a

Mini-project
Intercooled engine modeling and parametric sizing studies

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1. Goals

1. Design a 3-shaft bypass reference engine without intercooler, using a Gasturb model, based on the specification and assumptions that are provided
2. Use this model to compare several design options, without and with an intercooler
3. Use this model to perform engine sizing parametric studies, which should enable finding the design strategy differences induced by the addition of the intercooler

In the written report, you will describe your results and analyze them. Pay attention to the following grid evaluation, make sure you have a section of your report where you address each expectation. Please copy this grid on the front page of your report.

Item	*Breakdown*
Set up the model inputs	1
Set up the formulas and CONSTP/CONSTEFF iterations	1
Choose the main equations and explain them using the engine DoFs, set up the iterations, check the constraints	4
Parametric studies and explain	5
Optimize and explain	1
Intercooler : sizing at iso-OPR or iso-T3	3
Intercooler : parametric studies	2
Intercooler : optimize	1
Technological influences and explain	1
Overall presentation, report clarity and organization	1
Total	20

Please make screenshots of your equations (iterations) and formulas.
Please use plots rather than tables. Several parameters can be plotted on the same plot in Gasturb, which can be useful. The use of T-S diagrams can also be helpful.
Please make screenshots of your variables and optimization constraints.

Thermodynamic stations and symbols to be used are recalled in the appendix.

2. Aircraft specification and design assumptions

You will work by pairs on the engine design.

Aircraft target and engine specification

The aircraft target will be Short/Medium Range, typically A320 or B737 family, for which Safran Aircraft Engines and General Electric, through their joint venture called CFM International, designed the CFM56 or more recently, the LEAP engine. The table below provides the Top Level Aircraft Requirements (TLAR) from which the thrust specifications, described at a later stage, are derived.

Number of pax	-	150-200
Design range	nm	3000
Cruise altitude	ft	35000
Cruise mach number	-	0.8
Take-Off Field Length (TOFL)	m	< 2200
Time to climb (to ICA 33,000 ft)	min	25
Approach CAS	kts	146
One Engine Inoperative ceiling	ft	10000
MTOW	kg	80150
MLW	kg	72860

For this application, the technological features to be considered will be_consistent with the State of the Art of the components for an Entry Into Service (EIS) of 2025. Therefore, the LEAP-like engine specified below will be a fictional LEAP updated with the latest component technologies.

The software used for this project will be Gasturb, which only offers single point design capability. As you learnt during the lectures, engines are normally sized on several points but this is not possible with GasTurb. Here, the design point will be the Top Of Climb point (ToC), as this is the best compromise between fuel consumption optimization (cruise) and maximum thrust capacity in altitude (climb).

The other points (Take-off, Max Cruise, Max Continuous) will be considered during the off-design analysis.

Specification for the engine:

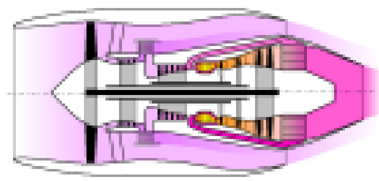
ALT (ft)	MACH	ΔISA (°C)	RATING	Thrust (lbf)	HP offtake (hp)	Bleed (lbm/s)
0	0.25	15	Take-Off	26000	230	0
35000	0.79	10	Max Climb	7100	255	1.14
35000	0.8	10	Max Cruise	3900	255	1.14
10000	0.45	10	Max Continuous	6300	420	1.82

Warning: in GasTurb, the thrust is given in kN, not lbf…

Engine design

The chosen engine architecture will be a 3-shaft bypass engine, with separate flows:

- The bypass is located just downstream of the fan
- The LP Turbine drives the fan (i.e. LP Compressor)
- The IP Turbine drives the booster (i.e. IP Compressor)
- The HP Turbine drives the HP Compressor
- The flows are not merged after the LPT, they are ejected in two separate nozzles.



