.   Example of a preliminary sizing matching chart

In this early design step only the selected operational and certification requirements posed to the aircraft are known. But as some more information about the notional aircraft, like its maximum lift coefficient, is already necessary during preliminary sizing first estimations for these values are taken from statistics of existing aircraft (see Section 1.2.7).

PreSTo offers the concurrent preliminary sizing of a propeller and a comparative jet version. For propeller aircraft, the estimation of the propeller efficiency η_P is an iterative and essential task as – in contrast to jet engines –

the available thrust of the engines is not given directly but has to be calculated from the available engine power.

For this purpose PreSTo uses a generic propeller model for propeller efficiency estimation, which is based on data prepared by the former aircraft design professor at HAW Hamburg K. Markwardt [19] and was transformed into an empiric equation [9]:

$$(1) \quad \eta_P = \left(-0.0002L + 0.9001\right)\left(1 - e^{-\left(0.134 L^{-0.3008}\right)V}\right) \quad .$$

In this equation the propeller efficiency η_P is expressed as a function of airspeed V and propeller disc loading L, which is defined as engine power P over air density ρ times propeller disc area S_D :

$$(2) \quad L = \frac{P}{\rho S_D}$$

The corresponding units for these empiric equations are kW·m/kg for the disc loading L and m/s for the airspeed V . The standard values of the empiric correlation factors may be edited by the user if required. The resulting graph of the propeller efficiency development versus airspeed and propeller disc loading is shown in Figure 3.

The model of the correlation of engine power decrease with rising altitude is based on the Pratt & Whitney PW120 turboprop family, which is e.g. used on the ATR 72, the reference aircraft in Section 2 of this paper [7], [20]. The derived equation reads as follows:

$$(3) \quad \frac{P_{CR}}{P_0} = 1.883 \cdot M_{CR}^{0.741} \cdot \sigma^{0.929} \quad .$$

The equation used for the estimation of the thrust decrease of jet engines with rising altitude is

$$(4) \quad \frac{T_{CR}}{T_0} = \left(3.962 \cdot 10^{-7} \mu - 1.21 \cdot 10^{-5}\right)\frac{1}{\text{ft}} h_{CR} \\ - 0.0248\mu + 0.7125 \quad [1].$$

This empiric equation was also derived from real engine data prepared by Markwardt [19]. The cruise altitude h_{CR} has to be entered in ft.

FIG 3. Propeller efficiency development versus airspeed and propeller disc loading
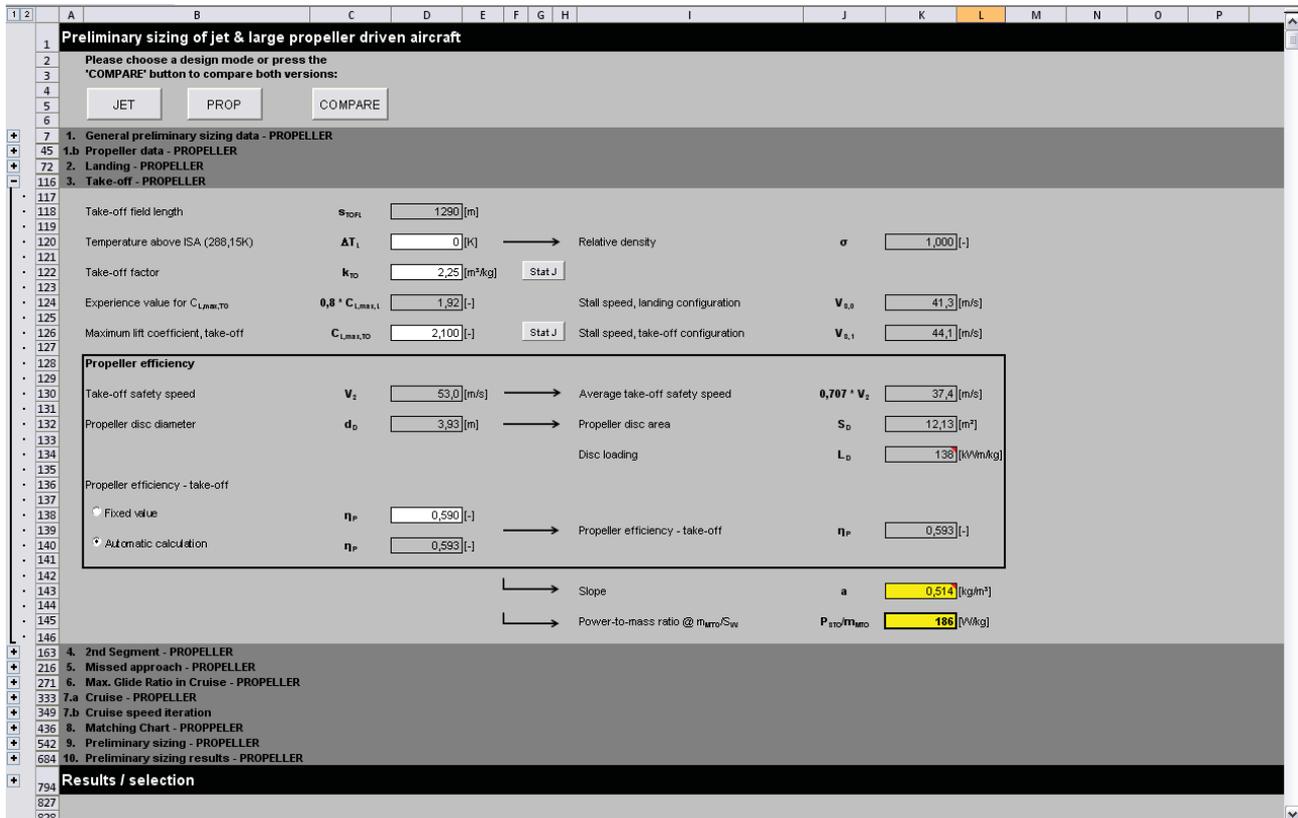
FIG 4. PreSTo preliminary sizing user interface (Section Take-off – propeller shown)

