JET PROPULSION LIBRARY

Overview

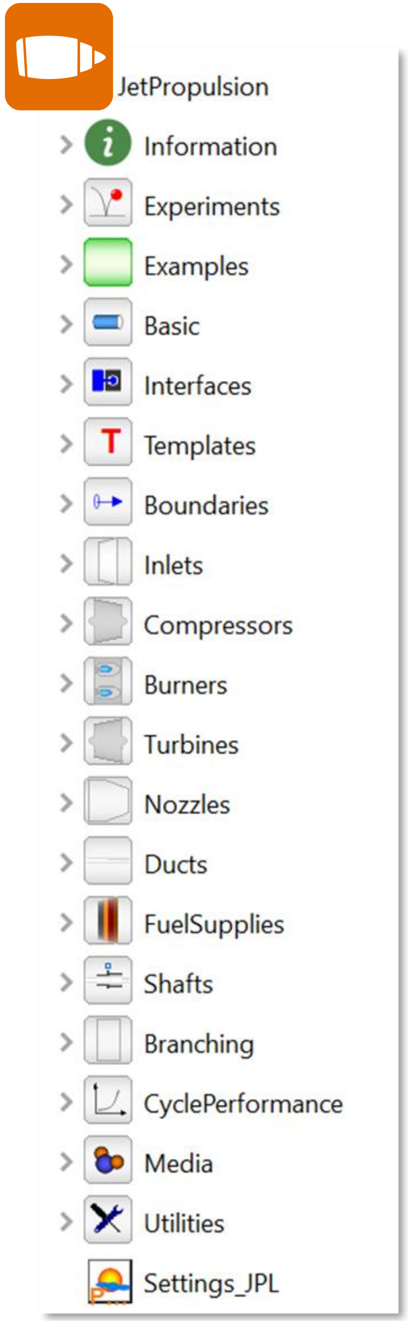
Modelon

AGENDA

- ❑ About Jet Propulsion Library
- ❑ Key Benefits
- ❑ Key Capabilities
- ❑ Key Applications
- ❑ Library Contents
- ❑ Latest Release

ABOUT JET PROPULSION LIBRARY

The library provides a foundation for the modeling and simulation of jet engines, including the model-based design of integrated aircraft systems.



KEY BENEFITS

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- Extensive library of pre-defined sub-systems and thermodynamic cycles
- Steady-state (on-design) and dynamic (off-design) capabilities within the same model
- Physics-based Solving (PbS) technology enhancing the steady-state simulations
- Same naming convention as NPSS
- Detailed volume dynamics with detailed thermodynamic capabilities
- Access to other physical domains through the Modelica language – for a more integrated aircraft
  - Heat exchanger models
  - Gears and mechanical components
  - Electrical components

KEY CAPABILITIES

KEY CAPABILITIES

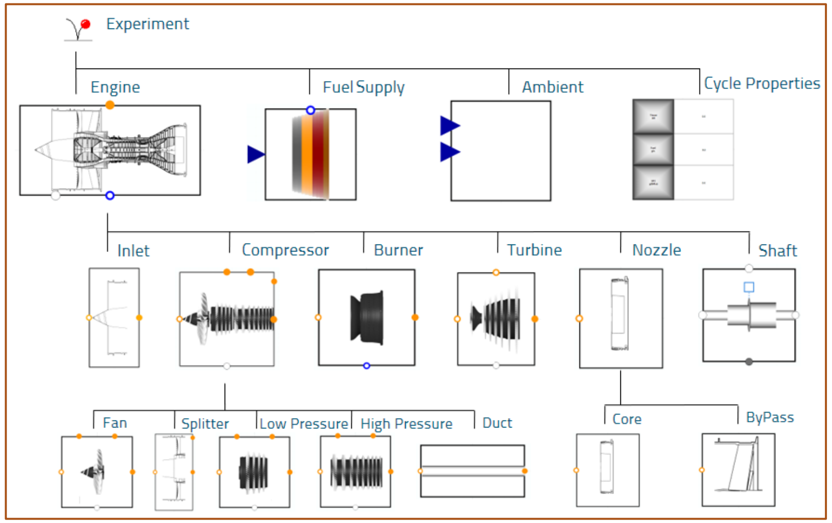
Library capabilities

- Extensive library of pre-defined sub-systems and thermodynamic cycles
  - Turbo jet
  - Turbo fan
  - Turbo prop, turbo shaft
  - With and without free power turbine
- On-design and off-design performance can be studied as well as steady-state and transient behavior based on a single model.
- This provides a fully rigorous foundation for sizing and performance computations and provides several advantages over existing domain-specific solutions due to the use of the Modelica language.

KEY CAPABILITIES

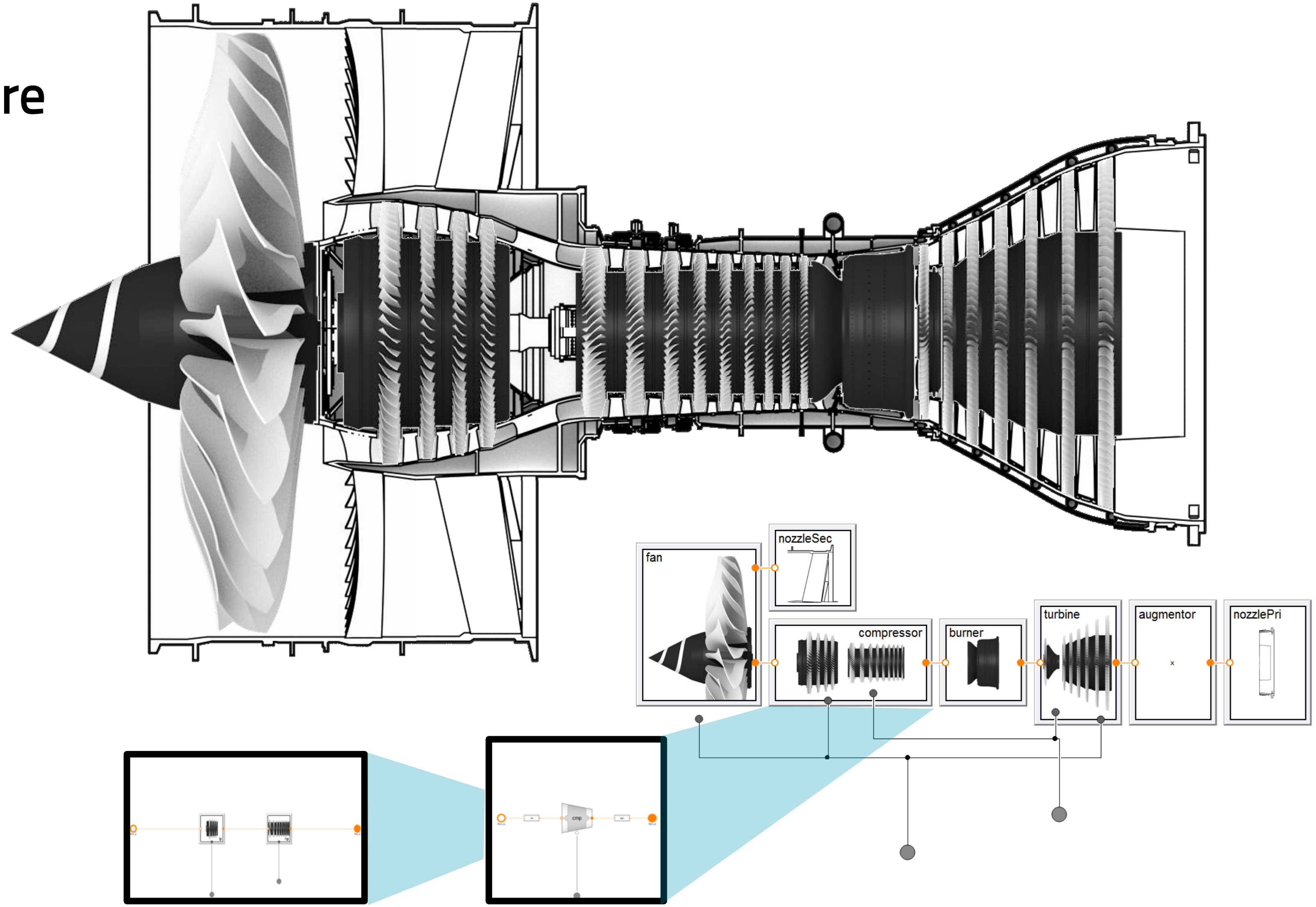
Model Architecture

- An aircraft engine contains a multitude of parts and subsystems. Conceptually, these can be organized in a hierarchy.
- For example, an engine contains a compressor, that in turn contain fan, low pressure, high pressure stages.
- In analogy with this, it is natural to organize a model of an engine similarly. This is how models in the Jet Propulsion Library are organized.



KEY CAPABILITIES

Model Architecture



KEY CAPABILITIES

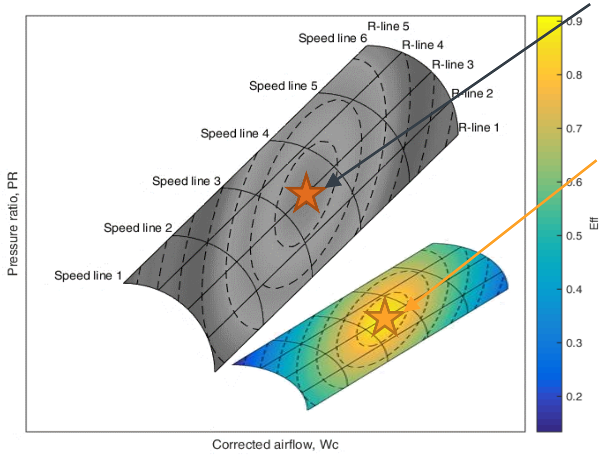
Simulation modes

- <u>On-design</u>
  - The user wants to compute the system (sizing) given intended operating conditions and performance
  - Always steady state
- <u>Off-design</u>
  - The user wants to compute the performance given system (sizing) and operating conditions
  - Either steady state or dynamic
  - “Normal simulation” in Modelica
- <u>PbS (Physics-based Solving) technology:</u>
  - Enhancement of steady-state simulation when using Modelon Impact.
  - Relies on Modelon insights about the physical properties of components and systems to achieve a structure of the system of equations that yields vastly superior numerical properties as compared to traditional tearing algorithms

KEY CAPABILITIES

Simulation modes

- On-design example 1: Duct
  - "You wants to compute the system (sizing)…."
    - What is the duct diameter?
  - "….given intended operating conditions and performance"
    - Such that the Mach Number at the design point will be 0.3?
- On-design example 2: Compressor
  - "Given performance and…"
  - "…intended operating conditions, …"
  - "…compute the system (sizing)."
    - What are design point scaling factors?



