DESIGN AND DEVELOPMENT OF A SIMULATION TOOL FOR AIRCRAFT PROPULSION SYSTEMS

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ABSTRACT

This document examines the study and process that led to the development of a simple ramjet engine simulation tool, and describes its capabilities and final aspect. The tool was developed using the PROOSIS **(1)**software and its capacity for connecting an experiment to Excel to be used as an interface. The end result is a tool prepared to simulate the performances of a typical turbojet and twin-spool turbofan **(see appendix)**. Input data selection and result viewing are performed through two Excel files prepared specifically for this purpose. The simulations that can be performed with the tool consist of the following: Design Calculation, Off-Design Performance Calculation (off-design point, mission analysis, operating line, transient), and Parametric Study (design and off-design combination).

The document is structured as follows: Introduction, Design Calculation, Performances, Parametric Study, Interface Development, Verification of Results and Conclusions.

Keywords: tool, PROOSIS, turbofan, turbojet, design, performances.

Note: The present document constitutes a summary of the final degree project (PFC) prepared by the author with the same title. To consult said PFC, please contact Empresarios Agrupados.

LIST OF VARIABLES AND ACRONYMS

PFC	Final Degree Project
PROOSIS	PRopulsion Object Oriented SImulation System
PR	Pressure ratio
Eff	Efficiency
NcRdes	Corrected speed relative to design on the scaled map
NcRdesMap	Corrected speed relative to design on the unscaled map
BETA	Parameter enabling unequivocal relationships between NcRdesMap and different PR on the compressor maps
ZETA	Parameter similar to BETA, but associated with turbine maps
T4t	End of combustion temperature
T41t	HT equivalent rotor inlet temperature
Eburner	Efficiency of combustion
Kburner	Combustor loading parameter
dPburner	Pressure drop in the combustor
Mach	Flight Mach number
Alt	Flight altitude
dTamb	Temperature difference with respect to standard atmosphere
RelBleed	Relative bleeding to the inlet of the component being bled
RelEnthBleed	Relative bleeding position in the component, as a function of enthalpy variation
ReldPBleed	Relative bleeding position in the component, as a function of stagnation pressure variation
RelNGVCooling	Bleeding used for equivalent NGV cooling
RelNoWorkCooling	Bleeding that produces no work in the equivalent rotor
N	Nominal speed
Ncorr	Corrected speed
MechEff	Mechanical efficiency
ShIner	Engine shaft inertia
PWRout	Power extraction
W	Mass flow
Tt	Stagnation temperature
Pt	Stagnation pressure
dP	Relative stagnation pressure loss
A	Area
WF	Fuel mass flow
Fn	Uninstalled thrust
SFC	Specific consumption
sFn	Uninstalled specific thrust
BPR	Bypass ratio
HPT	High pressure turbine
LPT	Low pressure turbine
HPC	High pressure compressor
IPC	Intermediate pressure compressor
D30	Duct 30
D50	Duct 50
Ov	Overboard

1 INTRODUCTION

Digital simulation is especially important during the preliminary design phase of a turbojet engine to achieve results that permit proper assessment of the different design options under consideration. In recent years, object-oriented modelling programs have been prevailing on the market. The main advantage of this type of software is the ability to encapsulate the sets of equations that rule a system into the components that make it up (writing in a way similar to the analytic form). The software subsequently rearranges them to solve them as appropriate.

This greatly facilitates the reuse of components to create other systems and the modification of component modelling.

The PROOSIS software program uses this simulation approach. The high simulation flexibility and modelling simplicity afforded by PROOSIS are offset by the initial complexity for a user who is not proficient in the use of this software, as it has a steep learning curve. Hence the importance in PROOSIS of being capable of generating already-prepared experiments, that can be used by unknowledgeable users to perform simulations. The generation of DECKS **(2)** and experiment linking with EXCEL **(3)** are functionalities included in the program that go along these lines.

The project discussed here takes advantage of the PROOSIS capabilities to develop a tool encapsulated in an experiment that allows performing typical turbojet simulations. Said experiment has been linked to an EXCEL spreadsheet to enable the user to perform simulations without having specific knowledge of PROOSIS. Both the configurations and simulations that can be performed with this tool are preset. The tool allows turbojet and twin spool turbofan simulations.

