ProSimPlus Application Example

Economic evaluation of a toluene hydrodealkylation process

EXAMPLE PURPOSE
This example presents the economic evaluation of a toluene hydrodealkylation process with ProSimPlus. The hydrodealkylation reactor is fed with pre-heated hydrogen and toluene. The products of the reaction (benzene, biphenyl and methane) and the residual reactants are separated by a flash and three separation units. The recycling allows to reinject a part of the residual reactants into the hydrodealkylation reactor. This example illustrates the use of the ProSimPlus "Economic evaluation" module on a process including different types of unit operations (reactors, columns, pumps, heat exchangers…).

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CORRESPONDING PROSIMPLUS FILES	*PSPS_EX_EN-HDA-Toluene-Process-Cost-FMM.pmp3* *PSPS_EX_EN-HDA-Toluene-Process-Cost-PEM.pmp3*

TABLE OF CONTENTS

1. INTRODUCTION

This example is carried out on a benzene production process by toluene hydrodealkylation. This process was especially used after the World War II to convert a toluene excess (produced as a consequence of the stop of its use in the TNT production) into benzene. This benzene is mainly used to produce cyclohexane that is a nylon precursor.

The diversity of equipment in this process allows to illustrate the use of the "Economic evaluation" unit in ProSimPlus. This unit aims to evaluate the investment and operating costs of a process. The economic evaluation is a step to determine the viability of a process.

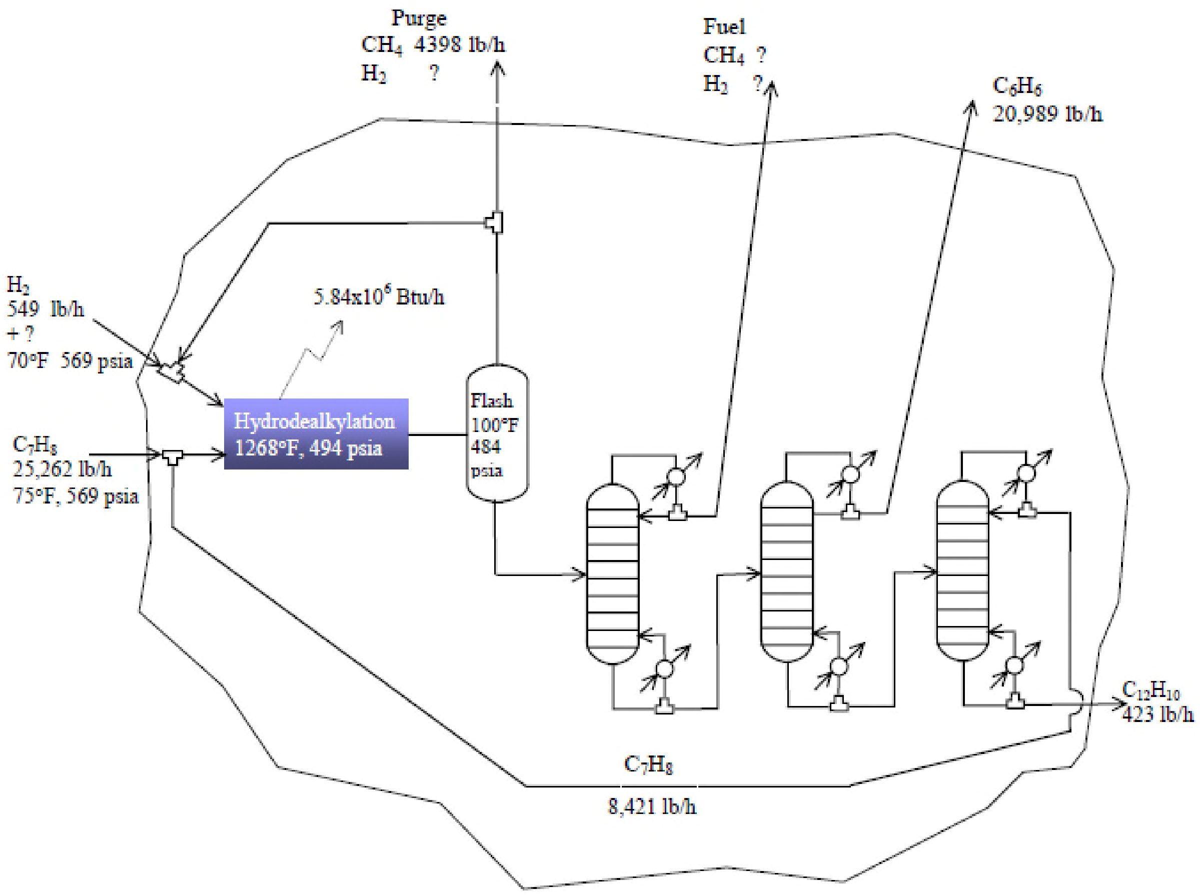
Two economic evaluation methods are available in this module: the Functional Modules Method (FMM) and the Pré-Estime Method (PEM) developed by CHAUVEL *et al.* [CHA03]. The FMM that is essentially based on process parameters (flowrates, pressures, temperatures…) gives a quick economic evaluation and a good order of magnitude for the investment costs. Whereas the PEM provides a more precise evaluation by taking into account the sizing characteristics of the equipment. Moreover the "Economic evaluation" unit allows the user to easily implement his own cost evaluation methods.

These two methods are used and compared in this example.

2. PROCESS MODELING

2.1. Process presentation

The principle diagram of the studied process is the following [SEI04]:



A part of the data necessary to build this example comes from the DOUGLAS book [DOU88].

The hydrodealkylation reactor is fed with hydrogen, benzene and the recycling streams at 650 °C and 36 bar.

The protocol to separate the reaction products is the following:

- A flash at the outlet of the reaction section allows to recycle the hydrogen that did not react
- A first distillation column allows the recovery of the light gases (CH_4 and H_2)
- A second column is used to purify the benzene
- A third column aims to collect the non-converted toluene at the top (recycled stream) and the biphenyl at the bottom

Two main specifications have been imposed in the process:

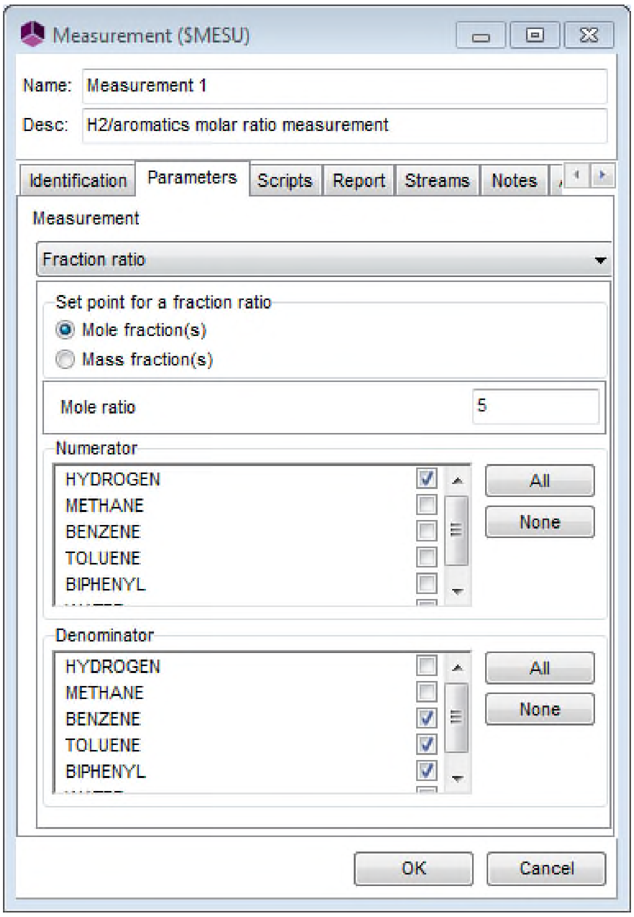
- A hydrogen to aromatics (benzene, toluene, biphenyl) molar ratio of 5% at the inlet of the R1 reactor to avoid cokefaction
  (Measurement between streams 4 and 5)
- A benzene production of 120 kmol/h
  (Measurement between streams 21 and 22)

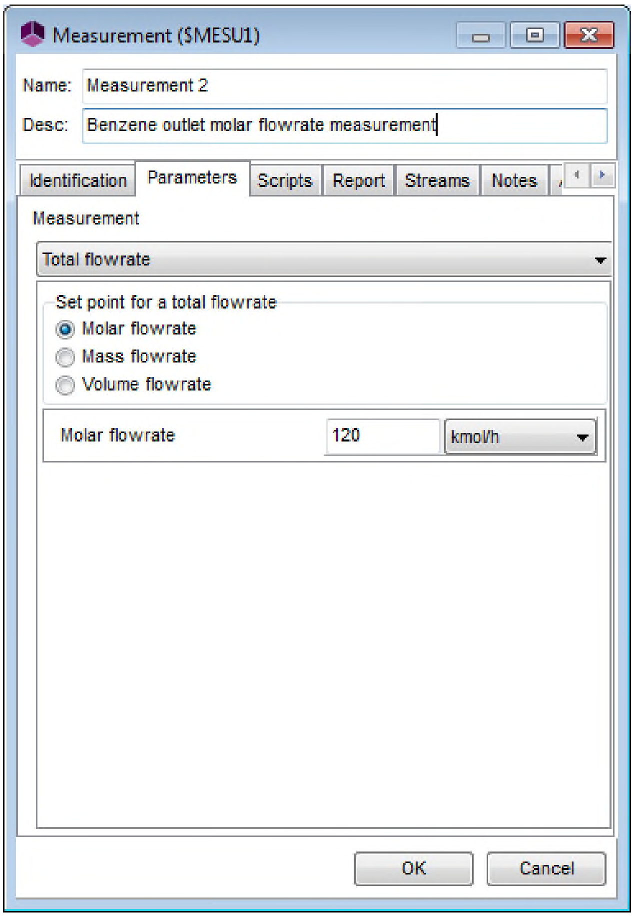
The two action variables are:

- The hydrogen feed total flowrate
- The toluene feed total flowrate

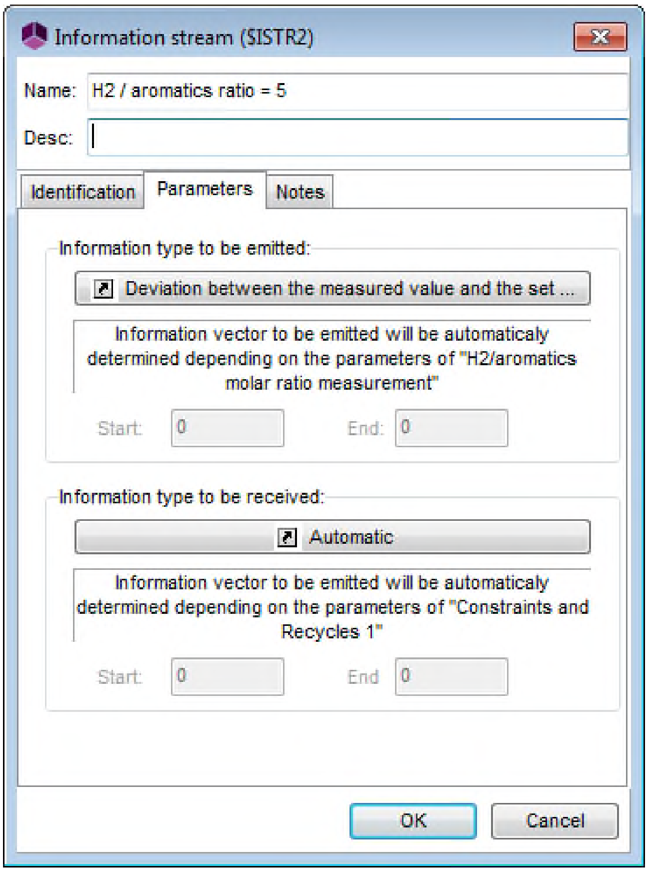
To take these specifications into account in ProSimPlus, a “Constraints and Recycles” block unit has been added to the flowsheet. This block unit is connected with two information streams to the measurements and feed unit operations as presented in the part **2.2 Process flowsheet**.