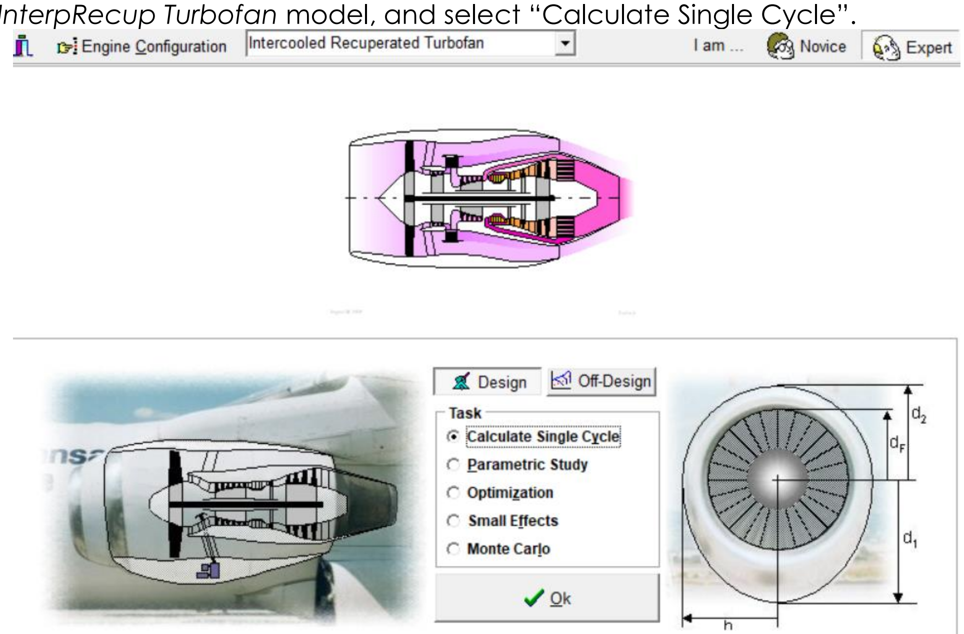
First, a reference engine will be designed without an intercooler, and then, an intercooler will be added and an optimization study will be performed.

3. Model

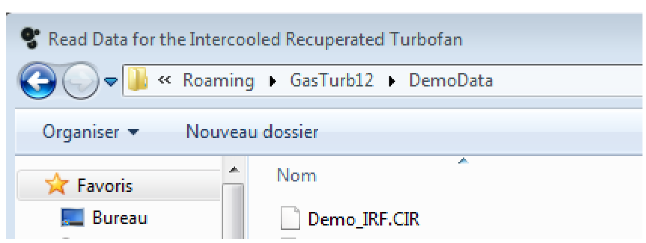
Introduction to Gasturb

Install Gasturb 9 on your personal laptop (Windows only). The installation files are available on the LMS.

Select the *InterpRecup Turbofan* model, and select "Calculate Single Cycle".



In order not to start from a blank model, choose the *Demo_IRF.CIR* file to load the basic data, when the *Read Data* window pops up.



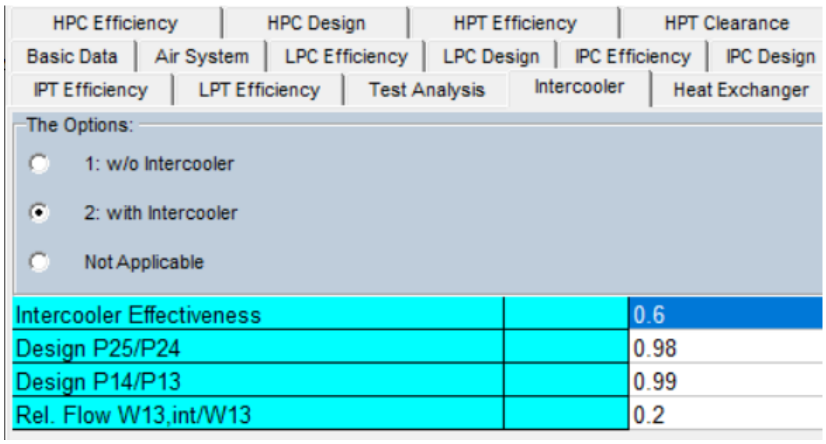
Save your project as *Reference engine - [your names]*. Note that GasTurb automatically saves your project regularly, under *Last_X_CIR*.

The architecture template used here in Gasturb features both an intercooler (heat exchanger located inside compression phase) and a recuperator, called "Heat exchanger", located on the core flow after the LPT expansion, enabling to reheat the combustor inlet mass flow. This second feature (recuperator / "heat exchanger") will not be considered in the frame of this mini-project, only focusing on the intercooler.