1.2.3. Fuselage

The design step "Fuselage" delivers a fuselage cross section, a floor plan and a first estimation of the overall fuselage length and shape [8], [10]. The user has the choice to work with three different aircraft versions with different numbers of passengers: a standard version using the number of passengers used in the "Preliminary sizing" section plus a stretch and a shrink version with arbitrarily less or more passengers. The possibility to use these versions was implemented to already check especially the fuselage cross section for later notional stretch and shrink versions with the same fuselage cross section. The initial input for a fuselage cross section definition is the number of seats abreast, meaning the number of passenger seats per seat row. A suggestion for this value is given by the equation

(5) $\quad n_{SA} = 0.45\sqrt{n_{PAX}} \quad$ [21].

From this number and in combination with the dimensions of the passenger, seat and aisle width a cabin diameter is determined and typical fuselage and floor thicknesses may be entered freely or selected from suggestions from different estimation methods. For the definition of the lower-deck compartment standard containers may be displayed to check for geometrical integrity.

The cabin layout is determined for a one-class arrangement. The number of seat rows is calculated from the total number of passengers and the previously defined number of seats abreast. Additional space for galleys, exits and lavatories is allocated by the program and may be added by the user. The total fuselage length results from the cabin length plus the lengths of the nose section and the tail cone; these parameters are calculated in relation to the fuselage diameter within (user defined) minimum and maximum limits.

1.2.4. Wing

The worksheet "Wing" delivers the wing's dimensions and its shape including a first estimation of aileron size and position [11]. For aileron sizing and positioning the so-called aileron volume method, which means aileron area times lever arm, is applied. Many design steps in this worksheet are aided by suggestions for possible input values based on the aircraft design lecture and additional aircraft design literature [5], [21], [22], [23]. Examples for such suggestions are

- Wing sweep relative to cruise Mach number,
- Wing taper ratio relative to wing sweep angle (Figure 5),
- Relative wing thickness relative to cruise Mach number.

Another step during wing definition is the selection of an airfoil. The geometric data of the selected airfoil is taken from a database of currently 122 airfoils and the airfoil is sketched (see Figure 6). An extension of the airfoil catalogue by the user is possible. At present, the selection of an airfoil section has no influence on further steps inside PreSTo, but it is used for airfoil adaptation of the generic CATIA V5 model and improves the realistic display of the PreSTo result (see Figure 20).

The final result of this worksheet is a sketch of the starboard wing in front view and top view including the aileron. Based on this wing geometry the available fuel tank volumes of all wing sections (center tank, inner trapezoid and outer trapezoid) are estimated using a method given by Torenbeek [22]. The result is compared to the required fuel volume determined in the "Preliminary sizing" section.
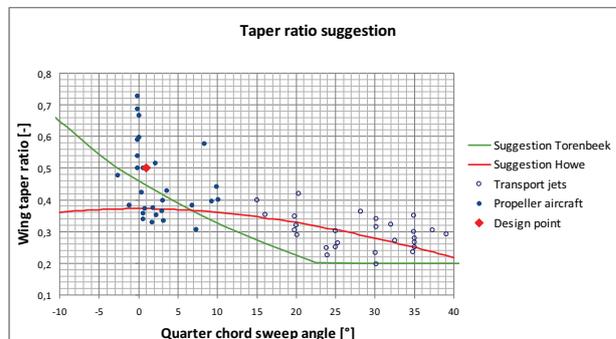
FIG 5. Example parameter suggestion chart (wing taper ratio versus quarter-chord sweep angle)
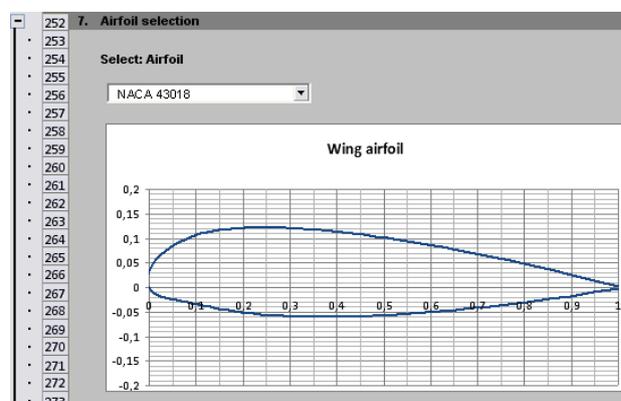
FIG 6. Wing airfoil selection

1.2.5. High-lift

The first step in the design step "High-lift" is the selection of the types of leading and trailing edge high-lift devices. The user may chose from a catalogue holding currently five types of leading edge and eight types of trailing edge high-lift devices. The positions and sizes of those devices are determined by means of suggestions from the aircraft design lecture and Howe [23].

The final outcomes are

- A wing sketch with all high-lift devices and ailerons (see Figures 15 and 16),
- A first approximate determination of the overall aircraft take-off and landing lift coefficients and
- A comparison to the initial estimates used in the preliminary sizing section.

