Development of a Java Framework for Parametric Aircraft Design

The Performance Analysis Module

UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II

Relatori:
prof. Fabrizio Nicolosi
prof. Agostino De Marco

Candidato:
Vittorio Trifari
M53/411

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Introducing JPAD - Java Programs for Aircraft Design

- A software toolchain for aircraft preliminary design and MDO
- A modern, user friendly, modular framework.
- Support for simultaneous management/analysis of several aircraft and/or 'varied' configurations of the same aircraft.
- Conceived for collaborative design activities.
- Interoperability with other tools/disciplines (CAD/CFD/FEM analysis).

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Main features

- Define a parametric representations of a complete aircraft with XML configuration/input files.
- Generate CAD geometries of aircraft assembly and sub-components. Measure lengths, areas, volumes.
- Perform various types of analysis (L0, L0.5, L1): **Aerodynamics**, **Stability & Control**, **Performance**, **Weight & Balance**, **Costs.**
- Exports analysis results in XML and Excel formats. Produce useful output charts for each analysis.
- Perform iterative analysis in order to reach an optimum configuration. (Work in progress)

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Java. Why?

- Language widely supported. This avoids the library to become obsolete due to the aging of the programming language used.
- The language promote the use of open source libraries, especially for I/O tasks and for complex mathematical operations.
- Widely supported GUI frameworks (SWT/JFace and JavaFX) and a GUI visual builders.
- Object-Oriented paradigm is naturally applied in the abstraction of typical Aircraft Design problems.
- Promotes modularity: easier to work with in an ever changing team.

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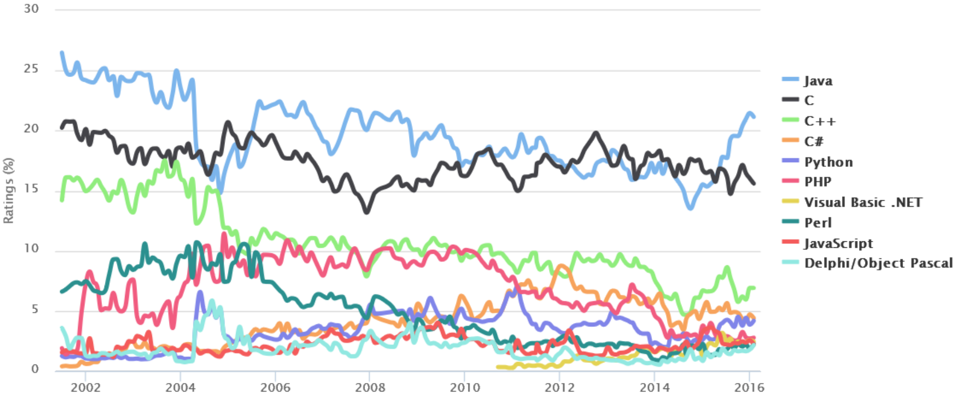
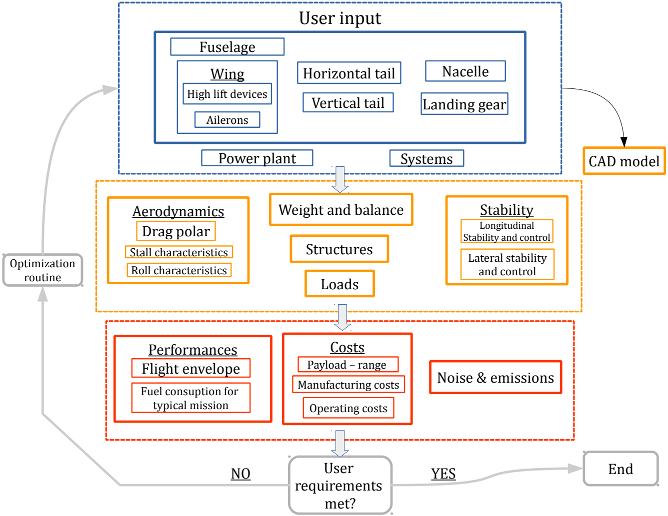
TIOBE Programming Community Index



JPAD typical work session



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Input file

The input file type chosen is the XML (*eXtensible Markup Language*). It is a markup language that defines a set of rules for encoding documents in a format which is both *human-readable* and *machine-readable*; moreover its design goals of emphasize simplicity, generality and usability across the Internet.

- *Markup Language* due to the use of tags that describes the content.
- *extensible* because the markup symbols are unlimited and self-defining, so that it is possible to use a personal tag for each data.

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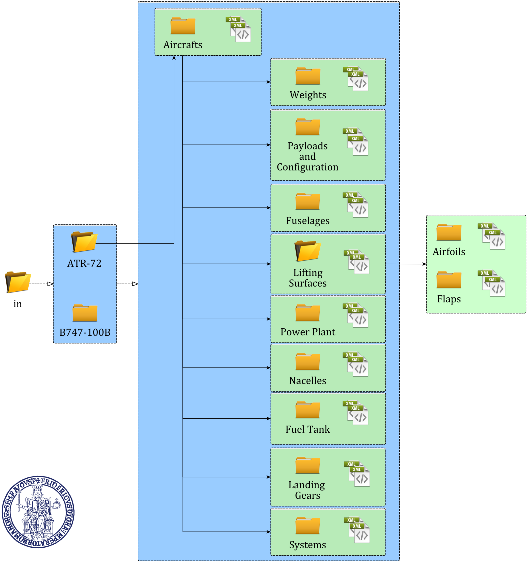
Input file structure prototype