Design point encoded in map

Design point per user intent

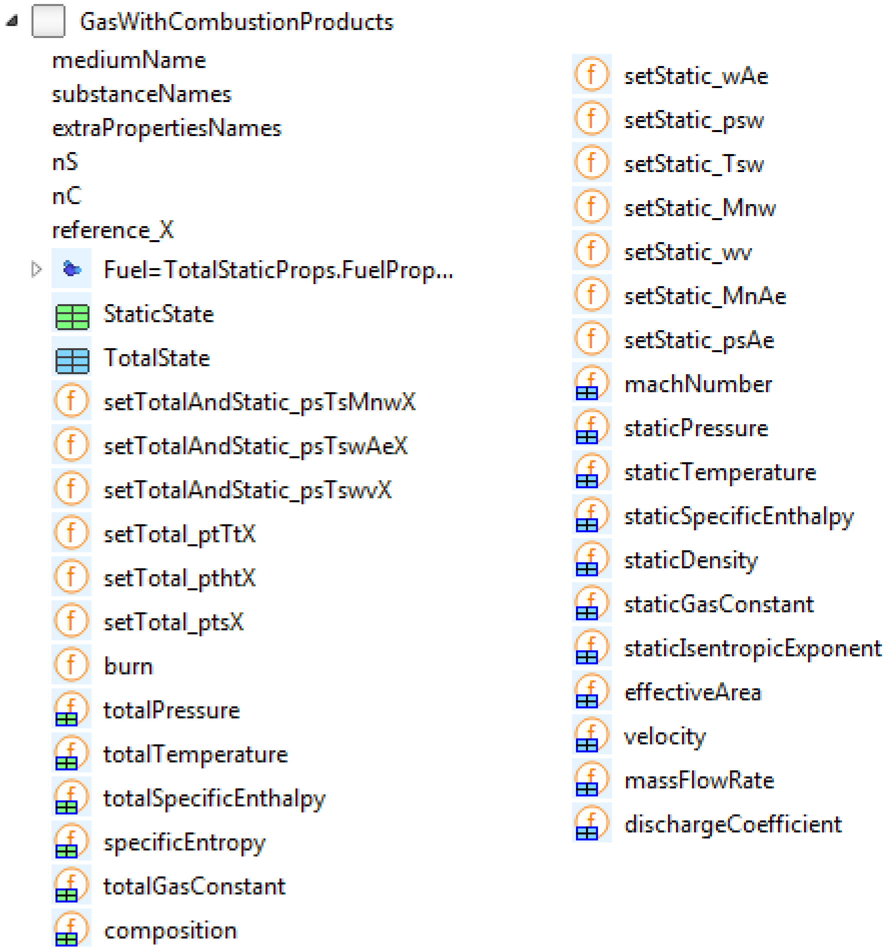
KEY CAPABILITIES

Fully rigorous thermodynamic properties

- Define entropy function (temperature-dependent part of entropy)

$$\phi(T) = \int_{T_{ref}}^{T} \frac{c_p}{R} \frac{dT}{T}$$

- E.g., total pressure $p_t = p_s \exp\left(\frac{\Phi_t - \Phi_s}{R}\right)$



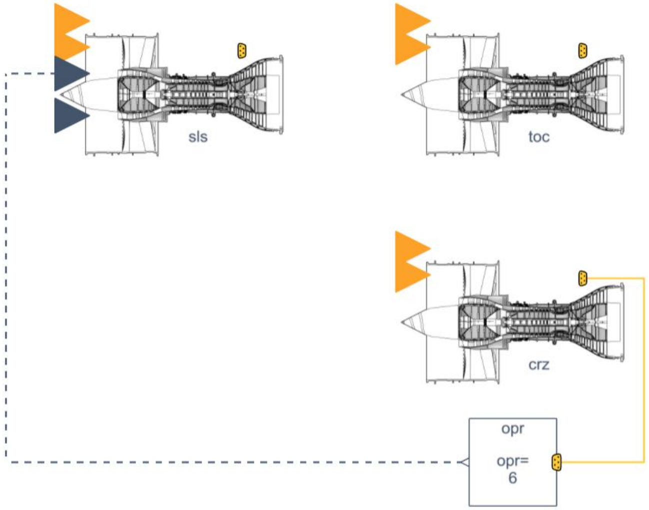
KEY APPLICATIONS

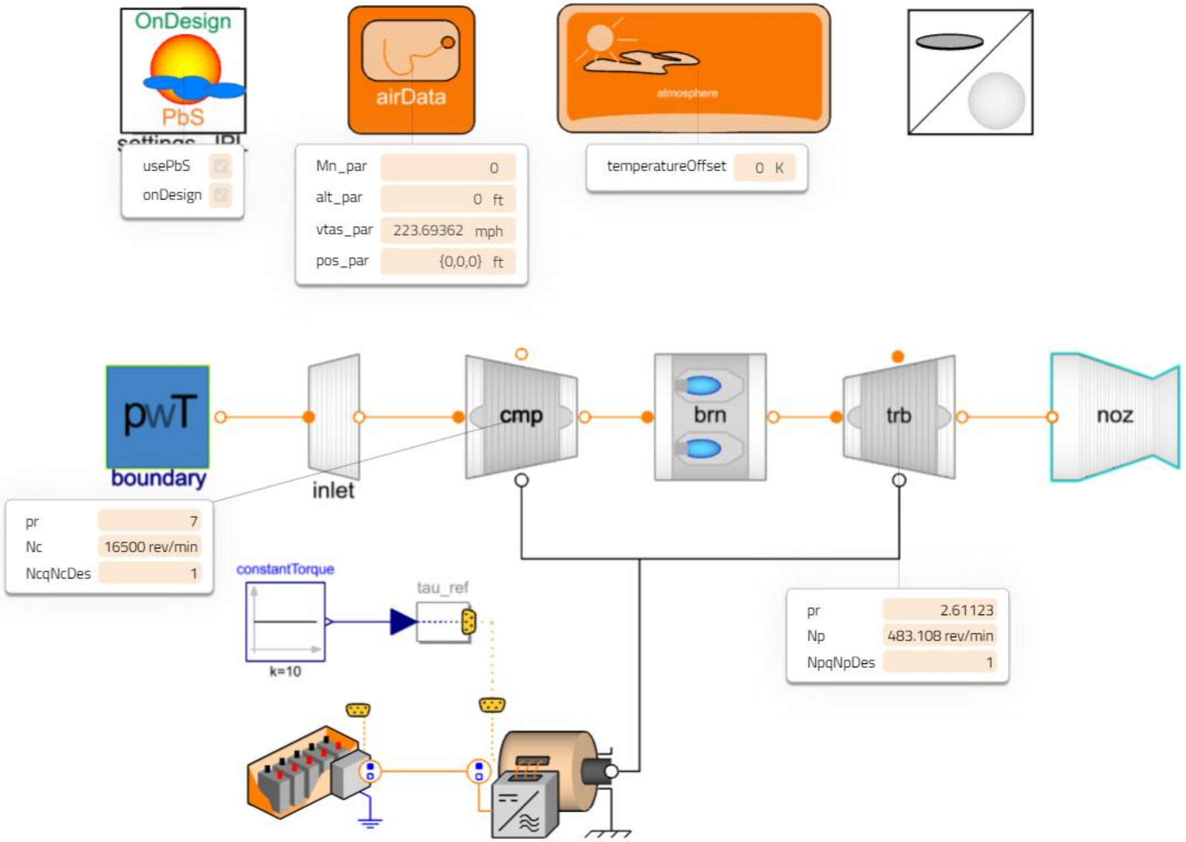
KEY APPLICATIONS

- Electrified turbojet [GE J85]
  - Steady-state (both on and off-design) simulation
  - Dynamic simulation

- Different operating conditions
- Bleed flow modelling
- Electrification

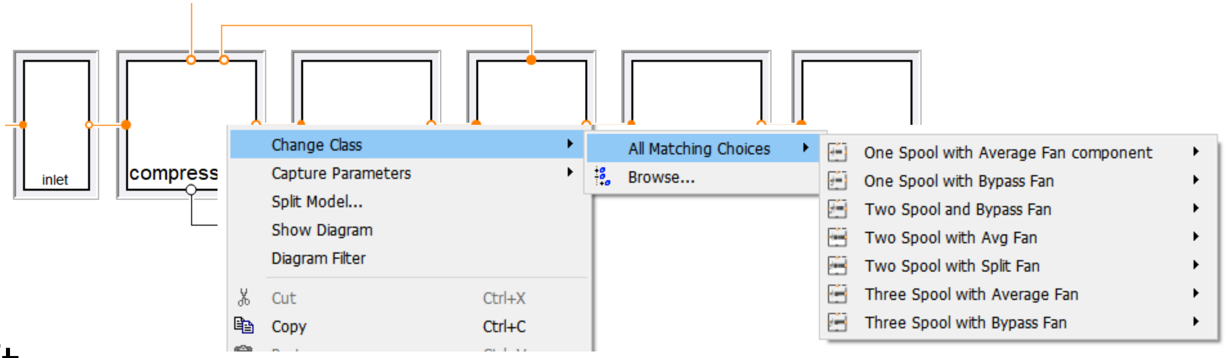
- Single and Multipoint design experiments

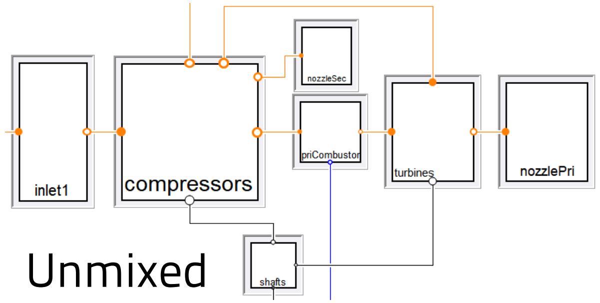




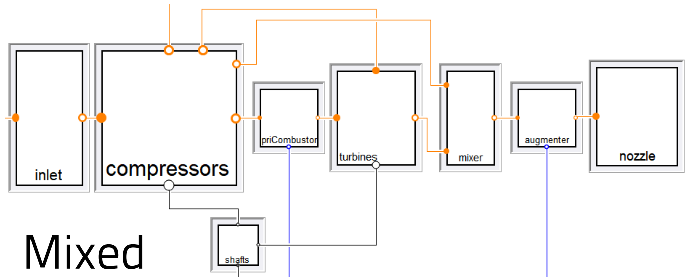
KEY APPLICATIONS

- Turbo jet
- Turbo fan
- Turbo prop, turbo shaft
- With and without free power turbine
- Innovative concepts for the more-electric aircraft
    - Gearboxes
    - Coupled thermal systems