The configurations (turbojet and turbofan) were created using the TURBO component library v3.2.2 developed by EA and NTUA, and prepared specially for gas turbine simulation **(4)**. It has been modified to better suit the needs of this project. Compressors include PR-type maps. Turbines are modelled with the assumption of an equivalent single-stage turbine. Outlet nozzles are of the converging type.

The selection of calculations performed, user input data and results displayed takes into consideration the discussion regarding the turbojet design process set forth in Mattingly **(5)** and the possibilities afforded by other aeronautical propulsion simulation programs (GasTurb, GSP, NPSS, PROOSIS, C-Mapss).

2 DESIGN CALCULATION

The design is used to scale the motor, and to position a reference point on the maps. Maps are used for the compressors, fan and turbines. The design is established for a user-selected flight condition, and design data are chosen considering those that are most interesting for the designer. For convenience purposes, the data and the results presented throughout the document correspond to the turbojet, as it contains fewer variables. However, it should be noted that for other configurations (turbofan), the type of data for each component is the same (the same data are always selected for compressor design, the difference being that in the turbofan, for example, there are 4 compressors in total).

Table 1. Turbojet Design Data

High Compressor	**High turbine**
PR	Eff
Eff	NcRdes
NcRdes	NcRdesMap
NcRdesMap	ZETA
BETA	
Flight Conditions	**Burner**
Mach	T4t
Alt	Eburner
dTamb	dPburner
Bleeds	**Turbine Cooling**
RelBleedOv	RelNGVCooling
RelEnthBleedOv	RelNoWorkCooling
RelBleedCoolHPT	
ReldPBleedCoolHPT	
Shaft	**Pressure losses**
N	PRinlet
MechEff	dPD30
ShIner	dPD50
PWRout	

Engine dimensioning can be performed in one of two ways: by selecting Fn or W1, as additional user-introduced input data.

The internal mathematical model generated also requires the selection of a number of variables in order to find an iterative solution in nonlinear boxes. Owing to the fact that many variables have a significant value (and that their number is high: 42 for the turbofan design calculation), and that calculation convergence depends directly on the proximity to the final value, a simple mathematical model was developed, based on the discussion in J.L. Montañés's "Motores de reacción y turbinas de gas" JL Montanes **(6)**, which estimates its value as a function of user-provided data. Mathematical model assumptions:

- Ideal gas
- Ideal gas mixture
- Choked nozzles

A8 is one of the values that require initialization and carry more mistakes. As can be seen in the figure below, the mathematical model gives a fair approximation of the calculated value (when T4t decreases, the nozzle is unchoked, which is the reason for the departure in that area).

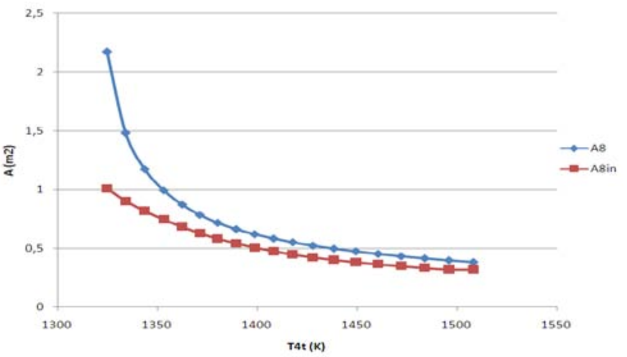

Figure 1. Simplified Model Comparison - PROOSIS Result

Results of interest to the user are shown: Tt, W, Pt at each stage, eff, PR, in each component, A8, and global cycle parameters: SFC, sFn, WF. A turbojet diagram containing the local results of the parameters involved in the cycle is also shown.

3 PERFORMANCES

In off-design performance, the user chooses a set of data common to all available simulations: Flight conditions, bleeding and cooling, combustion chamber load constant and power extraction. There are a smaller number than in design, since the engine is already fully scaled.

Table 2. Turbojet Performance Data

Flight Conditions	**Miscellaneous**
Mach	Kburner
Alt	PWRout
dTamb	
Bleeds	**Turbine Cooling**
RelBleedOv	RelNGVCooling
RelEnthBleedOv	RelNoWorkCooling
RelBleedCoolHPT	
ReldPBleedCoolHPT	

Selection of the control parameter is also required. This parameter is dependent on each type of performance, and is the one used for direct engine control.