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        <wings>
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                <position>
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                    <y unit="m"> 0.0</y>
                    <z unit="m"> 2.0</z>
                </position>
                <rigging_angle unit="deg">2.0</rigging_angle>
            </wing>
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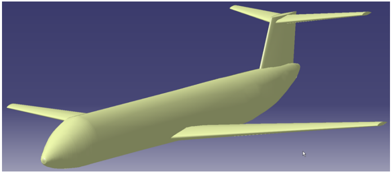
                    <y unit="m">0.0</y>
                    <z unit="m">0.0</z>
                </position>
            </fuselage>
        </fuselages>
    </aircraft>
</jpad_config>
```

JPAD Output

- XML
- Microsoft Excel
- Charts
- CAD model



Multiple aircraft analysis result comparisons

		ATR72	F100	A320	B747_100B
Description	**Unit**	**Value**	**Value**	**Value**	**Value**
Material density	kg/m³	2711.00000	2711.00000	2711.00000	2711.00000
Maximum zero fuel mass	kg	19998.24551	34774.75497	56206.95596	192272.98603
Maximum landing mass	kg	20698.42095	40968.19348	68104.61636	305739.45542
Maximum take off mass	kg	22998.24550	45516.48164	75668.59596	339684.42269
Fuselage mass	kg	3203.33333	5378.00000	8392.66667	32349.66667
Wing mass	kg	2332.50000	4722.00000	8519.00000	40195.00000
HTail mass	kg	212.00000	461.50000	619.50000	3429.50000
VTail mass	kg	275.00000	369.50000	459.00000	1938.33333
Nacelle mass	kg	143.50000	389.50000	753.00000	1321.50000
Landing gear mass	kg	763.00000	1656.33333	2076.00000	13485.50000
Structure mass	kg	7072.83333	13366.33333	21572.16667	96684.00000
Power plant mass	kg	1329.14176	4134.85560	7647.87160	22087.08000
Systems mass	kg	2324.25622	3231.22575	4447.76585	12935.29415
Furnishings and Equipment mass	kg	1252.00000	1853.00000	2891.00000	0
Manufacturer empty mass	kg	11978.23131	22585.41468	36558.80412	131706.37415
Crew mass	kg	306.05819	459.08729	535.60184	1377.26187
Operating Items mass	kg	585.95600	939.25300	1292.55000	4739.35000
Operating empty mass	kg	12870.24551	23983.75497	38386.95596	137822.98603
Passengers mass	kg	6732.00000	10791.00000	14850.00000	54450.00000
ZeroFuelMass	kg	19602.24551	34774.75497	53236.95596	192272.98603

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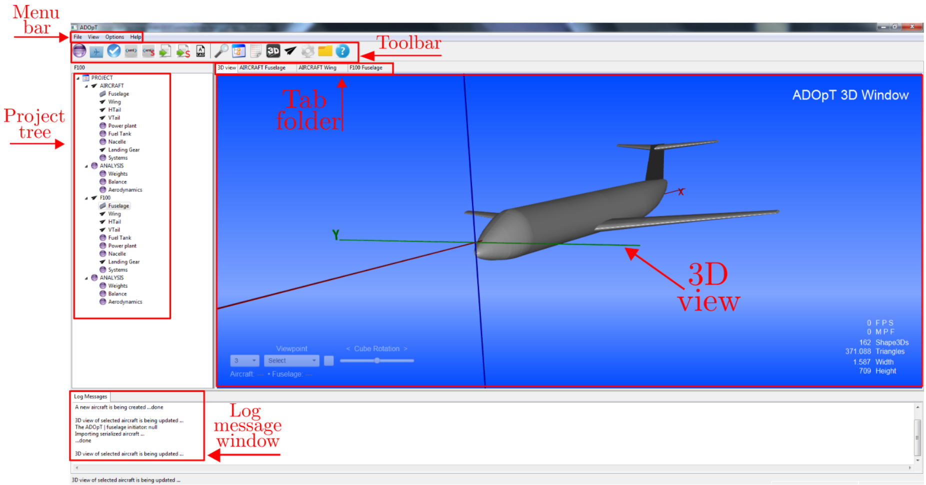
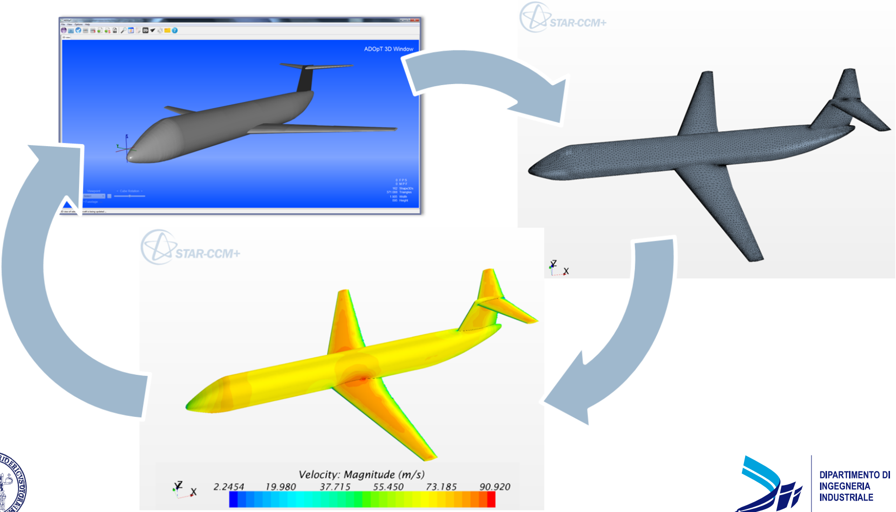
ADOpT GUI

- Menu bar, holds all the available actions.