1.2.6. Tailplane

In the "Tailplane" worksheet, first, the general arrangement of the tailplane is chosen by the user: conventional, T-tail or H-tail. Afterwards, the sizes and positions of the horizontal and vertical tails are estimated also using the volume method as in case of the ailerons earlier. The

geometric definition of horizontal and vertical tail is very similar to the process described for the wing. Also, for the vertical and the horizontal stabilizer airfoil sections may also selected by the user from the airfoil catalogue. Further improvements currently being incorporated into PreSTo at the time of writing this article aim at the consideration of

- The impact of the yawing moment of a swept wing in sideslip on the vertical tail design [12] and
- The influence of center of gravity (CG) travel during flight on the horizontal tail design [13].

1.2.7. Statistics for jets and propeller aircraft

Command buttons next to many input boxes during the design process call macros that show the related statistics worksheet and formats it in a way that the desired information are displayed and the adjacent chart is adapted (see Figure 7) [9].

1.2.8. Links to PrADO, CEASIOM and CATIA V5

Links to other programs used for aircraft design were setup in order to display, analyze and improve the initial PreSTo results. These programs are, as already mentioned, PrADO, CEASIOM and CATIA V5.

As link to PrADO a worksheet was created by a student that collects PreSTo results and prepares them as part of a PrADO input file [14]. This means that the required parameter names are used and that the correct definitions of the input arrays are prepared by PreSTo automatically. A fuselage length of 27.5 m, for example, is translated into the following PrADO input code:

```
<-LGR
  0  3   1   1
  27.5
```

This code means that the parameter "LGR" that describes the fuselage length is allocated input data of the data type "real" (3) in a 1x1-array.

Another student prepared a worksheet in which the PreSTo results are collected and prepared as input data for CEASIOM [15]. Here, the aircraft geometry is stored in the form of an xml-code that uses the correct parameter definitions for later entry into CEASIOM. The example input data for a fuselage length of 27.5 m reads as follows:

```
<Total_fuselage_length idx="1" type="double" size="1
    1">27.5</Total_fuselage_length>
```

As link to CATIA V5 a generic CATIA V5 aircraft model was created that is modified based on the PreSTo results. For this purpose, subroutines coded in VBA (Visual Basic for Applications) are used, which is the embedded programming language of both Excel and CATIA V5. At the time of writing this article this work is currently being done within the scope of a student project [16].

2. DESIGN AND COMPARISON OF REGIONAL FREIGHTER AIRCRAFT VERSIONS

This section shows how PreSTo is used for a comparative design of a set of different versions of one reference aircraft. The so-called "Full Freighter Version" of the regional aircraft ATR 72 was chosen as the reference aircraft. The reason for the selection of the ATR 72 and especially the freighter version is the importance of that aircraft for the joint research project "The Green Freighter" (GF) of the HAW Hamburg in collaboration with Airbus, the TU Braunschweig and the engineering office Bishop GmbH. Two aspects of that research project that ended in April 2010 were the setup of PreSTo as an integrated tool and its application to the investigation and comparison of
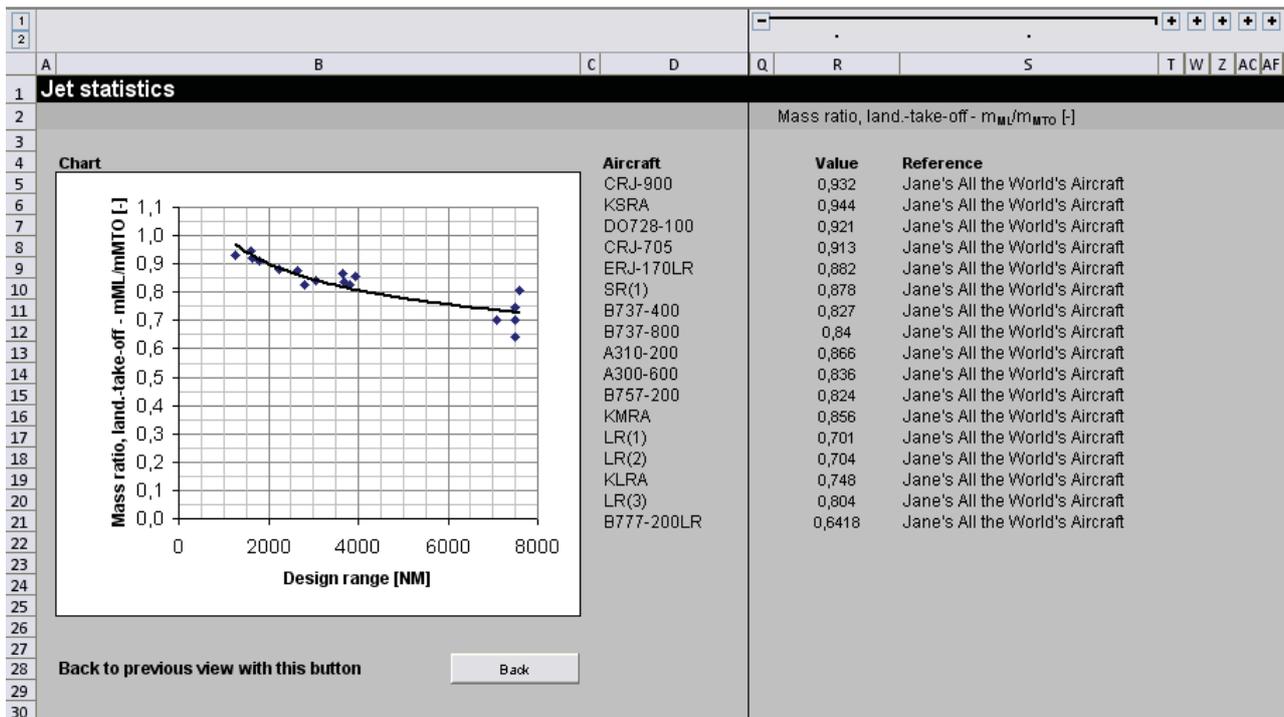
FIG 7.   Example statistics chart (ratio of maximum landing to take-off mass versus design range)

different theoretical freighter aircraft. More information on the Green Freighter project can be found on the internet on http://GF.ProfScholz.de.