In the tabs, you will find the whole set of input parameters. The main data are in the Basic data tab, the others are classified by subsystem.

Note: LPC = fan. The fan (or LPC) has an inner part (which deals with the core flow) and an outer part (which deals with the bypass flow).

The first part of the study consists in designing a reference engine with no intercooler. In order to do that, in the intercooler menu, click on with Intercooler and set the intercooler effectiveness to 0. Deactivate the Heat Exchanger, which is the Recuperator here.



By clicking on "*Ok*", you will launch the simulation and the result window pops up. If you change too many input parameters at the same time, the model may not converge anymore, so you need to change the parameters step by step. Check if your model still converges from time to time. If the following window appears, go back to the previous inputs and try smaller steps.

```
Invalid Result:
 Your input data do not lead to a reasonable
 cycle. Please check and correct your data!
```

In the result window, several tabs are available to see all the resulting cycle data. You should check that the results are consistent with what you intended to design.

Setting up the model

First, **deactivate the design of the IPC, HPC, and the Recuperator** (called **Heat exchanger** in Gasturb) in the corresponding submenus. **Keep the LPC design activated**. "Deactivating the design" means not considering the advanced compressor design features offered by Gasturb (aerodynamic loads, speeds, …) and focus on considering compressors as pressure increasers with a given efficiency. It does not mean "not designing LPC/HPC". Do not use HPT Clearance correction. Set the nozzle to Standard.
Major concern: every time you do a modification, save your input file.

Start by setting the ambient conditions and energy extractions as required for the Max Climb design point.
Then, set the component features of the model, see next page.

- Efficiencies (select isentropic)
- Pressure losses
- Cooling flows (secondary air system)
- Intercooler features (only for the second part of the study). **Efficiency should be at zero for the first part of this mini-project, so that the intercooler is not considered in the cycle calculation**

Composed Values (in the Define menu)
Composed Values allow you to define new parameters from Gasturb model inputs or outputs. Check both tabs to find the parameter you want. **Save your formulas at every modification.**

Define:

- CONSTEFF=(E13D12-1)/(E21D2-1)
- CONSTP=(P13Q12-1)/(P21Q2-1)
- Core size W25R3=W25*(T3/Tstd)^0.5 /(P3/Pstd), in kg/s
    - where Tstd=288.15 K and Pstd = 101.325 kPa
- The thermodynamic load of each turbine DH/T(Delta of enthalpy, also called specific work, divided by the total temperature of the turbine rotor inlet). Refer to the cross section (see last page) to get the right inlet temperature.
- Create a formula that converts the SFC into kg/h/daN (which is the commonly used unit)
- Create a formula that converts the thrust from kN to lbf (which is the commonly used unit)
- Create a formula that converts the fan diameter from metres to inches (which is the commonly used unit)

The additional parameters values you have defined are displayed at the bottom part of the cycle outputs, in a separate list.

Iteration (in the Define menu)
Iterations allow you to define new equations in the model.

- The **target** is what you want to impose in your new equation
- The **variable** is the parameter on which the model will iterate in order to reach your target.

Define:

- How P21Q2 (variable) can be calculated from CONSTP (target)
- How E21D2 (variable) can be calculated from CONSTEFF (target)

Please make a screenshot of your iterations and formulas.
Then, the actual sizing can begin!

4. Key engine designs comparison

Components technological features for all cases

- Inlet (Intake)
    - Efficiency (intake pressure ratio) = 0.997
- Fan/LP Compressor
    - Isentropic efficiency (outer LPC efficiency) = 0.94
    - Relationships between fan hub performance (primary flow) and fan tip performance (bypass flow):
        - CONSTEFF=(E13D12-1)/(E21D2-1)=0.29
        - CONSTP=(P13Q12-1)/(P21Q2-1)=1.74

(named ZPxqy in GasTurb, for instance ZP13q2 for the (outer) fan pressure ratio.)

