

## PROSIMPLUS APPLICATION EXAMPLE

# COGENERATION PLANT WITH STEAM TURBINES

### EXAMPLE PURPOSE

This example presents the simulation of a cogeneration plant fueled by natural gas (NG). The objective of the process is to merge the production of usable heat and electricity into a single process that can substantially reduce carbon emissions and energy costs. Electricity is produced through a cascade of turbines while the heat is recovered by heat exchangers.

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### CORRESPONDING PROSIMPLUS FILES

*PSPS\_EX\_EN-Power-plant.pmp3*

*Reader is reminded that this use case is only an example and should not be used for other purposes. Although this example is based on actual case it may not be considered as typical nor are the data used always the most accurate available. Fives ProSim shall have no responsibility or liability for damages arising out of or related to the use of the results of calculations based on this example.*

### Energy

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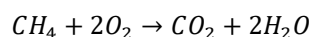
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## 1. PROCESS MODELING

### 1.1. Process description

This example presents the simulation of a cogeneration plant fueled by natural gas. Cogeneration plant can simultaneously produce electricity and heat from the same facility.

The energy production is provided by a natural gas boiler where the natural gas ( $\approx 90\% \text{CH}_4$ ) is burned with air. The following main reaction takes place:



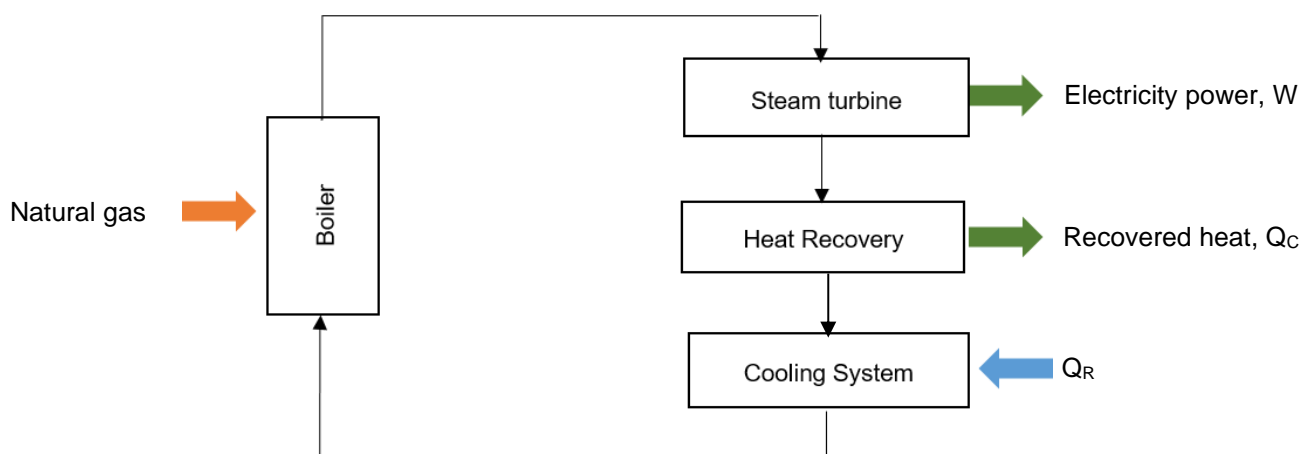
The steam produced by the boiler feeds a pressure cascade of multi-stage turbines to produce electricity. The pressure cascade helps to increase the electrical yield of the process. The process flowsheet is presented in paragraph 1.3 (screenshot of the simulation file). The pressure cascade is composed of 7 turbines which are: high-pressure turbines (HP), medium-pressure turbines (MP) and low-pressure turbines (LP).

Heat can still be recovered from the turbines outlet streams. To valorise them, the steam's heat coming from the turbines is recovered by heat exchangers. These heat exchangers could supply an urban heating network (not represented in this example).

The condensed water (at the outlet of the heat exchangers) is re-injected in the boiler.

The cogeneration power plant presented in this example produces 223 MW of electrical power and recover 23 MW of heat energy at different temperatures. The yield of this process is greater than 40%.

