CEAS COUNCIL OF EUROPEAN AEROSPACE SOCIETIES
Aerospace Europe
6th CEAS Conference

A Java Toolchain of Programs for Aircraft Design

Agostino De Marco,
Assistant professor
Department of Industrial Engineering (DII) – University of Naples "Federico II"
Via Claudio 21, 80125 Napoli - ITALY
E-mail: agodemar@unina.it

Vincenzo Cusati,
PhD Student
Department of Industrial Engineering (DII) – University of Naples "Federico II"
E-mail: vincenzo.cusati@gmail.com

Vittorio Trifari,
PhD Student
Department of Industrial Engineering (DII) – University of Naples "Federico II"

Manuela Ruocco,
PhD Student
Department of Industrial Engineering (DII) – University of Naples "Federico II"

Fabrizio Nicolosi,
Associate professor
Department of Industrial Engineering (DII) – University of Naples "Federico II"

Pierluigi Della Vecchia
Assistant professor
Department of Industrial Engineering (DII) – University of Naples "Federico II"

ABSTRACT

The purpose of this work is to provide a comprehensive overview of JPAD (Java toolchain of Programs for Aircraft Design), a java-based framework conceived as a fast and efficient tool useful as support in the preliminary design phases of an aircraft, and during its optimization process. The software platform is made to perform fast multi-disciplinary analysis of an established aircraft configuration and to search for an optimized configuration in a domain, whose boundaries are defined by the user. The following sections will focus on the description of the software structure and on the results obtained from a case study carried out assuming as baseline a regional turboprop aircraft model similar to ATR-72.

KEYWORDS: **AIRCRAFT DESIGN, SOFTWARE ENGINEERING, JAVA**

NOMENCLATURE

Latin
AEA – Association of European Airlines
AEO – All Engines Operative
ATA – Air Transportation Association of America
BFL – Balanced Field Length
DAF – Design of Aircraft and Flight technologies research group
ECAC – European Civil Aviation Conference
C_L – Lifting coefficient
DOC – Direct Operating Costs
FAR - Federal Aviation Regulations
GUI – Graphical user interface
ICAO – International Civil Aviation Organization
JPAD – Java toolchain of Programs for Aircraft Design
M – Mach number
MTOW – Maximum Take-Off Weight
OEI – One Engine Inoperative
OEW – Operating Empty Weight
Re – Reynolds number
T/W – Thrust ratio
TNAC – Transport Aircraft Noise Classification Group
V – Aircraft speed
W/S – Wing loading
XML - eXtensible Markup Language
XLS – Excel file format

Greek
α_b – angle of attack in body reference frame
α_w – angle of attack of the wing in local reference frame

Subscripts
$C_{L\,max}$ – Maximum lifting coefficient
$C_{M\,cg}$ – Pitching moment coefficient referred to the aircraft center of gravity
V_{sTO} – Aircraft stall speed in take-off configuration
Z_{cg} – vertical position of the center of gravity in body reference frame

1 INTRODUCTION

Nowadays the preliminary design phase of an aircraft is becoming very challenging due to the need for more demanding requirements which deals with different fields of applications. In this perspective, there is a certain need for simple design tools both in aircraft industries and academic research groups which can perform fast and reliable multi-disciplinary analyses and optimizations.
This paper provides a comprehensive overview of JPAD (Java toolchain of Programs for Aircraft Design), a Java-based open-source library conceived as a fast and efficient tool useful as support in the preliminary design phases of an aircraft, and during its optimization process. The library has been completely realized at the Department of Industrial Engineering of the University of Naples "Federico II" where is still in development.
The main goal of this library is to perform fast multi-disciplinary analyses of a parametrically defined aircraft model and to search for an optimized configuration. All the basic principles and approaches to aircraft preliminary design and analysis, followed during the development of the tool, are well described in some Aircraft Design textbooks. [1] [2] [3] [4] [5] [6] [7].
One of the main features of JPAD lies in the smart management of both the aircraft parametric model, which is conceived as a set of interconnected and parameterized components, and the available analyses. The library has been developed with the purpose of simplify the composition of the input file for the user and doing fast analysis with a satisfying grade of accuracy [8] [9]. Section 2 will show the library architecture ant its main advantages. Another key point is the possibility to easily interface JPAD with other external tools in order to achieve a higher level of accuracy.
As stated in [10], the JPAD library is an alternative to a plethora of similar software tools, both freeware and commercial. Most of these tools have an important history, and many of them have been in use for decades. Some of them were conceived with poor software design criteria, have a rigid textual input and come with no visualization features.
This is the main reason why JPAD has been developed paying a lot of attention to simplicity and flexibility. Moreover, it has been conceived as an open-source tool differently from the most popular aircraft design programs available, such as Advance Aircraft Analysis [11], RDS [12] or Piano [13].
JPAD is a general computational library that includes several modules, among which is important to highlight the aerodynamic and stability ones. These are based on several prediction methodologies, developed by the DAF research group of the University of Naples "Federico II", like the ones used for the fuselage [14] [15] or the vertical tail [16] [17] analyses. The capability to develop such methodologies derives from the experience gained by the group, both through numerical analyses and wind tunnel tests, during several years of activity in the field of application of regional turboprop and general aviation aircraft, as explained in [18] [19] [20].
Since JPAD must perform also multi-disciplinary optimizations, the DAF group has growth also in this field of application as described in [21] [22] [23] [24].

2 SOFTWARE STRUCTURE

To achieve a clear input file organization a considerable study has been done. The result is an input structure composed by different XML files with the purpose to allow users to easily manage all data needed to execute the desired analyses. In Fig. 1 the entire structure of the software is schematized. It is possible to clearly note that there are two main blocks: input and core.
The input block is defined by two main parts: aircraft and analyses definitions. The first one defines the aircraft model in parametric way using a main file (Aircraft.xml, see Fig. 3) which collects all the components, linking them to their related xml file (i.e. fuselage.xml, vtail.xml, and so on) which contains all geometrical data.
The second one defines all necessary data for each analysis presents into core module (see Fig. 2). Since the aircraft model contains only geometrical data, it is necessary to define several further data referred to each analysis.