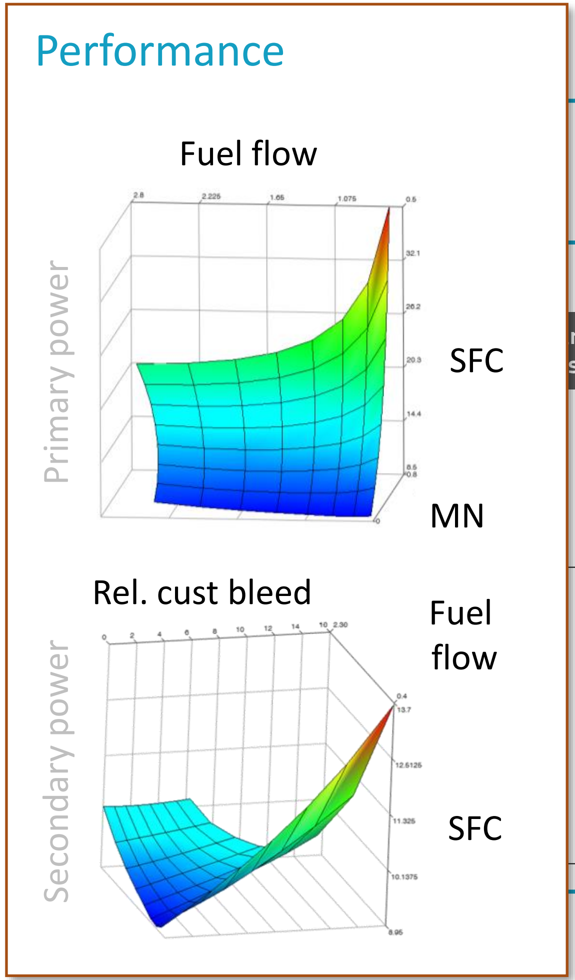


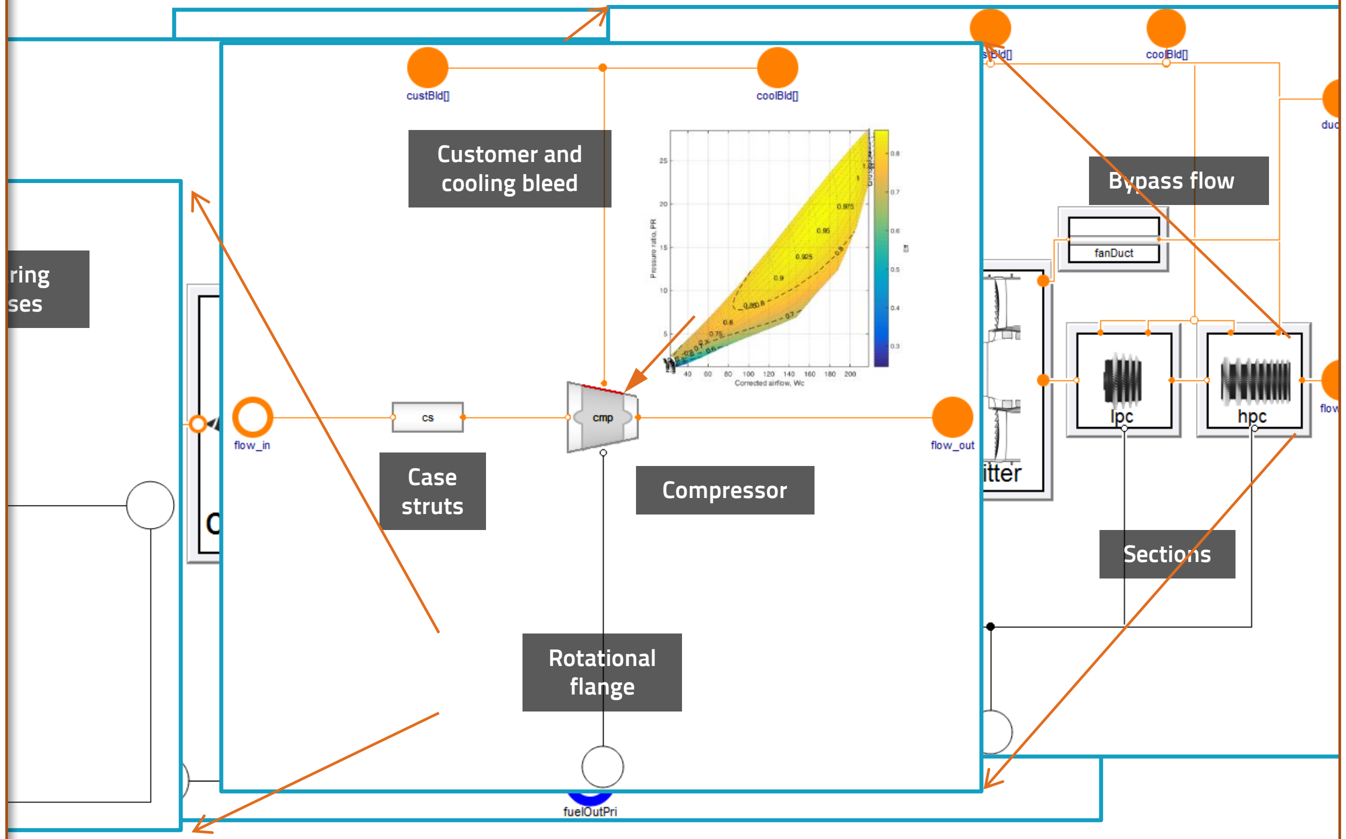
Unmixed

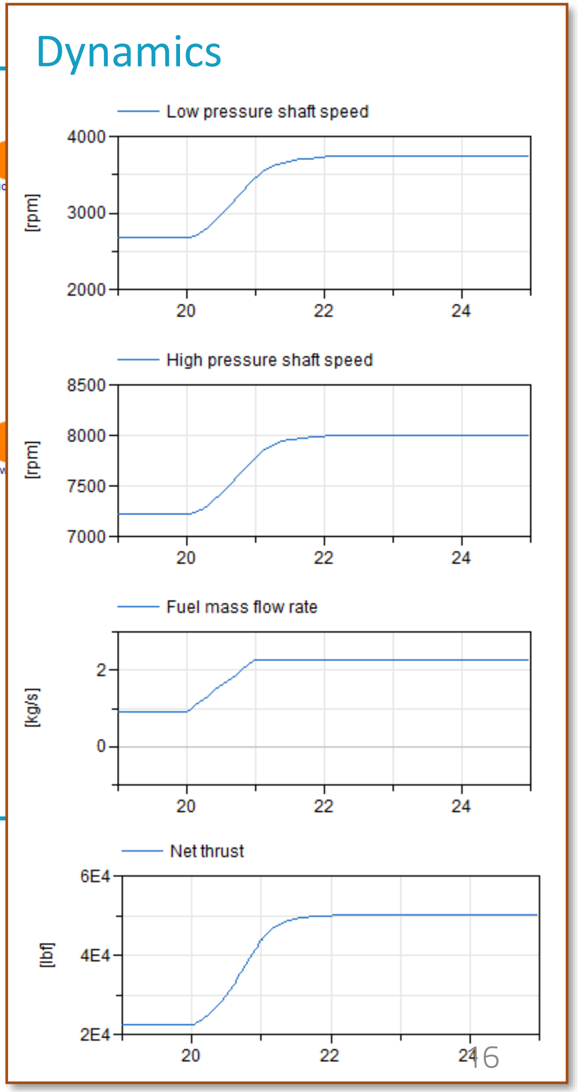


Mixed

KEY APPLICATIONS







KEY APPLICATIONS

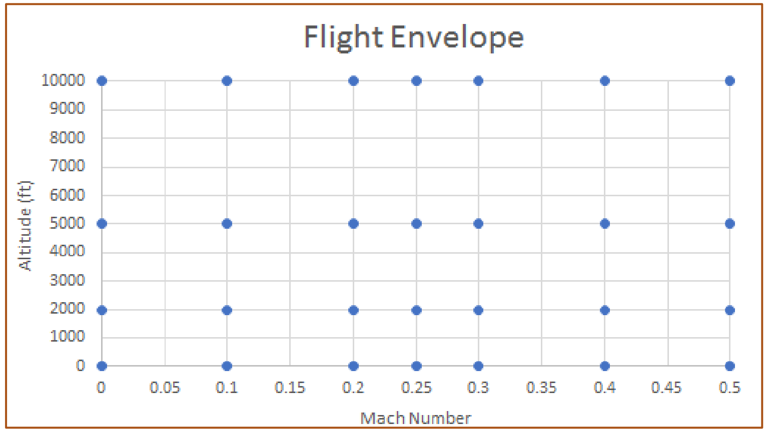
Flight Envelope study

- The best way to study the performance of a gas turbine engine is to run it through the combinations of altitudes and Mach numbers at which it is expected to operate.
- The operational domain of an engine as combinations of Mach number and altitude is known as the **flight envelope**.
- This flight envelope data varies from engine to engine based upon the design specification.
- There are two data formats in which a flight envelope can be represented:
  - grid data points
  - scattered data points
- JPL includes flight envelope data for the Pratt & Whitney's JT9D engine.

KEY APPLICATIONS

Flight Envelope study

- Figure below shows the **grid data flight envelope** with Mach number in abscissa and altitude in ordinate.
- Here the data points are fixed, same altitude values for each Mach number and this data structure will be easier to represent results (for example relationship between Altitude, Mach Number and Thrust).
- Getting important performance outputs like thrust at each of these points will give us an overview about the engine performance with respect to Mach number and altitude.
- Each of these data points are simulated using an automated plot script "plot" and results are analyzed.