Performance calculation also requires selecting values for a number of variables that must be initialized. In this case, it was decided to proceed to a parametric approach from on-design up to the point where performance begins, reusing the results of variables that need initialization to calculate the next point, thereby ensuring convergence.

The performances available in the tool are as follows:

- Off-design single point/ multi-point calculation. This calculates one or more operating points for certain off-design conditions. One of the following can be selected as control parameter: N, T4t, WF and Fn.
- Operating line calculation. The operating line is represented by choosing the first value of the control parameter (T4t ó NcRdesMapHPC/NcRdesMapFan), the last value, and the number of points to be represented.
- Transient calculation. The user selects time-control parameter (T4t or WF) pairs. Following linear interpolation to obtain the control law, it is integrated with the first order Adams-Moulton formula.

Additionally, it is possible to activate limiters in steady-state calculations (single point, multi-point, operating line). Active limiters delimit the value of the following variables (maximum, minimum, or both): T41t, N, Ncorr, PR.

Results are presented in the same manner as in the design with calculation of an off-design single point, in list mode for multi-point, operating lines in compressor and turbine maps, and the control parameter and speed as a function of time in transient calculation.

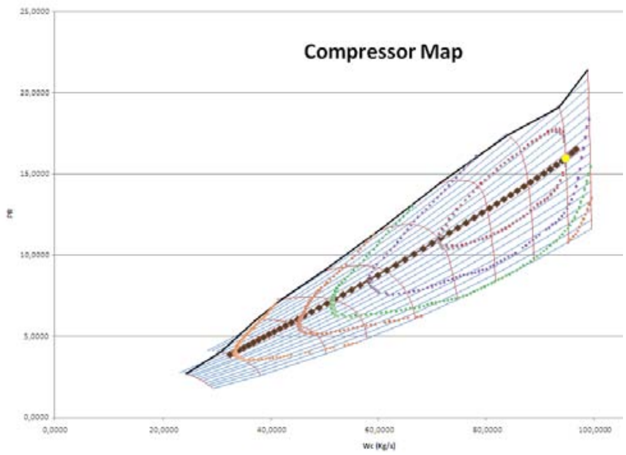

Figure 2. Turbojet Operating Line

4 PARAMETRIC STUDY

The preliminary design of an engine requires achieving a trade-off solution. The point selected must be optimal for the mission that is being designed. It is also necessary to check that the engine fulfils other critical flight conditions.

The purpose of the parametric study developed in this tool is to facilitate this decision. This study includes a two-parameter variation (these parameters are T4t and PR for the turbojet; they are selected among BPR, PRHPC, T4t and PRfan for the turbofan) on design; additionally, an off-design point (control parameter: Fn) is calculated for each design to verify that the engine also fulfils these conditions.

The following is the algorithm to calculate the solution and represent the results, which is implemented internally in the code:

1. Design point calculation. If the design is not valid (the calculation does not converge, or the calculated result is not within map limits), the next point of the parametric study is calculated, and the current point is ignored.
2. Setting changed to off-design and calculation of the corresponding off-design point, taking as a reference the valid design calculation obtained in 1 above. If it is a valid point, the on-design and off-design values of the variables involved in the parametric studies and in SFN and SFC performances are stored in matrices. Otherwise, the tool goes on to calculating the next point, not saving results.
3. Saving the values of variables that need to be initialized for off-design, if there is convergence. Once these values have been saved, they will be re-used for the rest of the parametric off-design leg, to reduce computing time.
4. Steps 1 and 2 are repeated for all points of the parametric study.
   If the result of step 1 is not valid, step 2 is skipped for that point, and step 1 is tried again for another point.
5. Once study calculations are completed, the cumulative values are represented in Excel tables, so the user can view the results.