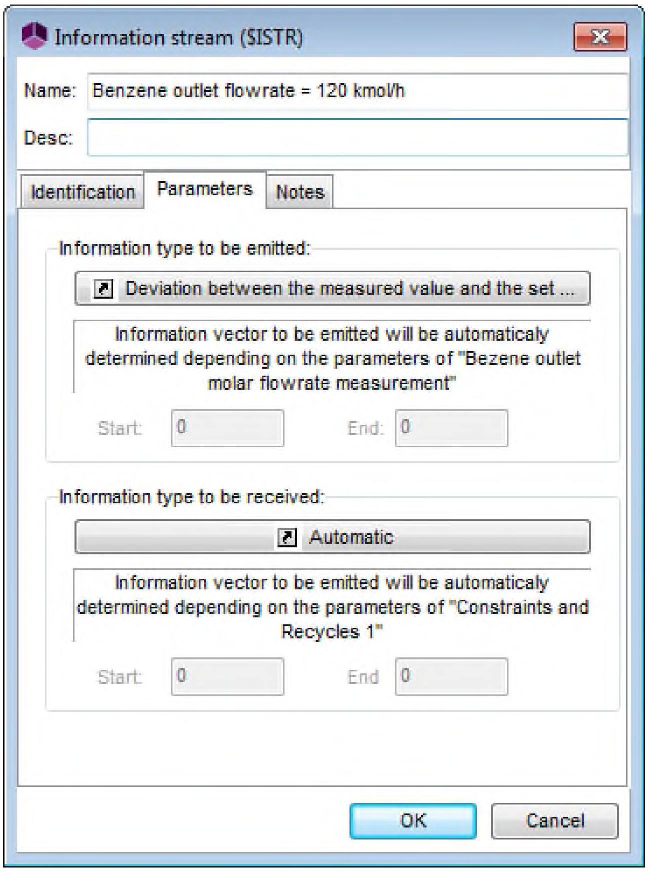
The data entered in the measurements are presented in the screenshots below:

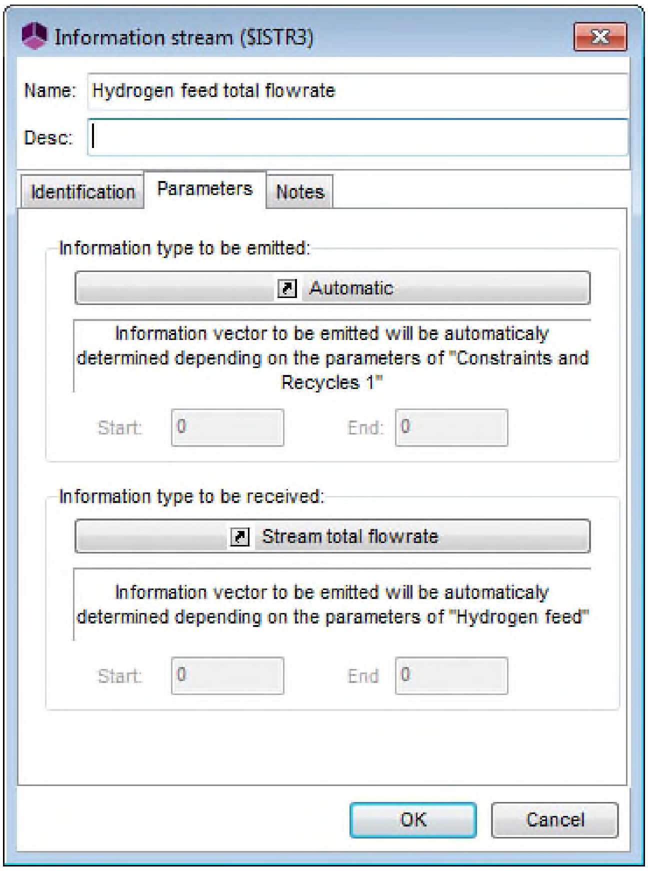


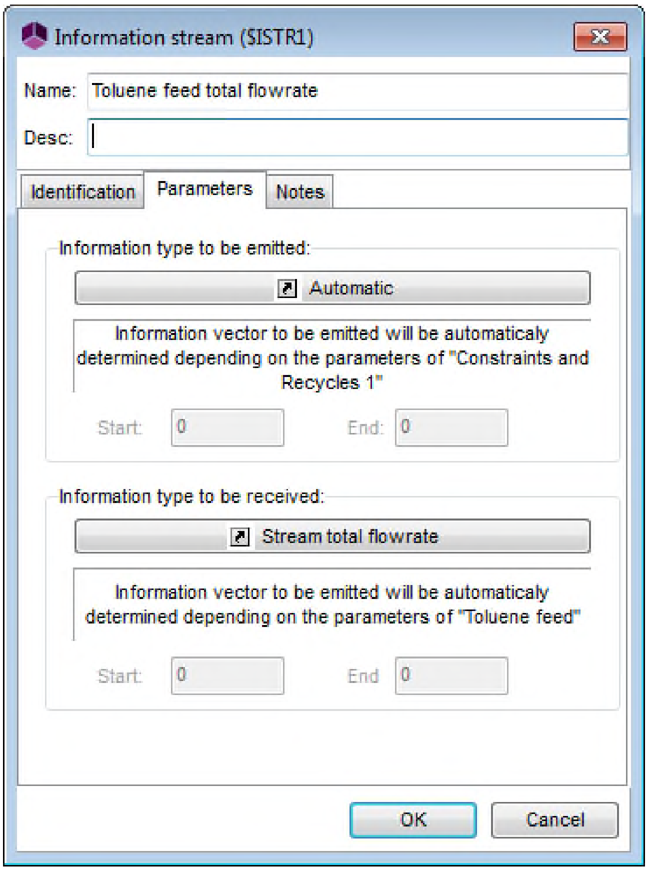


The information streams configuration parameters are presented in the screenshots below:

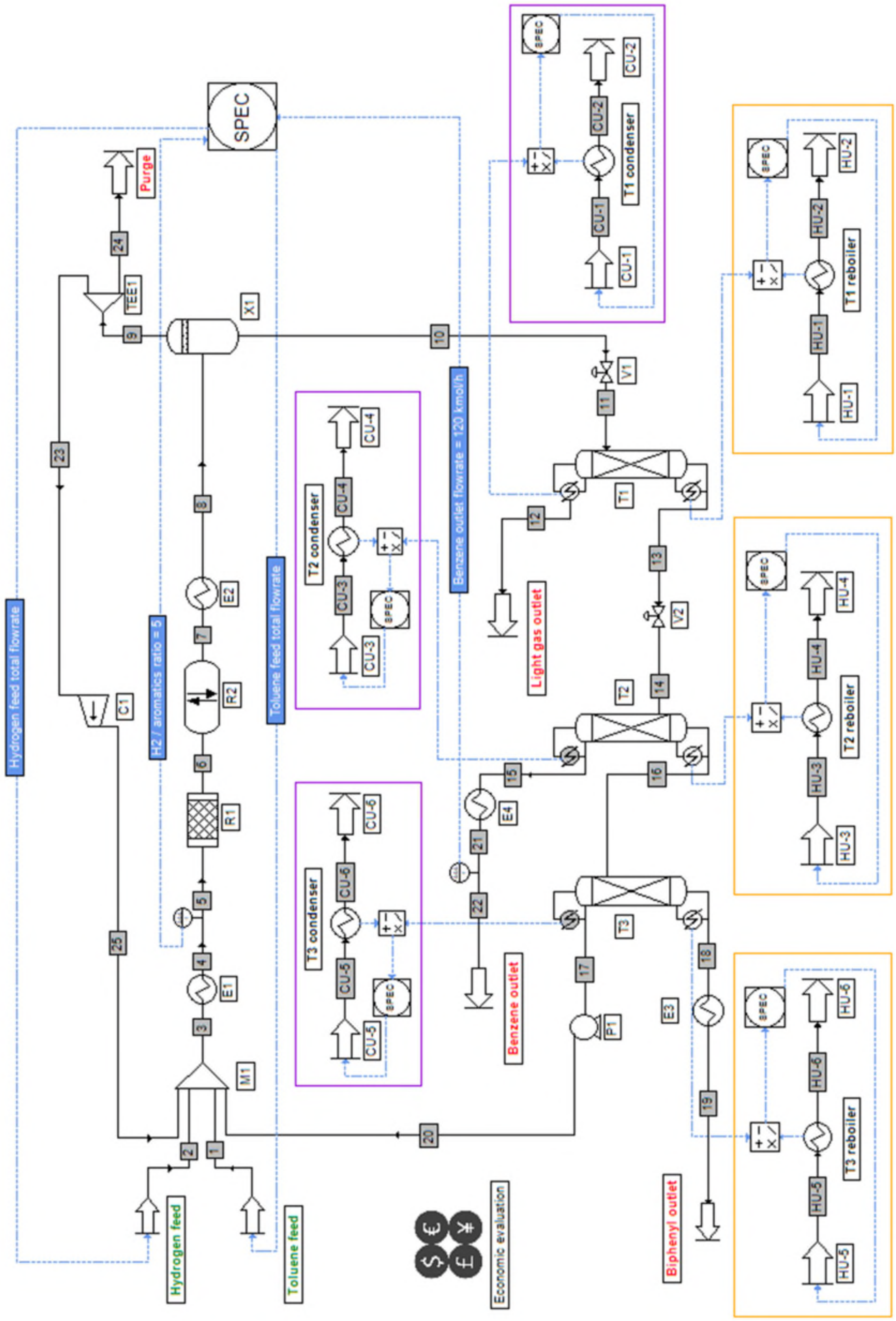








2.2. Process flowsheet



Flowsheet of the toluene hydrodealkylation unit

In order to improve the readability of the process flowsheet, the inlets and outlets (except the utilities) are respectively in green and red characters and the part of the process representing the column condensers and reboilers are respectively framed in purple and orange.

2.3. Compounds

The compounds taken into consideration in this example are listed in the table below:

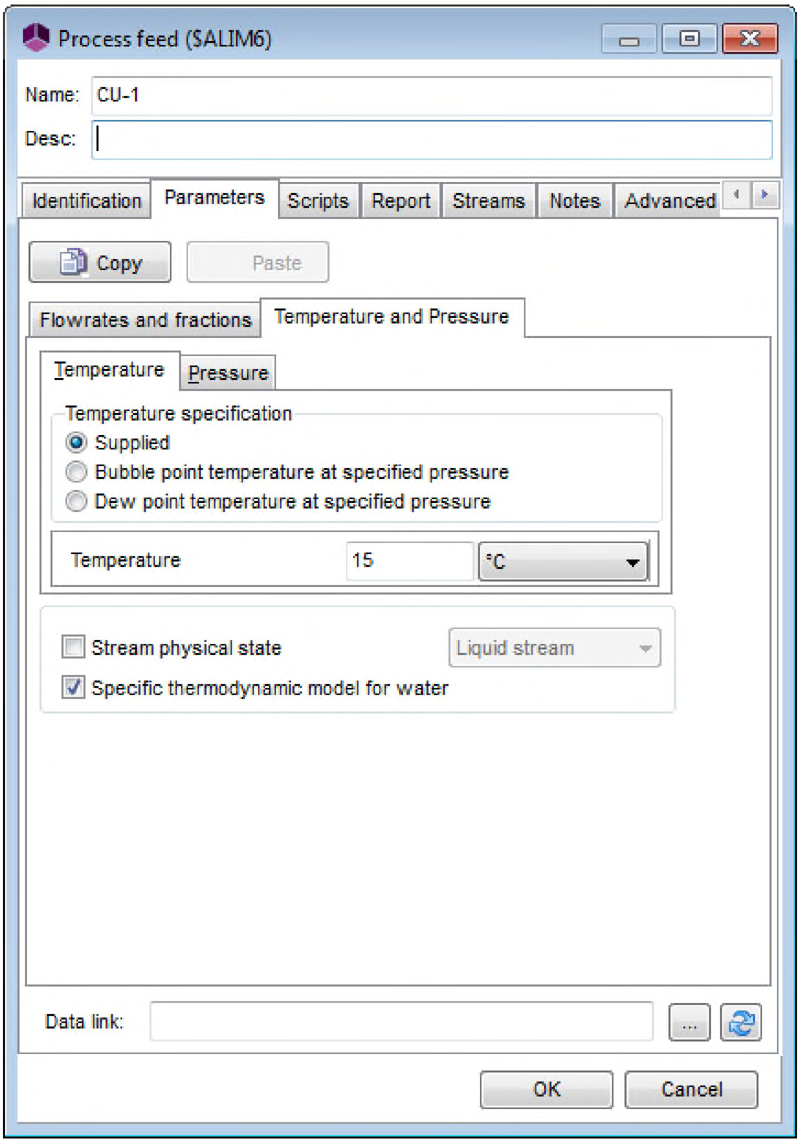
Name	Chemical formula	CAS number
Hydrogen	H_2	1333-74-0
Methane	CH_4	74-82-8
Benzene	C_6H_6	71-43-2
Toluene	C_7H_8	108-88-3
Biphenyl	$C_{12}H_{10}$	92-52-4
Water	H_2O	7732-18-5

Water is only considered as a utility and is not in contact with the other compounds.

2.4. Thermodynamic model

The system considered contains hydrocarbons, hydrocarbons derivatives and hydrogen. The working pressure never exceeds 100 bars. Consequently, the SRK model [SOA72] has been chosen. The binary interaction parameters for the SRK model are loaded from the ProSim database are used.

The specific thermodynamic model for water is used for the hot and cold utilities calculation (HU and CU). To use this model, the “Specific thermodynamic model for water” box has been ticked in the utility streams (HU-1, 3 and 5 and CU-1, 3 and 5) as shown below:



2.5. Chemical reactions

In the hydrodealkylation reactor, the following reaction takes place:

$$C_7H_8 + H_2 \rightarrow C_6H_6 + CH_4 \quad (\Delta H_R = -50 \text{ kJ/mol})$$

The toluene conversion ratio in this reactor is 0.75 (75%).

In ProSimPlus, the reaction is implemented in the "Simple reactor" unit operation (R1) and has been defined as follow:

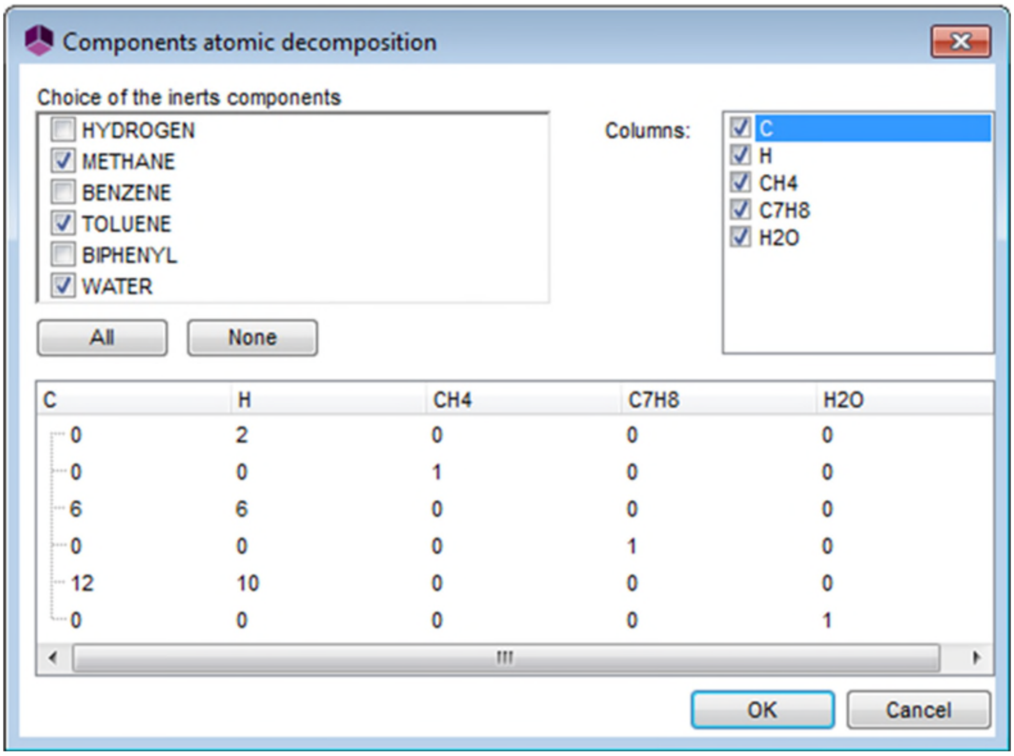
Reaction	$C_7H_8 + H_2 \rightarrow C_6H_6 + CH_4$
Reaction type	Controlled
Kinetic model	Instantaneous
Heat of reaction (kJ/mol)	-50

Furthermore, a secondary reaction occurs producing biphenyl from benzene:

$$2\ C_6H_6 \leftrightarrow C_{12}H_{10} + H_2$$

To model this reaction, the « GIBBS reactor » has been used (R2). The selected method is the minimization of Gibbs free energy. The physical state of the compounds is vapor.