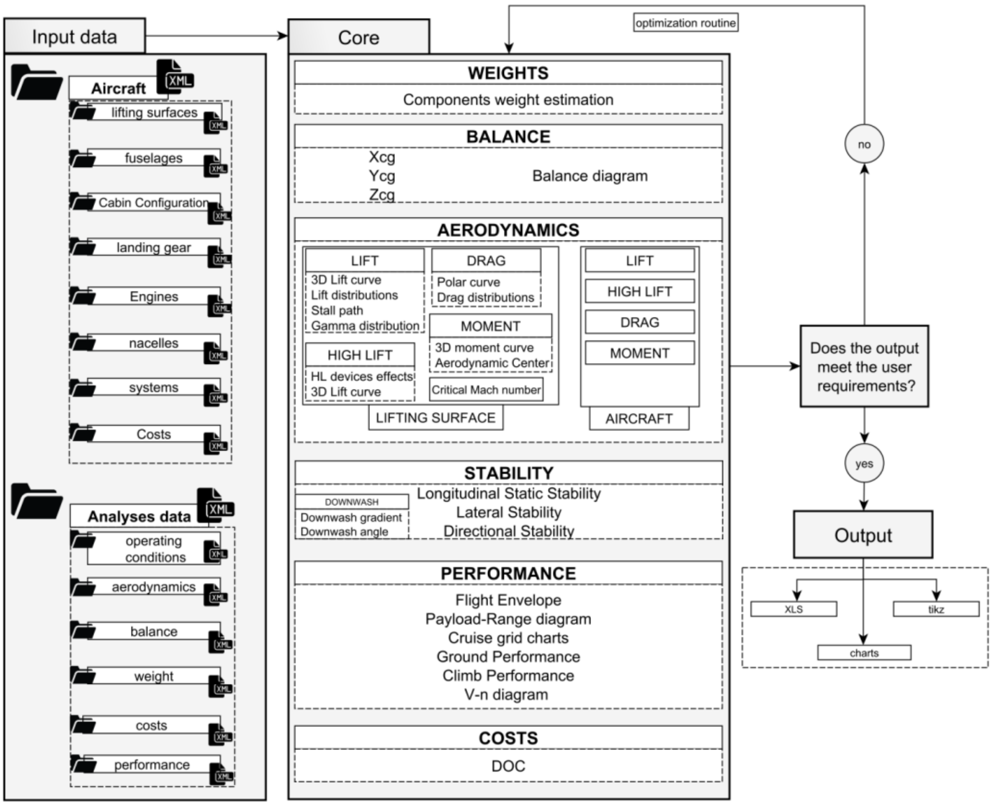

Figure 1: JPAD schematic flow-chart.

```
<?xml version="1.0" encoding="utf-8"?>
<jpad_config>
        <!-- Input data, shared across analysis tasks -->
        <global_data>
                <n_limit>2.5</n_limit>
                <cruise_lift_coefficient>0.45</cruise_lift_coefficient>
                <reference_range unit="nmi">825</reference_range>
                <maximum_altitude_at_maximum_speed unit="ft">16000</
                    maximum_altitude_at_maximum_speed>
                <maximum_cruise_mach_number>0.43</
                    maximum_cruise_mach_number>
                <optimum_cruise_altitude unit="ft">16000</
                    optimum_cruise_altitude>
                <optimum_cruise_mach_number>0.45</
                    optimum_cruise_mach_number>
                <block_time unit="h">1.5</block_time>
                <flight_time unit="h">1.35</flight_time>
        </global_data>
        <!-- Required analysis tasks -->
        <analyses id="JPAD Test analysis">
                <weights
                        file="analysis_weights.xml"
                        method_fuselage="JENKINSON"
                        method_wing="ROSKAM"
                        method_htail="JENKINSON"
                        method_vtail="JENKINSON"
                        method_canard=""
                        method_nacelles="TORENBEEK_1976"
                        method_landing_gears="ROSKAM"
                        method_systems="TORENBEEK_2013"
                        /> <!-- method_XXX="AVERAGED" if not present -->
                <balance
                        file="analysis_balance.xml"
                        method_fuselage=""
                        method_wing=""
                        method_htail=""
                        method_vtail=""
                        method_canard=""
                        /> <!-- method_XXX="AVERAGED" if not present -->
                <aerodynamics file="analysis_aerodynamics.xml"/>
                <performance file="analysis_performance.xml"/>
                <costs file="analysis_costs.xml"/>
        </analyses>
</jpad_config>
```

Figure 2: An example of the analysis.xml file.

Aircraft.xml

```xml
<?xml version="1.0" encoding="utf-8"?>
<jpad_config>
        <aircraft id="JPAD Test Aircraft DAF-2016" type="JET" regulations="FAR_25">
                <global_data>
                        <cabin_configuration file="cabin_configuration.xml">
                        </cabin_configuration>
                </global_data>
                <lifting_surfaces>
                        <wing file="wing.xml">
                                <position>
                                        <x unit="m">12.0</x>
                                        <y unit="m">0.0</y>
                                        <z unit="m">-0.5</z>
                                </position>
                                <rigging_angle unit="deg">2.0</rigging_angle>
                        </wing>
                        <horizontal_tail file="htail.xml">
                        <vertical_tail file="vtail.xml">
                </lifting_surfaces>
                <fuselages>
                        <fuselage file="fuselage.xml">
                </fuselages>
                <power_plant>
                        <engine file="engineTurbofan.xml">
                        <engine file="engineTurbofan.xml">
                </power_plant>
                <nacelles>
                        <nacelle file="nacelle.xml">
                        <nacelle file="nacelle.xml">
                </nacelles>
                <landing_gears file="landing_gear.xml">
                </landing_gears>
                <systems file="systems.xml">
                </systems>
</aircraft>
</jpad_config>
```

Wing.xml

```xml
<?xml version="1.0" encoding="utf-8"?>
<jpad_config>
        <aircraft id="JPAD Test Aircraft DAF-2016" type="JET" regulations="FAR_25">
                <global_data>
                        <main_spar_non_dimensional_position type="PERCENT_CHORD"
                            ref_to="LOCAL_CHORD">0.25</
                            main_spar_non_dimensional_position>
                        <secondary_spar_non_dimensional_position type="
                            PERCENT_CHORD" ref_to="LOCAL_CHORD">0.55</
                            secondary_spar_non_dimensional_position>
                        <composite_correction_factor>0.1</
                            composite_correction_factor>
                        <roughness unit="m">0.405e-5</roughness>
                </global_data>
                <equivalent_wing>
                        <surface unit="m^{2}">36.9</surface>
                        <aspect_ratio>13.09</aspect_ratio>
                        <non_dimensional_span_station_kink>0.363</
                            non_dimensional_span_station_kink>
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                        <twist_at_tip unit="deg">-2.5</twist_at_tip>
                        <dihedral unit="deg">2.5</dihedral>
                        <taper_ratio>0.556</taper_ratio>
                        <x_offset_root_chord_leading_edge unit="m">0.477</
                            x_offset_root_chord_leading_edge>
                        <x_offset_root_chord_trailing_edge unit="m">0.367</
                            x_offset_root_chord_trailing_edge>
                        <airfoils>
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                                <airfoil_kink file="naca63209.xml"/>
                                <airfoil_tip file="naca63209.xml"/>
                        </airfoils>
                </equivalent_wing>
                <panels>
                        <panel id="Inner panel">
                        </panel>
                        <panel id="Outer panel" linked_to="Inner panel">
                        </panel>
                </panels>
                <symmetric_flaps>
                </symmetric_flaps>
                <slats>
                </slats>
                <asymmetric_flaps>
                </asymmetric_flaps>
                <spoilers>
                </spoilers>
</aircraft>
</jpad_config>
```

Figure 3: An extract from a general aircraft.xml input file.