The ATR 72 is a propeller-driven regional aircraft of 22 t maximum take-off mass and a maximum payload of 8.1 t. In its passenger configuration, the aircraft has a capacity of up to 74 passengers in a one-class configuration [24], [25]. Figure 8 shows a PrADO- model of the aircraft.

FIG 8.   PrADO model of the original ATR 72 full freighter version

The investigated aircraft versions and their key design features are the following:

- V01:   Kerosene-powered, propeller-driven (Ref.),
- V02 :   Kerosene-powered, jet-driven,
- V03:   Liquid hydrogen-powered, propeller-driven,
- V04:   Liquid hydrogen-powered, jet-driven.

In general, the most important differences of the hydrogen-powered versions to the kerosene-powered ones result from the hydrogen's significantly lower density (70.8 kg/m³ in liquid state versus around 800 kg/m³ for kerosene) [26], [27], [28]. Moreover, hydrogen needs to be stored at cryogenic temperatures of about 20 K (-253 °C) to stay liquid. In consequence, hydrogen requires large tanks and thermal insulation of the tanks and components. These two issues cause a significant increase in the aircraft's operational empty mass. On the other hand, hydrogen features a very high heat of combustion H_{comb} of 122.8 MJ/kg, which is about three-times as much as that of kerosene (42.8 MJ/kg). Therefore, the maximum take-off masses of hydrogen-powered aircraft result are lower than the respective kerosene versions [29].

2.1.   Preliminary sizing

2.1.1.   Input data

For preliminary sizing the process described in Section 1 is applied. The top-level aircraft requirements (TLARs) posed to all aircraft versions are based on the real ATR's performance characteristics and are listed in Table 1. A larger cruise Mach number of 0.6 was selected for the jets due to the fact that the original cruise Mach number of 0.41 is very low for jet aircraft and causes significantly inferior aircraft designs [29], [30].

As a matter of fact, there is no data available on real hydrogen-powered transport aircraft that may be used as statistical decision support for necessary input parameters such as the specific fuel consumption (SFC) or the fuel used during the individual flight segments take-off, climb, decent and landing. Therefore, these values are estimated as energy equivalent to those of typical kerosene powered aircraft by means of the different heats of combustion of

kerosene and hydrogen:

$$(6) \quad SFC_{LH_2} \approx SFC_K \frac{H_{comb,K}}{H_{comb,H_2}} \quad .$$

Moreover, for the estimation of the relative operating empty mass (m_{OE}/m_{MTO}) a typical value of concurrently prepared PrADO analyses of the ATR 72 of 0.597 is used [29], and all propeller efficiency estimations are performed automatically using the integrated generic propeller model. The most important input values selected or estimated for preliminary sizing are collected in Table 2.

TAB 1.   Top-level aircraft requirements

Parameter	Value
Design range (@ max. payload)	500 NM
Maximum payload	8093 kg
Cruise Mach number	0.41* (Prop) 0.6 (Jet)
Landing field length	1067 m
Take-off field length	1290 m
Certification basis	CS-25, FAR Part 25
Distance to alternate airport	87 NM
Loiter time	45 min

*   Econ. cruise (248 kts in 7 km) [31]

TAB 2.   Comparison of input parameters: kerosene - hydrogen

Parameter	Kerosene versions		Hydrogen versions	
	Prop V01	Jet V02	Prop V03	Jet V04
Specific fuel consumption	198 mg/Wh [7]	18.4 mg/Ns [32]	69 mg/Wh	6.41 mg/Ns
Relative operating empty mass*	0.541	0.541	0.595	0.595
Relative max. landing mass**	0.97	0.97	0.99	0.99

* m_{OE}/m_{MTO}
** m_{ML}/m_{MTO}

2.1.2.   Matching charts

The matching charts resulting from the given TLARs and input values are shown in Figures 9 and 10. Figure 9 depicts the matching chart of the propeller-driven hydrogen version V03. For comparative reasons the design point of the kerosene-powered aircraft version V01 is also shown. Figure 10 holds the complete matching chart of the hydrogen jet version V04 and the design point of its kerosene competitor V02.

It can be seen that the design points of the hydrogen versions differ slightly from those of the kerosene versions. The first difference is that both allowable wing loadings of the hydrogen-powered aircraft are lower than those of the kerosene-powered aircraft. The reason for that are the higher landing masses of the hydrogen aircraft at the same landing field length requirement and the same