- Toolbar, holds the actions needed to interact with the application.
- Project tree, provides access to all the aircraft components and the analysis results any time.
- 3D view, shows the CAD model which can be updated each time.
- Log message window, tells the status of pending operations.
- Tab folder, contains all the windows opened.

ADOpT GUI - Layout



Interoperability



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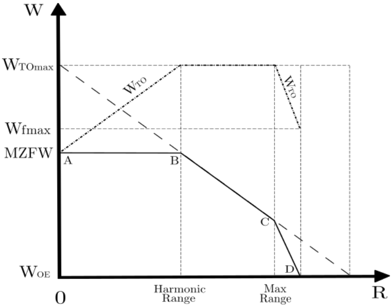
Payload-Range chart construction

- Point A: Maximum payload at zero range. (Already known)
- Point B: Range at maximum payload and maximum take-off weight.
- Point C: Range at maximum take-off weight with maximum fuel in fuel tanks.
- Point D: Range with maximum fuel in fuel tanks and no payload.



Breguet equation propeller aircraft

$$R = 603.5 \left(\frac{\eta_p}{SFC}\right) \left(\frac{L}{D}\right) \ln\left(\frac{W_i}{W_f}\right)_{\text{cruise}}$$

Breguet equation jet aircraft

$$R = \left(\frac{V}{SFCJ}\right) \left(\frac{L}{D}\right) \ln\left(\frac{W_i}{W_f}\right)_{\text{cruise}}$$

DIPARTIMENTO DI INGEGNERIA INDUSTRIALE

Payload-Range chart construction

- Point B: $W_{TO,\text{max}} = W_{OE} + W_{\text{payload,max}} + W_{\text{fuel}}$
- Point C: $W_{TO,\text{max}} = W_{OE} + W_{\text{payload}} + W_{\text{fuel,max}}$
- Point D: $W_{\text{TO}} = W_{\text{OE}} + W_{\text{fuel,max}}$

Payload-Range chart construction

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DIPARTIMENTO DI INGEGNERIA INDUSTRIALE

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- Point D: $W_{\text{TO}} = W_{\text{OE}} + W_{\text{fuel,max}}$

- $W_{\text{fuel}} = (1 - M_{ff}) \cdot W_{TO}$
- $M_{ff} = \frac{W_1}{W_{TO}} \cdot \frac{W_2}{W_1} \cdot \frac{W_3}{W_2} \cdot \frac{W_4}{W_3} \cdot \frac{W_5}{W_4} \cdot \frac{W_6}{W_5} \cdot \frac{W_7}{W_6} \cdot \frac{W_8}{W_7} \cdot \frac{W_9}{W_8} \cdot \frac{W_{10}}{W_9} \cdot \frac{W_{\text{final}}}{W_{10}}$

Payload-Range chart construction

- Point B: $W_{TO,\text{max}} = W_{OE} + W_{\text{payload,max}} + W_{\text{fuel}}$
- Point C: $W_{TO,\text{max}} = W_{OE} + W_{\text{payload}} + W_{\text{fuel,max}}$
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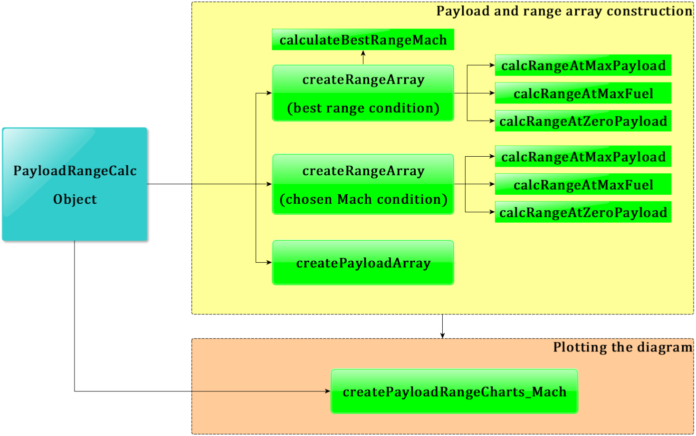
- For each point the couple Range-Payload can be calculated, where the payload for point C is obtained from the previous equations.