The atomic decomposition of the components in the reactor R2 is the following one:



2.6. Operating conditions

All the operating conditions required to define the process are summarized in this section. The data in green are initial values:

- ✓ Hydrogen feed

	Hydrogen feed
H_2 molar fraction	0.95
CH_4 molar fraction	0.05
Total molar flowrate (kmol/h)	200
Temperature (°C)	37.85
Pressure (bar)	37

- ✓ Toluene feed

	Toluene feed
C_7H_8 molar fraction	1
Total molar flowrate (kmol/h)	150
Temperature (°C)	37.85
Pressure (bar)	37

- ✓ Cold utilities (CU) and hot utilities (HU)

	T1 condenser CU-1	***T2 condenser CU-3***	***T3 condenser CU-5***	***T1 reboiler HU-1***	***T2 reboiler HU-3***	***T3 reboiler HU-5***
Mass fraction H_2O	1	1	1	1	1	1
Total mass flowrate (t/h)	1	100	100	10	10	10
Pressure (bar)	1	1	1	15	5	60
Temperature (°C)	15	15	15	Dew temperature	Dew temperature	Dew temperature

✓ Reactors

Operating parameters	*Reactor R1*	*Reactor R2*
Reactor type	Simple	Equilibrium
Reaction set	Hydrodealkylation	-
Outlet temperature (°C)	684	Inlet temperature
Outlet pressure (bar)	34.5	Inlet pressure

✓ Separator

Operating parameters	*Flash X1*
Separator type	Liquid-vapor separator
Temperature (°C)	38
Pressure (bar)	32

✓ Columns

Operating parameters	*Distillation column T1*	*Distillation column T2*	*Distillation column T3*
Column type	2-phase distillation column with partial condenser	2-phase distillation column with total condenser	2-phase distillation column with total condenser
Number of theoretical stages	10	40	7
Feed stage	2	20	2
Distillate flowrate (kmol/h): vapor (partial condenser) liquid (total condenser)	0.05*	120	Calculated
Molar reflux ratio	0.05	1.3	0.06
Reboiler heat duty (kcal/h)	Calculated	Calculated	353 943
Column head pressure (bar)	10.2	1.5	2
Column bottom pressure (bar)	10.2	2	2
Stages efficiency	1	1	1

*: Related to 1 kmol/h of total feed flowrate

T1 column additional specification:

Specification		***Product type***	***Compound***	***Value***	***Type***	***Action***
1:	Purity	Vapor distillate	BENZENE	0.01	Molar	Vapor distillate flowrate

T2 column additional specification:

Specification		***Product type***	***Compound***	***Value***	***Type***	***Action***
1:	Purity	Liquid distillate	BENZENE	0.995	Molar	Liquid distillate flowrate

✓ Heat exchangers

Name	***Type***	***Outlet temperature (°C)***	***Pressure drop (bar)***
E1	Cooler/Heater	650	1
E2	Cooler/Heater	38	0.5
E3	Cooler/Heater	38	0.2
E4	Cooler/Heater	30	0.5
T1 condenser	Cooler/Heater	25	0
T2 condenser	Cooler/Heater	25	0
T3 condenser	Cooler/Heater	25	0
T1 reboiler	Cooler/Heater	Bubble temperature	0
T2 reboiler	Cooler/Heater	Bubble temperature	0
T3 reboiler	Cooler/Heater	Bubble temperature	0

✓ *Compressor*

Operating parameters	***Compressor C1***
Exhaust pressure (bar)	37
Isentropic efficiency	0.65
Mechanical efficiency	1

✓ *Pump*

Operating parameters	***Pump P1***
Exhaust pressure (bar)	37
Volumetric efficiency	0.65
Mechanical efficiency	1

✓ *Mixer*

Operating parameter	***Mixer M1***
Outlet pressure (bar)	Equal to the lowest of the feed

✓ *Valves*

Operating parameter	***Expansion valve V1***	***Expansion valve V2***
Outlet pressure (bar)	10.2	1.8

✓ *Stream splitter*

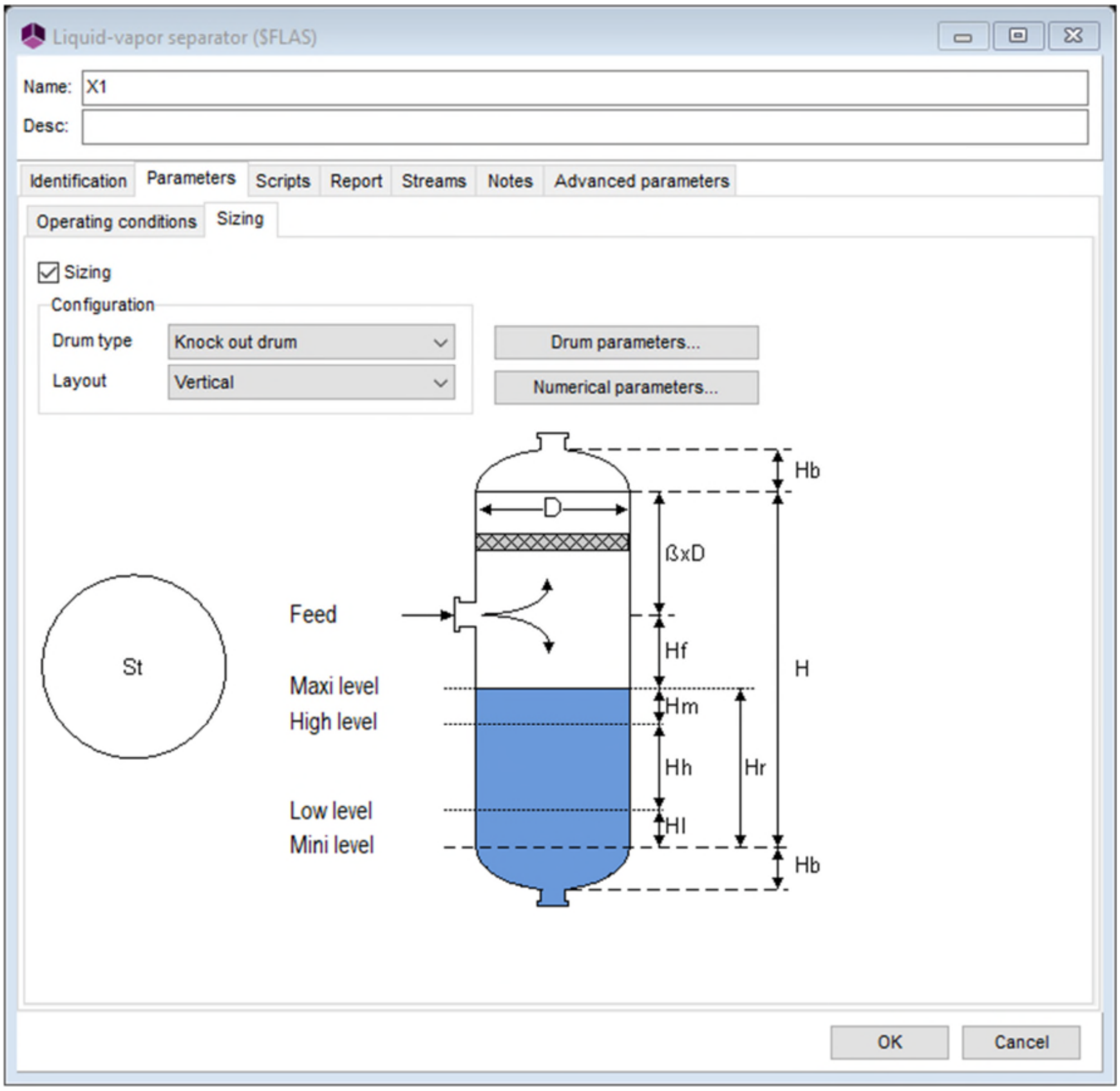
Operating parameters	***Stream splitter TEE1***
Splitting ratio stream 23	0.92
Outlet pressure (bar)	Equal to the feed pressure

2.7. Drum and distillation columns sizing

ProSimPlus allows to size equipment like drums or distillation columns. This sizing is particularly useful for an economic evaluation with the PEM.

2.7.1. X1 drum sizing

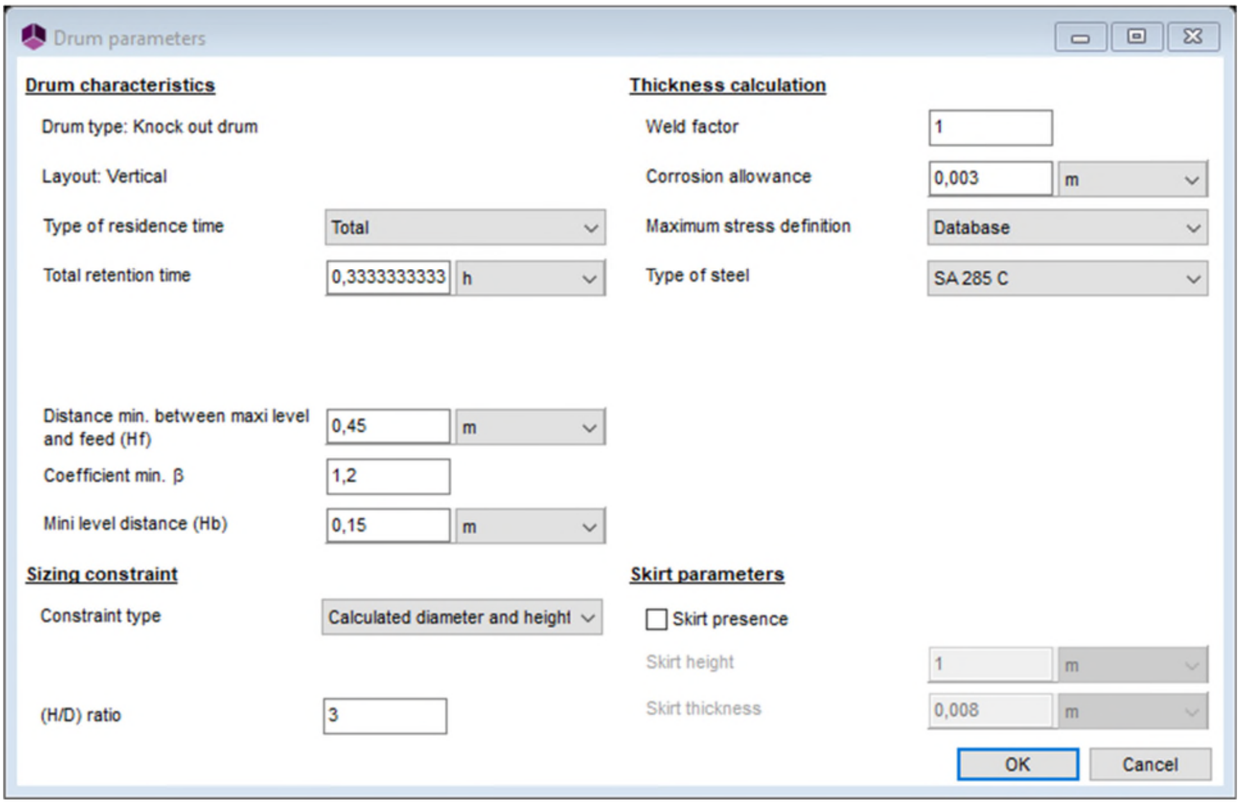
To size the X1 drum, the edition window of the X1 unit operation has to be opened, and the “Sizing” subtab of the “Parameters” tab has to be selected. The “Sizing” box has to be ticked and the configuration of the drum has to be defined. As shown below, the vertical knock out drum type has been chosen.



Click on the “Drum parameters” button and enter the required parameters as presented next page.