-
    - LPC inlet Mach number : 0.65
    - LPC inlet radius ratio : 0.35
    - LPC tip peed : 400 m/s (for acoustics)
- IP Compressor
    - Isentropic efficiency = 0.89
- HP Compressor
    - Isentropic efficiency = 0.90
- Combustion chamber (Burner)
    - Fuel Heating Value FHV = 43 115.8 kJ/kg
    - Combustion efficiency = 0.999
    - Pressure losses = 4.5% → therefore the burner pressure ratio is…
- HP Turbine
    - Isentropic efficiency = 0.93
- IP Turbine
    - Isentropic efficiency = 0.94
- LP Turbine
    - Isentropic efficiency = 0.95
- Pressure losses
    - P44Q43 = 0.98 (IPT interduct reference pressure ratio)
    - P48Q47 = 0.99 (LPT interduct reference pressure ratio)
    - P6Q5 = 0.995 (turbine exit duct pressure ratio)
    - P16Q13 = 0.988 (bypass duct pressure ratio)
- Shafts
    - HP shaft losses = 0.6 % PW HPC
    - IP shaft losses = 0.4% PW IPC
    - LP shaft losses = 0.15 % PW LPC
- Secondary Air System (GxWy given as % of W25)
    - G31W5 = 0.5% (HP leak to LPT exit)
    - G31W41 = 5% (HPT NGV cooling, NGV = Nozzle Guide Vane)
    - G31W43 = 6% (HPT cooling)
    - G28W45 = 2% (IPT NGV cooling)
    - G28W47 = 1% (IPT cooling)
    - CH28D25Q = 0.6 (relative enthalpy of IPT cooling air)
    - G26W5 = 1% (LPT cooling)
    - CH26D25Q = 0.7 (relative enthalpy of LPT cooling air)

Main sizing parameters

Sizing is free… How many degrees of freedom (DoFs) and therefore how many main equations are there for this architecture? Before you start, make sure you know what your main equations/DoFs will be, otherwise you will have trouble making your model converge.

GasTurb gives you by default the following main equations among its inputs (in Basic data tab):

- Outer Fan/LPC PR
- IPC PR
- HPC PR
- W2Rstd
- BPR
- Burner Exit Temperature T4

But it may be more convenient to use another set of main equations. The main equations should be chosen in order to make it easy to check the main constraints below.

The equations can be either directly imposed in the ***Design Point*** menu if the parameter is available as an input in GasTurb (among the list above), or via the ***Iterations*** menu if you want to impose a parameter that is not in the input list above. In that latter case, the iteration variable you want to trade against your desired parameter will necessarily be part of the input list above.

Equations or main equations refer to the engine's degrees of freedom. Main equations are not necessarily in the iterations, if the chosen parameter is already a Gasturb input.
Iterations are a Gasturb tool to set a main equation or a secondary parameter. Iterations are not necessarily main equations.

CONSTRAINTS to be checked by your first cycle:

- The **thrust** is an aircraft requirement (no choice here!)
- **P3Q25 = 21** is a study requirement, as the core is scaled up or down from the LEAP core
- The **fan diameter** is limited to **80in**, due to aircraft integration constraints.
- **45 < OPR < 60** : you can choose a first value in this range, but not the min or max value for now.
- **0.9 < P16Q6 < 1.3** (acoustic constraint → optimization of the exit velocity of both flows) : you can choose a first value in this range, but not the min or max value for now.
- T4 and T48 are limited to a max value (turbine life duration constraint)
  - T4 < 1820 K, don't choose the max value for now.
  - T48 < 1200 K
- DH/T is limited to a max value for each turbine (turbine feasibility constraint)
  - DH41/**T41**<400 J/kg/K
  - DH45/**T45**<150 J/kg/K
  - DH48/**T48**<450 J/kg/K

However, you cannot choose randomly your main equations in this list, some of them are redundant. Furthermore, you might not have enough sizing degrees of freedom (DoFs) to set all those constraints. Therefore, some of them will be ensured via an iteration, others will have to be checked thereafter.

Explain your choice of main equations/DoFs in your report (why you chose the equations that you chose), and as a consequence explain your iterations. Several choices are possible, there is not only one solution.

Display your cycle in the report. Compare the values of the constrained data to their limits.

5. Sizing parametric studies

Assumptions

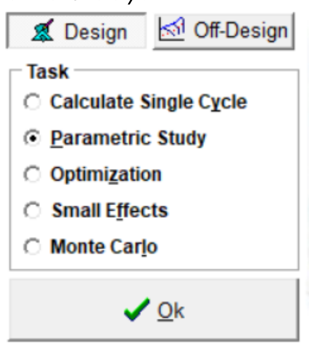
This part of the expected work aims at assessing the impact of a few selected sizing parameters on the overall performances.