### 1.2. Process block diagram



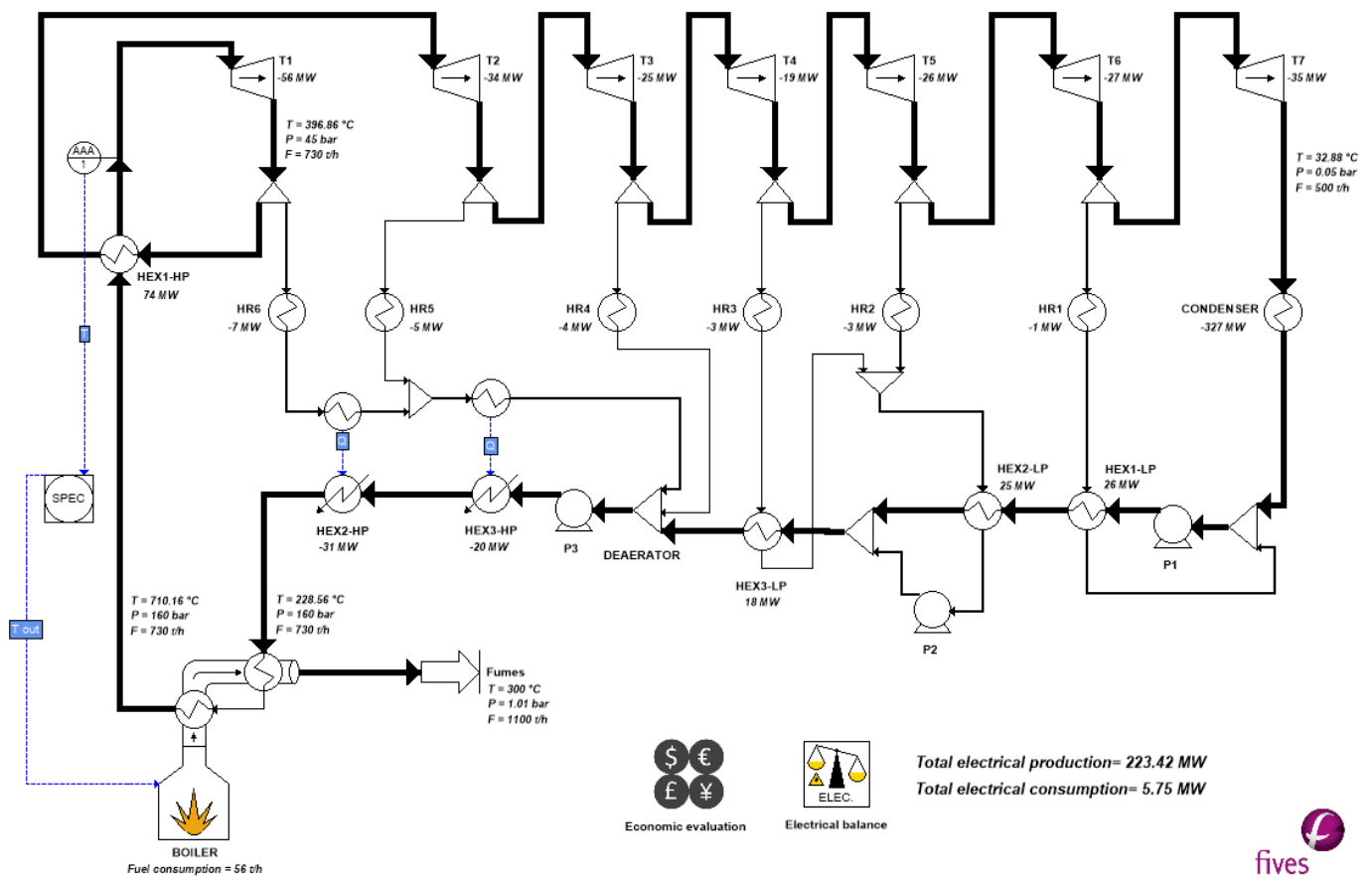
*Schematic diagram of cogeneration plant*

The cooling system is used to condensate the steam to reach the liquid state for the boiler. The heat recovery for this equipment is not presented in this example.

### 1.3. Simulation process

#### Power Plant

Steam Turbines



## 1.4. Compounds

Compounds taken into account in the simulation, their chemical formula and CAS(\*) number are presented in the following table. Pure components physical properties are extracted from the ProSimPlus standard database [WIL19].

Compound	Chemical formula	CAS number
Water	H <sub>2</sub> O	7732-18-5
Hydrogen	H <sub>2</sub>	1333-74-0
Carbon dioxide	CO <sub>2</sub>	124-38-9
Oxygen	O <sub>2</sub>	7782-44-7
Carbon monoxide	CO	630-08-0
Hydrogen sulfide	H <sub>2</sub> S	7783-06-4
Sulfur dioxide	SO <sub>2</sub>	7446-09-5
Sulfur trioxide	SO <sub>3</sub>	7446-11-9
Nitric oxide	NO	10102-43-9
Nitrogen	N <sub>2</sub>	7727-37-9
Methane	CH <sub>4</sub>	74-82-8

## 1.5. Thermodynamic models

Two thermodynamic “calculator” are defined to simulate the “Power Plant” process:

- “Water”: this calculator is composed by the “water” compound. Hence, it uses the “pure water” thermodynamic model.
- “Fumes”: this calculator holds all the components listed previously. The thermodynamic is the “ideal” profile.

The thermodynamic models used are documented in the thermodynamic help accessible from the calculator definition window.

