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Case Study: A SysML Gas Turbine Parametric Model

Executive Summary

A SysML parametric model of a gas turbine engine is presented and solved using the InterCAX parametric solver, ParaMagic. The example is used to illustrate several productive tactics in building executable models.

Introduction

Gas turbines are common components in systems for flight and power generation. In this paper, we present a SysML parametric model for a gas turbine. This model could be used as a building block in a larger system model to compute system performance parameters such as speed, range, or electrical power output.

A gas turbine, as shown in Figure 1, typically burns a mixture of fuel and compressed air in a combustion chamber. The hot expanding gases from the combustion drive a set of turbine blades coupled to a central rotating shaft, which in turn drives the compressor blades at the intake. Work can be extracted from the gas turbine either through the exhaust for propulsion or by coupling to the rotating shaft. The functional description of the process is shown in a SysML activity diagram, done in MagicDraw (No Magic), in Figure 2.

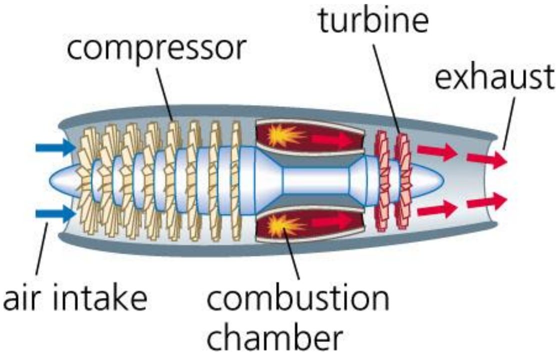


Figure 1 Gas Turbine Operation

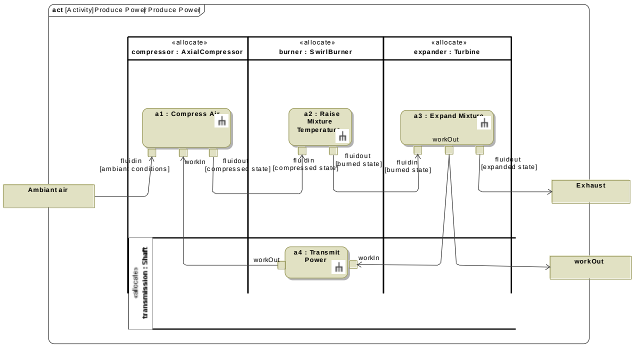


Figure 2 Activity diagram of as Turbine Operation

Model Structure

The SysML structural model is shown in Figure **3** and Figure **4**. The gas turbine system is composed of four parts: the compressor, burner, expander and transmission shaft.