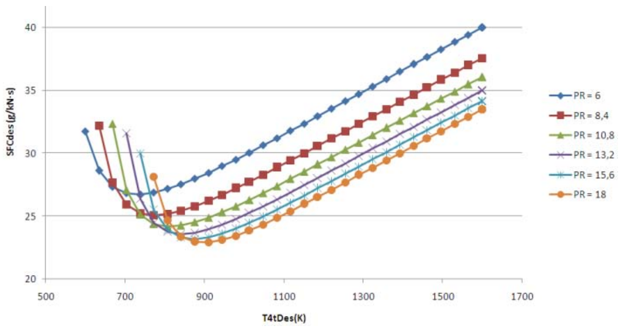

Figure 3. Turbojet - Parametric Study SFCdes = f (T4tdes, PRdes)

5 DEVELOPMENT OF INTERFACE

To develop the graphical interface, it was decided to link the experiment, which includes both the model and all the calculations performed, with an Excel file, using the PROOSIS functionality created to this end. Excel was chosen as an interface because of its high simplicity and easy result viewing. With this PROOSIS functionality, once an experiment has been loaded, it is possible to anchor any variable of the experiment to an Excel cell, varying its value, and observe its evolution throughout the simulation. Selection of data and results displayed is performed using this functionality. Two Excel files have been prepared especially for the simulations: one for the turbojet and the other for the turbofan.

The alternative process is to generate a "report sheet" that accumulates the value of selected variables throughout the simulation, and which is used for graphic representation of the results obtained (operating line, transient).

The calculation that will be simulated is selected in an Excel spreadsheet that features a series of SWITCHES to enable or disable a portion of the experiment, thereby performing one calculation or another.

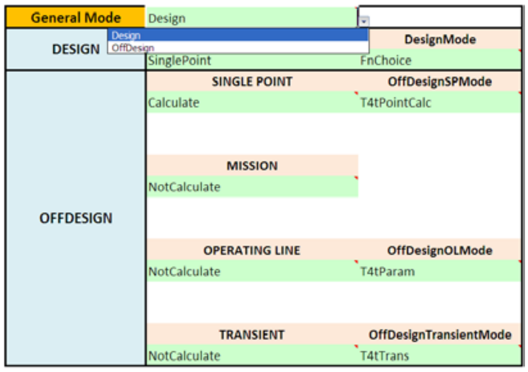

Figure 4. Selecting the simulation

After selecting the desired calculation and properly configuring the input data, the calculation is started by pressing "play".

Figure 5. Aspect of the PROOSIS add-in in Excel

Each calculation that can be carried out is developed (both in the selection of INPUTS and of OUTPUTS displayed) in a sheet of the Excel file.

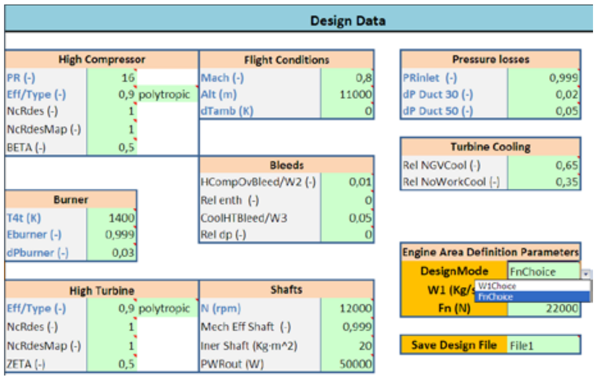

Figure 6. Design Data

Global Parameters	
Fn (N)	22000
sFn (N·s/Kg)	709,156131
SFC (g/kN·s)	30,6869319
OER (-)	2,97243004
OPR (-)	16
EPR (-)	4,86104628
EffComp (-)	0,85689558
EffOverall (-)	0,17845039
EffProp (-)	0,35611515
EffTh (-)	0,50110304
EffTrb (-)	1,00759431

WF (Kg/s)	0,6751125
T4t (K)	1400
FARinj (-)	0,02313857

Figure 7. Overall Design Results

OffDesign Single Point Data

General OD Parameters Choices	
Mach (-)	0,8
Alt (m)	11000
dTamb (K)	0
Kburner (-)	1,6
PWRout (W)	50000

Cooling OD	
Rel NGVCool (-)	0,65
Rel NoWorkCool (-)	0,35

OD Controller	T4tPointCalc
OD Controller	T4tPointCalc FnPointCalc NPointCalc WFPointCalc