The structure described above allows to generate different aircrafts, or different configurations of the same model, combining different components. Table 1 shows how to generate several aircrafts starting from a given reference model, by changing the wing and the power plant.

Table 1: Creation of different aircraft models from the same reference

REFERENCE	**NEW MODEL 1**	**NEW MODEL 2**	**NEW MODEL 3**
FUSELAGE	FUSELAGE	FUSELAGE	FUSELAGE
WING	**WING 1**	**WING 2**	**WING 3**
HORIZONTAL TAIL	HORIZONTAL TAIL	HORIZONTAL TAIL	HORIZONTAL TAIL
VERTICAL TAIL	VERTICAL TAIL	VERTICAL TAIL	VERTICAL TAIL
POWER PLANT	**POWER PLANT 1**	**POWER PLANT 2**	**POWER PLANT 3**
LANDING GEAR	LANDING GEAR	LANDING GEAR	LANDING GEAR

The possibility to generate a series of different aircrafts in a simple and fast way, allows to easily perform comparisons between these latter. For example, assuming different wings and engines as shown in Table 1, it is possible to estimate the effects that some design parameters have on a specific output. Fig. 4 shows how the FAR-25 take-off field length behaves with different values of the wing surface and the engine static thrust at fixed aircraft maximum take-off weight. This feature plays also a key role in the optimization process described in Fig. 1.

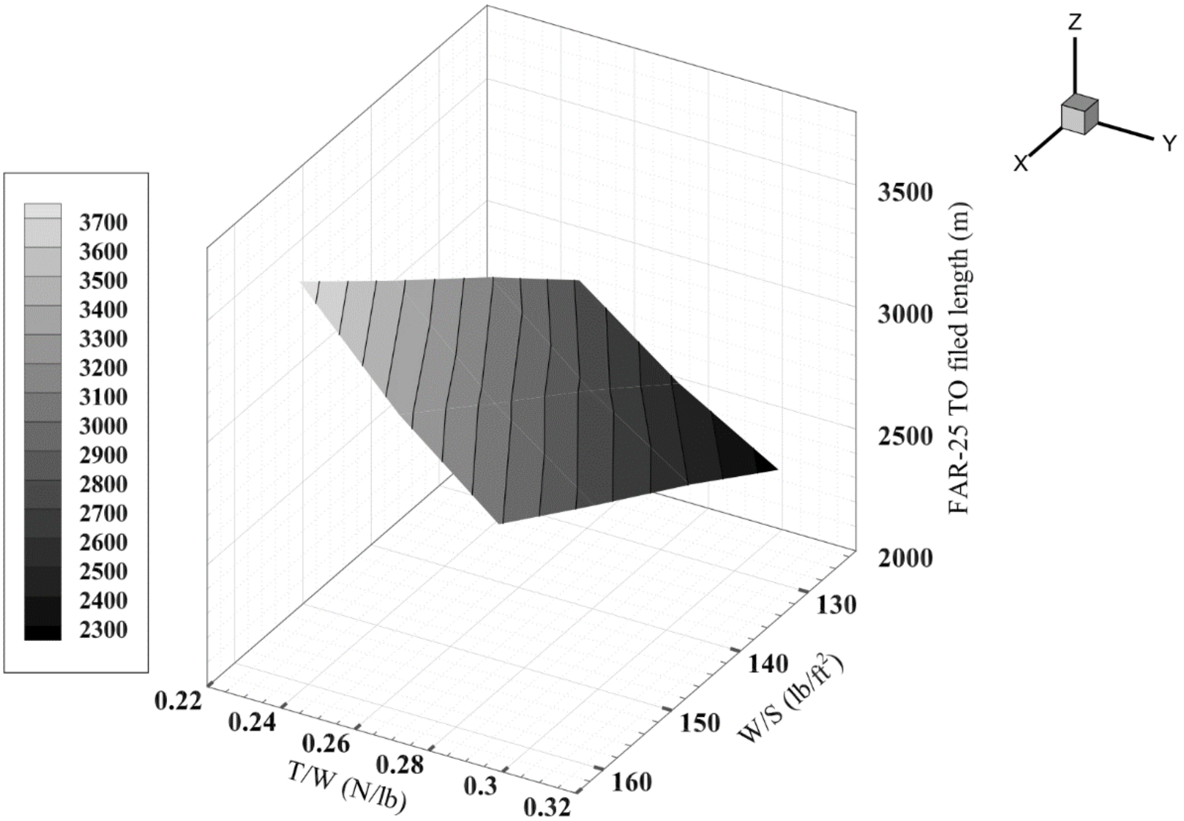


Figure 4: FAR-25 take-off field length at different wing loadings W/S and thrust-weight ratios T/W.

In the same way, it is possible to perform a complete analysis (those present into core block in Fig. 1), or a specific one, combining different analyses files (see Fig. 2). This allows an easier evaluation of generic cost function during optimization tasks resulting in reduced amount of computational costs required for this kind of operations.
Besides the input, the second main block is the core which manages all the available analyses. This contains several independent modules, as shown in the Fig. 1, that deals with following application fields.

- **Weights**: estimates the aircraft weight breakdown starting from a first guess maximum take-off weight and some mission requirements. In particular, it evaluates each aircraft component mass using well-known semi-empirical equations [1] [5] [6] [7]

- **Balance**: estimates the center of gravity position related to each weight condition and draws the balance diagram.
- **Aerodynamics and Stability**: the aerodynamics module estimates all the aerodynamic characteristics concerning lift, drag and moments coefficients at different operating conditions for each aircraft component (wing, tails, fuselage and nacelles). Whereas the stability module gives useful data about static stability of the whole aircraft considering non-linearity effects as well.
- **Performance**: evaluates most important aircraft performance such as Payload-Range diagram, mission profile, cruise flight envelope, ground performance, climb performance and the cruise grid chart.
- **Costs**: estimates the DOC breakdown.

JPAD allows to obtain different kind of output: charts and data in XLS format (as shown in Fig. 5). In this way, the comparison between two or more aircraft (or simply between slightly different configurations of the same aircraft) is easier and more efficient.