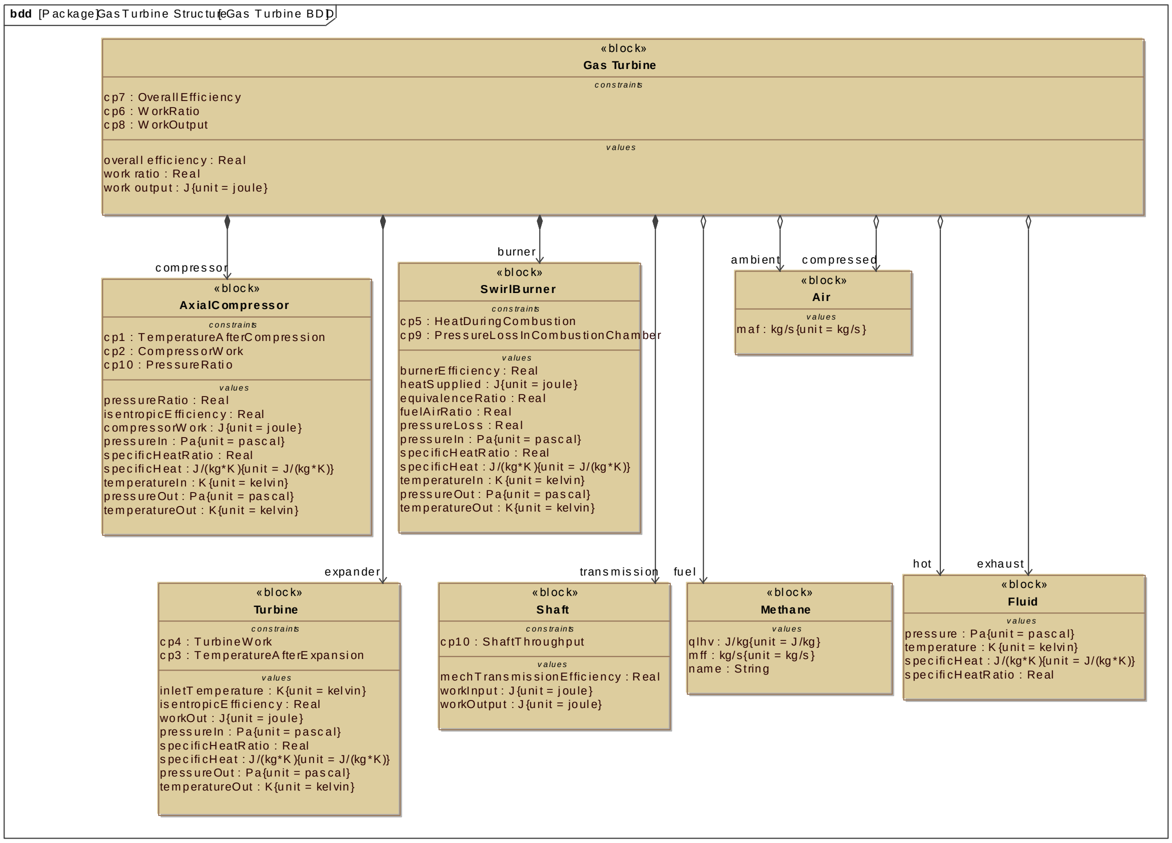


Figure 3 Gas Turbine Structure – Block Definition Diagram

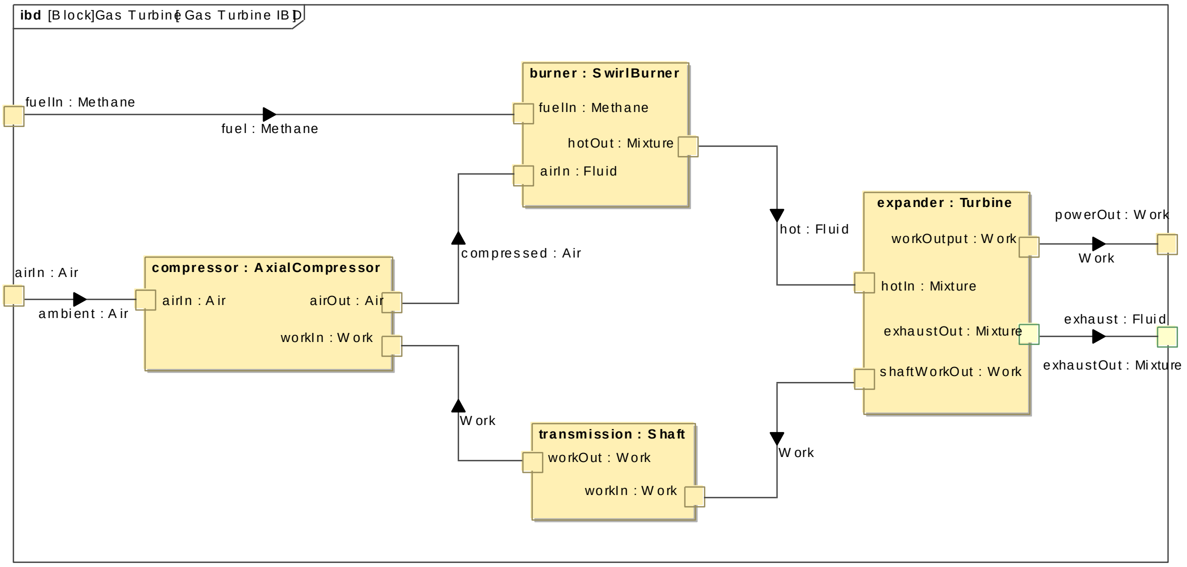


Figure 4 Gas Turbine Part Connections – Internal Block Diagram

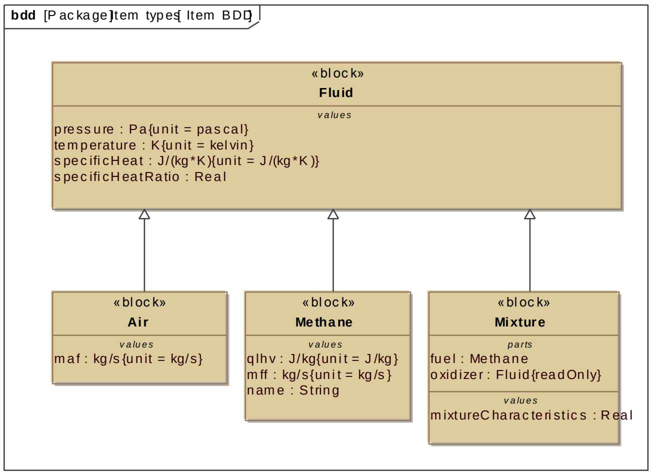


Figure 5 Gas Turbine model items

The interconnections between these parts are shown in the internal block diagram in Figure 4. To specify the fluid flow between components, we start by defining a set of items in Figure 5. We used these items to create shared (or reference) properties of the Gas Turbine block, as shown on the lower right in Figure 3. These shared properties serve as the item flows in the IBD, representing different stages of the fluid flow through the turbine. We use item properties for this because we will want them to appear in the appropriate parametric diagrams in the next section

Value types and Units

Readers can notice that value properties in the two block definition diagrams are assigned with their units. Further in the parametric diagrams, constraint parameters are also assigned with their units. This is important for checking the consistency of units of properties connected by binding connectors. Moreover, in the ParaMagic browser (see figure 12 and figure 13), value types are indicated in a column so that users can't mistake units. To bring units to the model, we use a block definition diagram as shown in figure above. We can create value types with SysML or we can import them from an existing library called QUDV (Quantities Units Dimensions and Values) Library.