Payload-Range Java class flowchart



Flowchart for best range and chosen Mach conditions comparison

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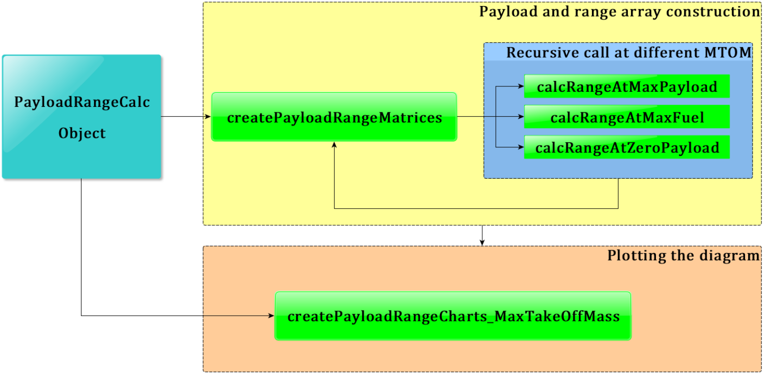
Payload-Range Java class flowchart



Flowchart for maximum take-off mass parameterization

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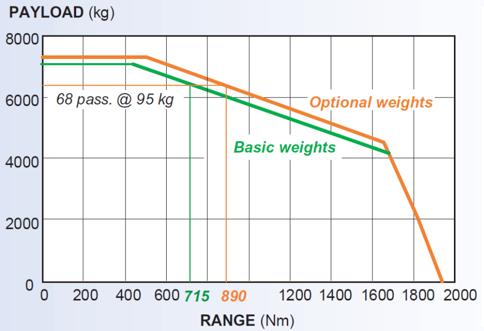
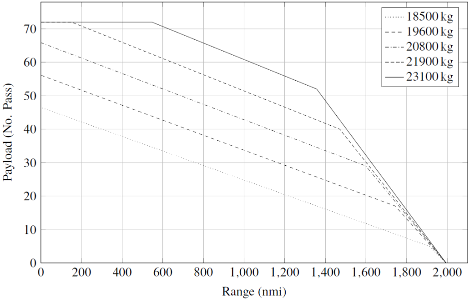
Payload-Range Java class output

	ATR-72	JPAD	Difference(%)
Range **Payload**	890 nmi 68 pass. at 95 kg	$\approx$ 820 nmi 65 pass. at 99 kg	$\approx$ 7.8%





ATR 72-500 data (MTOM optional 22 800 kg)

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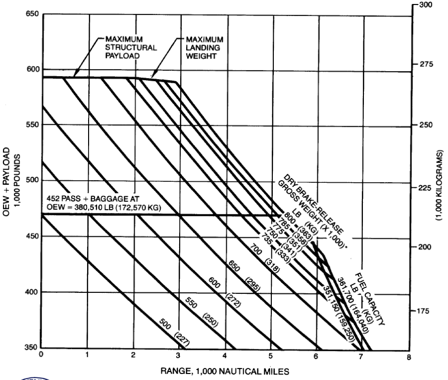
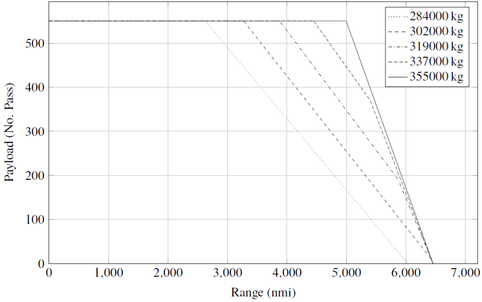
Payload-Range Java class output

	B747-100B	JPAD	Difference(%)
Range **Payload**	≈ 5200 nmi 452 pass. at 95 kg	≈ 5300 nmi 434 pass. at 99 kg	≈ 1.9%





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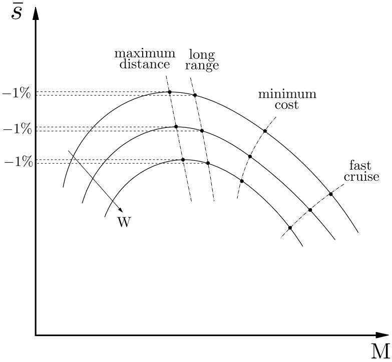
Specific Range and Cruise Grid chart

- Cruise grid chart is a very important tool for pilots because it allows to choose the correct speed, during the cruise phase, in order to follow some mission objectives like minimum fuel consumption or a fast cruise.
- In Breguet equations the focus is on the autonomy factor A.F..



Autonomy Factor Propeller

$$A.F. = \left(\frac{\eta_p}{SFC}\right)\left(\frac{L}{D}\right)$$

Autonomy Factor Jet

$$A.F. = \left(\frac{V}{SFCJ}\right)\left(\frac{L}{D}\right)$$

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Specific Range calculation

- From the aircraft weight in cruise condition the C_L can be calculated.
- With this C_L the related C_D can be calculated taking into account the wave drag, if present.
- From engine database the SFC can be easily calculated in the given flight condition.
- At a given speed, or with known propeller efficiency, the A.F. can be calculated.
- The specific range can be calculated from the A.F. dividing it by the aircraft weight in cruise.
- This can be done for several Mach numbers, between the maximum and minimum one from the flight envelope at that altitude, and several aircraft weights.

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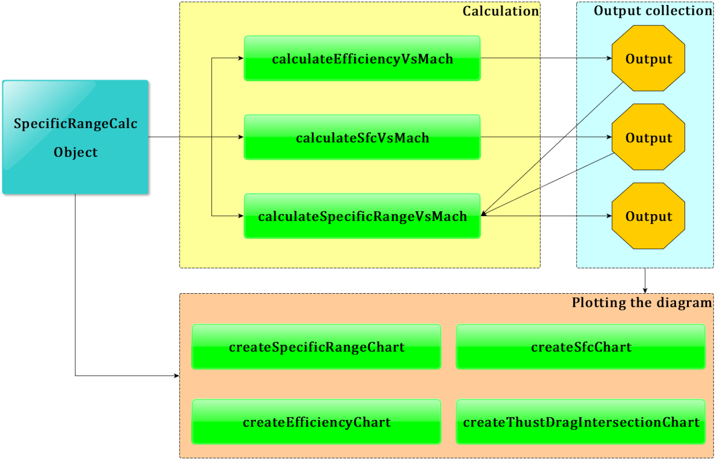
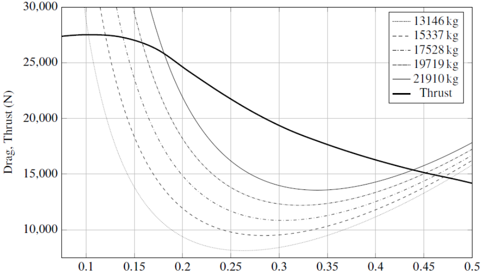