Description	Unit	Value
Ground roll distance	m	763.4976659
Rotation distance	m	165.4983558
Airborne distance	m	231.5465274
AEO take-off distance	m	1160.542549
FAR-25 take-off field length	m	1334.623931
Balanced field length	m	1225.663607
Ground roll distance	ft	2504.913602
Rotation distance	ft	542.9736083
Airborne distance	ft	759.6670847
AEO take-off distance	ft	3807.554295
FAR-25 take-off field length	ft	4378.687439
Balanced field length	ft	4021.20606
Stall speed take-off (VsTO)	m/s	53.67149021
Decision speed (V1)	m/s	55.82318509
Rotation speed (V_Rot)	m/s	56.35506473
Minimum control speed (VMC)	m/s	46.98027511
Lift-off speed (V_LO)	m/s	60.77409554
Take-off safety speed (V2)	m/s	63.95159767
Stall speed take-off (VsTO)	kn	104.3290307
Decision speed (V1)	kn	108.5115909
Rotation speed (V_Rot)	kn	109.5454822
Minimum control speed (VMC)	kn	91.32234902
Lift-off speed (V_LO)	kn	118.1353909
Take-off safety speed (V2)	kn	124.3119609
V1/VsTO		1.04
V_Rot/VsTO		1.05
VMC/VsTO		0.88
V_LO/VsTO		1.13
V2/VsTO		1.20
Take-off duration	s	31.51824683

TAKE-OFF | CLIMB | CRUISE | DESCENT | LANDING | MISSION PROFILE | PAYLOAD-RANGE

Figure 5: A detail of the output XLS file for the performance analysis.

An important element of JPAD is the graphical user interface (GUI). The GUI of JPAD is completely designed using the JavaFX library [25] and the related development tool JavaFX Scene Builder [26]. Building the GUI means to find a perfect compromise between functionalities and simplicity. In fact, JPAD must handle the management of an entire aircraft as well as complex multi-disciplinary analyses and optimizations. To make as easier as possible the use of this tool, a sort of wizard paradigm has been used to guide the user from the definition of the aircraft model to the output visualization, passing through the analyses manager.
At first, as shown in Fig. 6, the user must define all the folders in which the software expects to find the following resources:

- the input files;
- the external resources, such as engine decks and databases containing data about methodologies formulation;
- the folder in which all the output files and charts must be stored.

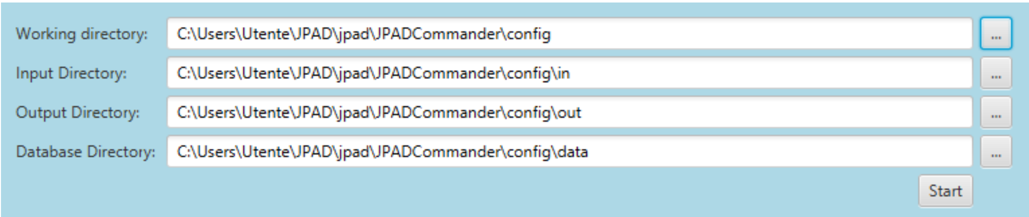


Figure 6: Definition of the required folders.

After that the user must follow the guideline of the main three buttons shown in Fig. 7. Focusing on the input manager, the user can simply define an aircraft model by loading it from an external XML file, or by choosing it among a list of possible default aircrafts.
The structure of this manager has been designed using different tabs; this with the aim of giving a complete overview of the aircraft, and its component, without having to manage too many data all in one time.
As shown in Fig. 8, each tab is provided with an input area with all the text fields related to every single data, a text area with a detailed overview of the object in exam, and the graphic representation of the component with its three views.

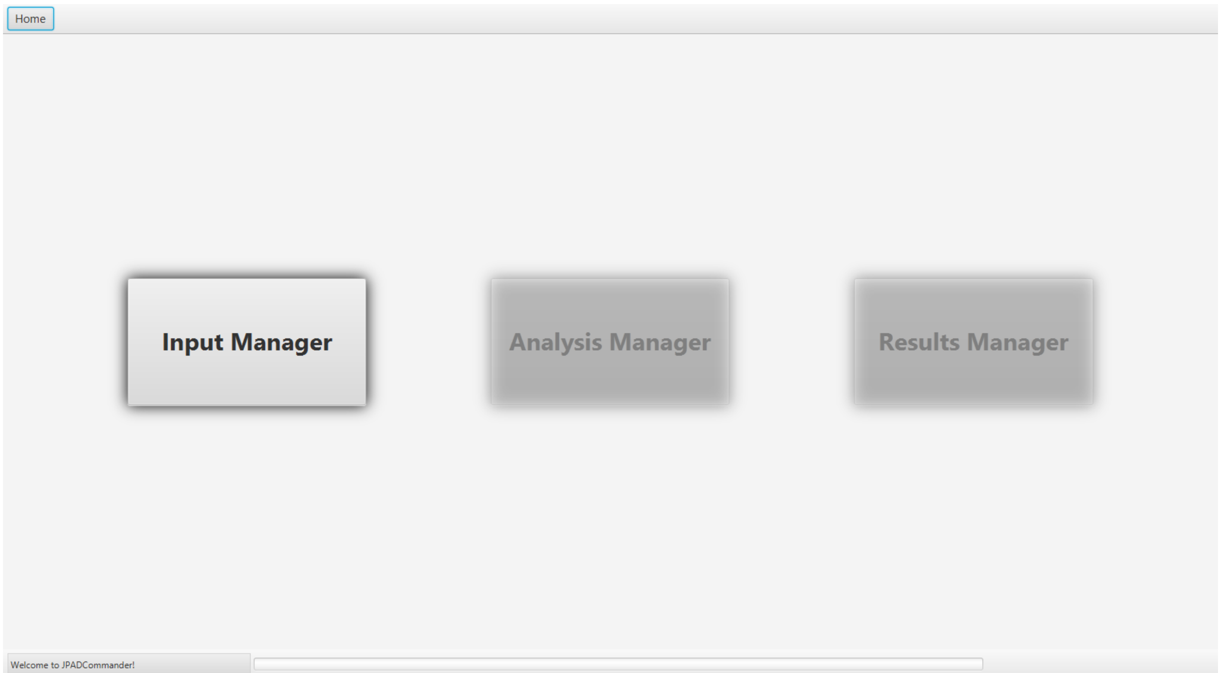


Figure 7: JPAD GUI main view.