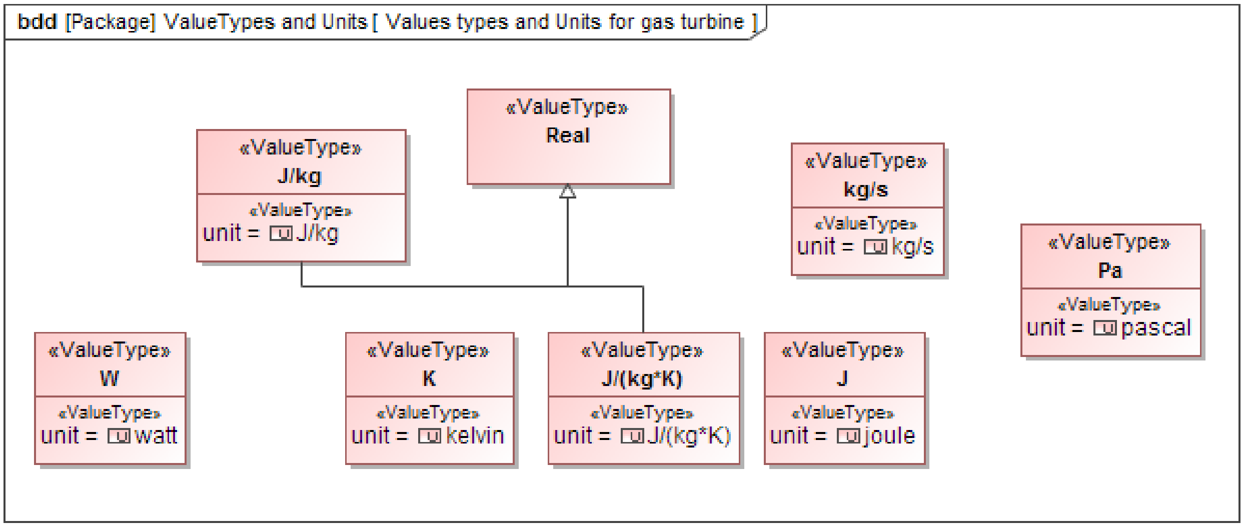


Figure 6 Values types and units for gas turbine model

Model Parametrics

We will use an object-oriented approach to the parametric modeling. Each of the four gas turbine components will have its own parametric diagram, as shown in Figure 7 through Figure 10, containing the quantitative relationships between pressure, temperature and energy (input or output) inside each stage. Capturing the constraints at the component level makes the part models more modular and re-usable, as well as simplifies tracing the calculations.

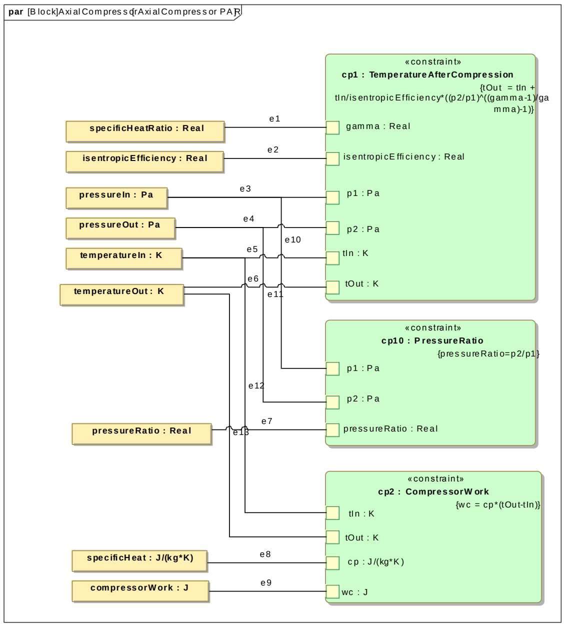


Figure 7 Axial Compressor _ Parametric diagram

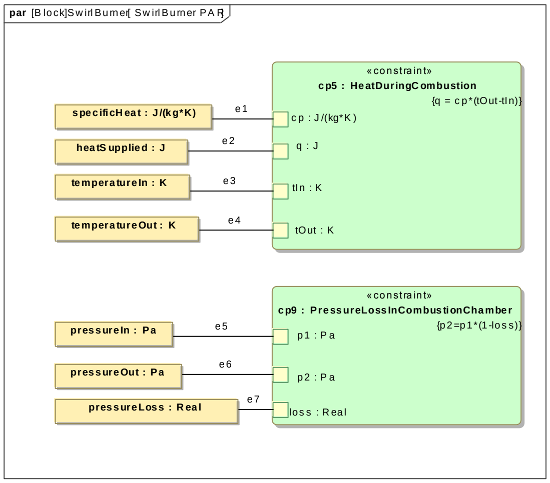
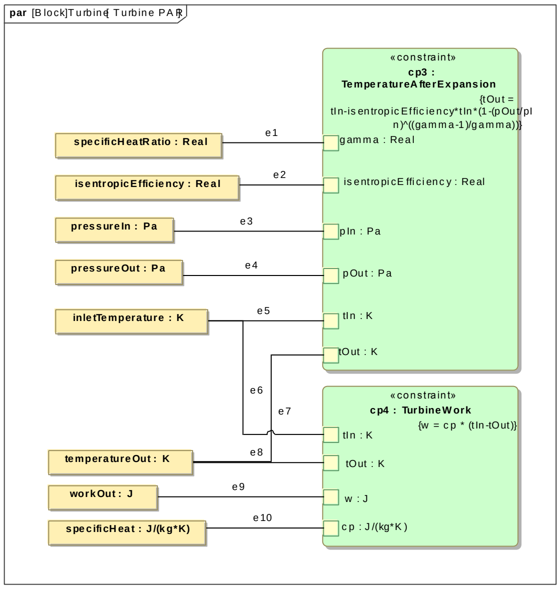