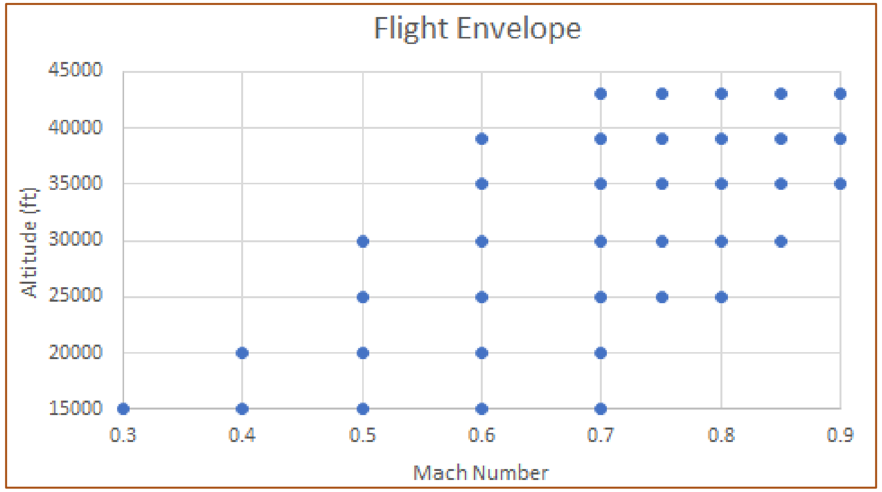
KEY APPLICATIONS

Flight Envelope study

- Figure below shows the **scattered data points flight envelope** with Mach number in abscissa and altitude in ordinate.
- The grid data point based flight envelope might have some points which are practically not feasible (low Mach number - high altitude combination and high Mach number - low altitude combination).
- The plot below is similar to an actual flight envelope where only the feasible points are plotted.
- Each of these data points are simulated

  using an automated plot script "plotGeneralized"

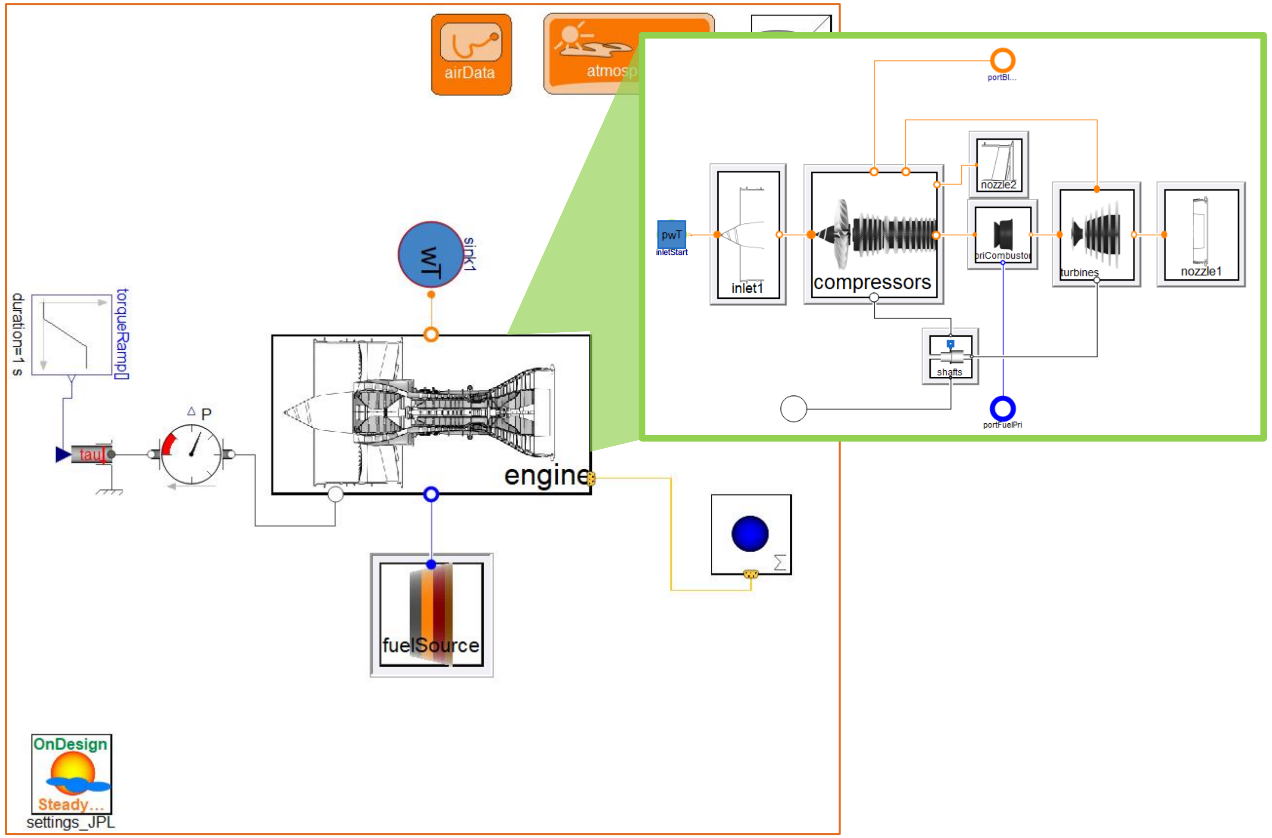
  and results are analyzed.



EXAMPLE: JT9D

Components:

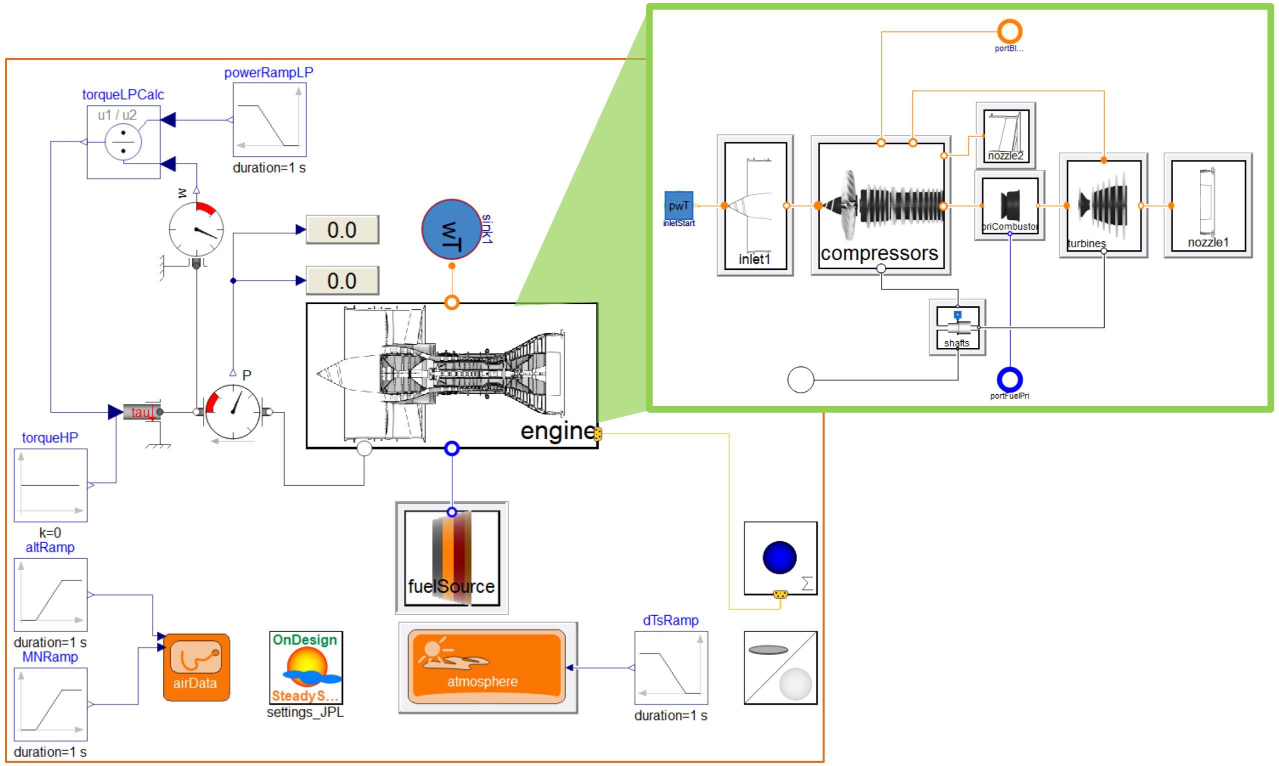
- Engine
  - Inlet
  - Compressor
  - Burner
  - Nozzle
  - Turbine
  - Shaft
- Fuel source
- Sinks/sources
- Cycle properties



EXAMPLE: GEARED TURBOFAN

Components:

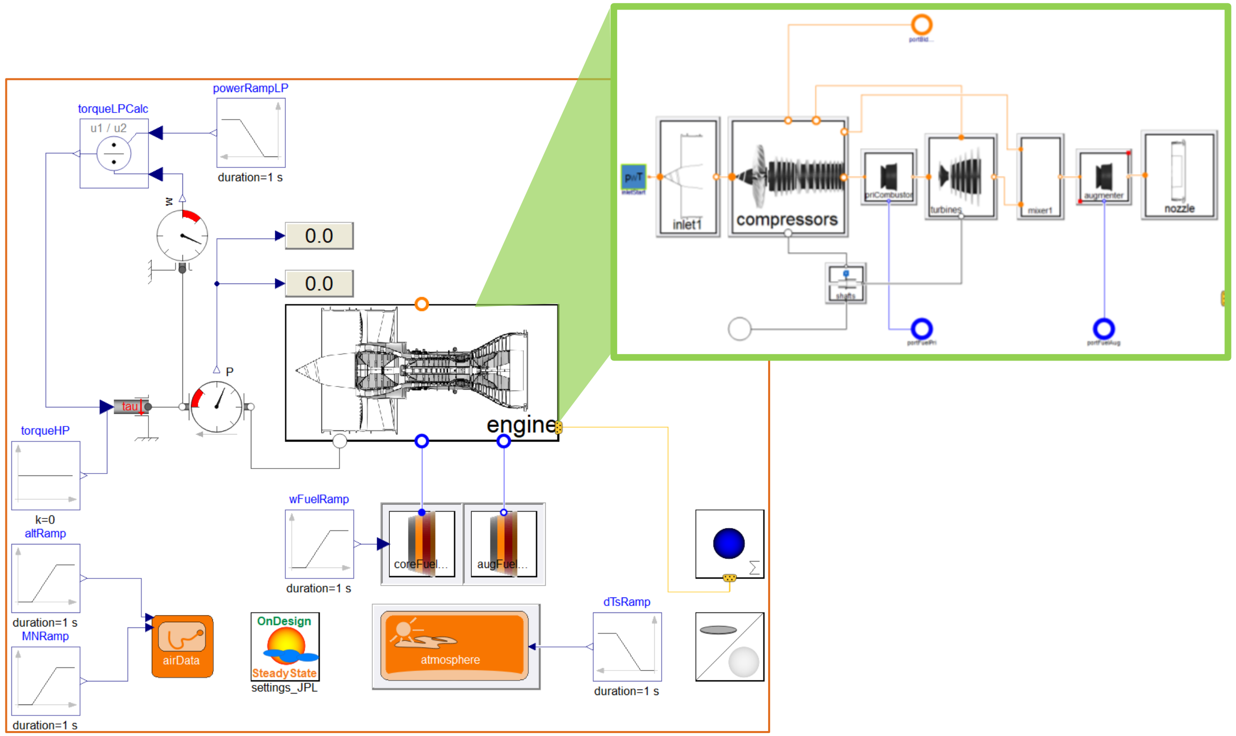
- Engine
    - Inlet
    - Compressor
    - Burner
    - Nozzle
    - Turbine
    - Shaft
    - Gears
- Fuel source
- Sinks/sources
- Cycle properties