Load Design File	File1

Bleeds OD	
Rel HComp OvBleed (-)	0,01
Rel enth (-)	0
CoolHTBleed/W3 (-)	0,05
Rel dP (-)	0

Figure 8. Performance Data: Calculation of an Off-Design Single Point

DesignPoint: Parameter Variation (General design is set in the previous tab)

Engine Areas Definition Parameters				DesignMode
W1 (Kg/s)	35	Fn (N)	22000	FnChoice
Parameters to be variated in design				
	N points	FirstValue		LastValue
Parameter1: PRcmp (-)	6	6		18
Parameter2: T4t (K)	30	600		1600

OffDesign Point Viability for Design

General OD Parameters Choices	
Mach (-)	0,8
Alt (m)	11000
dTamb (K)	0
Kburner (-)	1,6
PWRout (W)	50000

Cooling OD	
Rel NGVCool (-)	0,65
Rel NoWorkCool (-)	0,35

OffDesignParamControl: FnOD	
Fn OffDesign (N)	22000

Bleeds OD	
Rel HComp OvBleed (-)	0,01
Rel enth (-)	0
CoolHTBleed/W3 (-)	0,05
Rel dP (-)	0

Figure 9. Parametric Study Data

6 VERIFICATION OF RESULTS

The validity of the tool developed is checked by comparing it with other existing tools. To this end, the simulation of on-design and one off-design point was performed with the tool and with the GasTurb program **(534)**, which is the most similar to our tool because it simulates already-fixed configurations. To ensure greater model similarity and proper assessment of the results, the following considerations were taken into account:

- GasTurb maps assign a default value of 1 to NcRdesMap. Furthermore, the reference value for y is imposed in the off-design calculation tab (the values of BETA / ZETA = 0 5 and NcRdes = 1 are assigned for all maps).
- Calculation of the outlet nozzle in the tool depends on a table, which assigns the corresponding value as a function of the inlet conditions of the nozzle. In GasTurb, however, these values are user-selected. This explains why the largest differences in this simulation correspond to the quantities directly related to thrust.
- The definition of relative bleeds is different in both tools, so care is needed when introducing data.
- The maps are not the same, and therefore the off-design results obtained will vary due to this difference.
- The mass flow introduced into the engine for on-design conditions, for the purpose of engine sizing, is corrected in GasTurb but not in our tool.

Design:

Table 3. Selected Data in Turbojet

High Compressor	**High turbine**
PR=15	Eff=0.9 (polytropic)
Eff=0.88 (isentropic)	NcRdes=1
NcRdes=1	NcRdesMap=1
NcRdesMap=1	ZETA=0.5
BETA=0.5	
Flight Conditions	**Burner**
Mach=0.8	T4t=1450 K
Alt=11000 m	Eburner=0.999
dTamb=0 K	dPburner=0.03
Bleeds	**Turbine Cooling**
RelBleedOv=0.02	Rel NGVCooling=0.7
RelEnthBleedOv=0.5	RelNoWorkCooling=0.3
RelBleedCoolHPT=0.102	
ReldPBleedCoolHPT=0	
Shaft	**Pressure losses**
N=12000 rpm	PRinlet=0.99
MechEff=0.999	dPD30=0
ShIner=20	dPD50=0.02
PWRout=25000 W	

```
                W          T          P        WRstd
Station       kg/s         K         kPa       kg/s         FN         =     14,50 kN
 amb                    216,65     22,632                   TSFC       =   30,8282 g/(kN*s)
  1         20,134      244,44     34,509                   FN/W2      =    720,41 m/s
  2         20,134      244,44     34,164     55,000
  3         19,732      564,26    512,459      5,459        Prop Eff   =    0,3967
 31         17,718      564,26    512,459                   eta core   =    0,5081
  4         18,165     1450,00    497,085      8,306
 41         19,575     1392,37    497,085      8,771        WF         =   0,44716 kg/s
 49         19,575     1121,36    177,624                   s NOx      =   0,14491
  5         20,179     1106,15    177,624     22,553        XM8        =    1,0000
  6         20,179     1106,15    174,072                   A8         =    0,0993 m²
  8         20,179     1106,15    174,072     23,013        P8/Pamb    =    7,6914
Bleed        0,403      406,04    170,540                   WBld/W2    =   0,02000
----------------------------------------------              Ang8       =     10,00 °
P2/P1 = 0,9900   P4/P3 = 0,9700   P6/P5 0,9800              CD8        =    0,9800
Efficiencies:    isentr  polytr    RNI    P/P               W_NGV/W2   =   0,07000
 Compressor      0,8800  0,9157  0,409 15,000               WCL/W2     =   0,03000
 Burner          0,9990                 0,970               Loading    =    100,00 %
 Turbine         0,9106  0,9000  0,777  2,799               e45 th     =   0,90208
----------------------------------------------              far7       =   0,02266
Spool mech Eff   0,9990   Nom Spd     12000 rpm             PWX        =     25,00 kW
----------------------------------------------

hum [%]     war0       FHV      Fuel
  0,0     0,00000    43,124    Generic
```