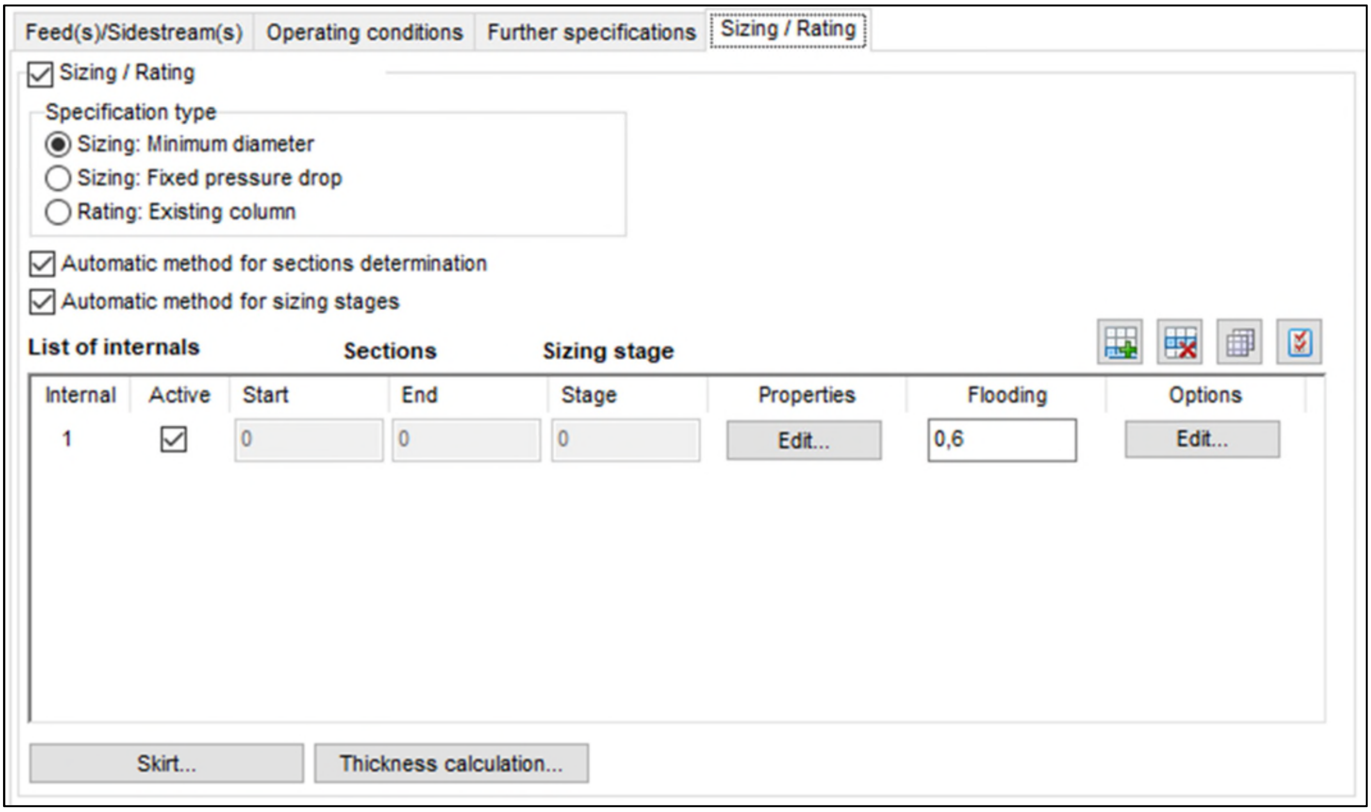
Each parameter has been set to default values except:

- Type of residence time: Total
- (H/D) ratio: 3
- Type of steel: SA 285 C



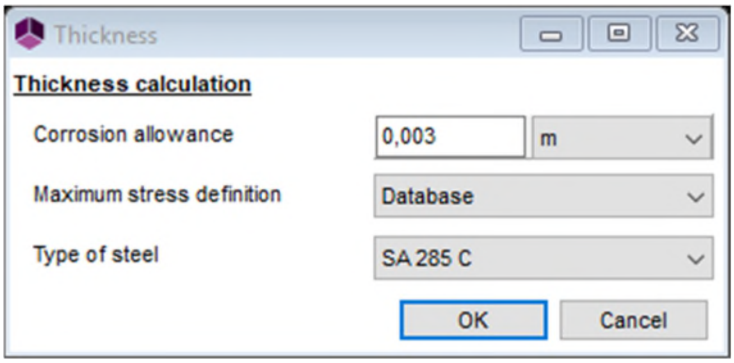
2.7.2. T1, T2 and T3 columns sizing

As for drums, to size the columns, proceed as follows: open the edition window and select the “Sizing / Rating” subtab of the “Parameters” tab. Then choose to size the columns for a “Minimum diameter” and enter the following configuration for the three columns:



The default parameters are used for the skirt and thickness of the column.

The SA 285 C steel is used for each of column. The user can change the type of steel in the dropdown list of the steel database. The type of steel and the corrosion allowance are parameters used in the calculation of the thickness of the sleeve (ferrule) and the bottom of the column.



To add an internal in the list of internals, click on the “Add” icon .

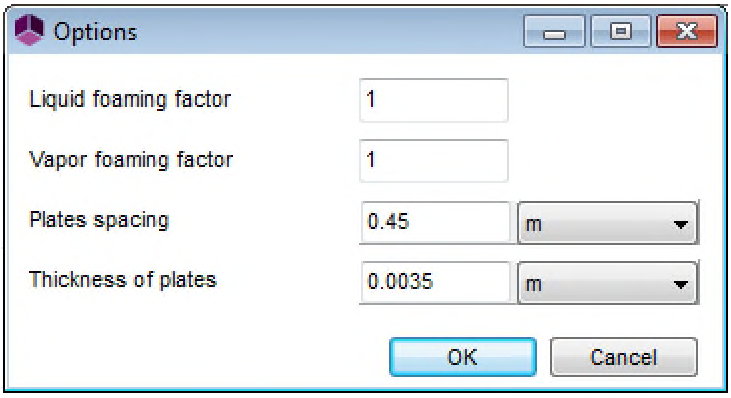
The data to be entered in the section “Properties” and “Options” (accessible by clicking on the respective “Edit…” buttons) are gathered below:

T1 column:

“Properties” section:

Internal type: select “Nutter valve trays” and let the parameter by default.

"Options" section: enter the following configuration:

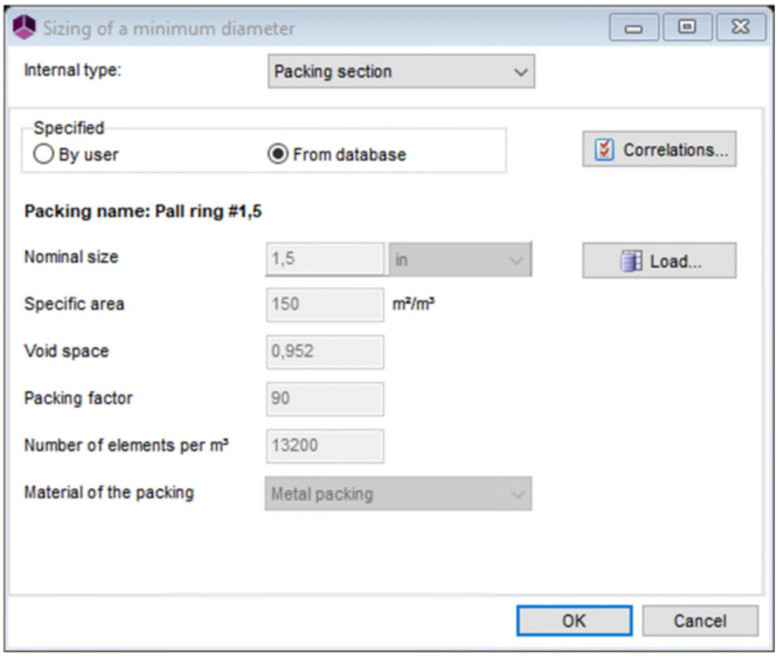


T2 column:

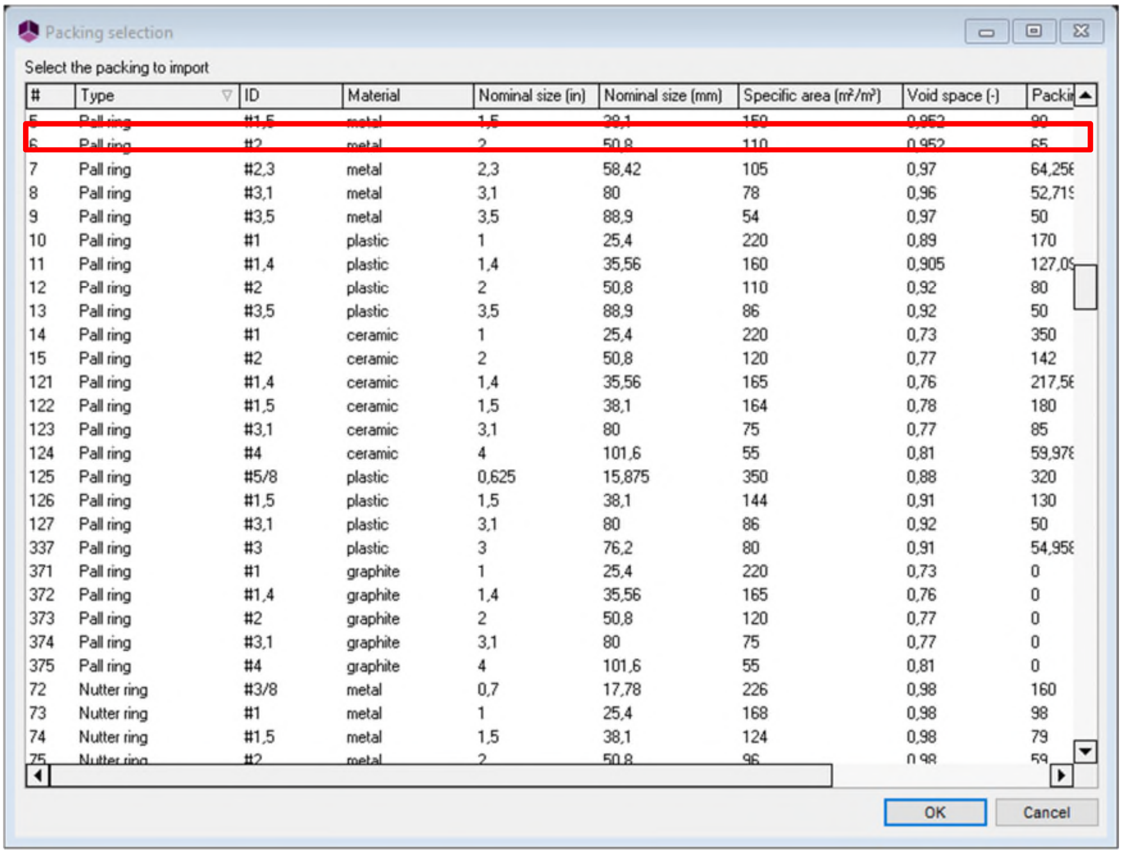
"Properties" section:

Internal type: select "Packing sections".

The packing is directly loaded from the packing data base ("Load" button):



The packing used is "Pall ring / 1,5 in / metal".



Packing selection

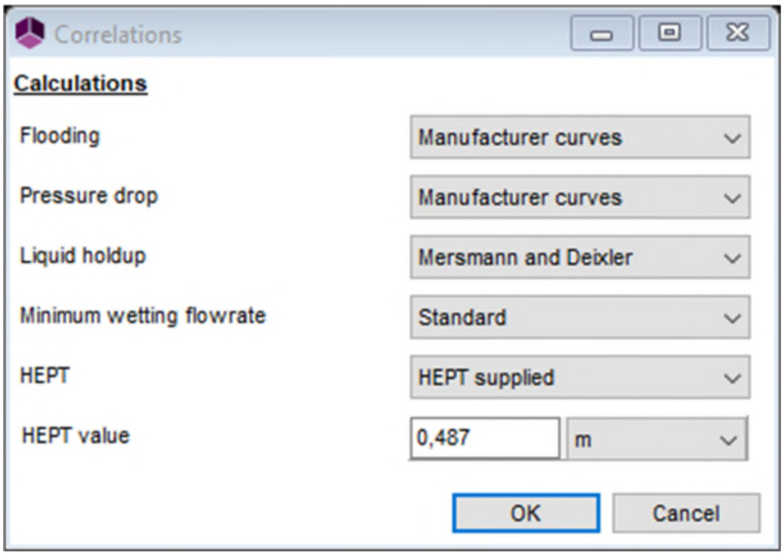
Select the packing to import

#	Type	ID	Material	Nominal size (in)	Nominal size (mm)	Specific area (m²/m³)	Void space (-)	Packi
5	Pall ring	#1,5	metal	1,5	38,1	150	0,952	90
6	Pall ring	#2	metal	2	50,8	110	0,952	65
7	Pall ring	#2,3	metal	2,3	58,42	105	0,97	64,25
8	Pall ring	#3,1	metal	3,1	80	78	0,96	52,71
9	Pall ring	#3,5	metal	3,5	88,9	54	0,97	50
10	Pall ring	#1	plastic	1	25,4	220	0,89	170
11	Pall ring	#1,4	plastic	1,4	35,56	160	0,905	127,0
12	Pall ring	#2	plastic	2	50,8	110	0,92	80
13	Pall ring	#3,5	plastic	3,5	88,9	86	0,92	50
14	Pall ring	#1	ceramic	1	25,4	220	0,73	350
15	Pall ring	#2	ceramic	2	50,8	120	0,77	142
121	Pall ring	#1,4	ceramic	1,4	35,56	165	0,76	217,5
122	Pall ring	#1,5	ceramic	1,5	38,1	164	0,78	180
123	Pall ring	#3,1	ceramic	3,1	80	75	0,77	85
124	Pall ring	#4	ceramic	4	101,6	55	0,81	59,97
125	Pall ring	#5/8	plastic	0,625	15,875	350	0,88	320
126	Pall ring	#1,5	plastic	1,5	38,1	144	0,91	130
127	Pall ring	#3,1	plastic	3,1	80	86	0,92	50
337	Pall ring	#3	plastic	3	76,2	80	0,91	54,95
371	Pall ring	#1	graphite	1	25,4	220	0,73	0
372	Pall ring	#1,4	graphite	1,4	35,56	165	0,76	0
373	Pall ring	#2	graphite	2	50,8	120	0,77	0
374	Pall ring	#3,1	graphite	3,1	80	75	0,77	0
375	Pall ring	#4	graphite	4	101,6	55	0,81	0
72	Nutter ring	#3/8	metal	0,7	17,78	226	0,98	160
73	Nutter ring	#1	metal	1	25,4	168	0,98	98
74	Nutter ring	#1,5	metal	1,5	38,1	124	0,98	79
75	Nutter ring	#2	metal	2	50,8	96	0,98	59

OK Cancel

By clicking on the "Correlations" button, the user can define the correlations used for the flooding, pressure drop, liquid holdup, minimum wetting flowrate and HEPT calculations.