Figure 8 Swirl Burner _ Parametric diagram



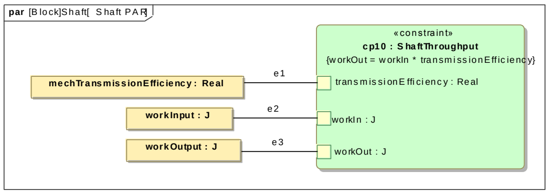


Figure 9 Turbine _ Parametric diagram

Figure 10 Shaft _ Parametric diagram

At the top level, in the Gas Turbine block, are the two parametric diagrams shown in Figure 11 and Figure 12. Figure 11 wires the value properties of the parts and item flows together. The structure of the diagram is almost identical to the IBD in Figure 4. The four part properties expose value properties such as input and output temperature and pressure, which are connected to the corresponding properties of the fluid flows before and after each stage.

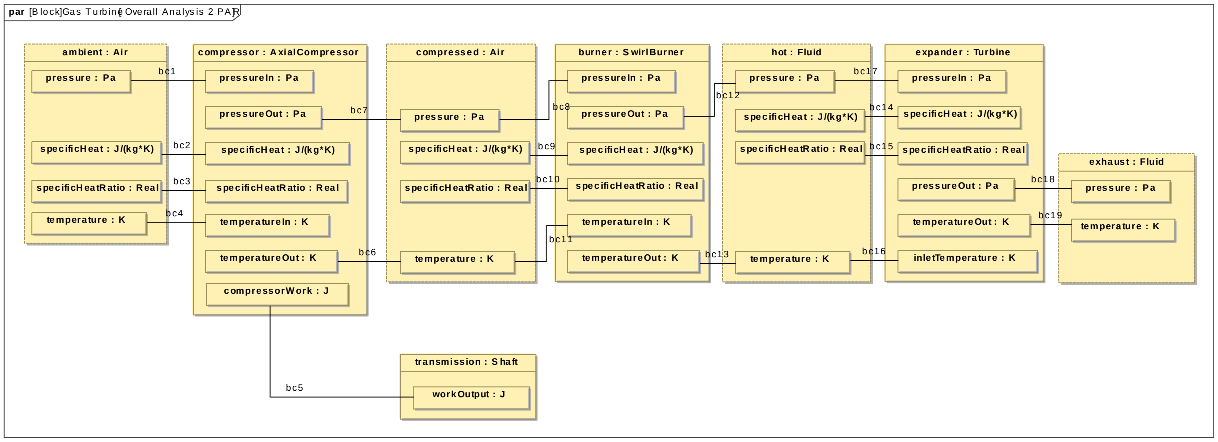


Figure 11 Equating value properties across interfaces – Parametric diagram

Figure 12 calculates a few system-level parameters, such as total work output and efficiency.