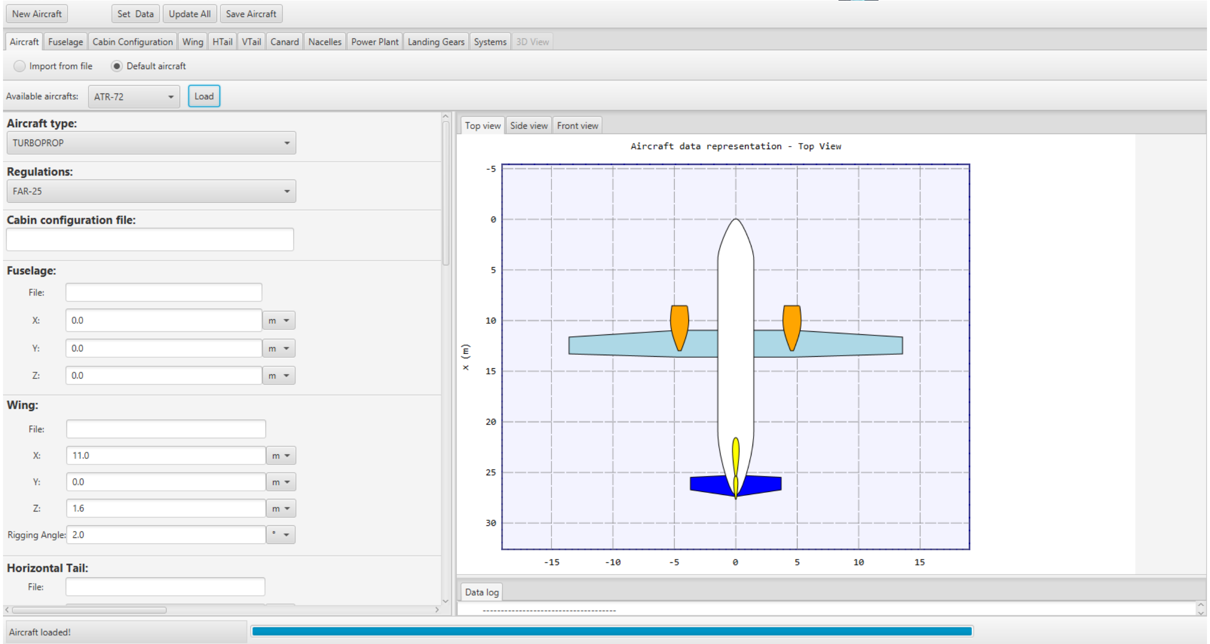


Figure 8: JPAD GUI input manager view.

3 CASE STUDY: ATR-72

To show the potentiality of the JPAD library, a multi-disciplinary analysis has been performed assuming a parametric aircraft model similar to the ATR-72. The analysis results that will be reported concerns lift and longitudinal static stability analysis (including the non-linear effects) as well as some of the main performance and the DOC. These latter will also be compared to public domain data from online brochures and flight manuals.

3.1 Aerodynamics and Longitudinal Stability

Using JPAD, is possible to evaluate the lift coefficient curve both of an airfoil, by means of the internal aerodynamic database based on [27], and of a 3D lifting surface as shown in the Fig. 9 using data in Table 2.

Table 2: ATR-72 model airfoil data

Station	Airfoil	*Re*	$C_{L\,max}$
Root	NACA 23018	$6.28{\cdot}10^6$	1.65
Kink	NACA 23018	$6.28{\cdot}10^6$	1.65
Tip	NACA 23015	$4.41{\cdot}10^6$	1.70

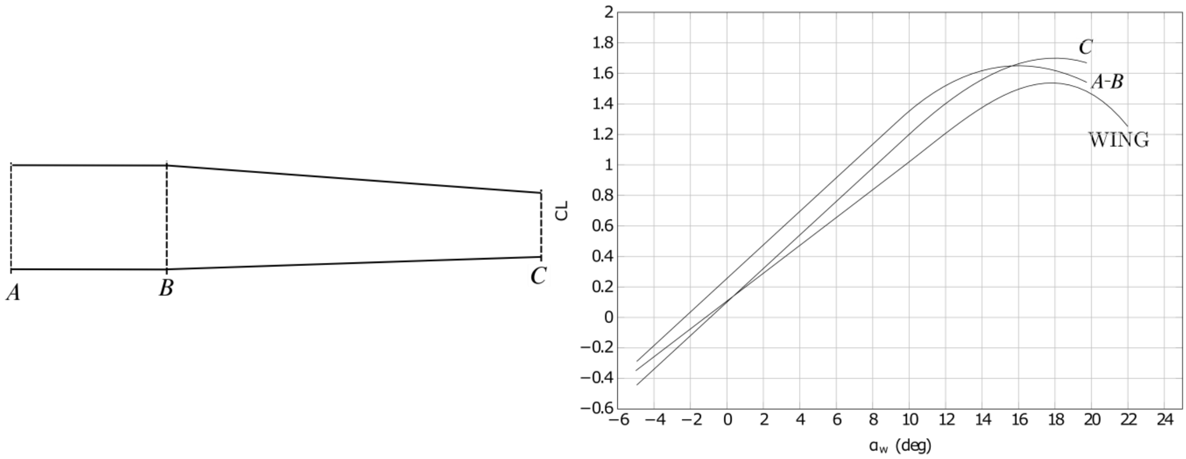


Figure 9: 2D and 3D lift results for regional turboprop. M=0.2. [28]

All aerodynamic results are then incorporated in the module in charge of the longitudinal static stability analysis, which can be executed for a given aircraft at a fixed flight condition.
An important JPAD innovation is that the downwash gradient and the related angle have been evaluated considering a variable distance between the horizontal tail and the vortex plane, improving the formulations proposed in [29]. In this way, the downwash calculation turns out to be more accurate.
The stability calculation considers also the propulsion effects, the fuselage pitching moment effect [14], and the pendular stability due to the axial component of the aerodynamic force.
The charts from Fig. 10 to Fig. 14 show the results obtained for the regional turboprop under examination.

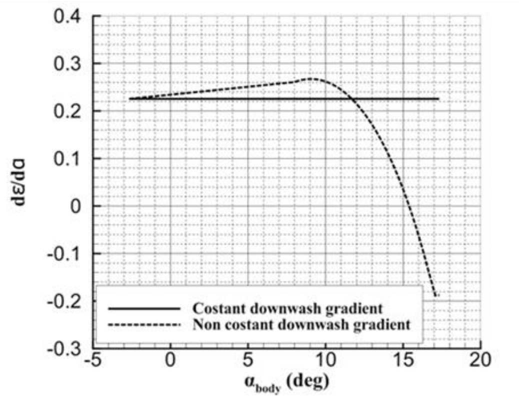


Figure 10: Variability of downwash gradient at M=0.4. [28]

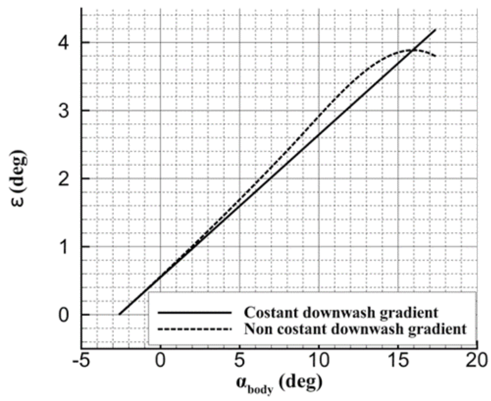


Figure 11: Variability of downwash angle at M=0.4. [28]