EXAMPLE: MIXED TURBOFAN

Components:

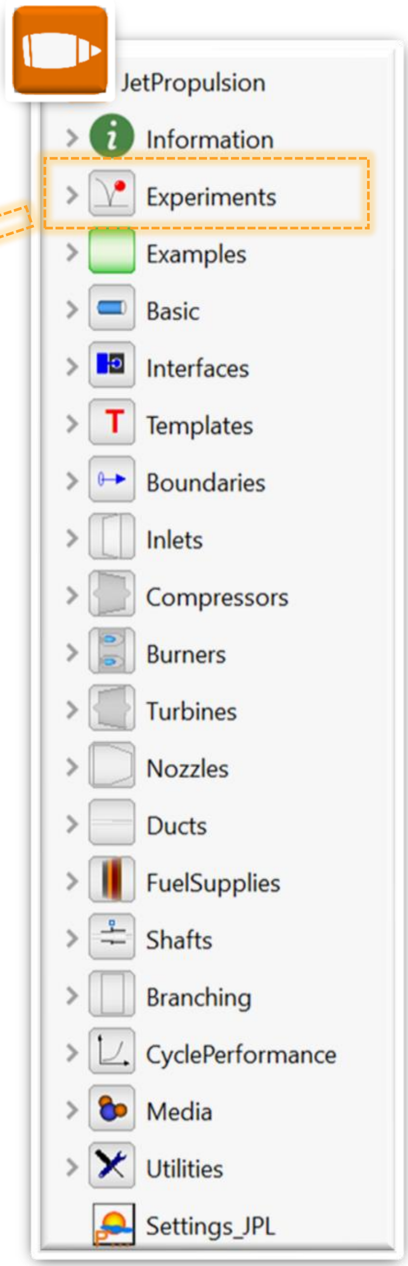
- Engine
  - Inlet
  - Compressor
  - Burner
  - Nozzle
  - Turbine
  - Mixer
  - Augmenter
  - Shaft
- Fuel source
- Sinks/sources

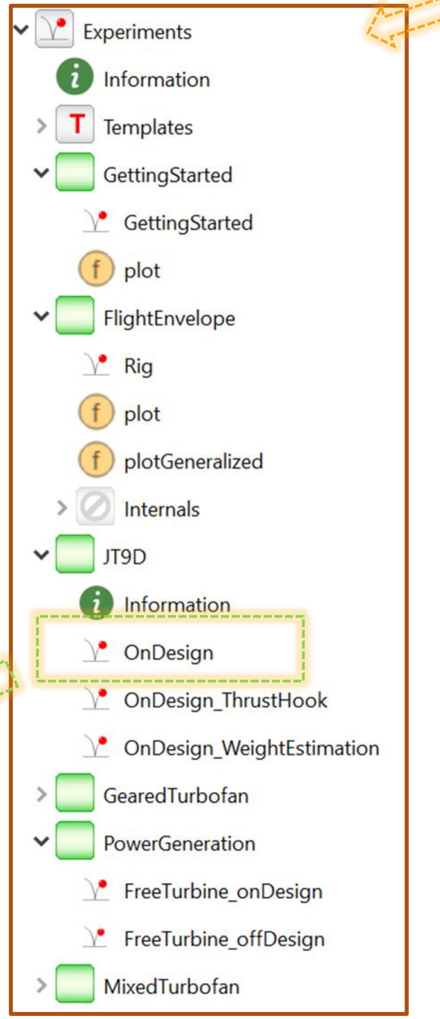


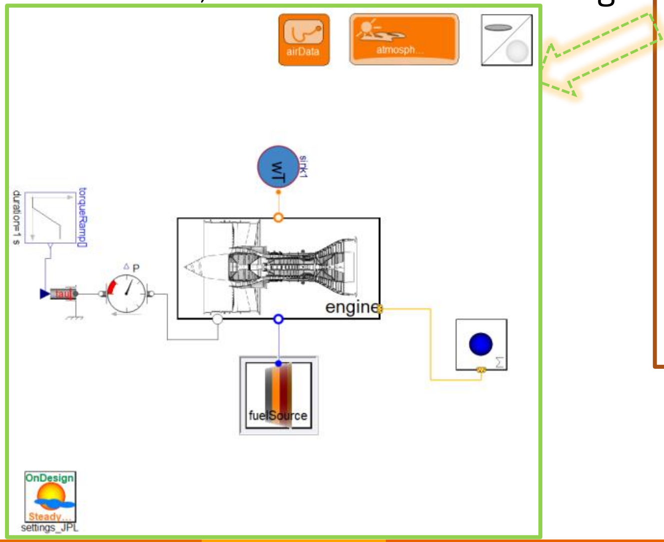
LIBRARY CONTENTS

EXPERIMENTS

- Experiments package contains executable example models.
  - JT9D engine example
  - Geared turbofan example
  - Mixed turbofan example
  - Examples for power generation
- CycleProperties block is added to each experiment models, which displays net thrust, fuel consumption and specific fuel consumption during simulation.
- Different use-case models like “Flight Envelope Rig” model are available in experiments package.
- It is recommended to go through tutorial available in JPL `(JetPropulsion.Information.UsersGuide.Tutorials)` for better understanding of experiment models.

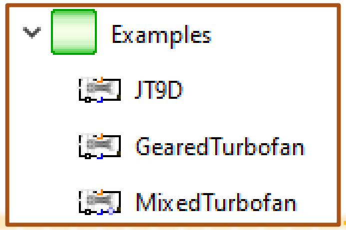




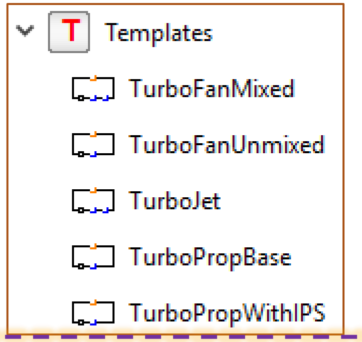


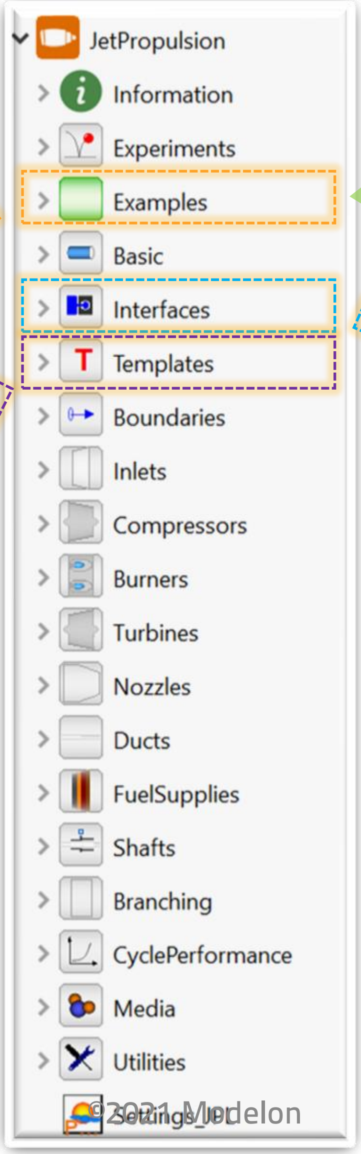
EXAMPLES, INTERFACES & TEMPLATES

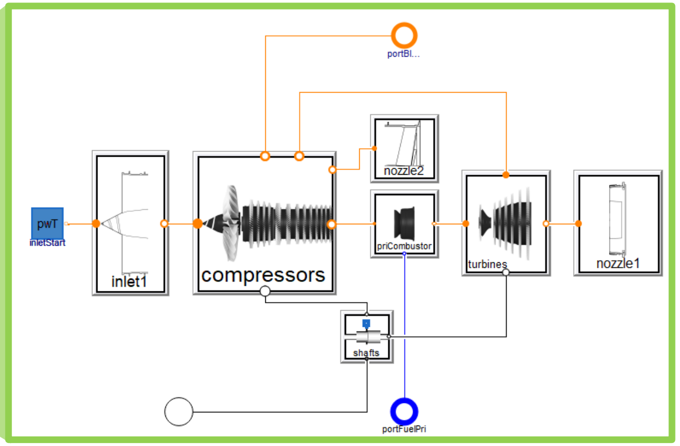
- Example models extend from templates.
- These models contain redeclare statements of individual components.
- Note: Example models are not executable.



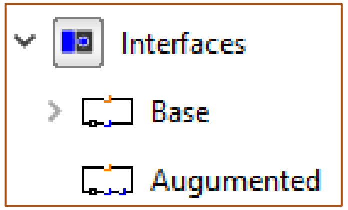
- Partial models representing different engine types
- These models extend interfaces and contain replaceable statements



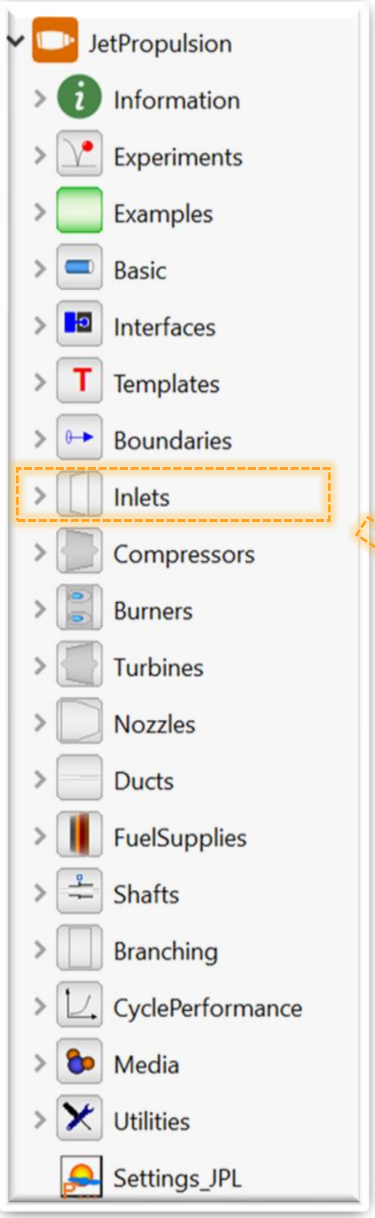


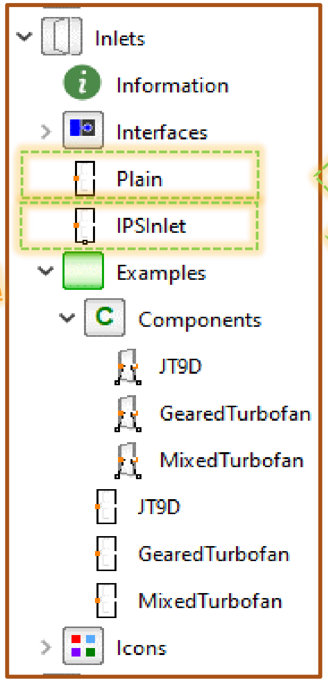


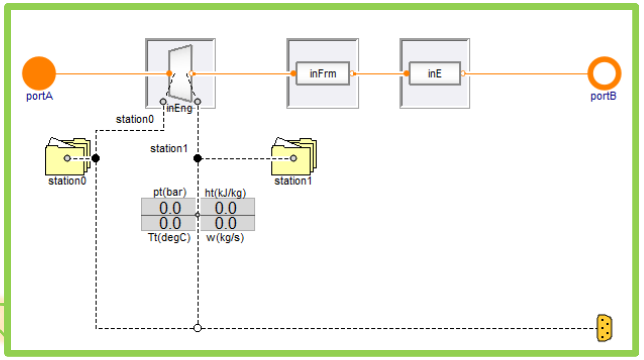
- Interfaces package contains partial models with connector instantiations.
- Two types;
  - Base
  - Augmented
- Note: flow port and flange is vectorized.