A first set of parametric studies will be done without the intercooler (efficiency = 0), then with the intercooler (efficiency = 0.65).

Parametric study

The use of what you have learnt in the course and practical sessions is highly recommended!

From the main page, click on *Parametric Study*.



The following 4 parametric studies are expected, by changing <u>one parameter at a time</u>. For each one, <u>please make a screenshot of your iterations</u>.

Warning: OPR and P16Q6 are not model inputs. You have to find which parameter you're going to use as a variable to do the parametric study. **If the OPR or P16Q6 is fixed thanks to an iteration, make sure you deactivate it for the trade study on the OPR or on P16Q6 respectively** (for example, if you have an iteration on P16Q6, deactivate it for the P16Q6 trade study).

P3Q25 will be kept at the design value (it is a scale from an existing core).

	Unit	Range	Fixed parameters
BPR	-	8-12	OPR, T4, P16Q6
OPR		45-60	Fan diameter, T4, P16Q6
T4	K	1680-1820	Fan diameter, OPR, P16Q6
P16Q6	-	0.9-1.3	Fan diameter, OPR, T4

The design constraints (fan diameter, turbine loads, and turbine temperatures) don't have to be met for the whole range, but explain why they are not.

If the plot doesn't go to the max value, it's because the model does not converge. Check why and change one of your main equations to make it work.

The following quantities evolutions against the variable parameters will be plotted:

- SFC (inversely proportional to thermo-propulsive efficiency)
- Core size W25R3=W25*sqrt(T3/Tstd)/(P3/Pstd)
- Core (=thermal) efficiency and propulsive efficiency
- Fan diameter
- Other parameters you think interesting depending on the parametric study you are doing.

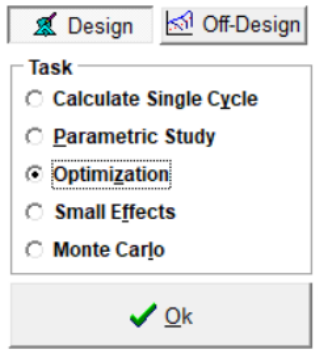
Pay attention to the range of the y axis : sometimes the variation is negligible (when it says "*10-3" for instance).

Analyze the results you obtained for each parametric study, using what you learnt during the Practical 2. What engine efficiency varies in each parametric study?

1. BPR: How does the fan pressure ratio evolve? Why?
2. OPR: at constant P3Q25, which compressor is impacted by the OPR increase? How does the core size vary and why?
3. T4: how does the core size vary and why? What about the BPR?
4. P16Q6: How does the fan pressure ratio evolve? Why?

Optimization

From the main page, click on *Optimization*.



Warning: deactivate all of your iterations (OPR, P16Q6, turbine loads…) except CONSTP, CONSTEFF, and thrust.

Choose the 4 optimization variables as the variables used for the previous parametric studies:

- BPR,
- the one you used to replace OPR,
- T4,
- the one you used to replace P16Q6.

Set up the following 6 constraints:

- Fan diameter,
- HP, IP and LP turbine loads,
- OPR,
- P16Q6.

Please make a screenshot of your constraints and variables. Set up the SFC as the "figure of merit" to be minimized.

Run the optimization with an *Endless random* search strategy, then check that your result is similar to or better than what you would have got with a *Systematic* search strategy.

Save your optimized cycle as *Optimized cycle – [your name]*.

Analyze the results based on the parametric studies you did, or based on what you learnt from the previous Practical sessions. Show the main parameters of the optimized cycle. Compare the optimized cycle to the initial one (SFC and other meaningful parameters, in %).

6. Intercooler

Intercooler technological features

Let's analyze the intercooler now. Based on your final cycle without intercooler (the one you got after the optimization), set up the following data.

- Hot flow pressure losses: PRh = 0.98
- Cold flow pressure losses: PRc = 0.99
- Heat exchanger effectiveness Eff = 0.65 (instead of 0 that you previously had)
- Cold flow into intercooler = 15% of W13

T4 should be kept constant here (disable any iteration you had on T4).