"Correlations" section: use the following configuration:



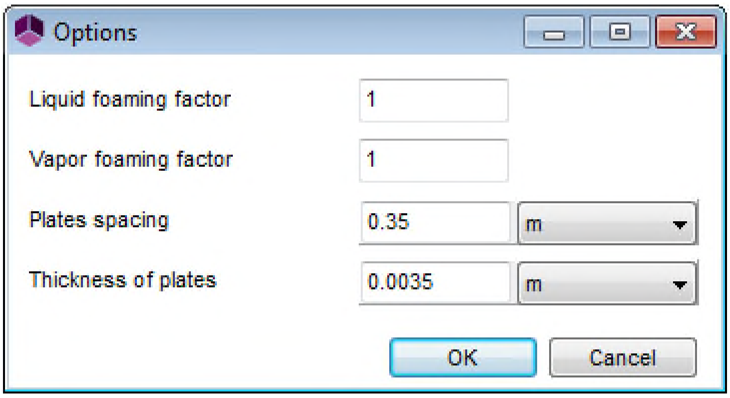
“Options” section: use default parameters.

T3 column:

"Properties" section:

Internal type: select "Nutter valve trays" and let the parameter by default.

"Options" section: enter the following configuration:



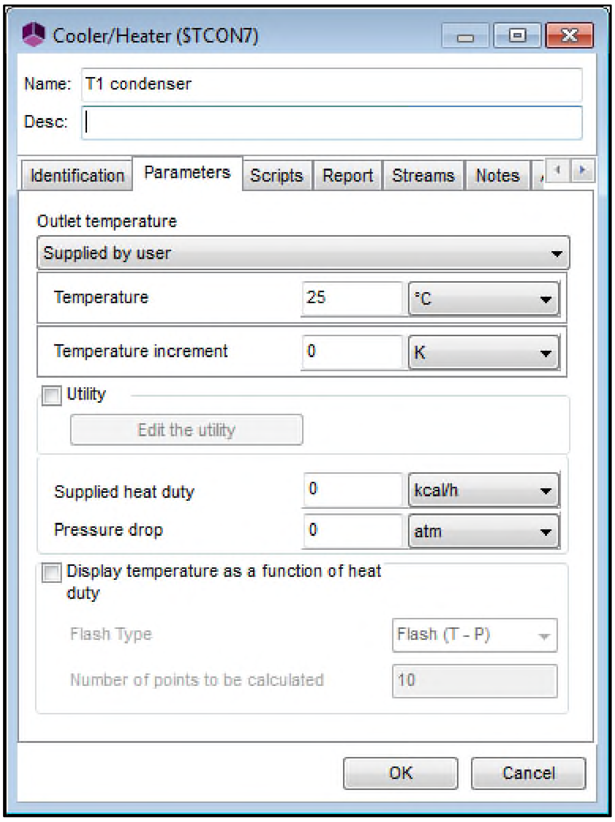
2.7.3. Utilities consumption in the T1, T2 and T3 columns

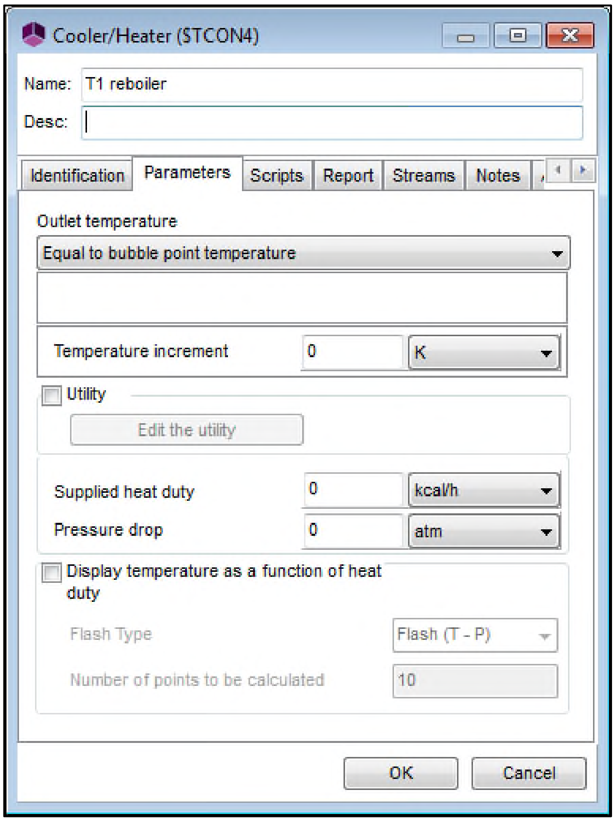
The condensers and reboilers have been simulated with "Cooler/Heater" unit operations. The physical characteristics of the utility used are gathered in the table presented in the paragraph: **2.6 Operating conditions.**

We use cooling water at 15°C and 1 atm for the condensers and saturated steam at different pressure levels in the reboilers.

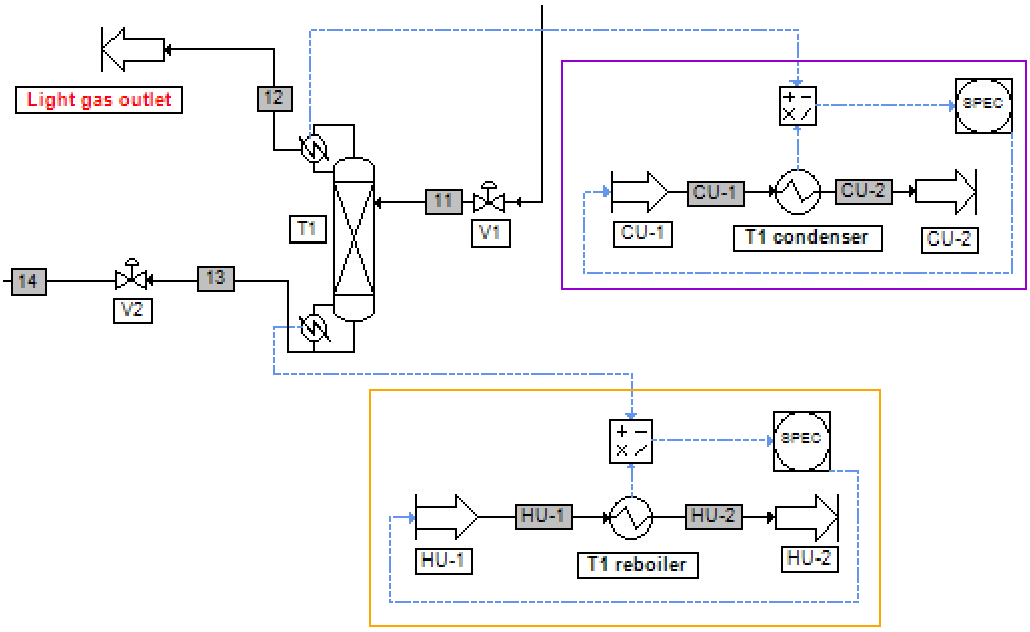
We impose the water temperature at the condensers outlet to be 25°C. In the reboilers, we want to use only the latent heat of condensation as heat duty. To do so, we set the outlet temperature to be the bubble temperature.

The following windows are showing the configuration used in the condenser and the reboiler of the column T1:

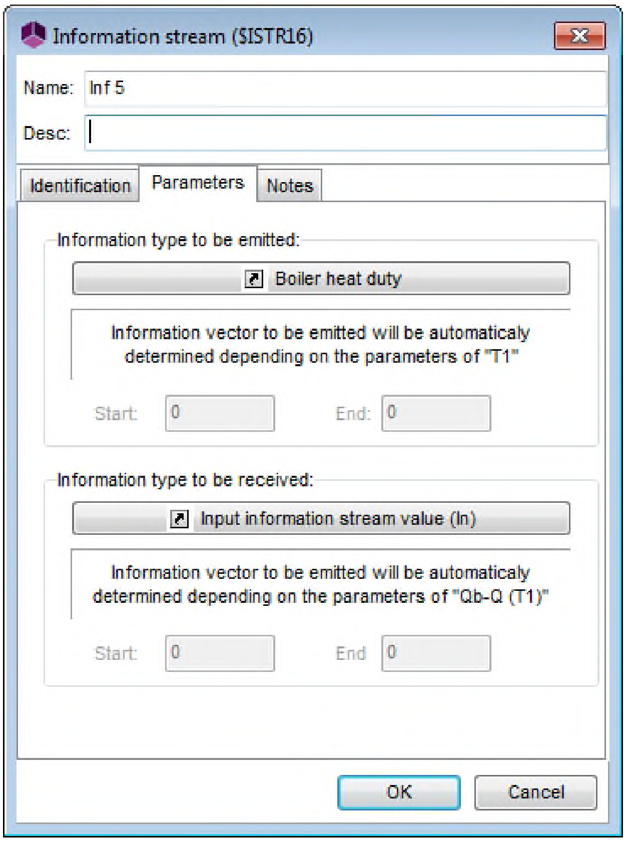


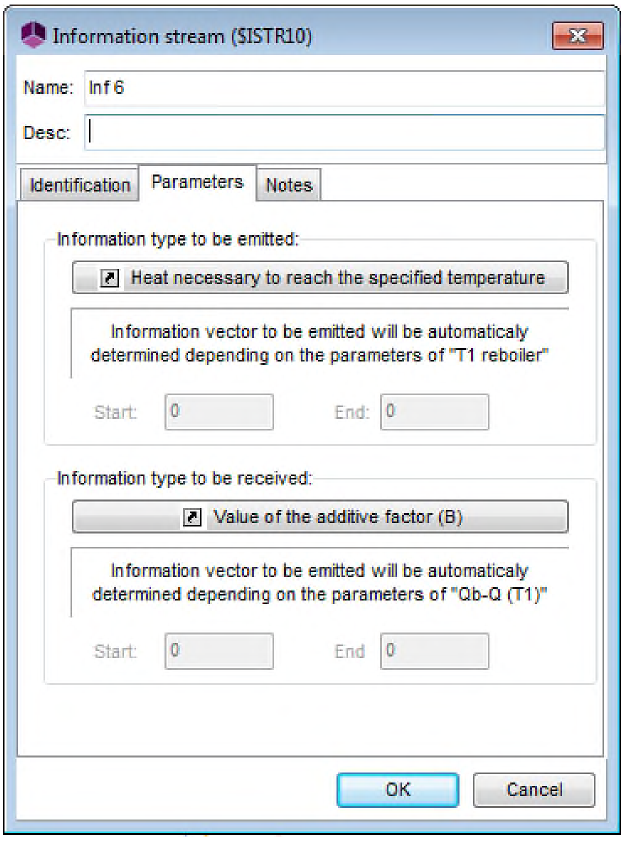


To determine the necessary utility flowrates needed, we use a SPEC block unit as presented below for the column T1:



The approach is the same for the reboilers and condensers of the different columns: we take the heat duty values of the reboiler (respectively the condenser) of the column and the "Cooler/Heater" unit operation using information streams. We link these streams to an "information stream handler" module as presented hereafter for the reboiler of the column T1:



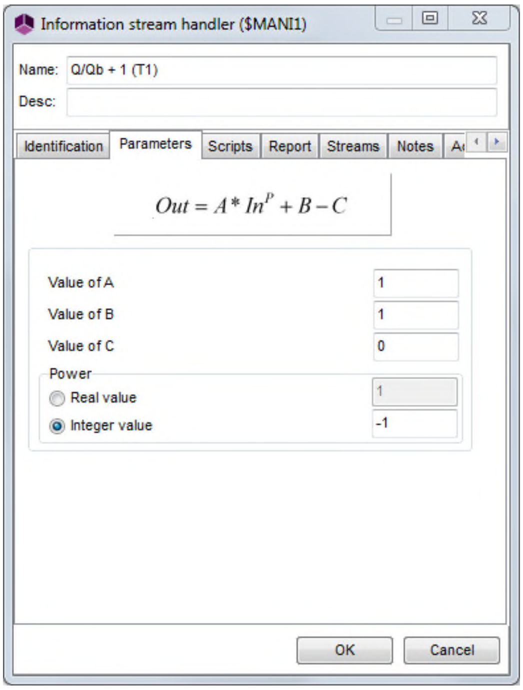


In the information stream handler, we want to calculate the deviation between the ratio of the reboiler (respectively the condenser) and the corresponding “Cooler/Heater” heat duties and 1.

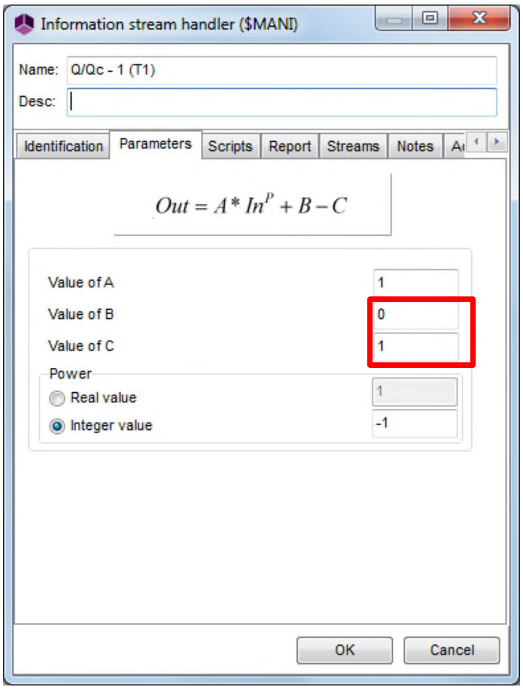
The reboiler and condenser heat duties are positive and the associated “Cooler/Heater” heat duties are respectively negative and positive. A particular attention to the signs while configuring “information stream handler” modules has then to be paid.