*\*CAS Registry Numbers® are the intellectual property of the American Chemical Society and are used by ProSim SA with the express permission of ACS. CAS Registry Numbers® have not been verified by ACS and may be inaccurate*

## 1.6. Initializations

The calculation sequence is automatically determined by ProSimPlus. Four tear streams are detected: “02” (outlet of the stream splitter “splitter HR6”), “30” (inlet of the pump “P1”), “37” (outlet of the mixer “Other Mixer 2”) and “46” (outlet of the heat exchanger “HEX2-HP”). The following initializations of the streams are used in the simulation:

Stream names	02	30	37	46
<b>Partial molar flowrate (t/h)</b>				
Water	700	550	600	700
Hydrogen	0	0	0	0
Carbon dioxide	0	0	0	0
Oxygen	0	0	0	0
Carbon monoxide	0	0	0	0
Hydrogen sulfide	0	0	0	0
Sulfur dioxide	0	0	0	0
Sulfur trioxide	0	0	0	0
Nitric oxide	0	0	0	0
Nitrogen	0	0	0	0
Methane	0	0	0	0
Temperature (°C)	370	30	50	250
Pressure (bar)	45.35	1.1	1.1	160

Remark: the thermodynamic model specific for pure water is used in all initialized streams.

## 1.7. Operating conditions

- ✓ Boiler
  - Operating parameters of the internal heat exchanger

Operating parameters	Value
Type of heat exchanger	Pure counter current
Fumes outlet temperature (°C)	300

- Operating parameters of the combustion

COMBUSTIVE					
Type	Air	Type of constraint: “Air excess” (%)	20	Inlet pressure (atm)	1
FUEL					
Type	Gas	Methane molar content (%)	90	Inlet pressure (atm)	1
		Ethane molar content (%)	5		
		Propane molar content (%)	1		
		Butane molar content (%)	0.2		
		CO <sub>2</sub> molar content (%)	1.6		
		Nitrogen molar content (%)	2.2		
Heat losses		5% of the heat of combustion			

The natural gas is defined in the "Advanced description" in the "Fuel" tab.

The molar mass, C/H ratio and LHV are automatically calculated by ProSimPlus. The stoichiometric coefficients of the reactions of combustion are obtained by clicking on the "Calculate the stoichiometric coefficients of conventional reactions" button.

*Side note: The "Load the compound of fumes" button could import the fumes calculator and define the fumes calculator as the boiler's calculator. A new calculator "Fumes" is added to the list of*

*calculators.*



- Other parameters of the boiler module:

Operating parameters	Value
Constraint of module	Useful power imposed
Outlet temperature of utility fluid (°C)	700
Operating mode	Nominal useful operating

## ✓ Expanders

Name	Specification	Outlet pressure (bar)	Mechanical efficiency (%)	Electrical efficiency (%)	Isentropic efficiency (%)
T1	Outlet pressure supplied by user	45	95	99	75.5
T2	Outlet pressure supplied by user	20	95	99	70
T3	Outlet pressure supplied by user	10	95	99	70
T4	Outlet pressure supplied by user	5.5	95	99	70
T5	Outlet pressure supplied by user	2	95	99	70
T6	Outlet pressure supplied by user	0.5	95	99	70
T7	Outlet pressure supplied by user	0.05	95	99	70

## ✓ Cooler/Heater

Name	Outlet temperature (°C)
CONDENSER	Equal to bubble point temperature
HR1	Equal to dew point temperature
HR2	Equal to dew point temperature
HR3	Equal to dew point temperature
HR4	Equal to dew point temperature
HR5	Equal to dew point temperature
HR6	Equal to dew point temperature
HEX2-HP-Bis	220
HEX3-HP-Bis	180



## ✓ Generalized heat exchangers

Name	Specification type: "Other"	Temperature deviation (°C)
HEX1-LP	Temperature difference between HS and CS on output	3
HEX2-LP	Temperature difference between HS and CS on output	3
HEX3-LP	Temperature difference between HS and CS on output	3
HEX1-HP	Temperature difference between HS and CS on output	3

## ✓ Simple heat exchangers

Name	Outlet temperature (°C)
HEX2-HP	Calculated
HEX3-HP	Calculated

## ✓ Centrifugal pumps

Operating parameters	P1	P2	P3
Exhaust pressure (bar)	5	5	160
Volumetric efficiency	0.65	0.65	0.65
Mechanical efficiency	0.95	0.95	0.95
Electrical efficiency	0.99	0.99	0.99
Constraint	Fixed liquid physical state	Fixed liquid physical state	Fixed liquid physical state

## ✓ Stream splitters

Name	Stream	Mass flowrate of stream (t/h)	Outlet pressure (bar)
HR1 splitter	26	40	Equal to the feed pressure
HR2 splitter	22	40	Equal to the feed pressure
HR3 splitter	18	30	Equal to the feed pressure
HR4 splitter	14	30	Equal to the feed pressure
HR5 splitter	10	30	Equal to the feed pressure
HR6 splitter	3	60	Equal to the feed pressure

**Remark:** all of the mixers (« Feed », « Other Mixer 1 », « Other Mixer 2 », « Other Mixer 3 » and « DEAERATOR ») are defined with default operating parameters (the outlet pressure is equal to the lowest of the feeds pressures)

## 1.8. Electrical balance

It is possible to perform an electrical balance in ProSimPlus by adding an "Electrical balance" module.