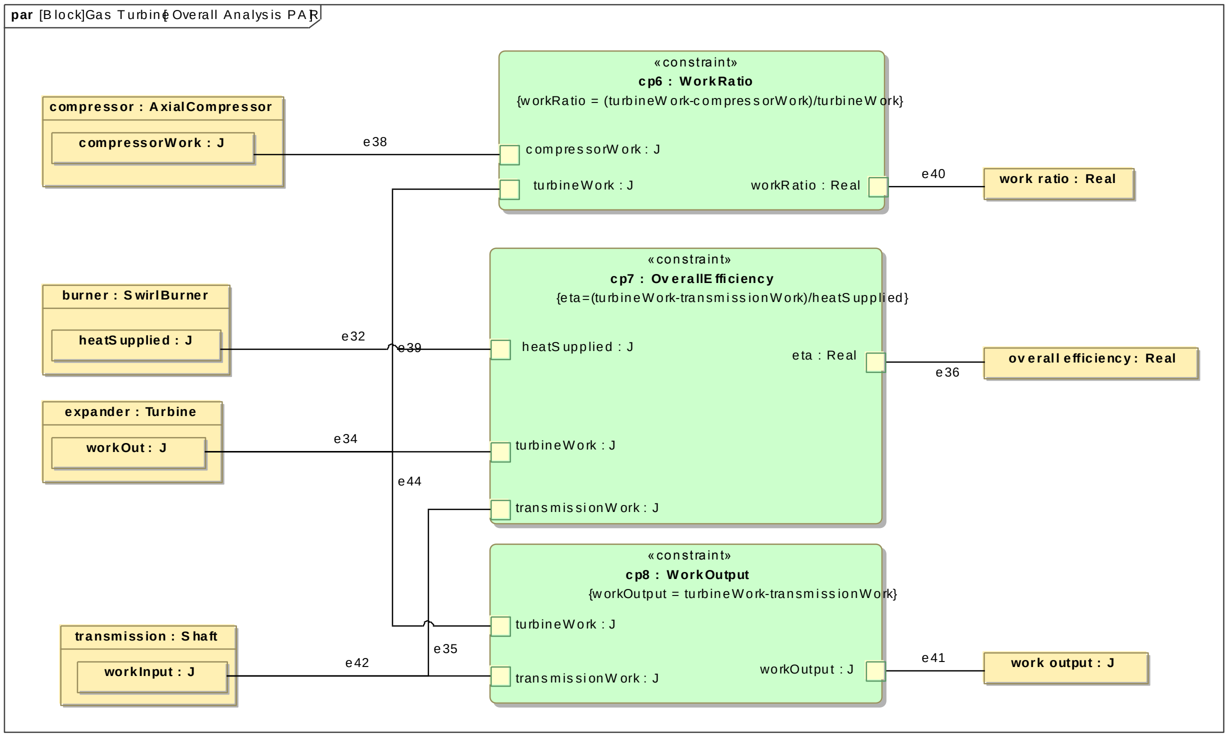


Figure 12 Overall system performance – Parametric diagram

Model Execution

The model has been solved for a representative set of input values using ParaMagic® from InterCAX, which connects the parametric model created in MagicDraw to a form solvable by the mathematical engine PlayerPro (Wolfram Research). The ParaMagic® browser before and after solution is shown in Figure 13 and Figure 14.

Trade Study

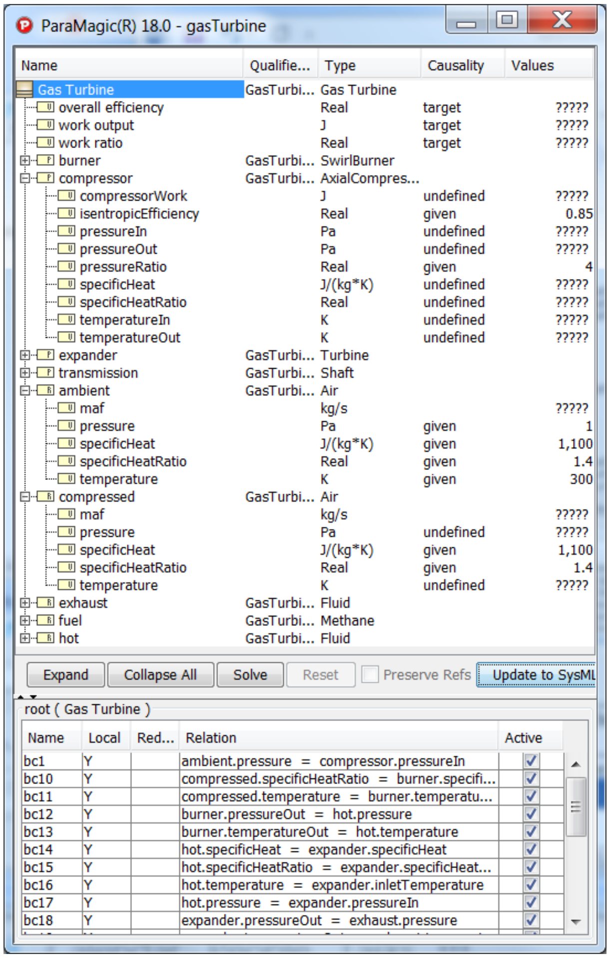
We connected the model to an Excel spreadsheet to evaluate five different set of input values. ParaMagic reads given values from the spreadsheet and sends results back.