maximum landing lift coefficient. Secondly, the power-to-mass ratio and the thrust-to-weight ratio of the hydrogen versions result as larger as the values of the kerosene versions. This is caused by the hydrogen aircraft's lower cruise glide ratios (see Table 4).
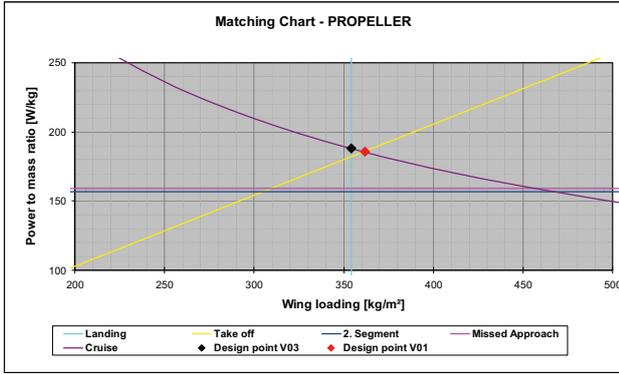
FIG 9. ATR 72 V03 (hydrogen, propeller) matching chart and V01 (kerosene, propeller) design point
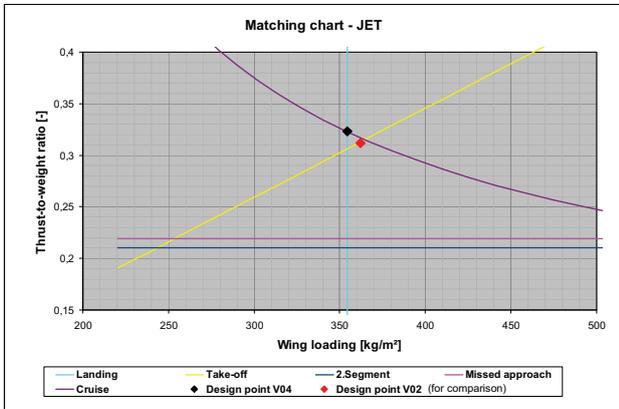
FIG 10. ATR 72 V04 (hydrogen, jet) matching chart and V02 (kerosene, jet) design point

Table 3 holds the resulting aircraft design points of the different aircraft versions in terms of wing loading and power-to-weight ratio for the propeller versions or thrust-to-weight ratio for the jet versions respectively.

TAB 3. Aircraft design points

Aircraft version	Wing loading	Thrust-to-weight ratio/ Power-to-mass ratio
V01 (K, Prop)	362 kg/m²	186 W/kg
V02 (K, Jet)	362 kg/m²	0.312
V03 (LH$_2$, Prop)	354 kg/m²	188 W/kg
V04 (LH$_2$, Jet)	354 kg/m²	0.323

2.1.3. Preliminary sizing results

Table 4 holds the resulting aircraft parameters of the individual aircraft versions.

The following general key findings can be extracted from these results:

- The required fuel volumes of the hydrogen versions are much larger than those of the kerosene versions,

which causes the need for additional space and therefore larger fuselages.
- The large tanks and larger fuselages of the hydrogen versions (see Section 2.2) cause higher aircraft empty masses and higher drag, which leads to lower glide ratios and higher engine power, respectively thrust requirements.
- The significantly smaller fuel masses of the hydrogen aircraft lead to lower maximum take-off masses.
- The mentioned differences are larger in case of the jet versions.

TAB 4. Preliminary sizing results

Parameter	Original ATR 72 [24], [25] [32]	Kerosene versions		Hydrogen versions	
		Prop V01	Jet V02	Prop V03	Jet V04
Cruise glide ratio	Not Disclosed	13.7	12.9	12.7	12.7
Cruise altitude	7.6 km*	5 km	9.8 km	4 km	10 km
Cruise speed	248 kts**	279 kts	350 kts	283 kts	349 kts
Maximum take-off mass	22 t	22.4 t	25.9 t	22 t	23.1 t
Maximum landing mass	21.35 t	21.7 t	25.1 t	21.8 t	22.9 t
Operating empty mass	11.9 t	12.1 t	14 t	13.1 t	13.8 t
Mission fuel fraction, standard flight	2 t	2.2 t	3.8 t	0.8 t	1.3 t
Required fuel volume	6.3 m³ ***	3.1 m³	5.1 m³	13.6 m³	19.9 m³
Wing area	61 m²	62 m²	72 m²	62 m²	65 m²
Take-off power/ take-off trust (one engine)	2.05 MW	2.1 MW	39.6 kN	2.1 MW	36.6 kN

*   Max. cruise altitude
**   Econ. cruise speed in 7 km [31]
***   Max. fuel capacity: 5 t

A comparison of the results of version V01 to the data of the original ATR 72 shows a good accuracy of the PreSTo results. The original maximum take-off, landing and operating empty masses are met within a region of 2 % to 8 %. The wing area and engine power are also met with an accuracy of 1.6 % to 2.4 %. Only the required fuel mass is calculated as 10 % too large. In total, these results are very good and acceptable for a preliminary re-sizing of an existing aircraft. Such a re-design offers the user the possibility to gain information on the non-disclosed aircraft data such as its maximum glide ratio or maximum lift-coefficients during landing and take-off. Reference [20] gives more information on this aspect of the application of PreSTo. In case of the ATR 72 PreSTo delivers

- A maximum glide ratio of 15.9,
- A maximum landing lift coefficient of 2.4 and
- A maximum take-off lift coefficient of 2.1.

2.2. Fuselage

2.2.1. Fuselage cross section

Fuselage cross sections prepared with PreSTo always have a circular shape. The inner and later on outer fuselage diameter may be determined on the basis of the payload dimensions. Currently, the fuselage section requires a number of passengers to define a fuselage (see Section 1.2.3). Thus, for the freighter versions in this example a substitutional number of 72 passengers is used (see Figure 12). The resulting number of four seats abreast (Eq. (5)) leads in combination with typical dimensions of passengers, seats and a typical aisle width of 46 cm to the fuselage cross section dimensions listed in Table 5.