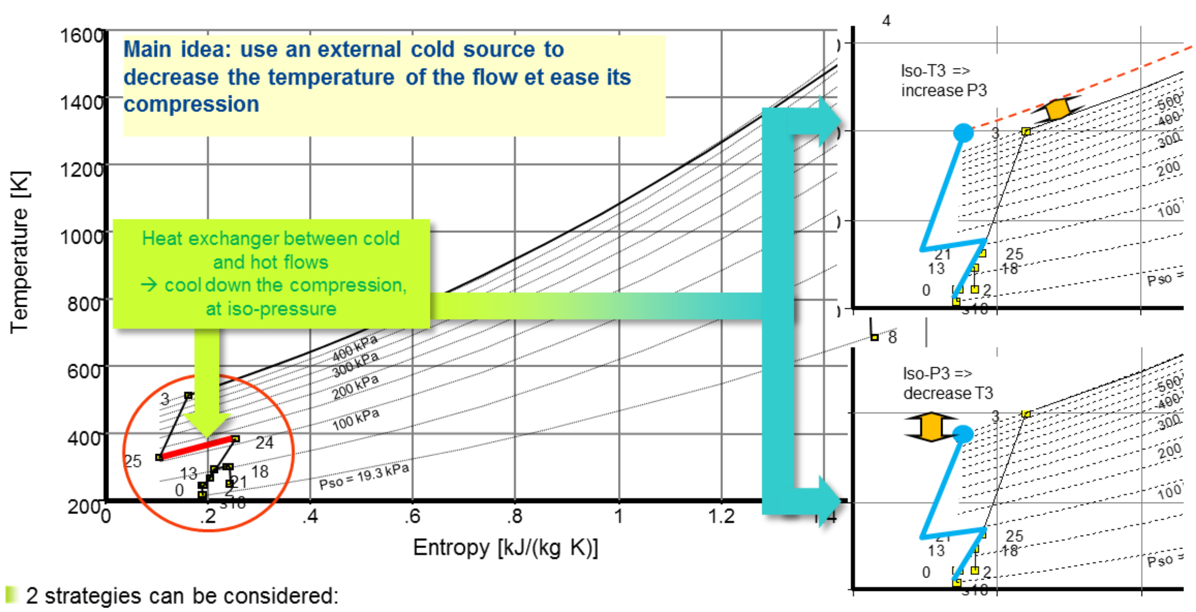
Save your project as *Intercooler - [your name]*.

Design a cycle with the same OPR as the optimized cycle without intercooler (use an iteration).
Design another cycle with the same T3 as the optimized cycle without intercooler (use an iteration, disable any iteration you had on OPR).
Pay attention to the cycle constraints (<u>including turbine loads</u>), they still should be met. Else, make adjustments to meet them.

What does the intercooler change? Use a T-S chart (that can be plot with Gasturb, with the additional capability to superimpose reference cycle and intercooled cycle) to explain what happens.

Display and compare the 3 cycles (SFC and other meaningful parameters, in %).

The rest of the studies will be done at **<u>same OPR</u>** than the previous cycle.



2 strategies can be considered:

- Sizing at iso-T3 vs engine with no intercooler → increase OPR → decrease SFC
- Sizing at iso-OPR vs engine with no intercooler → decrease T3 → decrease NOx emissions

Parametric study

The following 5 parametric studies are expected, by changing one parameter at a time. The one based on the cold flow into the intercooler is new compared to what you have done in the first part of the project, without intercooler.

	Unit	Range	Fixed parameters
BPR	-	8-12	OPR, T4, P16Q6
OPR		45-60	Fan diameter, T4, P16Q6
T4	K	1680K to 1820K	Fan diameter, OPR, P16Q6
P16Q6	-	0.9-1.3	Fan diameter, OPR, T4
Cold flow into intercooler	%	5% to 30%	Fan diameter, T4, P16Q6, OPR

Focus only on the differences brought by the intercooler compared to the previous parametric studies.

Optimization

Update the optimization by adding the cold flow percentage into the intercooler as a variable. Save your project as Optimized cycle with intercooler - [your name].

Analyze the results based on the parametric studies you did. Show the main parameters of the optimized cycle. Compare the optimized cycle to the initial one.