The correct configurations in the cases of the boiler and the condenser are given hereafter:

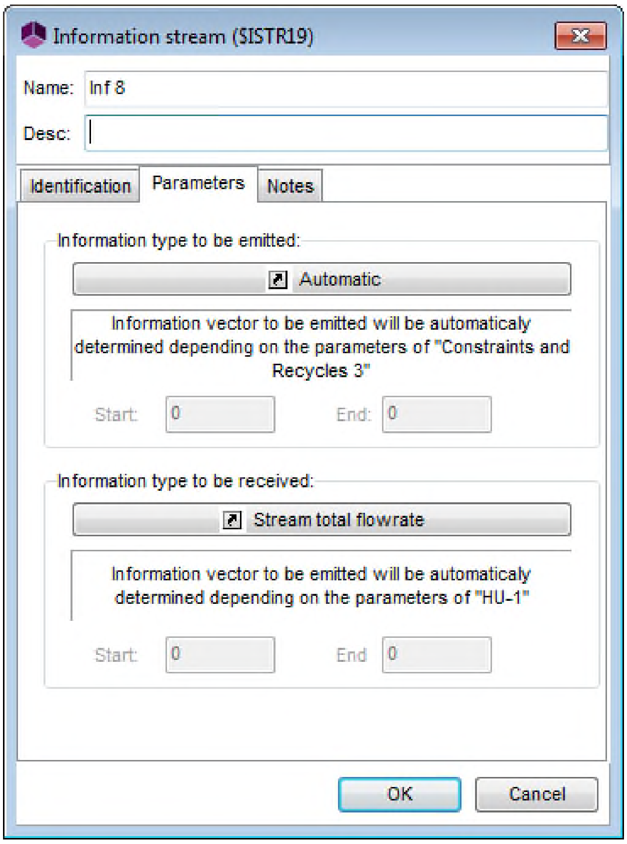
Reboiler



Condenser



The calculated deviation is then sent to the SPEC block unit. This SPEC block unit is linked to the utility process feed unit operation by an information stream configured as follow:



Thus, the SPEC block unit will adjust the utility flowrate in order to cancel the difference between the heat duties ratio and 1. This way, the "Cooler/Heater" unit operation will represent the boiler (respectively the condenser) and the calculated utility flowrate will correspond to the utility flowrate circulating in the reboiler (respectively the condenser). The obtained mass flowrates are summarized in the following table:

	T1 condenser CU-1	***T2 condenser CU-3***	***T3 condenser CU-5***	***T1 reboiler HU-1***	***T2 reboiler HU-3***	***T3 reboiler HU-6***
Mass flowrate (kg/h)	774	199 611	32 881	2 095	2 840	943

3. SIMULATION RESULTS

3.1. Comments on results

The calculation sequence (order of calculation of the unit operations) is automatically generated. The stream "5" is identified as "tear stream" and is initialized with the following characteristics:

	Tear stream "5"
H_2 molar fraction	0.36
CH_4 molar fraction	0.57
C_6H_6 molar fraction	0.005
C_7H_8 molar fraction	0.065
Total molar flowrate (kmol/h)	2600
Temperature (°C)	650
Pressure (bar)	36

Two input flowrates are adjusted in order to reach the right operating conditions for the hydrodealkylation reaction (H_2 to aromatics molar ratio of 5%) and the 120 kmol/h of benzene production with a molar purity of 99.5%.

The required feed flowrates are respectively 199.6 kmol/h for hydrogen and 127.9 kmol/h for toluene.

3.2. Mass and energy balances

This document only presents the most relevant stream results. In ProSimPlus, mass and energy balances are provided for every unit. Results are also available at the unit operation level (result tab in the configuration window).

Inlet/outlet streams (except utilities):

Streams		1	2	12	19	22	24
From		Toluene feed	Hydrogen feed	T1	E3	Measurement 2	TEE1
To		M1	M1	Light gas outlet	Biphenyl outlet	Benzene outlet	Purge
Partial flows		kmol/h	kmol/h	kmol/h	kmol/h	kmol/h	kmol/h
HYDROGEN		0	189.6	0.8	0	0	64.8
METHANE		0	10.0	8.4	0	0	128.7
BENZENE		0	0	0.09	3.3E-07	119.4	1.5
TOLUENE		127.9	0	3.6E-03	1.3E-01	0.6	0.2
BIPHENYL		0	0	1E-09	3.0	0	3E-05
WATER		0	0	0	0	0	0
Total flow	kmol/h	127.9	199.6	9.2	3.1	120.0	195.1
Mole fractions							
HYDROGEN		0	0.950	0.082	0	0	0.332
METHANE		0	0.050	0.908	0	0	0.659
BENZENE		0	0	1.0E-02	1E-07	0.995	8E-03
TOLUENE		1	0	4E-04	0.041	0.005	9E-04
BIPHENYL		0	0	1E-10	0.959	0	2E-07
WATER		0	0	0	0	0	0
Physical state		Liquid	Vapor	Vapor	Liquid	Liquid	Vapor
Temperature	°C	37.85	37.85	18.75	38	30	38
Pressure	bar	37.0	37.0	10.2	1.8	1.0	32.0
Enthalpic flow	kcal/h	-1 095 998	18 343	-849	-44 548	-940 762	8 135
Vapor molar fraction		0	1	1	0	0	1

Inlet/outlet streams (hot utilities):

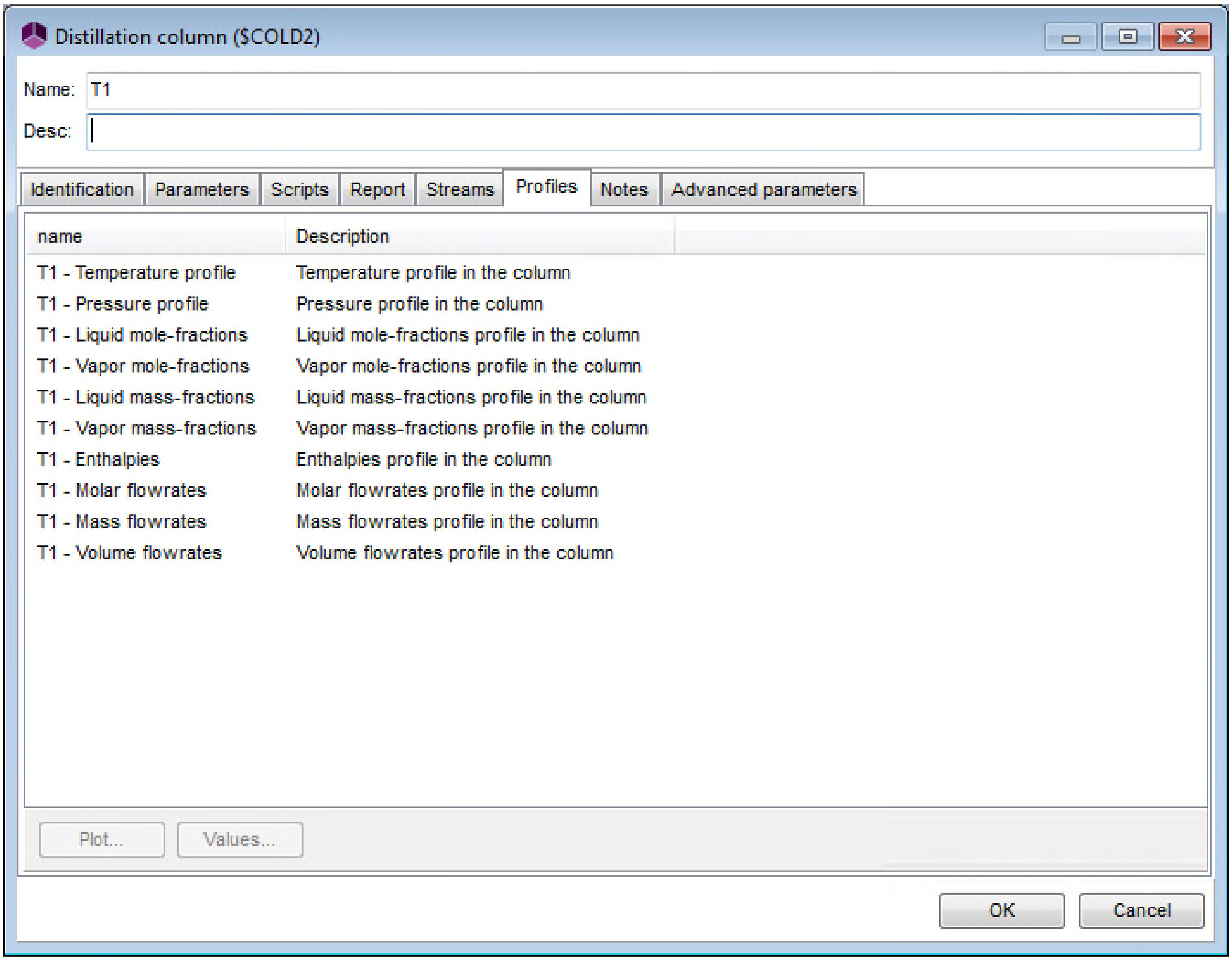
Streams		HU-1	HU-2	HU-3	HU-4	HU-5	HU-6
From		HU-1	T1 reboiler	HU-3	T2 reboiler	HU-5	T3 reboiler
To		T1 reboiler	HU-2	T2 reboiler	HU-4	T3 reboiler	HU-6
Partial flows		kmol/h	kmol/h	kmol/h	kmol/h	kmol/h	kmol/h
WATER		116.3	116.3	157.6	157.6	52.3	52.3
Total flow	kmol/h	116.3	116.3	157.6	157.6	52.3	52.3
Mole fractions							
WATER		1	1	1	1	1	1
Physical state		Vapor	Liquid	Vapor	Liquid	Vapor	Liquid
Temperature	°C	198.3	198.3	151.9	151.9	275.6	275.6
Pressure	bar	15.0	15.0	5.0	5.0	60.0	60.0
Enthalpic flow	kcal/h	122 186	-852 310	136 547	-1 294 340	53 300	-300 643
Vapor molar fraction		1	0	1	0	1	0

Inlet/outlet streams (cold utilities):

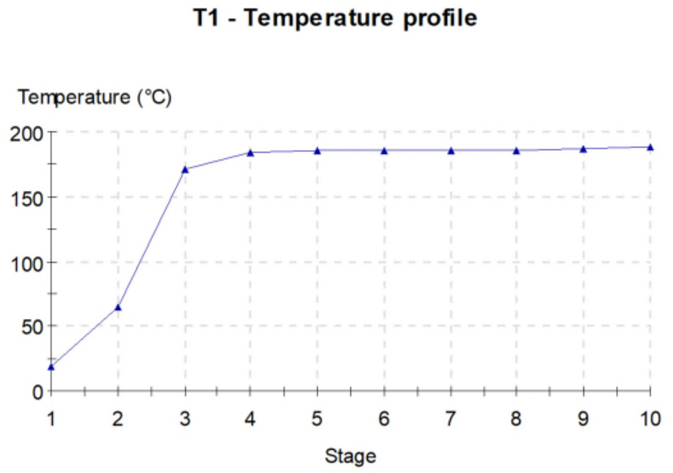
Streams		CU-1	CU-2	CU-3	CU-4	CU-5	CU-6
From		CU-1	T1 condenser	CU-3	T2 condenser	CU-5	T3 condenser
To		T1 condenser	CU-2	T2 condenser	CU-4	T3 condenser	CU-6
Partial flows		kmol/h	kmol/h	kmol/h	kmol/h	kmol/h	kmol/h
WATER		42.9	42.9	11 080.1	11 080.1	1 825.2	1 825.2
Total flow	kmol/h	42.9	42.9	11080.1	11080.1	1825.2	1825.2
Mole fractions							
WATER		1	1	1	1	1	1
Physical state		Liquid	Liquid	Liquid	Liquid	Liquid	Liquid
Temperature	°C	15.0	25.0	15.0	25.0	15.0	25.0
Pressure	bar	1.0	1.0	1.0	1.0	1.0	1.0
Enthalpic flow	kcal/h	-459 378	-451 643	-118 526 712	-116 531 022	-19 524 602	-19 195 857
Vapor molar fraction		0	0	0	0	0	0

3.3. Column profiles

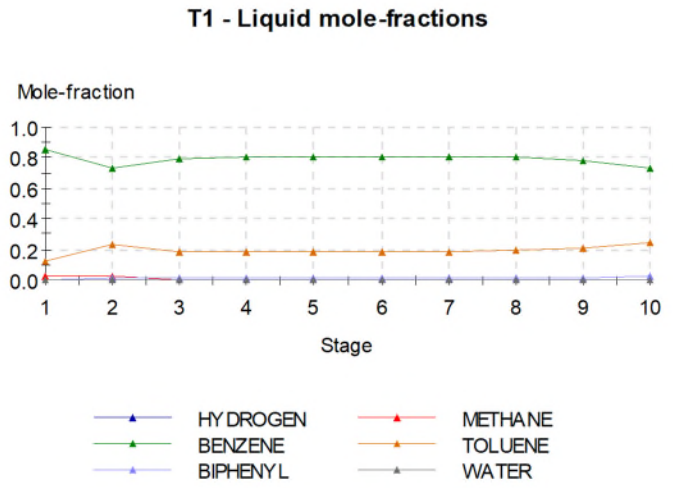
Composition profiles can be accessed after the simulation in each column configuration window, in the “Profiles” tab. Double clicking on the profile will generate the corresponding graph. It is important to note that, in ProSimPlus, the first stage correspond to the condenser and the last stage to the reboiler (numbering from top to bottom).