TAB 5. Fuselage cross section dimensions

Parameter	Value
Fuselage inner diameter	2.61 m
Fuselage outer diameter	2.89 m
Floor lowering from horizontal line of symmetry	0.8 m
Floor thickness	0.13 m

These values fit well to the original ATR's data. The maximum fuselage width of the oval fuselage of the ATR 72 is 2.87 m [31]. The resulting fuselage cross section sketch including the circumferential line of an LD3 container (turned by 90 degrees) is shown in Figure 11. In the following design step the determined fuselage cross section is kept constant for all aircraft versions. Thus the data collected in Table 5 apply to all versions.
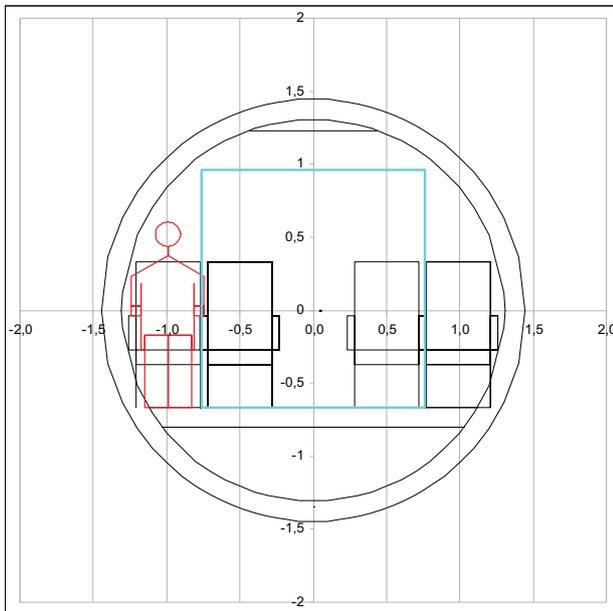
FIG 11. Fuselage cross section

2.2.2. Floor plan and overall fuselage

The definition of an aircraft floor plan is presented with relation to the 72 passengers cabin layout of the ATR 72 as shown in Figure 12. For this purpose the cabin layout of the passenger cabin is re-modeled with x-offsets of the left-hand and right-hand seat row blocks plus additional space for doors, emergency exits, lavatories and galleys. The result of the kerosene aircraft versions is shown in Figure 13. For comparative reasons to the freighter version the circumferential lines of seven LD3 containers have been added to the sketch. It can be seen that it is well possible to re-model the original cabin layout, and that the resulting floor plan is capable to store the seven LD3-containers of the original ATR 72 full freighter version. However, this design step requires a relatively large amount of user input and interaction.

For the hydrogen-powered aircraft versions only one stretched fuselage is set up for both versions. Hence, the larger jet hydrogen volume requirement is sizing. Figure 14 shows the adapted fuselage of the hydrogen versions. The fuselage is stretched in order to accommodate two liquid hydrogen tanks forward and aft of the cargo compartment (magenta colored). The tanks are estimated as integral tanks throughout the full fuselage cross section. Their inner diameter results from the outer fuselage diameter less an estimated structure and insulation thickness of 15 cm. Thus their length results in first approximation as

$$(7) \quad l_{LH2} = \frac{V_{LH2}}{2} \cdot \frac{4}{\left(d_{F,i} - 2t_{INS}\right)^2 \cdot \pi} = 1.9 \text{ m} \quad .$$

FIG 12. Real ATR 72 floor plan (72 pax)
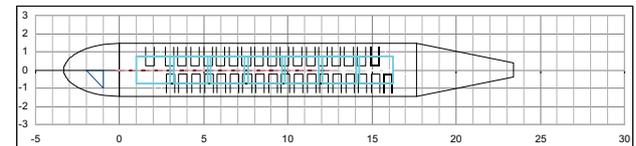
FIG 13. Fuselage top view and floor plan of kerosene versions V01 and V02
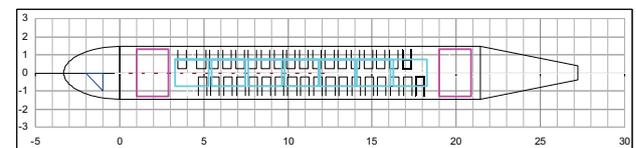
FIG 14. Fuselage top view and floor plan of hydrogen versions V03 and V04

This leads to the final overall fuselage dimensions listed in Table 6. These results fit well with the values of the original ATR 72; its available cargo compartment volume, for example, is 76 m³ [29]. In contrast to the original aircraft, the cargo compartment, respectively cabin, the PreSTo sketch does not extend into the tail cone but stops at the end of the circular center fuselage section.

TAB 6. Fuselage dimensions

Parameter	Kerosene versions	Hydrogen versions
Main deck length	17.6 m	21.4 m
Main deck volume	75.8 m³	92.2 m³
Fuselage length	26.7 m	30.5 m

2.3. Wing and high-lift devices

In the PreSTo worksheets "Wing" and "High-lift" the wing is shaped and equipped with high-lift devices according to the specifications determined during preliminary sizing. Thus, some central wing parameters such as the wing area, span and aspect ratio are already fixed, and the most important parameters determined in these design steps are

- The wing sweep angle,
- The wing position (low wing, high wing),
- The overall wing and individual trapezoids' taper ratios,
- The wing airfoil and thickness distribution,
- The aileron size and position and
- The types, sizes and positions of the leading and trailing edge high-lift devices.

The most important input parameters to perform this work are the aircraft's cruise Mach number and the landing and take-off lift coefficients estimated during preliminary sizing.