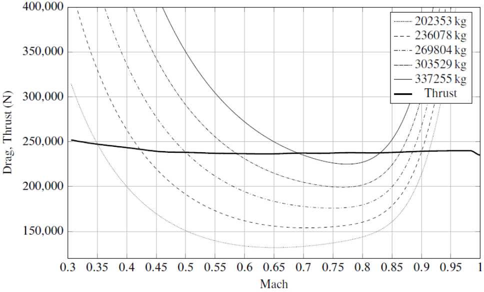
Specific Range Java class flowchart



Specific Range Java class output

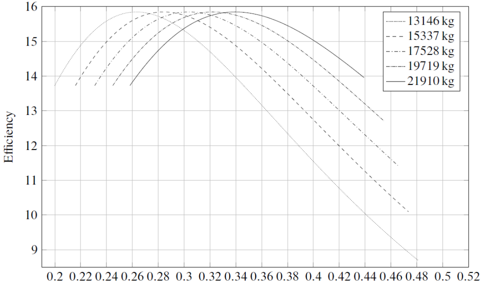


ATR-72
(6000m, M=0.43)

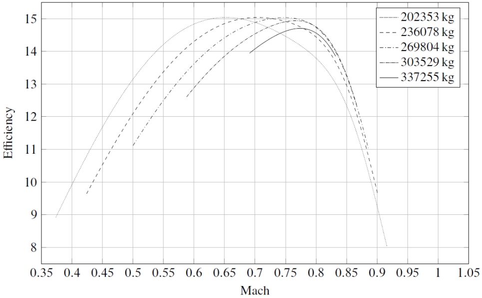


B747-100B
(10000m, M=0.83)

Specific Range Java class output



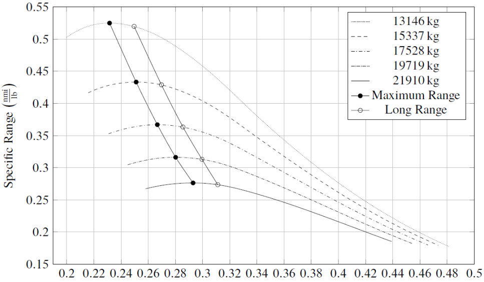
ATR-72
(6000m, M=0.43)



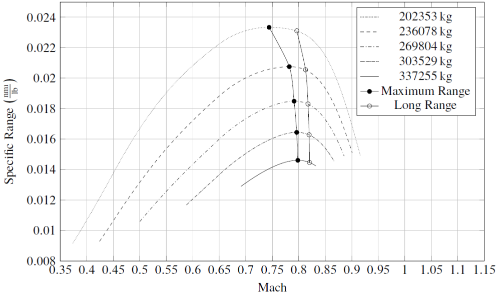
B747-100B
(10000m, M=0.83)

DIPARTIMENTO DI INGEGNERIA INDUSTRIALE

Specific Range Java class output



ATR-72
(6000m, M=0.43)



B747-100B
(10000m, M=0.83)

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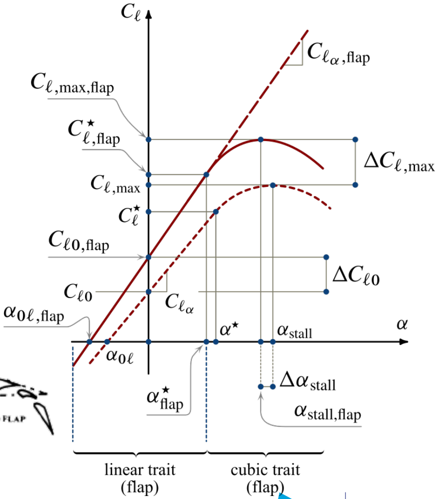
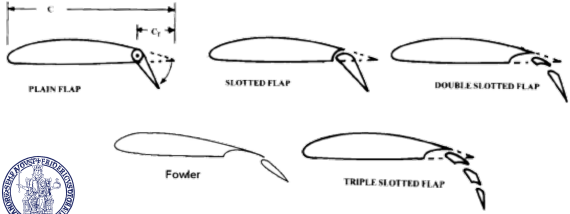
Trailing-edge devices effects

- Higher C_L at a given angle of attack and higher $C_{L\max}$.
- Lower stalling angle of attack.
- Lower zero-lift angle due to increasing camber.





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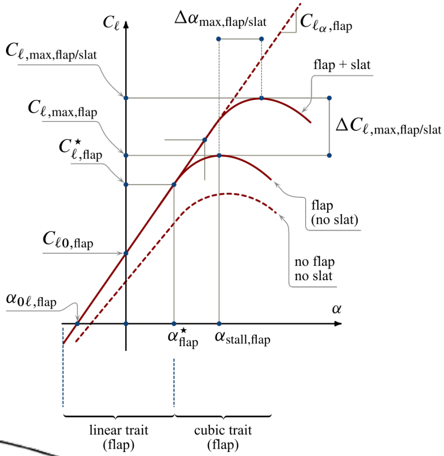
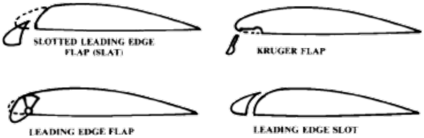
Leading-edge devices effects

- Extension of the linear trait of the lift curve with an increase of the stalling angle of attack and of the $C_{L\max}$
- Higher zero-lift angle caused by leading edge deflection which reduce the actual angle of attack.
- Higher slope of the linear trait of the lift curve.





Calculation methodologies

- Charts, semi-empirical equations and experimental data have been used to evaluate high lift devices effects. (e.g.: *Glauert's linearized theory for thin airfoils with flaps, DATCOM, Young and Hufton experimental data*)

- Effects to evaluate:
  - ΔC_{l0}, ΔC_{L0}
  - $\Delta C_{l\mathbf{max}}$, $\Delta C_{L\mathbf{max}}$
  - $C_{L\alpha,\mathbf{flap}}$
  - $\Delta\alpha_{\mathbf{stall,airfoil}}$, $\Delta\alpha_{\mathbf{stall,wing}}$
  - $\Delta C_{D\mathbf{0}}$
  - $\Delta C_{M,\ \mathbf{c/4}}$

High Lift Devices Java class flowchart

CalcHighLiftDevices Object

Calculation

CalcHighLiftDevices Constructor

- Links user inputs to class fields
- Recognize flaps types and links them to thei typical maximum deflection and database index
- Calculates maximum lift coefficient and the stalling angle of the wing in clean configuration

calculateHighLiftDevicesEffects

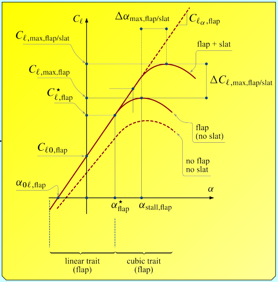
calcCLatAlphaHighLiftDevice (Amount<Angle> alpha)

plotHighLiftCurve

Output collection