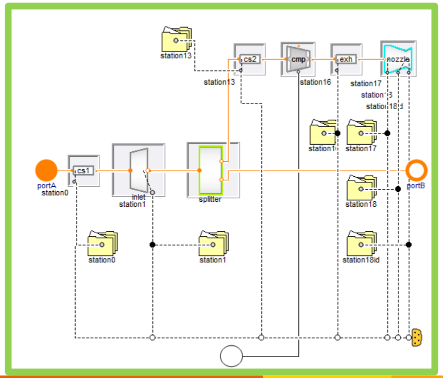
INLETS





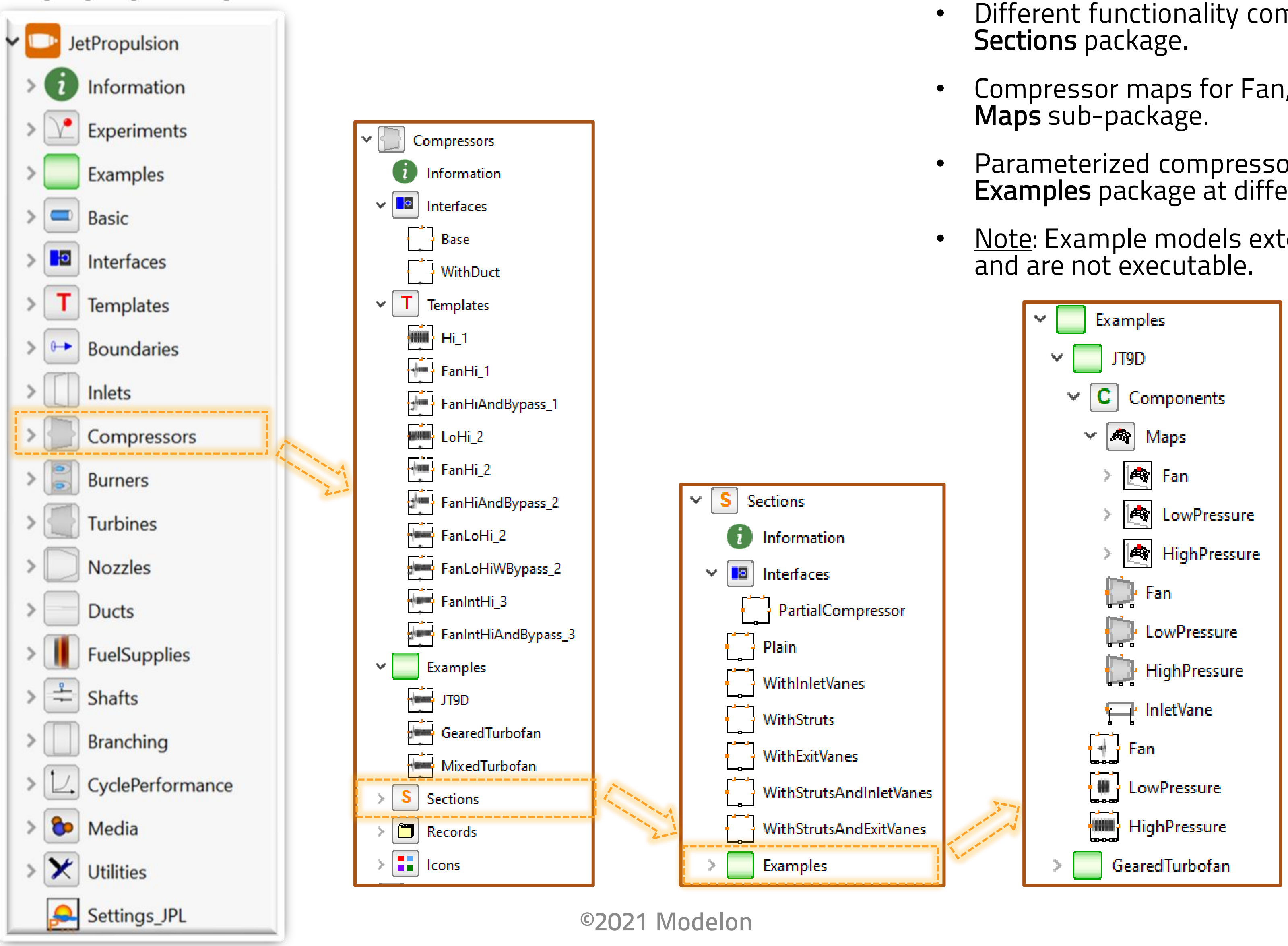


- Inlets package contains aircraft's engine **Inlet** component.
- Each sub-component in inlet is made replaceable.
- Interfaces partial models are kept inside **Interfaces** package.
- Two types:
  - **Plain**: one in & out port
  - **IPSInlet**: Inlet Particle Separator (IPS) inlet, contains additional configuration for particle separation.
- Configured example models are kept inside **Examples** package.



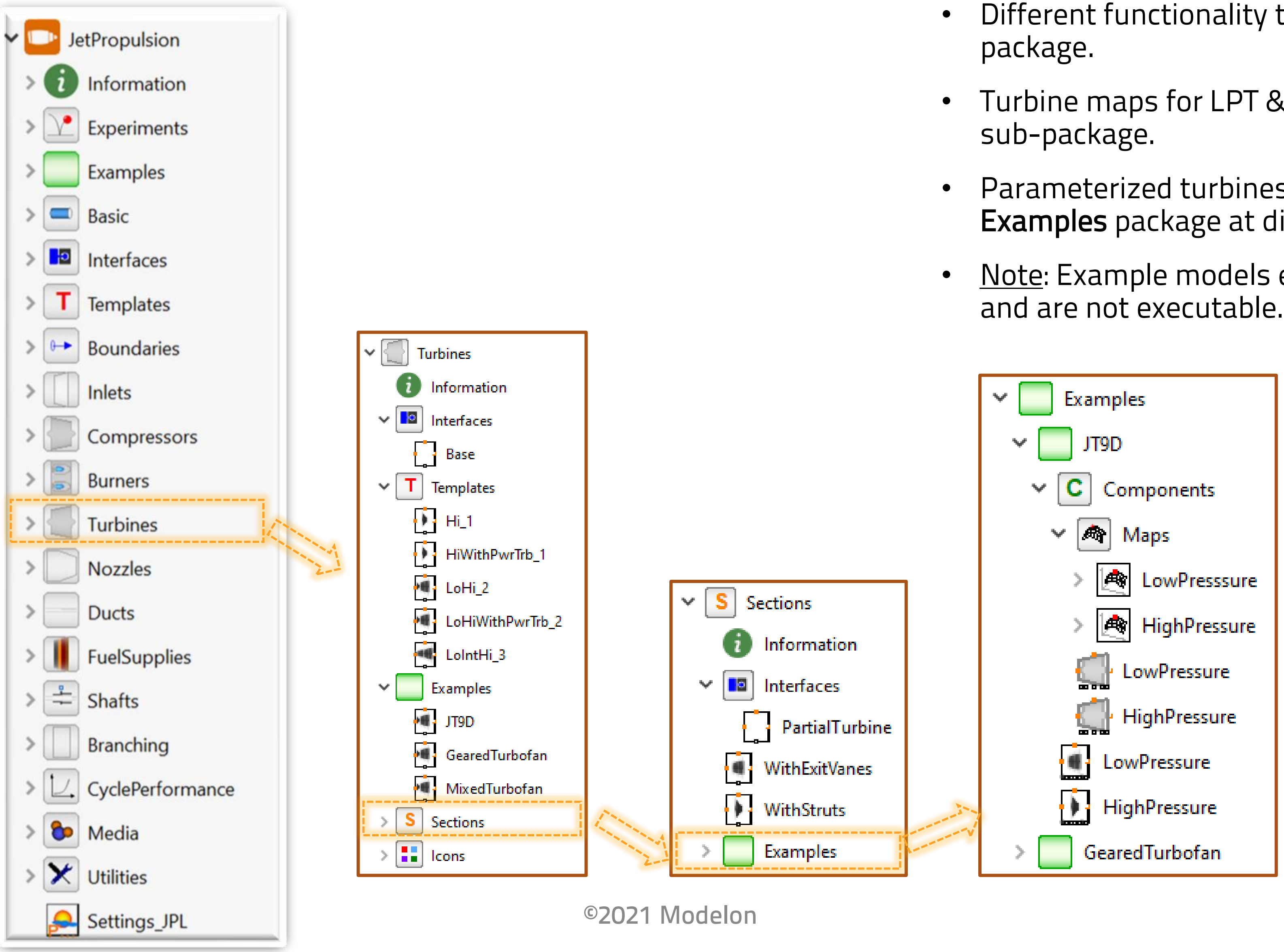
COMPRESSORS

- Compressor package contains aircraft's engine **compressor** component.
- Different functionality compressors are kept inside **Sections** package.
- Compressor maps for Fan, LPC & HPC are kept inside **Maps** sub-package.
- Parameterized compressor examples are kept inside **Examples** package at different levels.
- Note: Example models extend from compressor templates and are not executable.