Technology influence

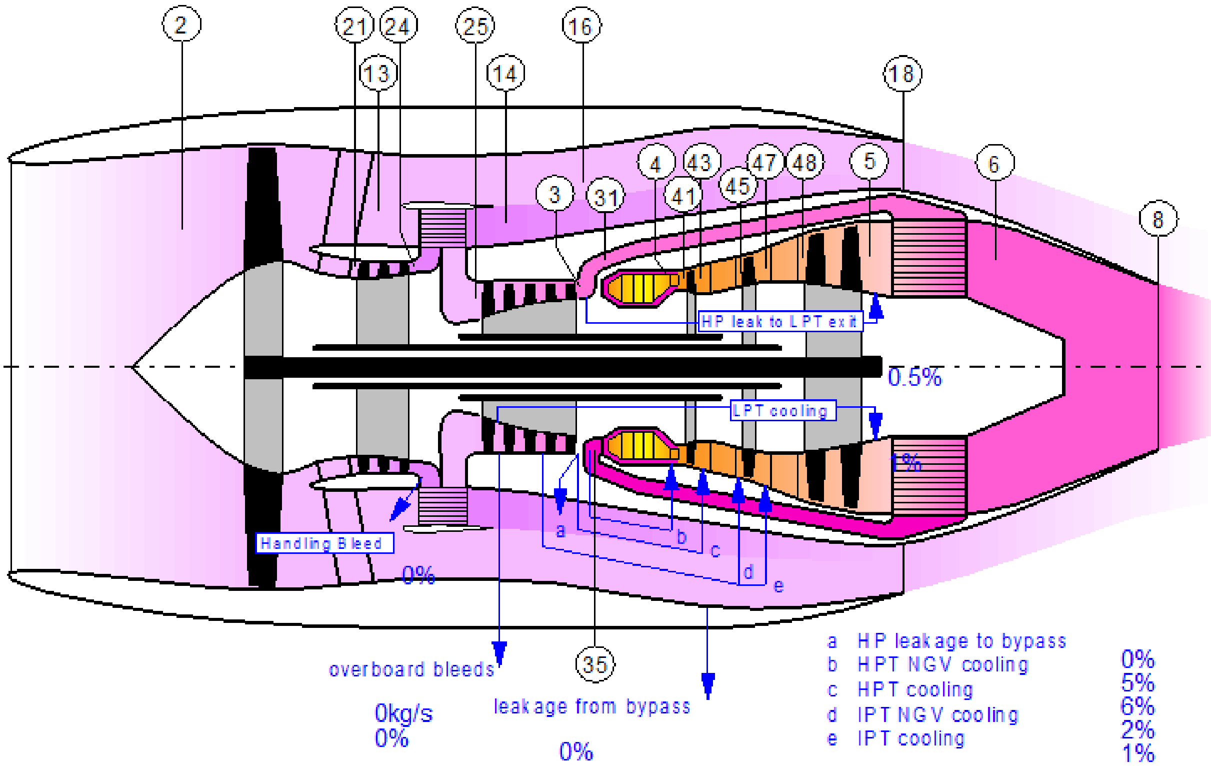
The model will finally be used to assess the relative impact of the intercooler technology assumptions on the SFC level, with respect to the optimized cycle. No need to use the Optimization tool for that.

- Heat exchanger efficiency: +0.01
- Hot flow pressure ratio P25/P24: +0.01 (i.e. pressure loss <u>decrease</u> by 1pt)
- Cold flow pressure ratio P14/P13: +0.01 (i.e. pressure loss <u>decrease</u> by 1pt)

The relative impacts on SFC will be sorted out by order of magnitude, and conclusions will be drawn about the most influent technology items.

7. APPENDIX: Thermodynamic stations

Three Spool Separate Flow Turbofan with intercooler and recuperator.



Symbols:

W	mass flow
A	geometrical area
P	total pressure
Ps	static pressure
T	total temperature
Ts	static temperature
WF	fuel mass flow
FAR	fuel to air ratio (= fuel mass flow / pure air mass flow)
Fn	net thrust
SFC	specific fuel consumption (WF/Fn)
PW	power
BPR	bypass ratio = (bypass mass flow/core mass flow = W16/W25)
V	speed
XM	Mach number