ΔCl0, ΔCL0
ΔClmax, ΔCLmax
CLα
Δα stall
ΔCD0
ΔCM_C/4

CL at a given angle of attack on the lift curve with deflected flaps



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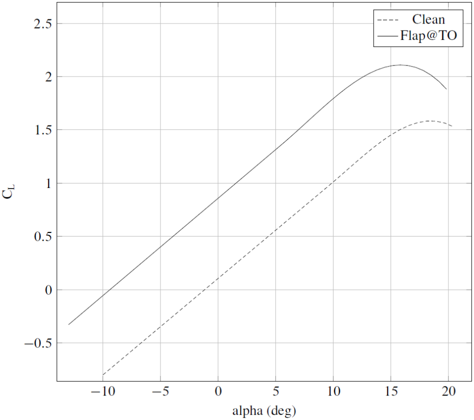
High Lift Devices Java class output

ATR-72 @ Take-Off

- 2 Single slotted flap
- $\frac{c_f}{c} = 0.38$
- $\delta_f = 20°$
- $\eta_{\text{in, flap1}} = 0.08;\ \eta_{\text{out, flap1}} = 0.35$
- $\eta_{\text{in, flap2}} = 0.35;\ \eta_{\text{out, flap2}} = 0.8$

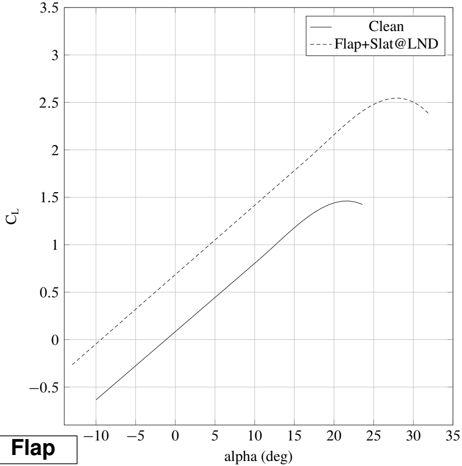
	No Flap	**Flap**
α_{stall}	18.46°	15.82°
$C_{L\text{max}}$	1.58	2.11
$C_{L\text{star}}$	0.98	1.36
$C_{L\alpha}$ (1/rad)	5.19	5.24



High Lift Devices Java class output

B747-100B @ Landing

- 2 Triple slotted flap + 3 Krueger slat
- $\frac{c_f}{c} = \begin{bmatrix} 0.18, & 0.18 \end{bmatrix}$
- $\frac{c_s}{c} = \begin{bmatrix} 0.09, & 0.136, & 0.187 \end{bmatrix}$
- $\delta_f = 30°; \quad \delta_s = 15°$
- $\frac{c'}{c}_{\text{slat}} = 1.1$
- $\eta_{\text{in, flap}} = \begin{bmatrix} 0.104, & 0.411 \end{bmatrix}$
- $\eta_{\text{out, flap}} = \begin{bmatrix} 0.357, & 0.636 \end{bmatrix}$
- $\eta_{\text{in, slat}} = \begin{bmatrix} 0.192, & 0.414, & 0.692 \end{bmatrix}$
- $\eta_{\text{out, slat}} = \begin{bmatrix} 0.364, & 0.648, & 0.961 \end{bmatrix}$

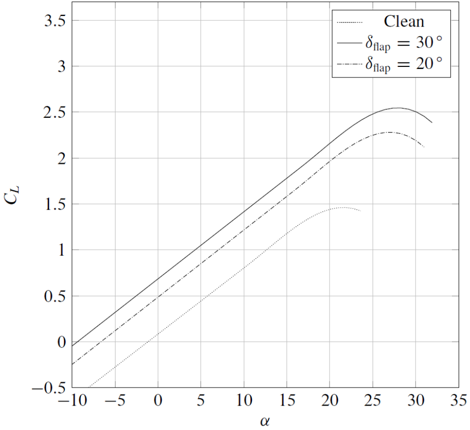


	No Flap	Flap
α_{stall}	21.59°	27.91°
$C_{L\text{max}}$	1.46	2.55
$C_{L\text{star}}$	0.83	1.90
$C_{L\alpha}$ (1/rad)	4.121	4.186

DIPARTIMENTO DI INGEGNERIA INDUSTRIALE

High lift devices effect - sensibility analysis

Input data B747-100B @ Landing		Baseline results	
Variables	**Value**	**Variables**	**Value**
δ_f	30°	$C_{L\max}$	2.55
$\frac{c_f}{c}$	0.18	$\alpha_{\max}$	28°
Trailing edge devices type	Triple Slotted		
δ_s	15°		



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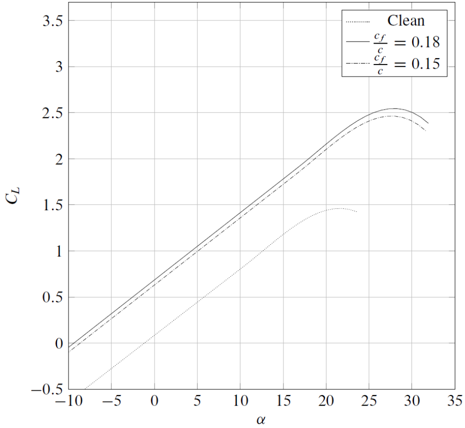
Trailing edge devices type	Triple Slotted		
δ_s	15°		



High lift devices effect - sensibility analysis

Input data B747-100B @ Landing		Baseline results	
Variables	**Value**	**Variables**	**Value**
δ_f	30°	$C_{L\max}$	2.55
$\frac{c_f}{c}$	0.18	$\alpha_{\max}$	28°
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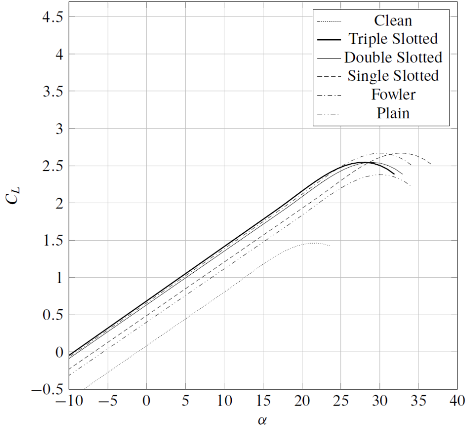

High lift devices effect - sensibility analysis

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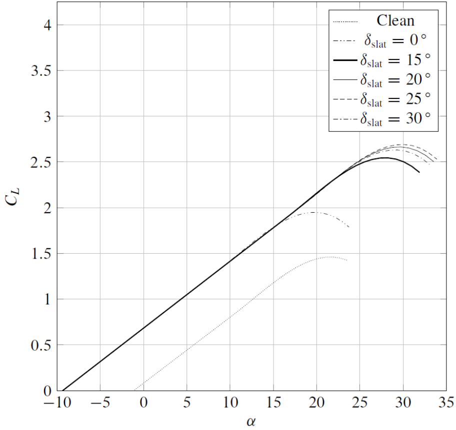