Figure 10. GasTurb on-design results

Global Parameters	
Fn (N)	14373,64422
sFn (N·s/Kg)	713,8990873
SFC (g/kN·s)	31,13726265
OER (-)	2,798336579
OPR (-)	15
EPR (-)	5,095527146
EffComp (-)	0,88
EffOverall (-)	0,175869502
EffProp (-)	0,349066874
EffTh (-)	0,503827534
EffTrb (-)	1,137863254

WF (Kg/s)	0,447555935
T4t (K)	1450
FARinj (WF/W31) (-)	0,025258924

Figure 11. On-design results with the tool

Performances: Calculation of an Off-Design Point

Table 4. Off-design data selected

Flight Conditions	Miscellaneous
Mach=0	Kburner=1.6
Alt=0	PWRout=0
dTamb=0	
Bleeds	**Turbine Cooling**
RelBleedOv=0	RelNGVCooling=0.7
RelEnthBleedOv=0	RelNoWorkCooling=0.3
RelBleedCoolHPT=0.1	
ReldPBleedCoolHPT=0	
OD controller: T4t	1600K

```
Summary | Oper.Point | Compr | Turb | Air System

                W          T          P        WRstd
Station       kg/s         K         kPa       kg/s         FN         =     49,09 kN
 amb                    288,15    101,325                   TSFC       =   26,4025 g/(kN*s)
  1         51,257      288,15    101,325                   FN/W2      =    957,81 m/s
  2         51,257      288,15    100,312     51,774
  3         51,257      644,38   1401,386      5,542        Prop Eff   =    0,0000
 31         46,131      644,38   1401,386                   eta core   =    0,4356
  4         47,427     1600,00   1357,865      8,339
 41         51,015     1539,22   1357,865      8,798        WF         =   1,29621 kg/s
 49         51,015     1245,81    489,113                   s NOx      =   0,32722
  5         52,553     1229,75    489,113     22,490        XM8        =    1,0000
  6         52,553     1229,75    479,385                   A8         =    0,0993 m²
  8         52,553     1229,75    479,385     22,947        P8/Pamb    =    4,7312
Bleed        0,000      468,82    476,222                   WBld/W2    =   0,00000
----------------------------------------------              Ang8       =     10,00 °
P2/P1 = 0,9900   P4/P3 = 0,9689   P6/P5 0,9801              CD8        =    0,9800
Efficiencies:    isentr  polytr    RNI    P/P               W_NGV/W2   =   0,07000
 Compressor      0,8863  0,9191  0,990 13,970               WCL/W2     =   0,03000
 Burner          0,9998                 0,969               Loading    =     32,60 %
 Turbine         0,9144  0,9046  1,891  2,776               e45 th     =   0,90579
----------------------------------------------              far7       =   0,02529
Spool mech Eff   0,9990   Speed       12502 rpm             PWX        =      0,00 kW
----------------------------------------------

hum [%]     war0       FHV      Fuel
  0,0     0,00000    43,124    Generic
```