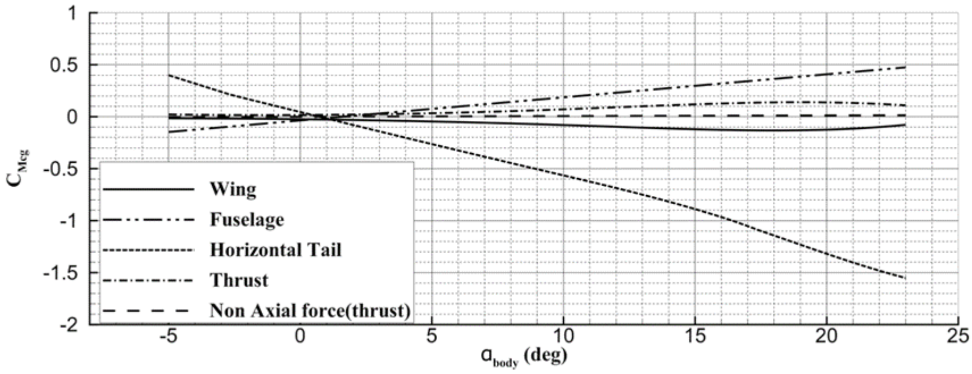


Figure 12: $C_{M\mathrm{cg}}$ vs. α_b of aircraft components – Cruise condition. [28]

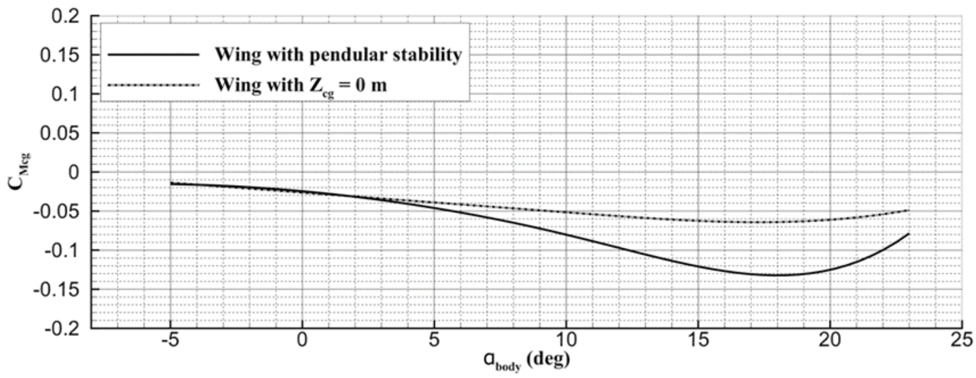


Figure 13: $C_{M\mathrm{cg}}$ vs. α_b for the wing with and without pendular stability – Cruise condition. [28]

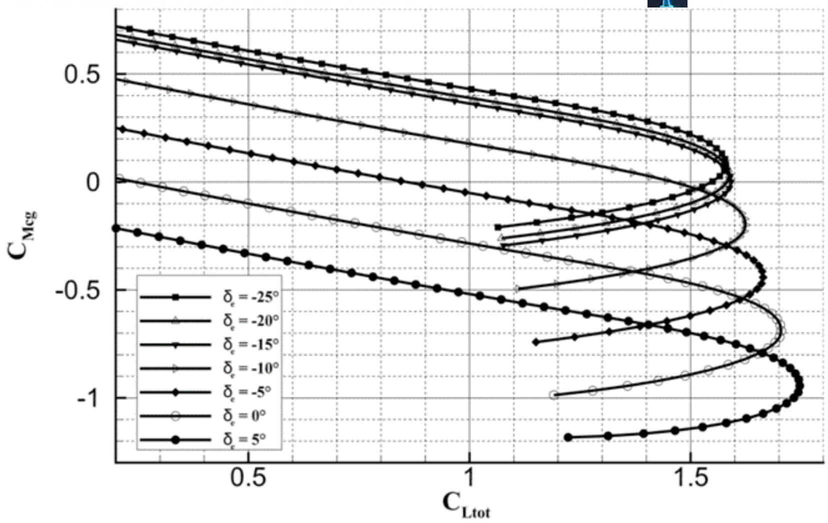


Figure 14: $C_{M\text{cg}}$ vs. $C_{L\text{tot}}$ with elevator deflections – Cruise condition. [28]

3.2 Performance

Most of the performance analyses carried out by JPAD are simulation-based to achieve a higher fidelity level with respect to classical semi-empirical formulations. One remarkable example can be found in [10] concerning the ground performance evaluation.
JPAD can perform in less than 30 seconds the following performance calculations using the results of the aerodynamics and stability module.

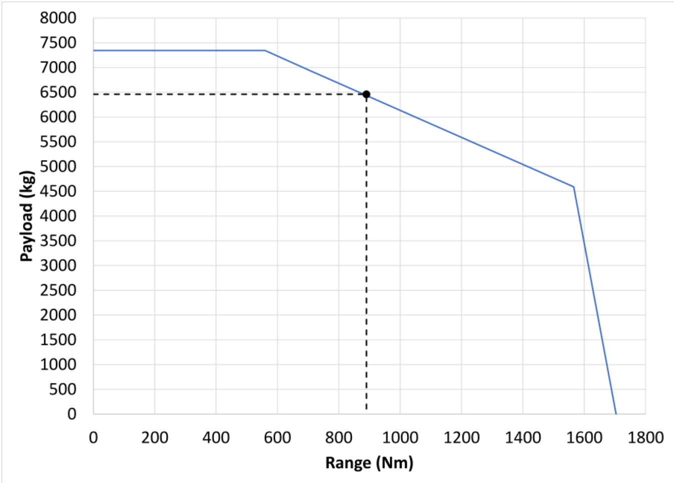
- Take-off
- Climb (AEO and OEI)
- Cruise
- Descent
- Landing
- Mission profile analysis
- Payload-Range
- Flight maneuvering and gust envelope

To show the level of accuracy achieved by JPAD, some relevant performance will be compared with the data from the brochure of the ATR-72 [30]. Fig. 15 to Fig. 17 show respectively the Payload-Range chart, the balanced field length evaluation and the cruise flight envelope; while Table 3 provides the above-mentioned numerical comparisons. To perform these analyses a turboprop engine deck has been modeled starting from the ones proposed in literature.

Table 3: Numerical comparisons between JPAD performance and public domain data

PERFORMANCE	JPAD	ATR-72 brochure [30]	Difference (%)
Design Range (with 68 passengers at 95kg)	890 Nm	890 Nm	<1.0%
Balanced Field Length	1225 m	1223 m	<1.0%
FAR-25 Landing Field Length	1162 m	1048 m	10.9%
Max cruise Mach number at 17kft	0.440	0.444	<1.0%
Service ceiling AEO	26709 ft	25000 ft	6.8%
Service ceiling OEI	14712 ft	14200 ft	3.6%

As can be seen from Table 3, the maximum difference between the JPAD output and the brochure data is never bigger than 11% proving the reliability of the library. The biggest difference can be found in the FAR-25 landing field length and this may be due to the use of a simplified semi-empirical evaluation of the airborne phase, or to the uncertainty of some simulation parameters of the ground roll phase.