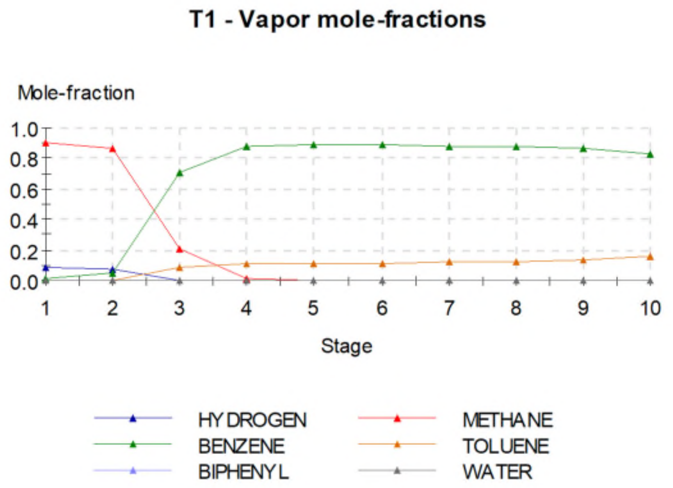
T1 column



Temperature profile in the column

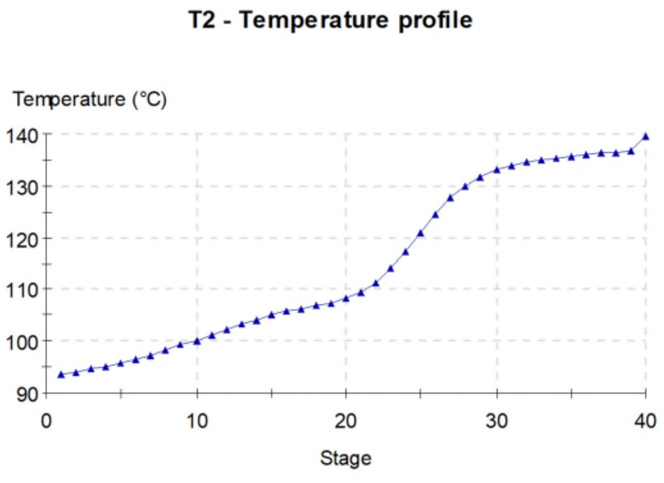


Liquid mole-fractions profile in the column

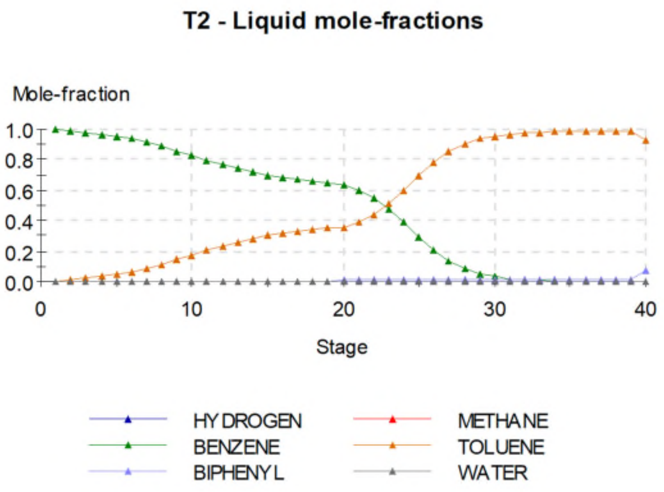


Vapor mole-fractions profile in the column

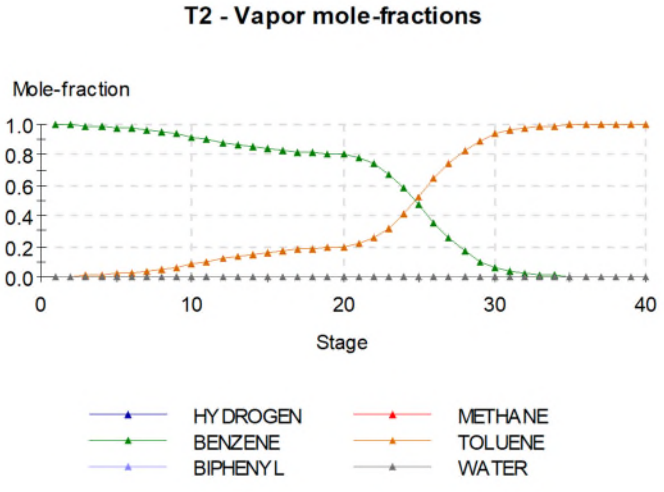
T2 column



Temperature profile in the column

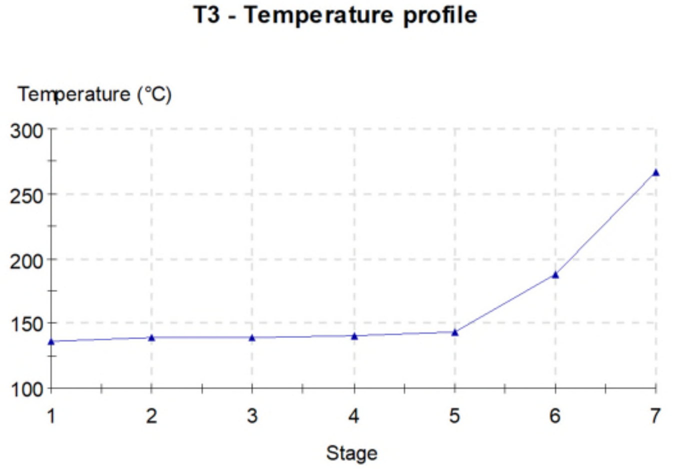


Liquid mole-fractions profile in the column

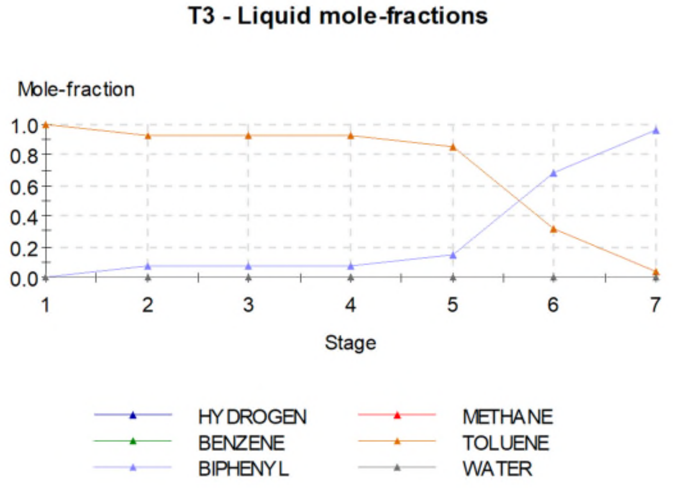


Vapor mole-fractions profile in the column

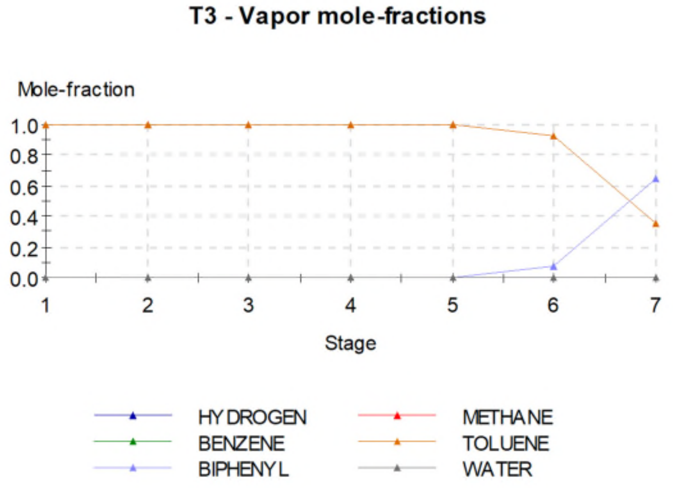
T3 column



Temperature profile in the column



Liquid mole-fractions profile in the column



Vapor mole-fractions profile in the column

3.4. Sizing results

The sizing results of the concerned unit operations are accessible in the simulation report. The sizing results that will be used for the economic evaluation are presented hereafter:

X1 drum:

Height (m)	5.1
Diameter (m)	1.7
Thickness (mm)	30.8

T1 column:

Internal diameter (m)	1.022
External diameter (m)	1.050
Height (m)	4.05
Shell thickness (mm)	14

T2 column:

Internal diameter (m)	1.288
External diameter (m)	1.300
Height (m)	19
Shell thickness (mm)	6

T3 column:

Internal diameter (m)	0.69
External diameter (m)	0.70
Height (m)	2.45
Shell thickness (mm)	5

4. ECONOMIC EVALUATION

The ProSimPlus economic evaluation deals with the following points:

- Calculation of equipment **initial** and **secondary investment** costs
- Calculation of equipment **residual value** at the end of the time horizon
- Calculation of equipment **maintenance** costs
- Calculation **operating gains** and **costs**
- Calculation of **economic indicators**
- **Schedule**
- **Economic indicators** profiles

The economic indicators are:

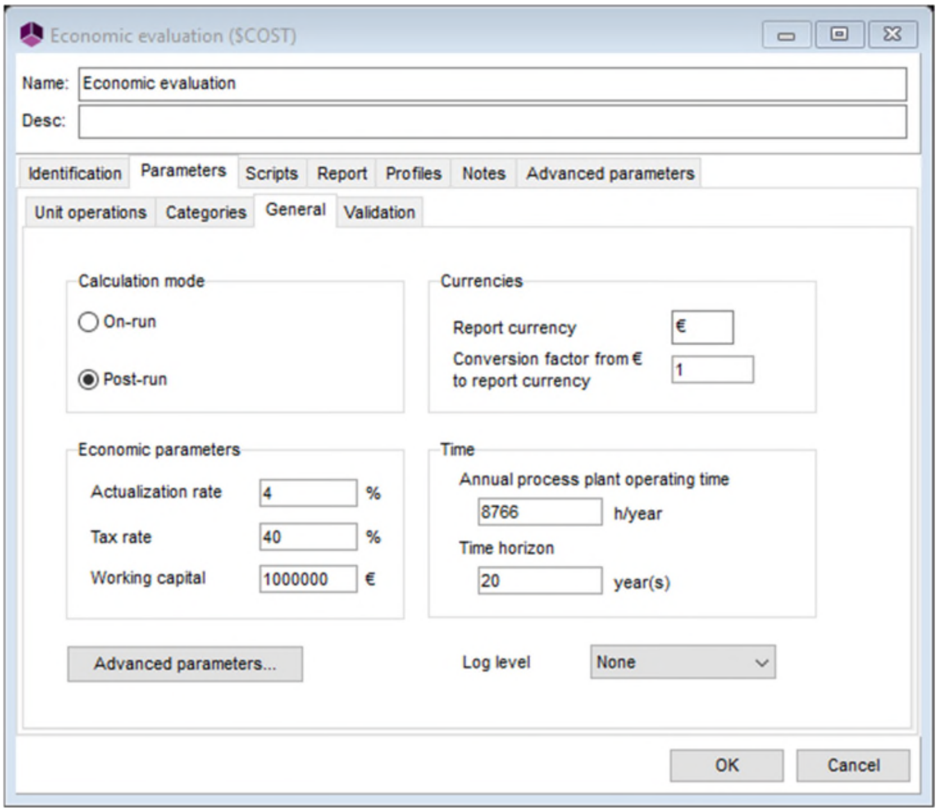
- **Pay out time**
- **Rate of return**
- Equipment **residual values**
- **Cumulative discounted cash flow** of the process
- **Net discounted value** of the process

This economic evaluation is carried out by adding the "Economic evaluation" unit operation on the flowsheet as shown hereafter:

This next section describes the parameters used for the economic evaluation and the corresponding results.

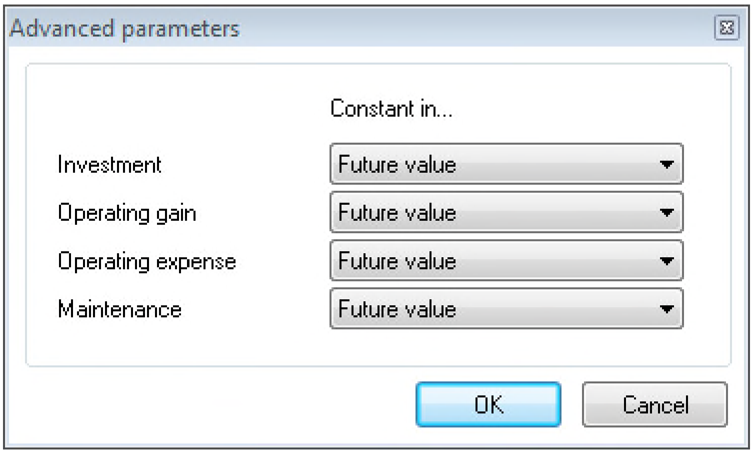
4.1. Economic evaluation general parameters

The general parameters entered in this example are shown below:



Since no result of the economic evaluation unit is used for optimization purpose here, the “Post-run” calculation mode has been chosen. The default currency (€) has been kept. The annual process plant operating time corresponds to the maximum (a continuous operation of the plant 24 hours a day for 365.25 days a year). For more information about the general parameters, please refer to the Online Help.

The advanced parameters chosen for this example are the following ones:



4.2. Initial investment cost

In ProSimPlus, two methods are available to carry out the calculation of the initial investment cost of the equipment. These methods (the Functional Modules Method (FMM) and the Pré-Estime Method (PEM)) are described in the "Manual for Process Economic Evaluation – New, revised and expanded edition" from CHAUVEL *et al.* [CHA03].