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ODE set for the AOE take-off distance calculation

State space representation $\dot{\vec{x}} = \vec{f}(\,\vec{x}\,;\,u\,)$

$$\begin{Bmatrix} \dot{s} \\ \dot{V} \\ \dot{\gamma} \\ \dot{h} \end{Bmatrix} = \begin{Bmatrix} f_1(\,s,\ V,\ \gamma,\ h;\ \alpha) \\ f_2(\,s,\ V,\ \gamma,\ h;\ \alpha) \\ f_3(\,s,\ V,\ \gamma,\ h;\ \alpha) \\ f_4(\,s,\ V,\ \gamma,\ h;\ \alpha) \end{Bmatrix} \quad \text{with} \quad \begin{Bmatrix} x_1 = s \\ x_2 = V \\ x_3 = \gamma \\ x_4 = h \end{Bmatrix} \quad \text{and} \quad u = \alpha$$

- $f_1(\,\vec{x}\,,\,u\,) = x_2$
- $f_2(\,\vec{x}\,,\,u\,) = \dfrac{g}{W} \begin{cases} T(x_2) - D(x_2,u) - \mu\,[W - L(x_2,u)] & \text{if } \mathcal{S}(x_2,u) < 1 \\ T(x_2)\cos u - D(x_2,u) - W\sin x_3 & \text{if } \mathcal{S}(x_2,u) \geq 1 \end{cases}$
- $f_3(\,\vec{x}\,,\,u\,) = \dfrac{g}{W\,x_2} \begin{cases} 0 & \text{if } \mathcal{S}(x_2,u) < 1 \\ L(x_2,u) + T(x_2)\sin u - W\cos x_3 & \text{if } \mathcal{S}(x_2,u) \geq 1 \end{cases}$
- $f_4(\,\vec{x}\,,\,u\,) = x_2\ \sin x_3$

$$\mathcal{S}(x_2,u) = \frac{L(x_2,u)}{W\cos x_3}$$

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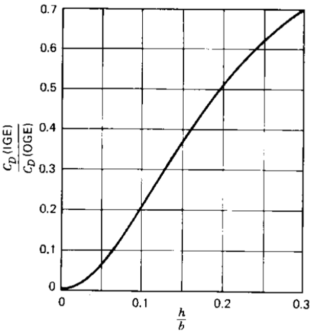
ODE set for the AOE take-off distance calculation

State vector and input $\vec{x} = \{x_1 = s;\ x_2 = V;\ x_3 = \gamma;\ x_4 = h\}\ ;\ u = \alpha$

- $T(x_2)$ is read from the engine database related to the take-off setting.
- $D(x_2, u) = \frac{1}{2}\,\rho\,(x_2 + V_w \cos x_3)^2\, S\, C_D(u)$
  - $C_D(u) = C_{D0} + (\Delta C_{D0})_{\text{flap+lg}} + K_g\, \frac{C_L^2}{\pi \AE e}$
    - $K_g = -622.44x^5 + 624.46x^4 - 255.24x^3$ $47.105x^2 - 0.6378x + 0.0055$
- $L(x_2, u) = \frac{1}{2}\,\rho\,(x_2 + V_w \cos x_3)^2\, S\, C_L(u)$
  - $C_L(u)$ is the one from the lift curve with flaps, and eventually slats, deflected.

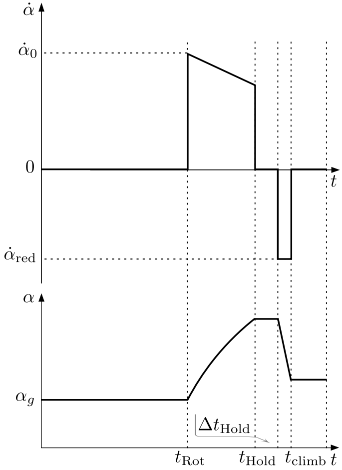


ODE set for the AOE take-off distance calculation

$$u(t) = \left\{ \begin{array}{ll} \alpha_g & \text{if } t < t_{Rot} \\ \alpha_1(t) & \text{if } t \geq t_{Rot} \end{array} \right\}$$

$$\alpha_1(t) = \dot{\alpha}(t)\, dt$$

$$\dot{\alpha}(t) = \left\{ \begin{array}{ll} \dot{\alpha}_0 \; (1 - k_\alpha \; \alpha) & \text{if } t_{Rot} \leq t < t_{Hold} \\ 0 & \text{if } t_{Hold} \leq t < t_{Hold} + \Delta t_{Hold} \\ \dot{\alpha}_{red} & \text{if } t_{Hold} + \Delta t_{Hold} \leq t < t_{climb} \\ 0 & \text{if } t \geq t_{climb} \end{array} \right\}$$