Figure 15 shows the final wing sketch of the kerosene-powered and propeller-driven version V01 including all high-lift devices as well as the aileron. For comparative reasons the wing shape and aileron position of the original ATR 72 is also shown. It can be seen that the PreSTo sketch is already very realistic and resembles the original wing planform very much. The only differences are slightly different aileron positions and the wing sweep of the outer part of the original wing that is not suggested by PreSTo at the cruise Mach number 0.41.
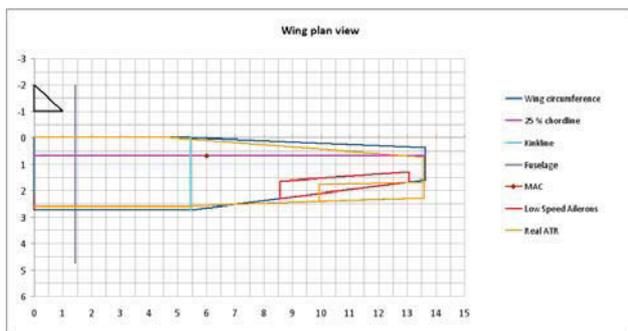
FIG 15. Final PreSTo wing sketch of version V01 including high-lift devices and aileron

Figure 16 shows the PreSTo wing sketch of version V04 (hydrogen, jet) against the original ATR 72's wing. In this example the wing of the PreSTo design is swept backwards by 7.2° as a result of the larger cruise Mach number of 0.6.

FIG 16. Wing shape V04 to real ATR 72

2.4. Tailplane

Before the fuselage, wing and tail can be positioned accurately the approximate sizes of the horizontal and vertical tail surfaces are calculated by means of the tail volume method as stated earlier. The required lever arms for this initial sizing are estimated based on the real ATR 72's geometry in case of the kerosene versions and on statistical data in case of the hydrogen aircraft versions [1], [21].

Table 7 lists the main parameters of the horizontal and vertical tailplanes. Figures 17 and 18 depict sketches of the horizontal and vertical tail sized and shaped using PreSTo.

TAB 7. Tailplane parameters

Parameter	Original ATR 72 [31]	Kerosene versions	Hydrogen versions
Lever arm horizontal tail	13.9 m	14 m	16 m
Lever arm vertical tail	12 m	11.5 m	13.5 m
Horizontal tail area	11.7 m²	V01: 9 m² V02: 11.5 m²	V03: 7.9 m² V04: 8.7 m²
Vertical tail area	12.5 m² *	V01: 11.2 m² V02: 13.9 m²	V03: 9.5 m² V04: 10.2 m²

* Excluding dorsal fin
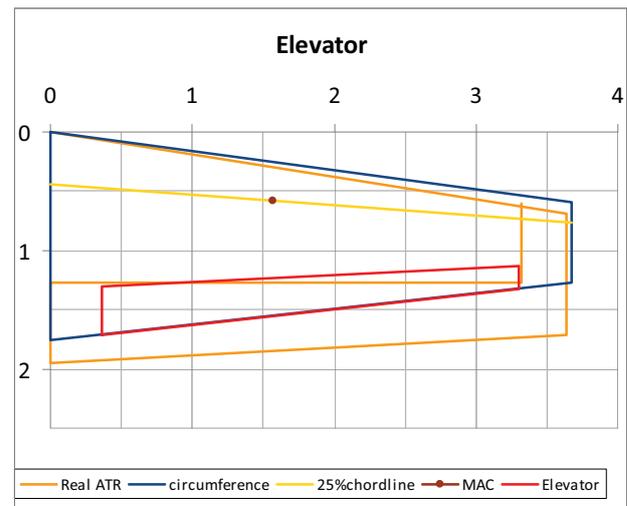
FIG 17. Horizontal tail V01 to real ATR 72
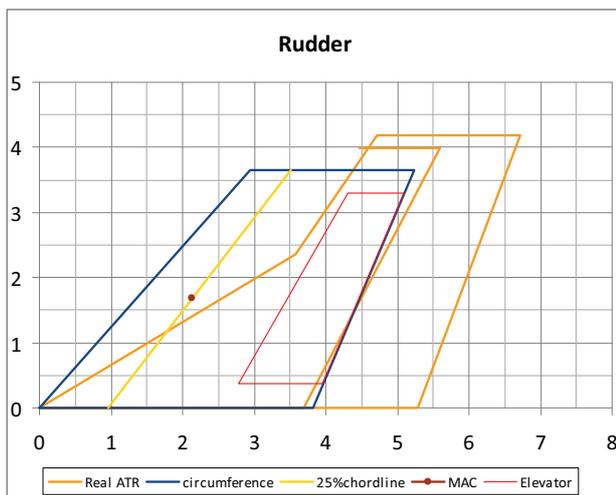
FIG 18. Vertical tail V01 to real ATR 72

It becomes apparent that the resulting tail surfaces of the hydrogen versions are smaller than those of the kerosene versions. This is due to the stretched fuselages and increased lever arms. Also, PreSTo delivers a 23 % smaller horizontal tailplane of the kerosene version V01 than that of the original aircraft. This stems at least partly from the fact that the tailplane of the original ATR 72 is still the same as that of the shorter ATR 42 despite its larger tail lever arm. This enlarges the ATR 72's horizontal and vertical tail volumes to 163 m³ and 150 m³ respectively although a quick size estimation using the tail volume method based on real aircraft [1] states that about 130 m³ would be sufficient for both tail volumes. Thus, the original ATR 72's tailplane may be regarded as oversized, and for an initial sketch of the tail the determined values lie within an acceptable order of magnitude. A second step for a more accurate sizing of the tailplane after the integration of fuselage, wing and tailplane that is based on flight mechanics [1] is being implemented at the time of writing this article.