Scenarios	Compressor pressure ratio	Turbine Inlet Temperature (K)	Overall Efficiency	Work Output (J/kg)	Work Ratio
1	4.7	1389	0.26	252,146	0.54
2	5.6	1563	0.29	326,705	0.57
3	8	1480	0.32	311,810	0.50
4	6	1751	0.30	403,419	0.61
5	3.8	1666	0.24	317,215	0.64

Table 1 Trade Study Results as a function of Pressure Ratio and Inlet Temperature

Discussion

The parametric model discussed here is not the only possible approach. A model built entirely at the Gas Turbine block level, with all value and constraint properties belonging to that block, would have fewer elements and binding connectors. However, the object-oriented approach shown here is easier to understand, modify and re-use. The correspondence between the activity diagram in Figure 2, the IBD in Figure 4 and the parametric diagram in Figure 11 is helpful at keeping the relationships straight. The item properties appear in the each diagram and identify specifically the input and outputs of each stage.

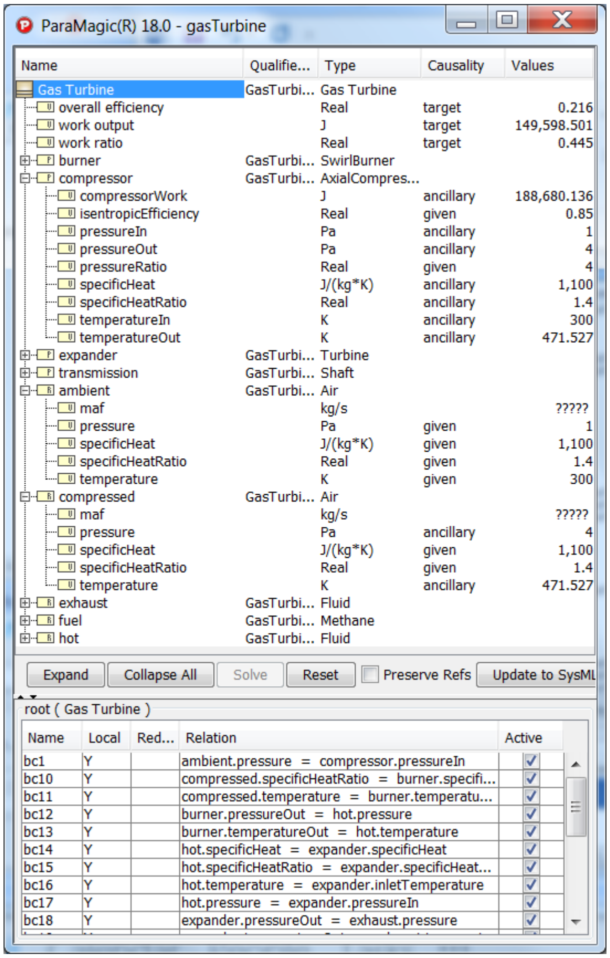


Name	Qualifie...	Type	Causality	Values
Gas Turbine	GasTurbi...	Gas Turbine		
overall efficiency		Real	target	?????
work output		J	target	?????
work ratio		Real	target	?????
burner	GasTurbi...	SwirlBurner		
compressor	GasTurbi...	AxialCompres...		
compressorWork		J	undefined	?????
isentropicEfficiency		Real	given	0.85
pressureIn		Pa	undefined	?????
pressureOut		Pa	undefined	?????
pressureRatio		Real	given	4
specificHeat		J/(kg*K)	undefined	?????
specificHeatRatio		Real	undefined	?????
temperatureIn		K	undefined	?????
temperatureOut		K	undefined	?????
expander	GasTurbi...	Turbine		
transmission	GasTurbi...	Shaft		
ambient	GasTurbi...	Air		
maf		kg/s		?????
pressure		Pa	given	1
specificHeat		J/(kg*K)	given	1,100
specificHeatRatio		Real	given	1.4
temperature		K	given	300
compressed	GasTurbi...	Air		
maf		kg/s		?????
pressure		Pa	undefined	?????
specificHeat		J/(kg*K)	given	1,100
specificHeatRatio		Real	given	1.4
temperature		K	undefined	?????
exhaust	GasTurbi...	Fluid		
fuel	GasTurbi...	Methane		
hot	GasTurbi...	Fluid		

root (Gas Turbine)