Figure 12. GasTurb Results

Stage	W (Kg/s)	Tt (K)	Pt (Pa)
0	50,58415413	288,15	101325
2	50,58415413	288,15	100311,75
30	50,58415413	642,3074771	1385858,79
31	45,52573872	642,3074771	1385858,79
4	46,80624988	1600	1343158,636
41	50,34714067	1539,143227	1343158,636
44	51,86466529	1231,927711	482889,8394
50	51,86466529	1231,927711	482889,8394
7	51,86466529	1231,927711	473278,1967
8	51,86466529	1231,927711	473278,1967

	Isoentropic Eff (-)	Polytropic Eff (-)	PR/PQ (-)
Inlet			0,99
High Compressor	0,886711965	0,919322433	13,81551802
High Turbine	0,906873721	0,896269634	2,781501135
Burner	0,999829933		0,969188669
Duct 30			1
Duct 50			0,980095579

Global Parameters	
Fn (N)	48001,69133
sFn (N·s/Kg)	948,9471982
SFC (g/kN·s)	26,67637598
OER (-)	2,781501135
OPR (-)	13,81551802
EPR (-)	4,718073373
EffComp (-)	0,886711965
EffOverall (-)	0
EffProp (-)	0
EffTh (-)	0,428556093
EffTrb (-)	1,135579991

WF (Kg/s)	1,280511166
T4t (K)	1600
FARinj (WF/W31) (-)	0,028127191

Figure 13. Tool results

7 CONCLUSIONS

From the theoretical standpoint, the tool developed provides interesting results that are obtained in a simple and robust manner, despite the constraints imposed by the fact that the available calculations are not very extensive, engine control is direct, and there are only two configurations currently available.

This tool allows evaluating the power of PROOSIS to configure and encapsulate complex experiments so they can be used externally by unknowledgeable users.

8 SOURCES

1. **EA International: EcosimPro/PROOSIS.** http://www.ecosimpro.com/. [En línea]
2. **Empresarios Agrupados Internacional.** *Manual User PROOSIS 3.4.* s.l. : EAI, 2014. págs. 561-608.
3. **Empresarios Agrupados Internacional.** *Manual User PROOSIS 3.4.* s.l. : EAI, 2014. págs. 978-992.
4. **A. Alexiou, T. Tsalavoutas.** *Introduction to Gas Turbine Modelling with PROOSIS*. s.l. : EAI, 2011.
5. **Jack D. Mattingly, William H. Heiser, David T. Pratt.** *AIRCRAFT ENGINE DESIGN.* s.l. : AIAA Educational Series, 2002.
6. **Montañés García, J.L.** *Motores de Reacción y Turbinas de Gas.* s.l. : Publicaciones E.T.S.I. Aeronáuticos Madrid, 2007.