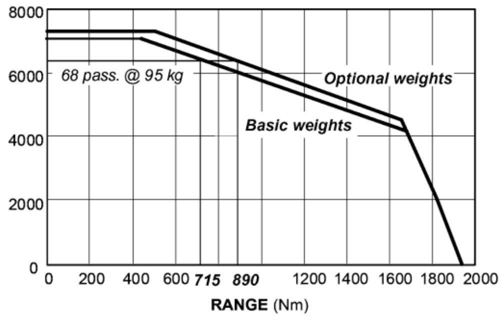


Figure 15: Payload-Range comparison between JPAD (left) and the ATR-72 brochure [30] (right) for the optional weights condition.

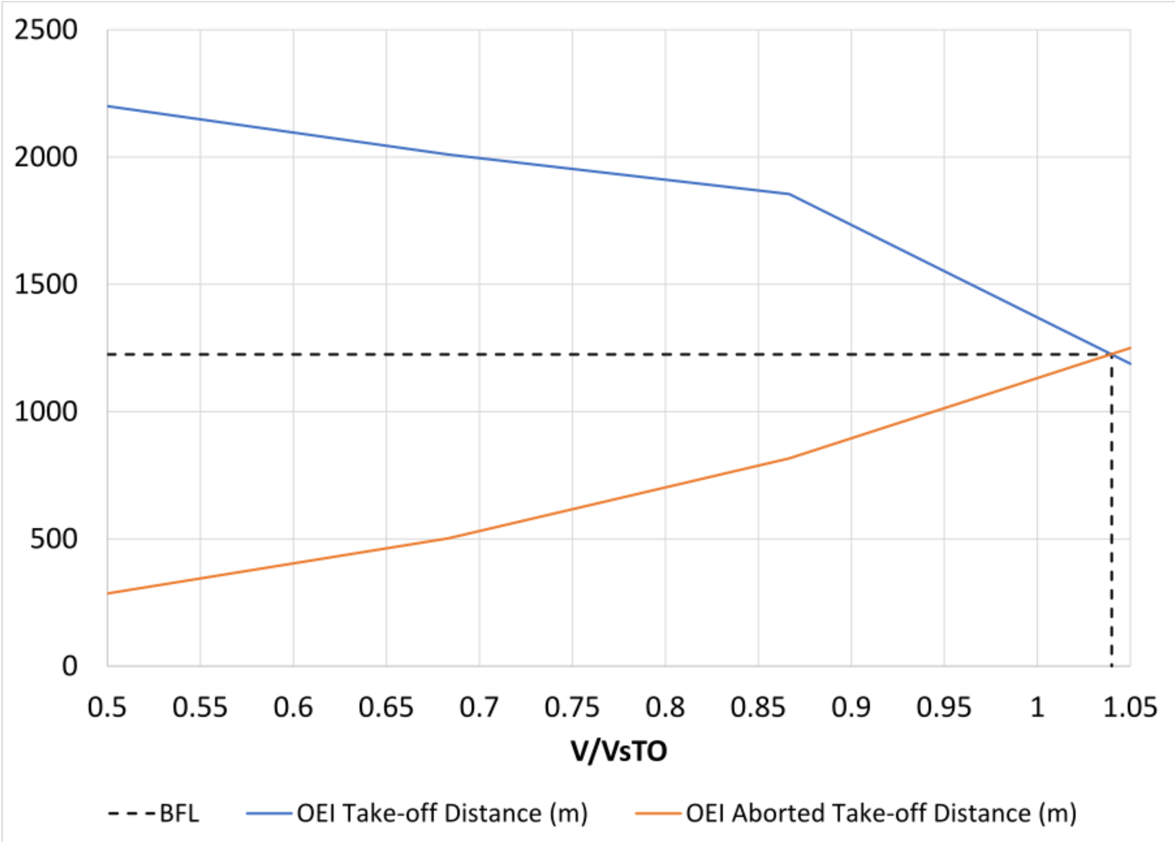


Figure 16: Balanced Field Length evaluation in JPAD

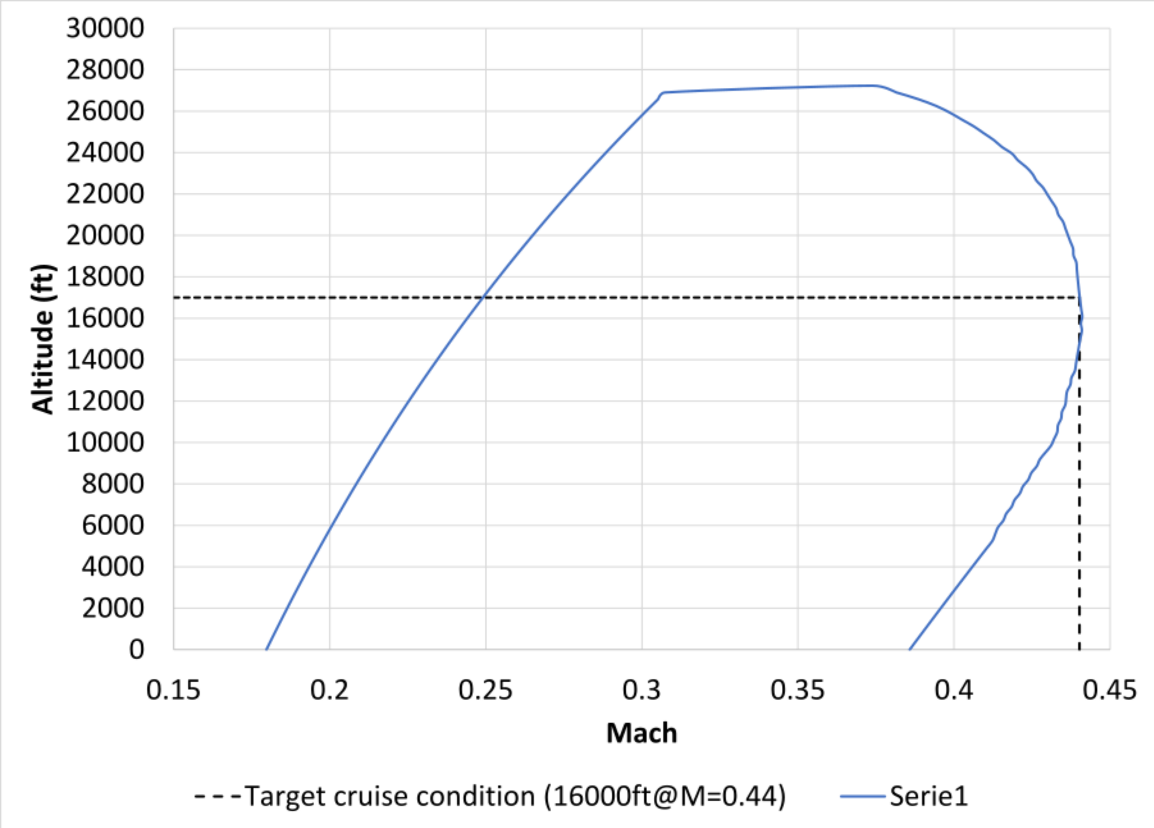


Figure 17: Cruise flight envelope evaluation in JPAD

3.3 Costs

An import feature of JPAD is the capability of the estimation of the Direct Operating Costs (DOC). This concerns flight operations and consider different items:

- **Capital costs**: depreciation, interest, and insurance.
- **Fuel cost**.
- **Charges**: landing, navigation, ground handling, noise, emissions.
- **Crew costs**: flight and cabin.
- **Direct maintenance**: airframe and engine

To estimate these cost items, the methodologies defined by AEA [31] for capital, fuel, a part of charges (landing, navigation and ground-handling) and crew costs has been implemented while the ATA [32] method has been used for direct maintenance costs. Noise charges are calculated by using the formulation recommended by the Transport Aircraft Noise Classification Group (TNAC) within the European Civil Aviation Conference (ECAC) [33] [34]. The emissions charges are estimated using formulation prescribed by ICAO in annex 16 volume 2 [35].
In this section, to compare the JPAD results with respect to data present in a ATR-72 brochure [30], only the cash DOC composed by fuel, crew, maintenance and charges has been considered. In Table 4 and Table 5 the economic assumptions and weights and performance data used for the comparison are respectively resumed.

Table 4 Economic assumptions for DOC

Economic Assumptions		
Life span	12	years
Residual value	0.2	
No. seats	68	
Aircraft price	14.4	Mil.$
Engine price (each)	1.0	Mil.$
Spares	1.84	Mil.$
Interest	5.0%	per year
Insurance	1.0%	per year
No. of flights	2700	flights
Utilisation	2484	hr/year
Block Time	0.92	hr
Block Fuel (mission)	611	kg
Fuel Price	0.8	$/gal

Table 5 Data for DOC estimation

Performance		
Range (Mission)	200	nm
Mach cruise	0.44	
Power	2750	shp
SFC	0.45	lbm/lbs*hr
TO Thrust	7700	lbs
No. Engines	2	
Weights		
MTOW	22000	kg
OEW	12950	kg
PAYLOAD	7050	kg
FUEL max	5000	kg
Engine Weight	480	kg
Airframe Weight	11990	kg

The results are shown in Table 6 in terms of cash DOC per trip and pie charts in Fig. 18 and Fig. 19. It is possible to see a good agreement except for the airframe maintenance. This is due to lack of public domain data, both for engine and airframe, which can be useful to conceive a more accurate methodology. The difference in landing charges may be due to the different data environment. In fact, ATR-72 brochure refers to US environment while JPAD uses the formulation suggested by European airliners.

Table 6 JPAD costs results comparison

	BROCHURE ($/trip) [30]	**JPAD ($/trip)**
Fuel	182	183
Engine maintenance	120	148
Airframe maintenance	117	261
Crew	145	147
Landing fee	109	135
Total cash DOC	**673**	**868**

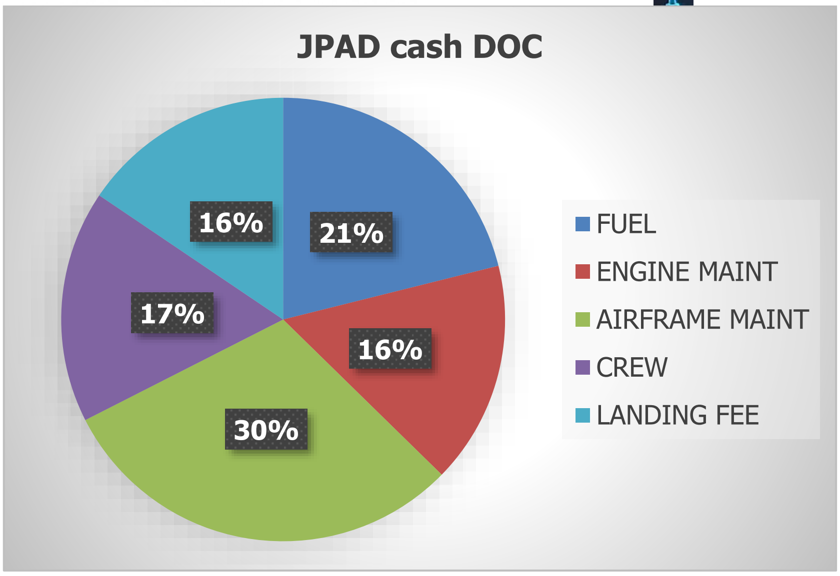


Figure 18 JPAD estimation of cash DOC for ATR-72

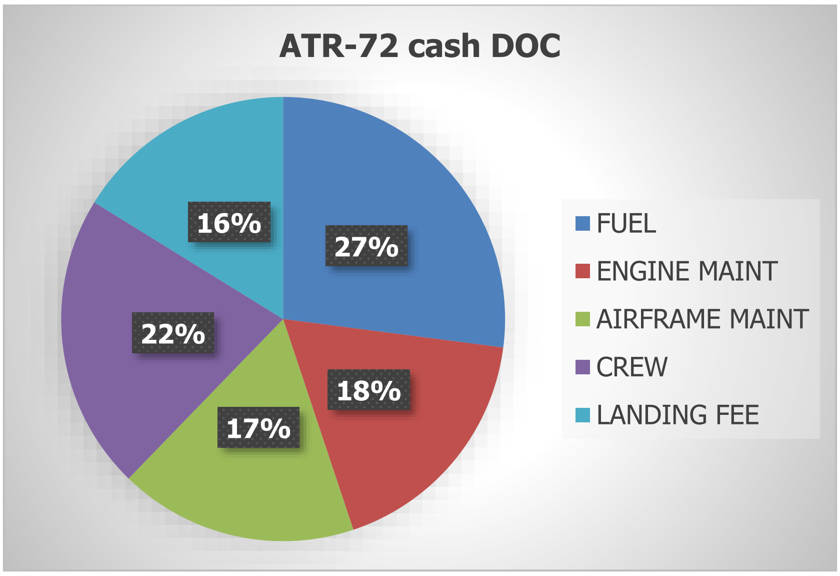


Figure 19 Cash DOC ATR-72 [30]

ACKNOWLEDGMENT

The research presented in this paper has been performed in the framework of the project CERVIA PON03PE_00124_1 (Metodi di CERtificazione e Verifica Innovativi ed Avanzati) proposed by DAC (Campania Aerospace District) and financed by the Italian MIUR (Italian Ministry for Research and Education).

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