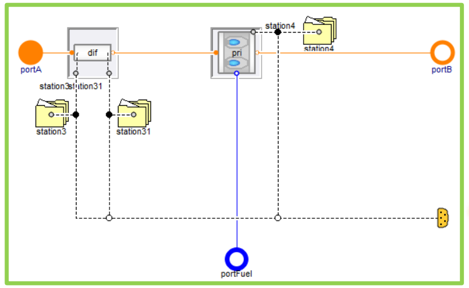
TURBINES

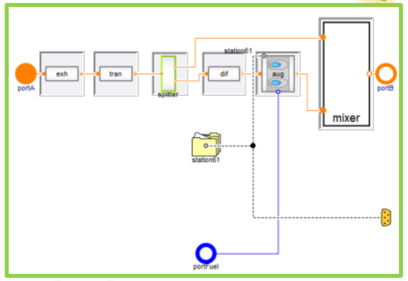
- Turbines package contains aircraft engine's **turbine** component.
- Different functionality turbine are kept inside **Sections** package.
- Turbine maps for LPT & HPT are kept inside **Maps** sub-package.
- Parameterized turbines examples are kept inside **Examples** package at different levels.
- Note: Example models extend from turbine templates and are not executable.

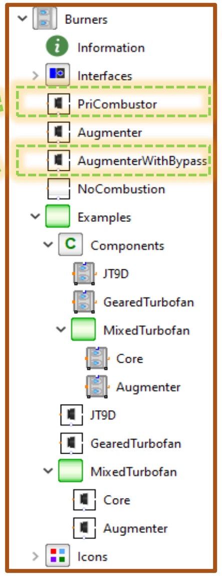


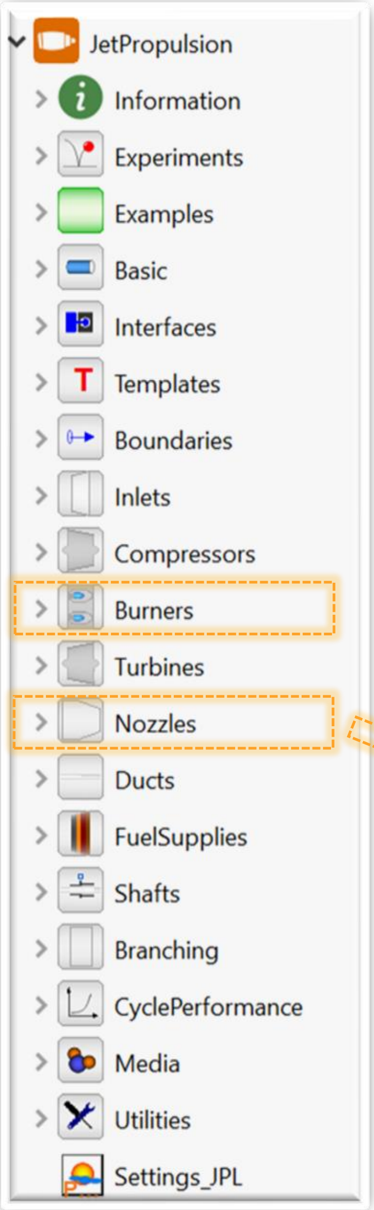
BURNERS & NOZZLES

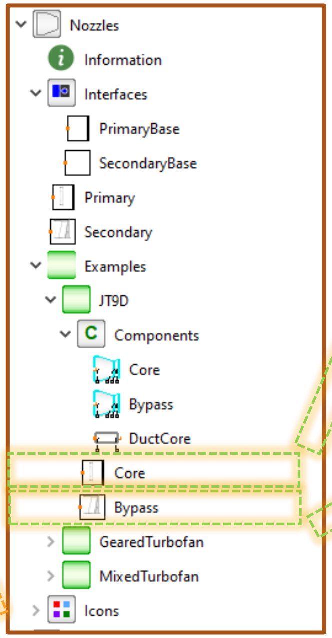
- Burner package contains aircraft's engine **combustor** component.
- Types:
  - Primary combustor
  - Augmenter
  - Augmenter with bypass
  - No-combustion
- Parameterized burner example is kept inside **Examples** package.

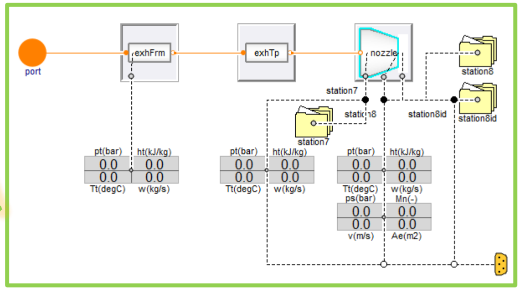


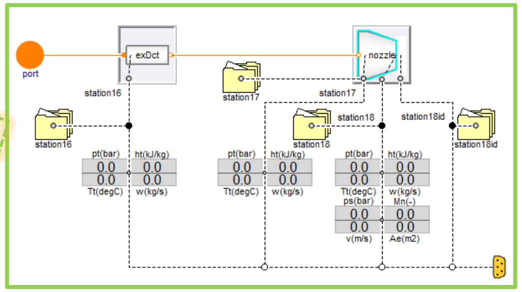






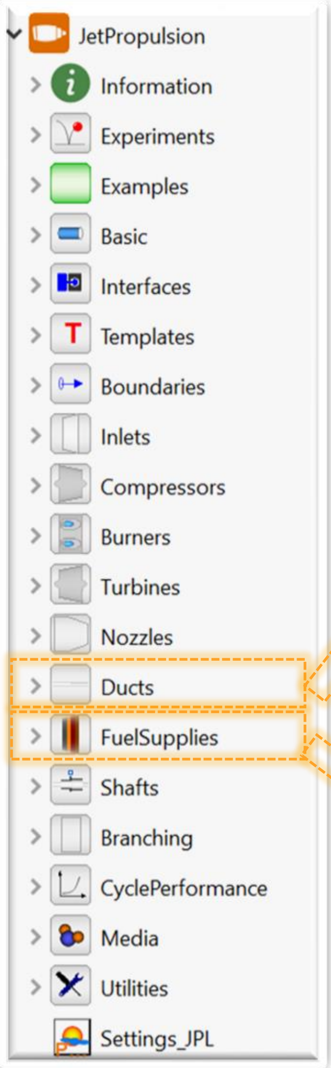


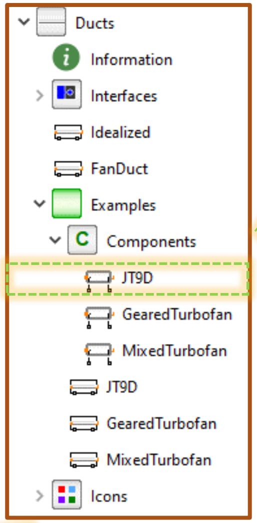


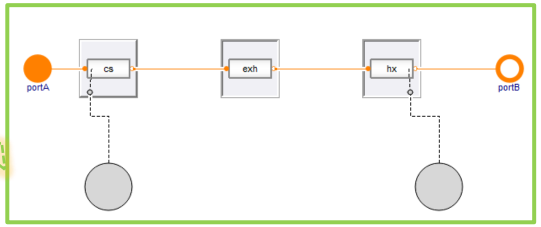


- Nozzle package contains aircraft engine's **nozzle** component.
- Two types:
  - Core nozzle
  - Bypass nozzle
- Parameterized nozzle examples are kept inside **Examples** package.

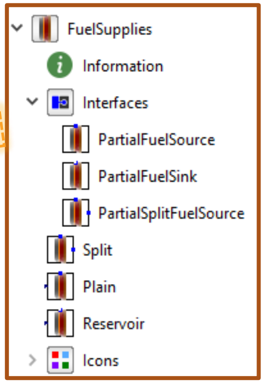
DUCTS & FUELSUPPLIES





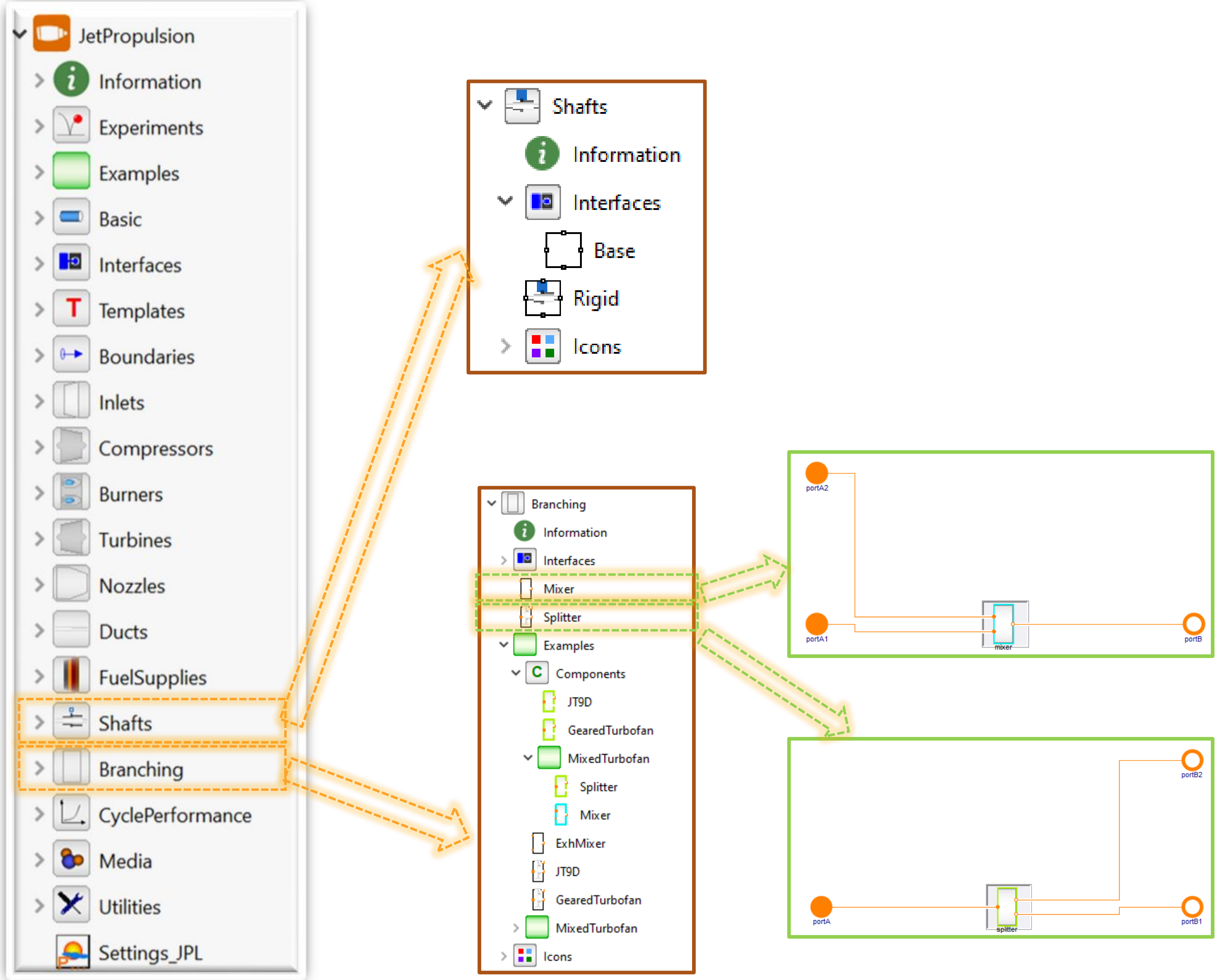


- Ducts package contains aircraft's engine **duct** component.
- That is, they represent pressure loss factor between components
- Two types:
  - Idealized
  - Fan duct