Add the module on the flowsheet (no material or information connection is required) and select the unit operations that consume and produce electricity for the balance:

Electrical balance (\$BELE)

Name: Electrical balance

Desc:

Identification Parameters Scripts Report Notes Advanced parameters

Configuration Advanced options

Unit operation	Unit operation type	Type	Balance
P1	Centrifugal pump	Consumption	<input checked="" type="checkbox"/>
P2	Centrifugal pump	Consumption	<input checked="" type="checkbox"/>
P3	Centrifugal pump	Consumption	<input checked="" type="checkbox"/>
T1	Expander	Production	<input checked="" type="checkbox"/>
T2	Expander	Production	<input checked="" type="checkbox"/>
T3	Expander	Production	<input checked="" type="checkbox"/>
T4	Expander	Production	<input checked="" type="checkbox"/>
T5	Expander	Production	<input checked="" type="checkbox"/>
T6	Expander	Production	<input checked="" type="checkbox"/>
T7	Expander	Production	<input checked="" type="checkbox"/>

OK Cancel

## 1.9. Economic evaluation

It is possible to perform an economic analysis in ProSimPlus by adding an "Economic evaluation" module.

Firstly, add the module on the flowsheet (no material or information connection is required).

For this example, only the operational costs and gains (OpEx) are analysed.

**Economic evaluation (\$COST)**

Name: Economic evaluation  
Desc:

Identification Parameters Scripts Report Profiles Notes Advanced parameters

Unit operations Categories General Validation

Expenses Operational expenditure (OpEx) Reset prices from database

+ T1	<input checked="" type="checkbox"/>	Expander	✓
HR6 splitter	<input type="checkbox"/>	Stream splitter	
+ T2	<input checked="" type="checkbox"/>	Expander	✓
HR5 splitter	<input type="checkbox"/>	Stream splitter	
+ T3	<input checked="" type="checkbox"/>	Expander	✓
HR4 splitter	<input type="checkbox"/>	Stream splitter	
+ T4	<input checked="" type="checkbox"/>	Expander	✓
+ P3	<input type="checkbox"/>	Centrifugal pump	
HEX3-LP	<input type="checkbox"/>	Generalized heat exchanger	
Feed	<input type="checkbox"/>	Other mixer	
Mesure	<input type="checkbox"/>	Measurement	
+ BOILER	<input checked="" type="checkbox"/>	Boiler	✓
+ Fumes	<input checked="" type="checkbox"/>	Process outlet	✓
HEX1-HP	<input type="checkbox"/>	Generalized heat exchanger	
+ HR6	<input checked="" type="checkbox"/>	Cooler/Heater	✓

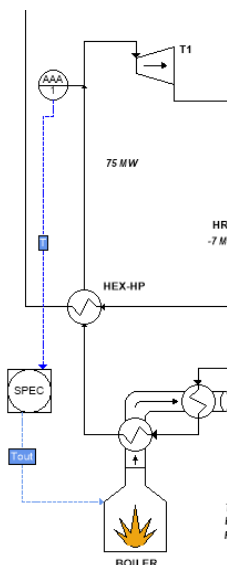
OK Cancel

The unit operations included in the economic evaluation are:

- The turbines (T1 to T7) with a constant price for the electricity produced of 35 €/MWh;
- The heat exchangers (HR1 to HR6) with a gain of 60 €/MWh;
- The boiler with the price of the natural gas of 450 €/t ( $\approx$  33 €/MWh).

### 1.10. Specification of “T1”’s inlet steam temperature

The steam’s temperature is fixed at 570°C on the outlet of the heat exchanger “HEX1-HP”. To do so, it is necessary to include a module called “Constraints and Recycles (SPEC)” as illustrated below:



A measurement module is used to define the set point for temperature in the utility stream at the heat exchanger’s outlet. Hence, its configuration:

Operating parameter	Value
Temperature (°C)	570

The approach is the following: the module measures the temperature at the outlet of heat exchanger “HEX1-HP” and compare to the one set in the measurement module. The difference value between these two temperatures will be sent out to the SPEC module via an information stream.