Name	Local	Red...	Relation	Active
bc1	Y		ambient.pressure = compressor.pressureIn	☑
bc10	Y		compressed.specificHeatRatio = burner.specifi...	☑
bc11	Y		compressed.temperature = burner.temperatu...	☑
bc12	Y		burner.pressureOut = hot.pressure	☑
bc13	Y		burner.temperatureOut = hot.temperature	☑
bc14	Y		hot.specificHeat = expander.specificHeat	☑
bc15	Y		hot.specificHeatRatio = expander.specificHeat...	☑
bc16	Y		hot.temperature = expander.inletTemperature	☑
bc17	Y		hot.pressure = expander.pressureIn	☑
bc18	Y		expander.pressureOut = exhaust.pressure	☑

Figure 13 ParaMagic browser, before solution (partially expanded)



Name	Qualifie...	Type	Causality	Values
Gas Turbine	GasTurbi...	Gas Turbine		
overall efficiency		Real	target	0.216
work output		J	target	149,598.501
work ratio		Real	target	0.445
burner	GasTurbi...	SwirlBurner		
compressor	GasTurbi...	AxialCompres...		
compressorWork		J	ancillary	188,680.136
isentropicEfficiency		Real	given	0.85
pressureIn		Pa	ancillary	1
pressureOut		Pa	ancillary	4
pressureRatio		Real	given	4
specificHeat		J/(kg*K)	ancillary	1,100
specificHeatRatio		Real	ancillary	1.4
temperatureIn		K	ancillary	300
temperatureOut		K	ancillary	471.527
expander	GasTurbi...	Turbine		
transmission	GasTurbi...	Shaft		
ambient	GasTurbi...	Air		
maf		kg/s		?????
pressure		Pa	given	1
specificHeat		J/(kg*K)	given	1,100
specificHeatRatio		Real	given	1.4
temperature		K	given	300
compressed	GasTurbi...	Air		
maf		kg/s		?????
pressure		Pa	ancillary	4
specificHeat		J/(kg*K)	given	1,100
specificHeatRatio		Real	given	1.4
temperature		K	ancillary	471.527
exhaust	GasTurbi...	Fluid		
fuel	GasTurbi...	Methane		
hot	GasTurbi...	Fluid		

root (Gas Turbine)

Name	Local	Red...	Relation	Active
bc1	Y		ambient.pressure = compressor.pressureIn	☑
bc10	Y		compressed.specificHeatRatio = burner.specifi...	☑
bc11	Y		compressed.temperature = burner.temperatu...	☑
bc12	Y		burner.pressureOut = hot.pressure	☑
bc13	Y		burner.temperatureOut = hot.temperature	☑
bc14	Y		hot.specificHeat = expander.specificHeat	☑
bc15	Y		hot.specificHeatRatio = expander.specificHeat...	☑
bc16	Y		hot.temperature = expander.inletTemperature	☑
bc17	Y		hot.pressure = expander.pressureIn	☑
bc18	Y		expander.pressureOut = exhaust.pressure	☑

Figure 14 ParaMagic browser, after solution (partially expanded)

It is also worth noting that models of real systems like a gas turbine contain feedback loops; in this case, the shaft driven by the expander powers the compressor that pressurizes the combustion chamber. In such cases, the heuristic algorithm may need to accommodate simultaneous equations. Parametric solvers that take a sequential approach—solving one equation at a time—may not converge (or converge quickly) to a solution in such cases.

About the Authors

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