- FuelSupplies package contains aircraft's engine **fuel source** component.
- That is, fuel is fed into the engine through these components
- Three types:
  - Split
  - Plain
  - Reservoir

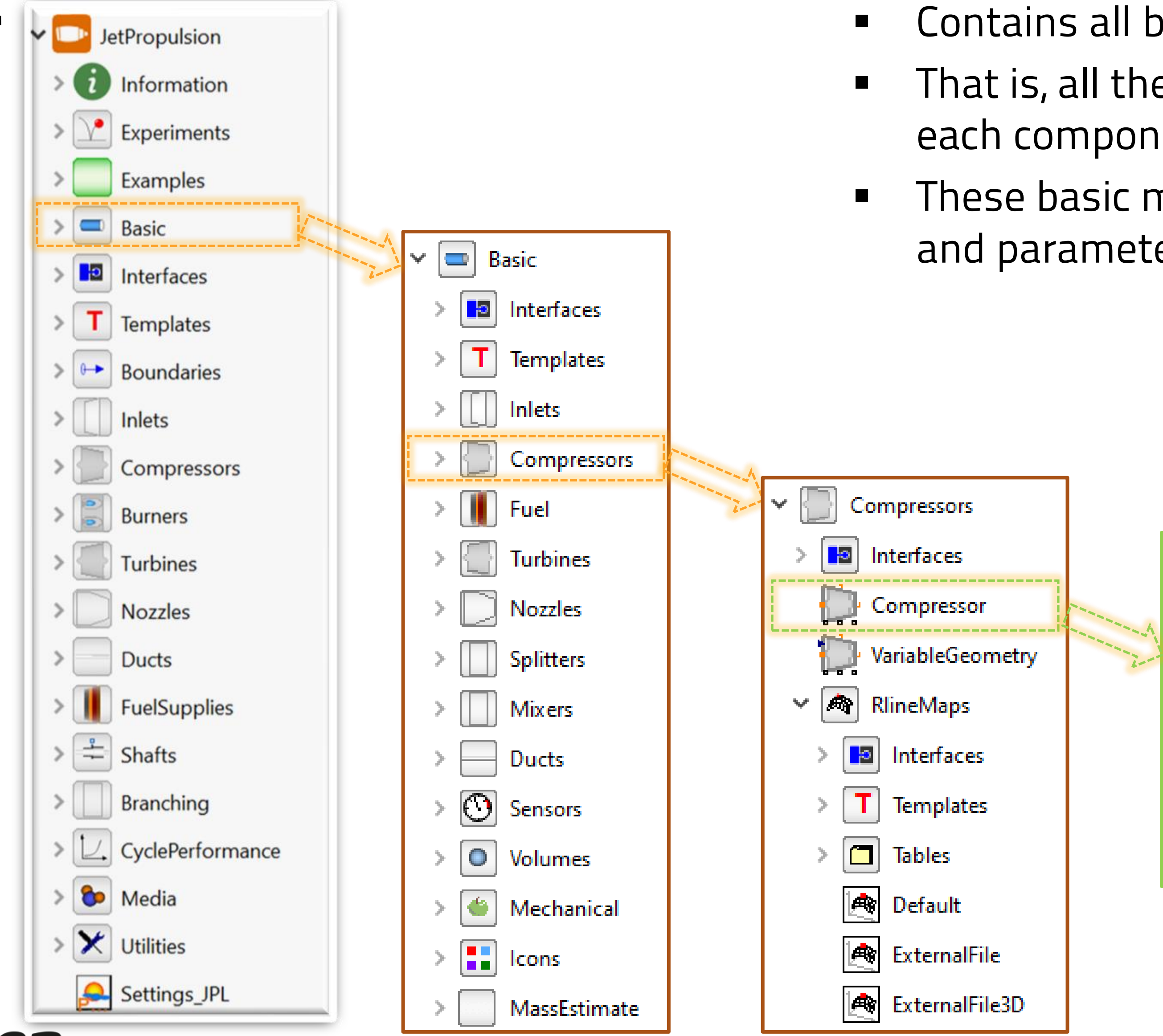
SHAFTS & BRANCHING



- Shafts package contains aircraft's engine **shaft** component.
- That is, they represent the mechanical connection between compressor and turbine through the combustion chamber.

- Branching package contains the aircraft's engine **splitter** and **mixer** component.
- Splitters are used in Turbofan engines for separating core and bypass flow.
- Mixers are used in Turbofan engines for mixing core and bypass flow after the turbine.
- Parameterized splitter and mixer examples are kept inside **Examples** package.

BASIC



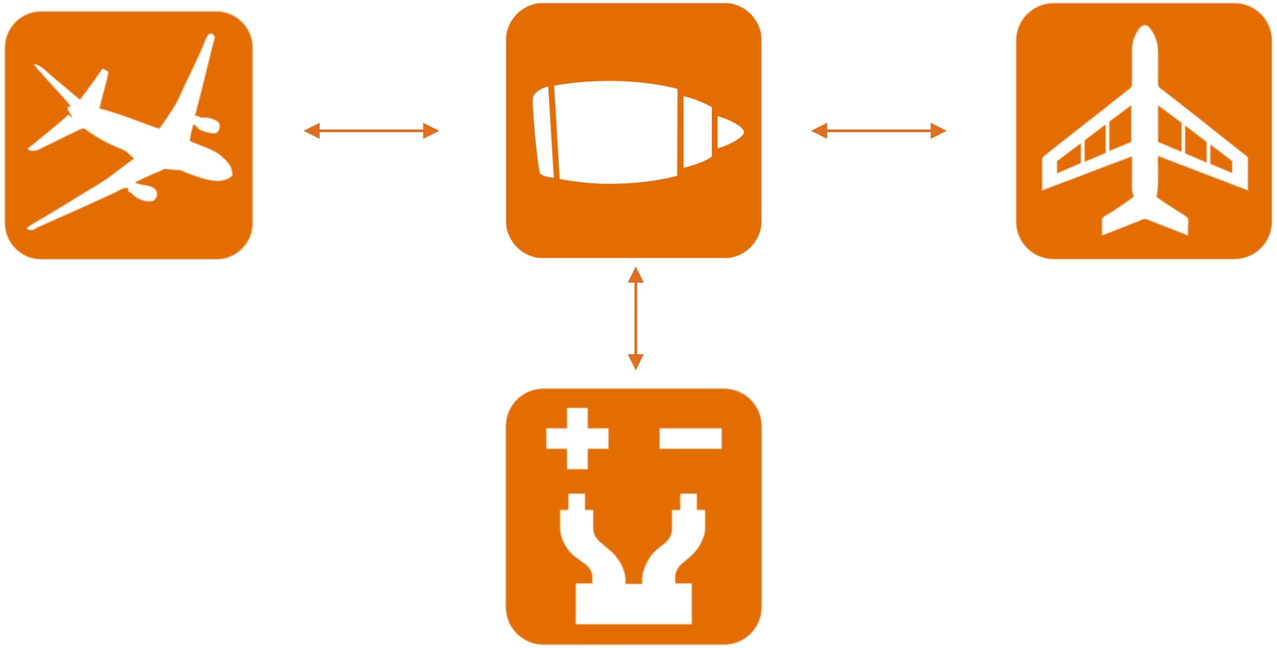

```
htBld = fill(htIn, nBld) + fracWorkBld*(((htIdealOut - htIn)/eff + htIn) - htIn);
ptBld = fill(ptIn, nBld) + fracpBld*(ptOut - ptIn);
pwrBld = wBld .* (htBld - fill(((htIdealOut - htIn)/eff + htIn), nBld));
for i in 1:nBld loop
  statetBld[i] = Medium.setTotal_pthtX(
    ptBld[i],
    htBld[i],
    inStream(portA.X),
    stack=getInstanceName() + "(statetBld[" + String(i) + "])");
end for;
TtBld = Medium.totalTemperature(statetBld);

// Bleed sums
wBldSum = sum(wBld);
pwrBldSum = sum(pwrBld);

// Overall power including bleed calculations
pwr = pwrWithoutBld - pwrBldSum;
trq = pwr/Modelon.Units.Conversions.from_rpm(N);
flange.tau = -trq;
wOut = (wIn - wBldSum);
```

- Contains all base models used in JPL.
- That is, all the equations, correlations, etc. for each component in JPL are defined.
- These basic models are used in example models and parameterized.

MODELON COMPATIBILITY

RECOMMENDED MODELON LIBRARY COMPATIBILITY

- Electrification Library
- Aircraft Dynamics Library
- Fuel Systems Library



LATEST RELEASE

RELEASE:2021.2

Enhancements

- Replaced old environment models in BasicAmbient with a package of new environment models from Modelon base library, including separate models for atmosphere and individual vehicles
- The U.S. Standard Atmosphere 1962 version has been upgraded to 1976 version
- The new ambient Settings_JPL has been simpilfied and the parameters & variables of the standard atmospheric conditions will be computed from Atmosphere and AirData from the Modelon base library
- Mass estimation models (compressor, turbine, duct, burner) now includes an optional flow path coordinate for calculating the gas turbine length
- A new method for calculating duct length (based on Kaiser 2020) as a function of radius, is added to the weight estimation of Duct
- Complete review of all experiment-annotations
- In the turbine cooling models, added option to have physical limits on the cooling effectiveness by setting enableLimiting=true. to TbuMaxPrscrPar

RELEASE:2021.2

Enhancements

- Enhanced documentation to turbine cooling models
- Adding Kurzke cooling models
- Clarified the equations for thrust calculations in the Nozzle model
- Additional thermodynamic property functions speedOfSound(), totalDensity(), dynamicViscosity()
- Improved initialization of complete gas turbine cycles using readDesignData from XML-files
- Added functionality to fix synthesis variable outputs in the control blocks for easier debugging and renamed select parameters such as TbuPrscrMax to TbuMaxPrscrPar