Moreover, the PreSTo sketch shows that the shape of the vertical tail has larger differences to that of the original ATR 72. The original vertical tail blends into a dorsal fin in its lower parts giving it a triple-trapezoid shape. Here, the quick and simplified 'tail volume' method using a single-trapezoid shape cannot take into account all the flight behavior factors that led to the original vertical tail and its triple-trapezoid shape. The calculated area, however, of the vertical tail excluding the dorsal fin is calculated as only 10 % smaller than that of the original ATR 72. A possible explanation is again the oversized tailplane of the original aircraft.

2.5. PrADO, CEASIOM, CATIA V5

Figures 19 and 20 show the resulting models in CEASIOM and CATIA V5 that have been modified by the PreSTo results of the ATR 72 version V01. The preparation of these models occurred to a wide extent automatically.
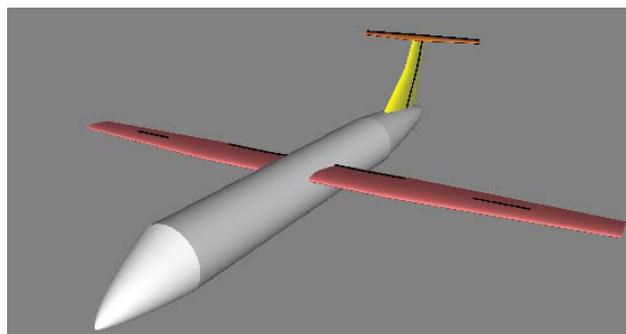
FIG 19. Display of PreSTo-result in CEASIOM (V01 shown)
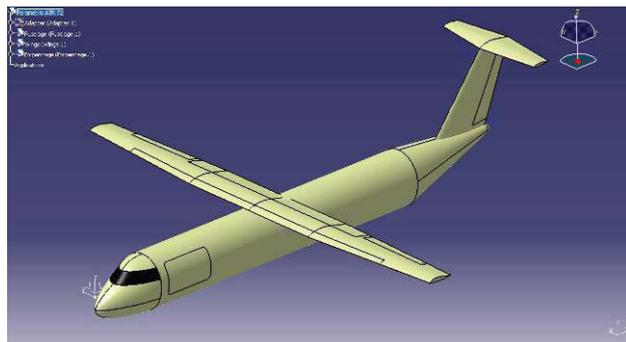
FIG 20. Display of PreSTo-result in CATIA V5 (V01 shown)

The PrADO model of the ATR 72 is shown in Figure 8. However, the preparation of a PrADO model requires so many input parameters that the PrADO-model still has to be set up manually. Nevertheless PreSTo is valuable tool for the work with PrADO especially in case of completely new aircraft designs. Here, PreSTo can be used to determine initial values for e.g. wing area, engine size or flight altitude that can be optimized using PrADO afterwards.

3. RESULTS AND CONCLUSIONS

PreSTo is a valuable tool for the hands-on education in aircraft design. It enables a quick determination of the initial size and shape of a notional new aircraft or the re-design of existing transport aircraft. The exemplary re-design process of the ATR 72 in PreSTo delivered results in realistic order of magnitude. The results of the preliminary sizing section like masses, wing area and power demand lie within a region of 2 % to 8 % deviation; only the required fuel mass is calculated as 10 % too large. An area of possible improvements is the tailplane design section, and important extensions, first and foremost a mass estimation section, are still required. Both issues are currently being worked on.

PreSTo is also valuable in combination with more comprehensive aircraft design tools such as PrADO. In contrast to PrADO PreSTo does not *analyze* but *design* a new notional aircraft. PreSTo delivers initial suggestions for the aircraft's size and shape that can be used as starting values for analyses and optimizations of the aircraft using PrADO.

PreSTo is a 'living' program. It is constantly being improved and extended especially by student projects. The

reports of all mentioned student projects can be downloaded from http://Bibliothek.ProfScholz.de.

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NOMENCLATURE

$d_{F,i}$	Fuselage inner diameter
H_{comb}	Heat of combustion
L	Propeller disc loading, $L = \dfrac{P}{\rho S_D}$
M	Mach number
m_{ML}	Maximum landing mass
m_{MTO}	Maximum take-off mass
m_{OE}	Operating empty mass
n_{PAX}	Number of passengers
n_{SA}	Number of seats abreast
P	Propeller engine Power
S_D	Propeller disc area
T	Jet engine thrust
t_{INS}	Insulation thickness
V	Airspeed
V_{LH2}	Liquid hydrogen tank volume
η_P	Propeller efficiency
μ	Jet engine bypass ratio
ρ	Air density
σ	Relative air density, $\sigma = \dfrac{\rho}{\rho_0}$

Indices

CR	Cruise
H_2	Hydrogen
K	Kerosene
0	At mean sea level (MSL)

ABBREVIATIONS

ATR	Avions de Transport Régional
CAD	Computer Aided Design
CATIA	Computer Aided Three-Dimensional Interactive Application
CEASIOM	Computerised Environment for Aircraft Synthesis and Integrated Optimisation Methods
CG	Center of Gravity
CS	Certification Specification
EASA	European Aviation Safety Agency
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FL	Flight Level (FL100 = 10,000 ft)
GF	Green Freighter
HAW	University of Applied Sciences (German: Hochschule für Angewandte Wissenschaften)
LH2	Liquid Hydrogen
MSL	Mean Sea Level
PrADO	Preliminary Aircraft Design and Optimization program
PreSTo	Aircraft Preliminary Sizing Tool
SFC	Specific fuel consumption
TLAR	Top-Level Aircraft Requirement
V5	Version 5
VBA	Visual Basic for Applications

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