The configuration of the information stream is presented below:

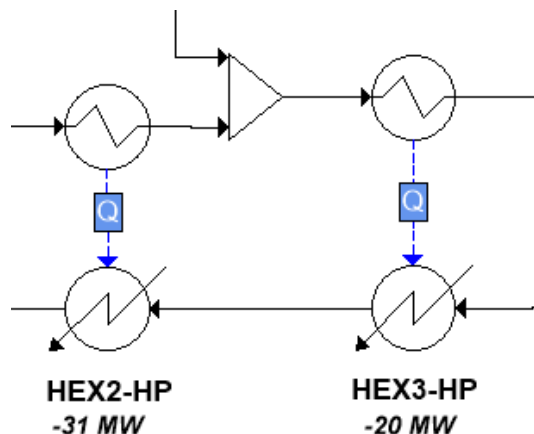
The screenshot shows the 'Information stream (\$ISTR1)' configuration window. It has a title bar with a close button. Inside, there are fields for 'Name' (containing 'T') and 'Desc'. Below these are three tabs: 'Identification', 'Parameters', and 'Notes'. The 'Identification' tab is selected. It contains two sections: 'Information type to be emitted:' and 'Information type to be received:'. The 'emitted' section has a dropdown menu with 'Deviation between the measured value and the set ...' selected, followed by a text box stating 'Information vector to be emitted will be automatically determined depending on the parameters of "Mesure"'. Below this are 'Start' and 'End' input fields, both containing '0'. The 'received' section has a dropdown menu with 'Automatic' selected, followed by a text box stating 'Information vector to be emitted will be automatically determined depending on the parameters of "Spec"'. Below this are 'Start' and 'End' input fields, both containing '0'. At the bottom are 'OK' and 'Cancel' buttons.

In order to achieve the set temperature at the outlet of the heat exchanger, the SPEC module must be connected to an action variable via an information stream. The information stream is connected to the boiler from the SPEC module. The configuration of the information stream is presented below:

The screenshot shows the 'Information stream (\$ISTR2)' configuration window. It has a title bar with a close button. Inside, there are fields for 'Name' (containing 'T out') and 'Desc'. Below these are three tabs: 'Identification', 'Parameters', and 'Notes'. The 'Identification' tab is selected. It contains two sections: 'Information type to be emitted:' and 'Information type to be received:'. The 'emitted' section has a dropdown menu with 'Automatic' selected, followed by a text box stating 'Information vector to be emitted will be automatically determined depending on the parameters of "Spec"'. Below this are 'Start' and 'End' input fields, both containing '0'. The 'received' section has a dropdown menu with 'Value of utility outlet temperature provided' selected, followed by a text box stating 'Information vector to be emitted will be automatically determined depending on the parameters of "BOILER"'. Below this are 'Start' and 'End' input fields, both containing '0'. At the bottom are 'OK' and 'Cancel' buttons.

### 1.11. Determination of heat duty in the simple heat exchangers

Some heat is still available from the outlet of HR system and can be recovered in order to heat up the water at the inlet of the boiler. The condensates are cooled in the heat exchangers “Cooler/Heater 1” and “Cooler/Heater 2”. Both of the heat exchangers are linked to the simple heat exchangers via information streams:



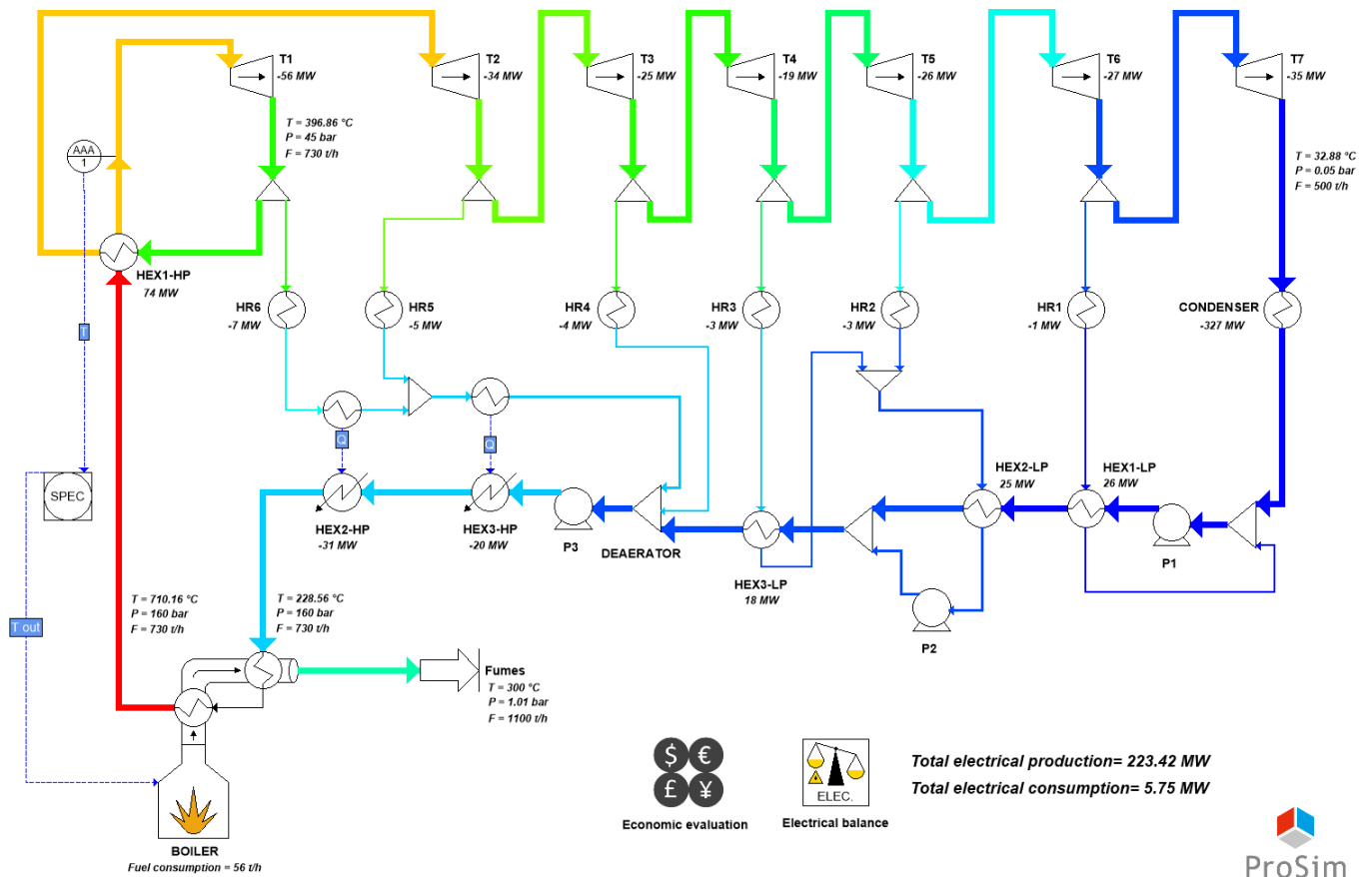
The information streams coming out of the “Cooler/Heater 1” and “Cooler/Heater 2” send the information of the heat duty to the simple heat exchangers “HEX2-HP” and “HEX3-HP”.

The parameters of the two information streams are as follow:

The screenshot shows the 'Information stream (\$ISTR10)' dialog box. The 'Name' field is set to 'Q'. The 'Desc' field is empty. The 'Identification' tab is selected, showing the 'Information type to be emitted' as 'Heat necessary to reach the specified temperature' and the 'Information type to be received' as 'Heat duty'. Both types have a start and end value of 0. The 'Parameters' and 'Notes' tabs are also visible.

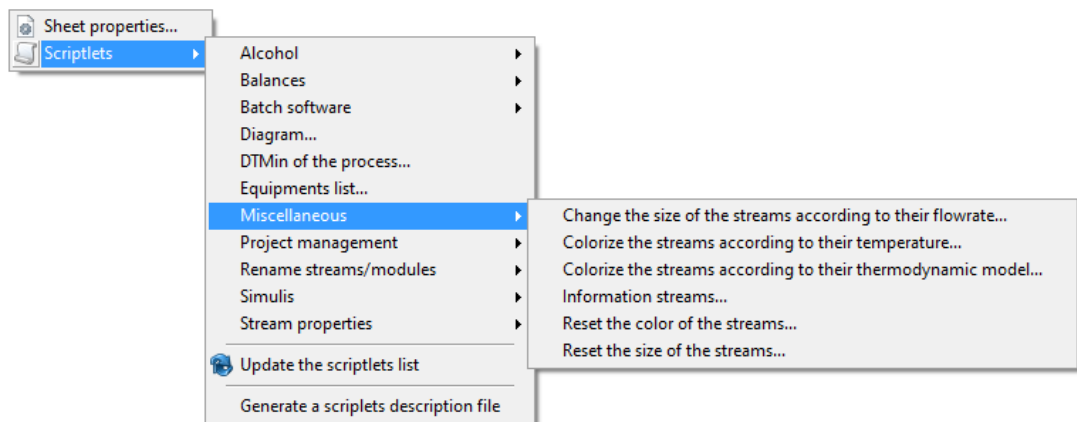
## 1.12. “Tips and tricks”