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ODE set modification for the take-off in OEI condition

OEI continued take-off

- There is a discontinuity in thrust at a specific failure speed V_{ef}.
- $T(x_2)$ is still read from the database but considering a number of engines reduced by one from the time t_{ef} at which the engine failure occurs.

OEI aborted take-off

- The take-off run, up to the engine failure speed V_{ef}, is the same as the continued take-off one.
- The pilot reacts at a time t_{act} (generally 3 s after t_{ef}) setting $T(x_2)$ to 0 and activating brakes. The equation f_2 changes in the following.

$$f_2(\vec{x}\,,\,u) = \frac{g}{W}\left\{-D(x_2,u) - \mu_{\text{brakes}}\big[W - L(x_2,u)\big]\right\}$$

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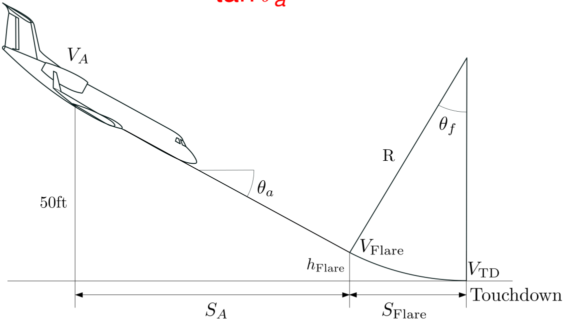
Landing distance calculation

Air run

- $\left[n = 1.2,\ V_{\text{Flare}} = 1.23\ V_s\right] \rightarrow R = \dfrac{V^2}{g\,(n-1)} = \dfrac{V_{\text{Flare}}^2}{0.2\ g}$
- $\left[\theta_a \approx 2° \div 3°\right] \rightarrow h_{\text{Flare}} = R\,(1 - \cos\theta_a)$
- $\left[\theta_a,\ R,\ h_{\text{Flare}}\right] \rightarrow S_A = \dfrac{50 - h_{\text{Flare}}}{\tan\theta_a};\quad S_{\text{Flare}} = R\sin\theta_a$



Landing distance calculation

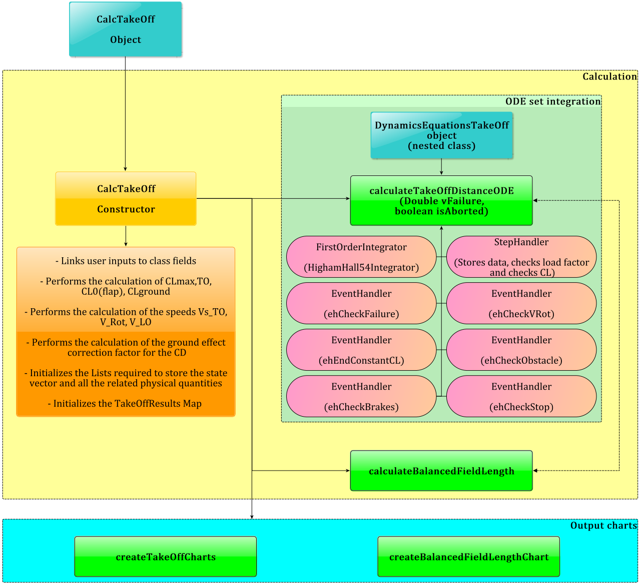
Ground run

$$\left\{ \begin{array}{c} \dot{s} \\ \dot{V} \end{array} \right\} = \left\{ \begin{array}{c} f_1(s,\ V) \\ f_2(s,\ V) \end{array} \right\} \quad \text{with} \quad \left\{ \begin{array}{c} x_1 = s \\ x_2 = V \end{array} \right\}$$

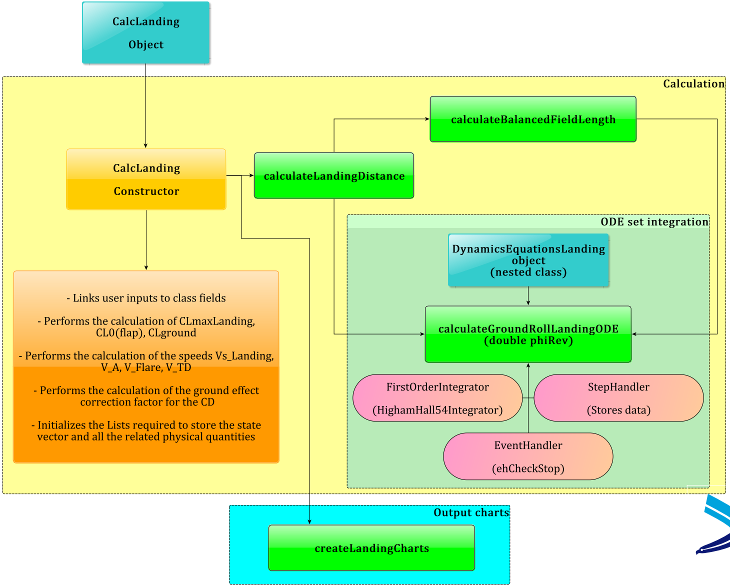
- $f_1(\vec{x}\,,\ u) = x_2$
- $f_2(\vec{x}) = \frac{g}{W} \left\{ \begin{array}{ll} -T_{\text{Rev}}(x_2) - D(x_2) - \mu\left[W - L(x_2)\right] & \text{if } t \leq t_{\text{fr}} \\ -T_{\text{Rev}}(x_2) - D(x_2) - \mu_{\text{brakes}}\left[W - L(x_2)\right] & \text{if } t > t_{\text{fr}} \end{array} \right\}$

t_{fr} is related to the end of the *free-roll distance* (which represents the distance covered while the pilot reduces the power to idle, retracts the flaps, deploys the spoilers, and applies the brakes) and it's set at 3 s.

Take-Off Java class flowchart



Landing Java class flowchart



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