APPEN

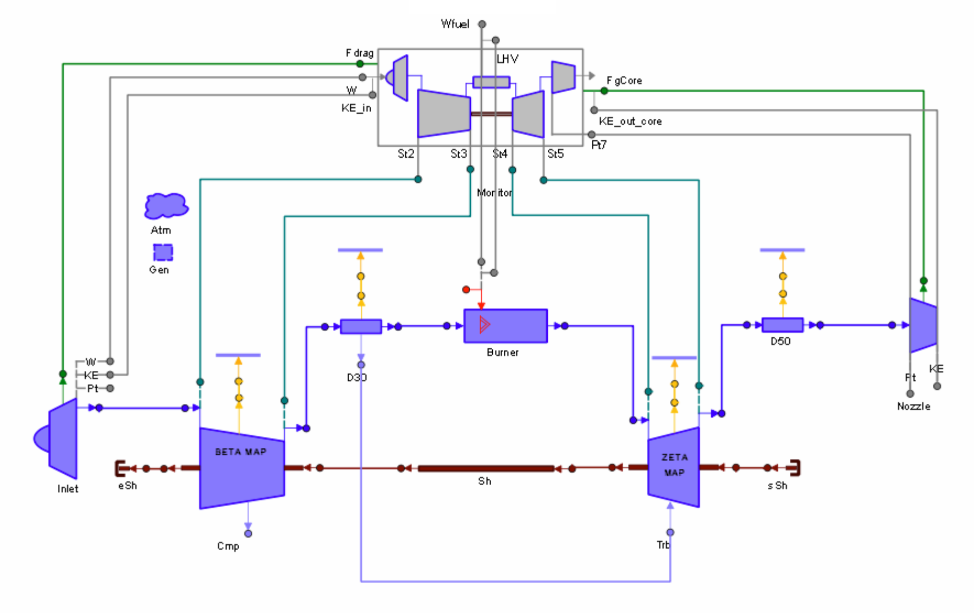

Figure 14. Turbojet Configuration Diagram

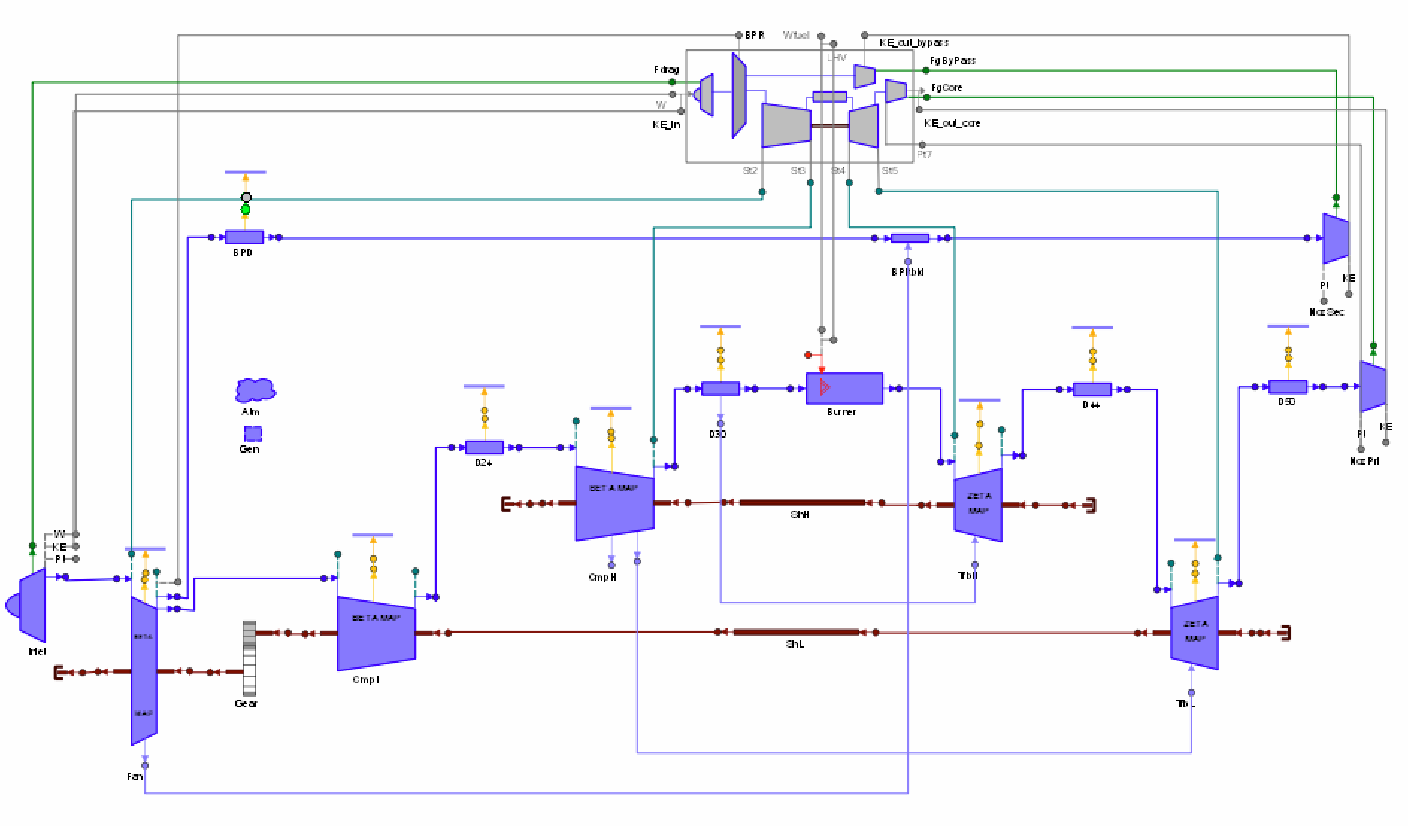

Figure 15. Turbofan Configuration Diagram