### Power Plant

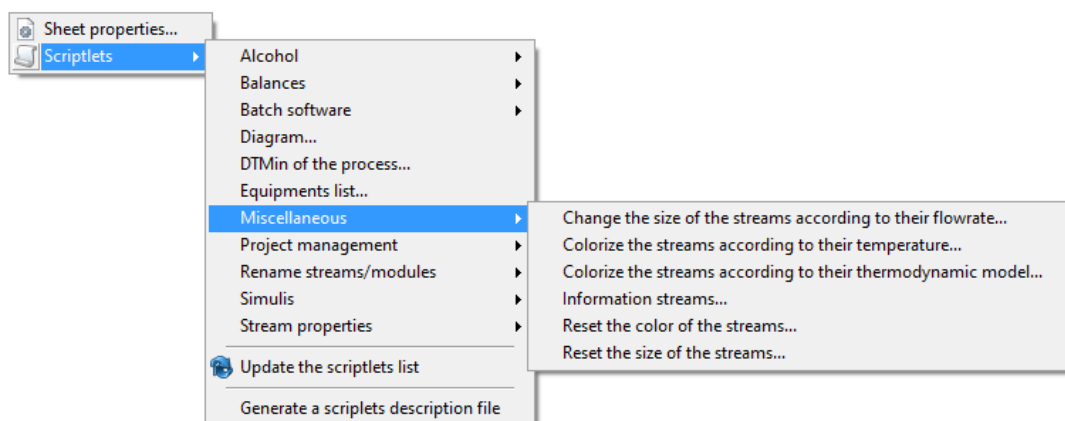


- ✓ The material streams of the flowsheet can be colored depending on the temperature using the “Scriptlets” functionality. The colors varied from red which represents the hottest stream to blue which represents the coolest stream in the process.

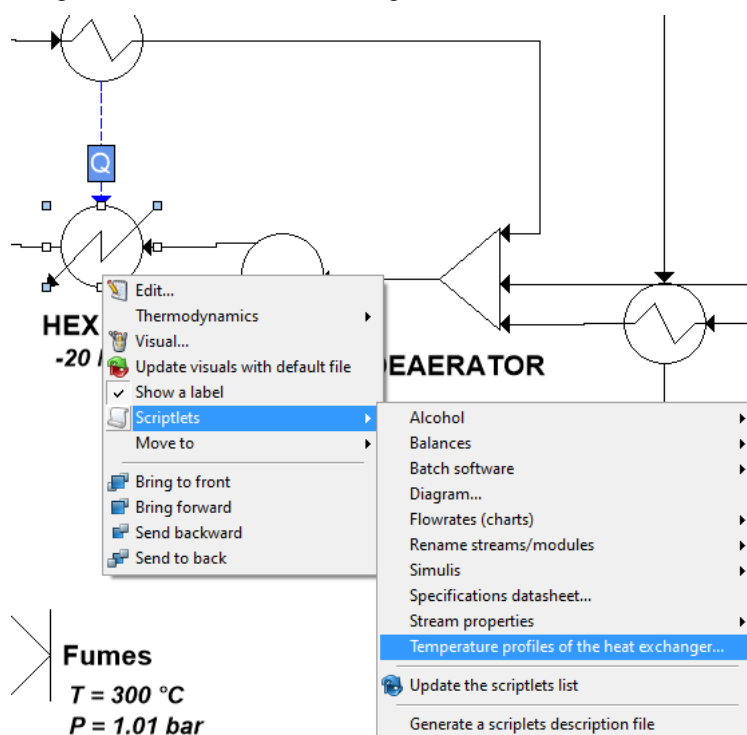
The scriptlet is applied by right-clicking on the background of the flowsheet:



The thickness of the streams can also be adjusted depending on its flowrate. The streams thicknesses become proportional to the (mass or molar depending on user choice) flowrate of the stream.



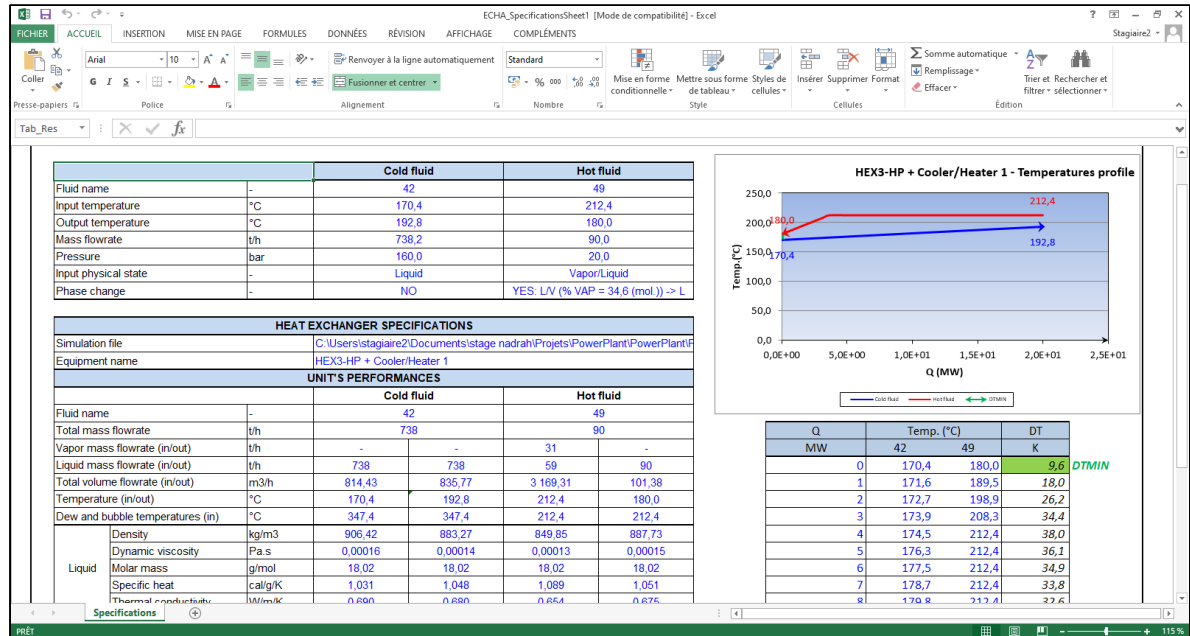
- ✓ The temperature profile in the heat exchanger can be shown using the “Scriptlets” functionality. To use the scriptlet, the user has to right-click on the heat exchanger module:



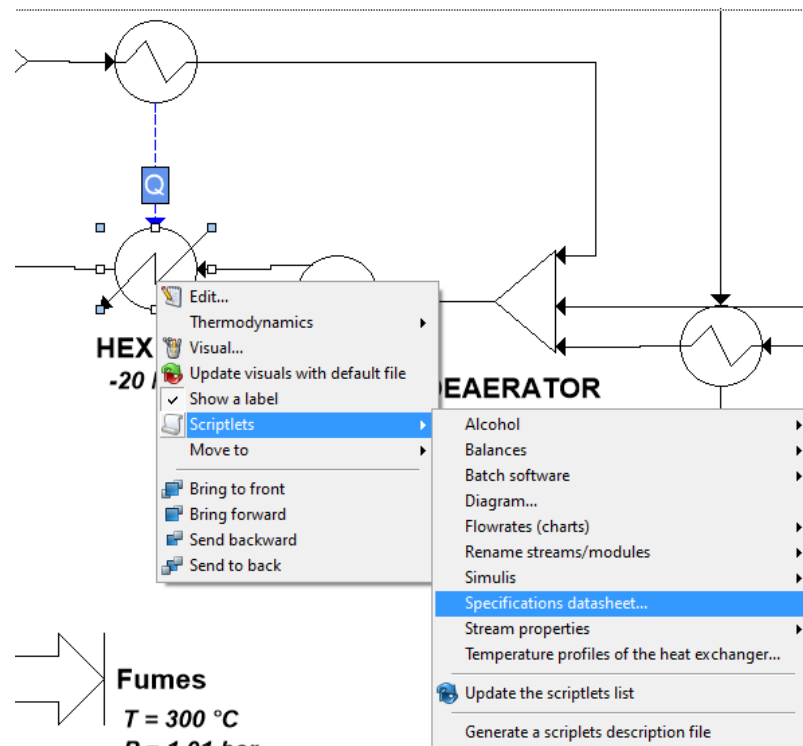
*Remark: the temperature profile is not available on the Cooler/Heater that is not linked with other heat exchanger by an information stream.*



- ✓ With these “Scriptlets” functionalities, it is also possible to generate a data sheet for an heat exchanger describing all the mass (or molar) and energy balances of the inlet and outlet streams in the heat exchanger along with the temperature profile. The data sheet is in the Microsoft™ Excel sheet format as presented below:



To do so, the user just has to right-click on the corresponding heat exchanger:



## 2. RESULTS

### 2.1. Electrical power produced

All main results are summarized in the following table:

Simulation result	Notation	Value
T1 (MW)	A	56
T2 (MW)	B	35
T3 (MW)	C	25
T4 (MW)	D	19
T5 (MW)	E	26
T6 (MW)	F	27
T7 (MW)	G	35
Electrical power W (MW)	$H (= A+B+C+D+E+F+G)$	223
Natural gas mass flowrate (t/h)	I	56
Useful power of the boiler (MW)	J	582
Energy yield (%)	$K (= (H/J) \times 100)$	38.3

### 2.2. Heat recovered

Simulation result	Notation	Value
HR1 (MW)	L	1
HR2 (MW)	M	3
HR3 (MW)	N	3
HR4 (MW)	O	4
HR5 (MW)	P	5
HR6 (MW)	Q	7
Heat recovered $Q_R$ (MW)	$R (= L+M+N+O+P+Q)$	23

### 2.3. Economic evaluation

The operating gains reach 62 M€/yr for electricity production and 9 M€/yr for heat recovery for the district network.  
The operating expenses are of 200 M€/yr.

### 3. REFERENCES

- [WIL19] Wilding, W. V.; Knotts, T. A.; Giles, N. F.; Rowley, R. L. DIPPR Data Compilation of Pure Chemical Properties; Design Institute for Physical Properties, AIChE: New York, NY (2019)