They allow to calculate:

- The equipment **base prices** (prices **before** the application of correction factors related for instance to the type, the material and the operating conditions of the equipment)
- The equipment **unassembled real prices** (prices **after** the application of correction factors previously mentioned and **before** the additional cost for **assembly**)
- The equipment **assembled real prices** (real prices **after** the application of the additional cost for **assembly** and of a size correction factor in the case of the PEM)
- The **equipment categories prices** (sum of the assembled real prices of the equipment belonging to a category).

In this example, the economic evaluation was carried out using each of the two methods.

Most of the data required by these two methods are already pre-filled with default values when adding the "Economic evaluation" unit on the flowsheet. A part of the data has to be supplied by the user like for equipment sizing data when using the PEM or for equipment material choice.

In this example, all the unit operations of the flowsheet except the feeds, the measurements, the valves, the mixer and the stream splitter are taken into account for the initial investment calculation. The considered unit operations are gathered in the following table:

Considered unit operations
C1
E1
E2
E3
E4
P1
R1 + R2
T1
T1 condenser
T1 reboiler
T2
T2 condenser
T2 reboiler
T3
T3 condenser
T3 reboiler
X1

Remark: the reactor of the process is simulated using two unit operations (a simple reactor unit operation and an GIBBS reactor unit operation). These two unit operations represent in reality one single reactor. Thus, for this economic evaluation, the reactor price is evaluated considering only one unit operation noted R1+R2 in this document.

4.2.1. Functional Modules Method (FMM)

The FMM has the advantage of not requiring equipment sizing data. It uses the operating parameters that are mostly pre-filled by gathering of the simulation results to calculate the base prices. Carbon steel is the default value for the material correction factors but other choices are available in the ProSimPlus database. For some unit operations, the assembly correction factors depend on technological or operating aspects. In this case, the default values can also be modified by the user.

The first step of the FMM is to choose the functional module used to calculate the cost of each operation. A default value is assigned to each ProSimPlus unit operation but this value can be modified.

For this example, the functional modules chosen for each unit operation are:

Unit operation	Module type (FMM)
C1	Compression
E1	Heating furnace
E2	Heat exchanger
E3	Heat exchanger
E4	Heat exchanger
R1 + R2	Homogeneous fixed bed reactor with external pump system
T1	Distillation
T2	Distillation
T3	Distillation
X1	Drum

Remark: the FMM calculates the price of a unit operation (distillation, compression, reaction…). The “Distillation” functional module of the FMM includes automatically the condenser and the reboiler. Thus, the “Ti condenser” and “Ti reboiler” (i = 1 to 3) unit operations prices must not be calculated otherwise their price will be considered twice.

For each functional module, parameters are required to calculate the operation base price. Parameters are pre-filled and related to the simulation results, others have to be manually entered. The following table summarizes the parameters to be manually entered for the FMM in this example:

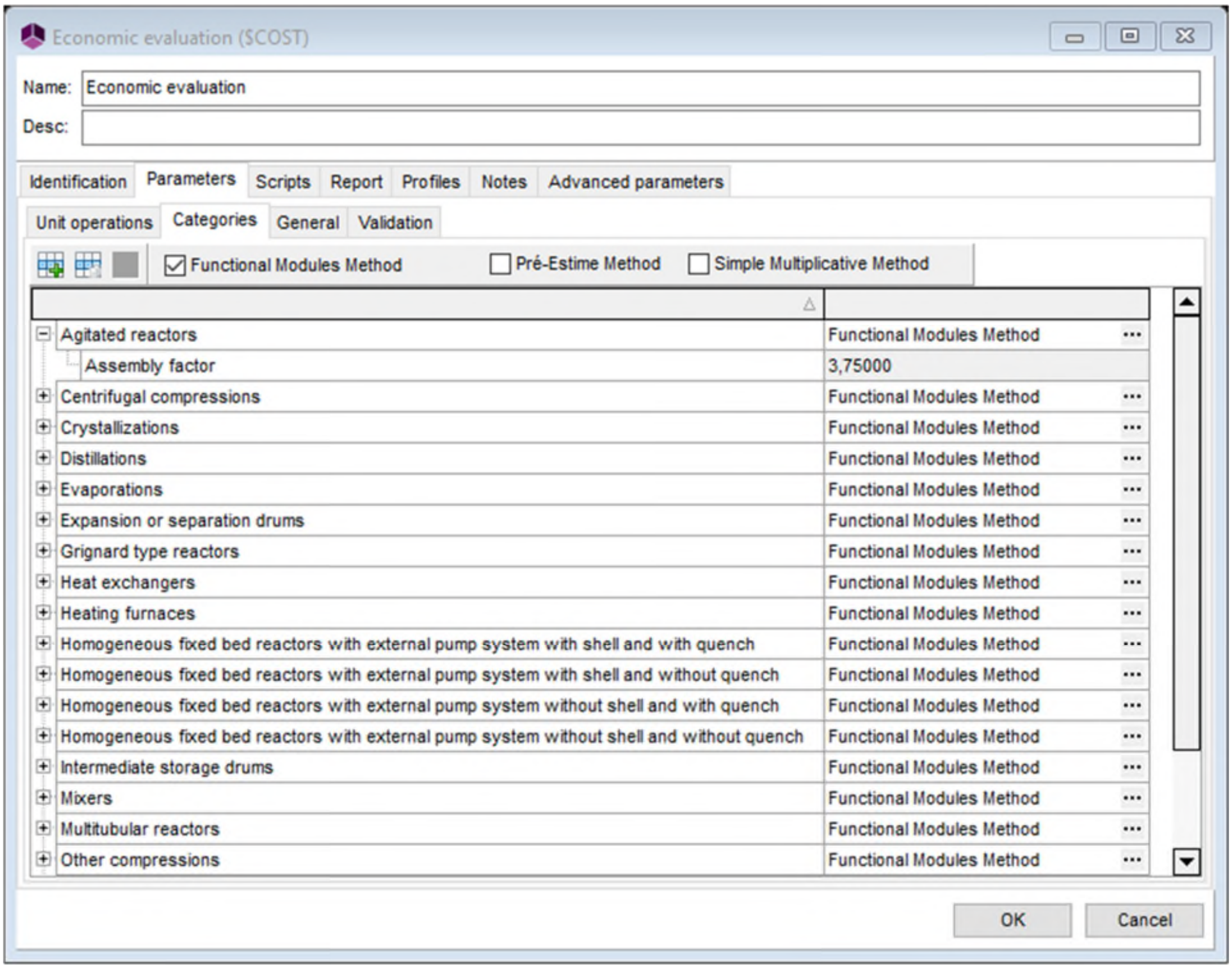
Module	Parameters	
C1	**Compression factor (-)**	1.1563
E2	**Heat overall transfer coefficient (kcal/h/m²/°C)**	500
E3	**Heat overall transfer coefficient (kcal/h/m²/°C)**	600
E4	**Heat overall transfer coefficient (kcal/h/m²/°C)**	500
R1 + R2	**Molar flowrate (kmol/h)**	2611
R1 + R2	**Residence time (s)**	10
T1	**Average relative volatility (-)**	50
T2	**Average relative volatility (-)**	2.23
T3	**Average relative volatility (-)**	33.73

The following table presents the base prices obtained using the FMM:

UNIT OPERATION NAME	EQUIPMENT /SUB-EQUIPMENT	BASE PRICE (€)
C1	Compressor	393 287.56
	Compression (FMM)	393 287.56
E1	Cooler/Heater	698 381.40
	Heating furnace (FMM)	698 381.40
E2	Cooler/Heater	33 589.71
	Heat exchanger (FMM)	33 589.71
E3	Cooler/Heater	1 109.08
	Heat exchanger (FMM)	1 109.08
E4	Cooler/Heater	5 503.11
	Heat exchanger (FMM)	5 503.11
R1	Simple reactor	229 999.95
	Homogeneous fixed bed reactor with external pump system (FMM)	229 999.95
T1	Distillation column	11 545.61
	Distillation (FMM)	11 545.61
T2	Distillation column (total condenser)	85 527.25
	Distillation (FMM)	85 527.25
T3	Distillation column (total condenser)	13 108.57
	Distillation (FMM)	13 108.57
X1	Liquid-vapor separator	719 491.56
	Drum (FMM)	719 491.56

Correction factors have to be applied to determine the unassembled and assembled real prices of the equipment.

The following table gathers this correction factors from the ProSimPlus database:



The unassembled and assembled real prices obtained are presented in the following table:

UNIT OPERATION NAME	EQUIPMENT /SUB-EQUIPMENT	UNASSEMBLED REAL PRICE (€)	ASSEMBLED REAL PRICE (€)
C1	Compressor	393 287.56	1 144 466.81
	Compression (FMM)	393 287.56	
E1	Cooler/Heater	768 219.54	984 717.78
	Heating furnace (FMM)	768 219.54	
E2	Cooler/Heater	45 346.10	107 151.16
	Heat exchanger (FMM)	45 346.10	
E3	Cooler/Heater	1 109.08	3 149.78
	Heat exchanger (FMM)	1 109.08	
E4	Cooler/Heater	5 503.11	15 628.83
	Heat exchanger (FMM)	5 503.11	
R1	Simple reactor	229 999.95	1 885 999.62
	Homogeneous fixed bed reactor with external pump system (FMM)	229 999.95	
T1	Distillation column	11 545.61	39 139.62
	Distillation (FMM)	11 545.61	
T2	Distillation column (total condenser)	85 527.25	289 937.37
	Distillation (FMM)	85 527.25	
T3	Distillation column (total condenser)	13 108.57	44 438.04
	Distillation (FMM)	13 108.57	
X1	Liquid-vapor separator	719 491.56	1 957 017.04
	Drum (FMM)	719 491.56	

The category total price is simply the sum of the assembled real prices of the equipment belonging to the category. The following table gathers the obtained results:

Category (FMM)	Equipment in the category	Category price (€)
Drums	X1	1 957 017
Compression	C1	1 144 466
Distillation	T1, T2, T3	373 515
Heat exchangers	E2, E3, E4	125 929
Heating furnaces	E1	984 718
Homogeneous fixed bed reactors with external pump system with shell and without quench	R1 + R2	1 885 999
Total	**(Process)**	**6 471 646**

4.2.2. Pré-Estime Method (PEM)

In the PEM, the evaluation of the initial investment cost is based on sizing aspects. In some complex cases (reactors and columns for example), the equipment can be divided into sub-equipment whose prices are separately evaluated. The following table gathers the equipment types (for the PEM) used for the prices calculation of each ProSimPlus unit operation:

Unit operation	Equipment type (PEM)
C1	**Centrifugal compressor**
E1	**Heating furnace**
E2	**Air-cooler**
E3	**Tube-type heat exchanger**
E4	**Tube-type heat exchanger**
P1	**Centrifugal pump (driver included)**
R1 + R2	**Pressure vessel (Reactor)**
	Shell
	Bottoms
	Accessories
T1	**Pressure vessel (Column)**
	Shell
	Bottoms
	Skirt
	Accessories
	Trays (8) (Valve, Carbon steel, 3.5 mm)
T1 condenser	**Tube-type heat exchanger**
T1 reboiler	**Tube-type heat exchanger**
T2	**Pressure vessel (Column)**
	Shell
	Bottoms
	Skirt
	Accessories
	Packing (Pall rings, Carbon steel, 1.5 in)
T2 condenser	**Tube-type heat exchanger**
T2 reboiler	**Tube-type heat exchanger**
T3	**Pressure vessel (Column)**
	Shell
	Bottoms
	Skirt
	Accessories
	Trays (5) (Valve, Carbon steel, 3.5 mm)
T3 condenser	**Tube-type heat exchanger**
T3 reboiler	**Tube-type heat exchanger**
X1	**Pressure vessel (Drum)**
	Shell
	Bottoms
	Accessories

Key: In bold letters: full equipment, in thin letters: sub-equipment

One or more parameters are required to determine the base price of equipment or sub-equipment. Like for the FMM method, some parameters are directly derived from the simulation results and others have to be entered by the user in the interface of the module. The following table shows, for this example, all the parameters to be filled in by the user and necessary for the PEM.

Unit operation	Equipment type (PEM)	Parameter	Value
E2	Air-cooler	Air inlet temperature (°C)	20
		Fluid designation	Cooling: light hydrocarbons
E3	Tube-type heat exchanger	Exchange area (m²)	1.8
E4	Tube-type heat exchanger	Exchange area (m²)	14.1
R1 + R2	Shell	Diameter (mm)	2000
		Weight (kg)	10374
	Bottoms	Diameter (mm)	2000
		Weight (kg)	2961
	Accessories	Weight (Shell + Bottoms) (kg)	13335
T1 condenser	Tube-type heat exchanger	Exchange area (m²)	128.6
T1 reboiler	Tube-type heat exchanger	Exchange area (m²)	176.3
T2 condenser	Tube-type heat exchanger	Exchange area (m²)	26.4
T2 reboiler	Tube-type heat exchanger	Exchange area (m²)	138.5
T3 condenser	Tube-type heat exchanger	Exchange area (m²)	16.5
T3 reboiler	Tube-type heat exchanger	Exchange area (m²)	64.8

The reactors weights have been calculated with the method presented in CHAUVEL *et al.* [CHA03]:

The shell weight is determined as follows:

$$shell\ weight\ (kg) = 24.7\ .D'.H.e$$

Where D': shell diameter (m)

H: shell height or length (m)

e: shell thickness (mm)

The bottoms weight is calculated as follows:

$$bottoms\ weight\ (kg) = unit\ weight.e$$

Where e: bottoms thickness (here considered equal to the shell thickness) (mm)

unit weight: bottoms weight (kg) for a unit thickness (1 mm)

The curve giving the unit weight as a function of the shell diameter is available in [CHA03]. By regressing this curve, we obtain the following equation:

$$unit\ weight\ (kg) = \exp(2.83 + 2.23\ln(D') - 0.32\ln(D')^2 + 0.13\ln(D')^3)$$

To calculate the skirt weight, we use the same equation as for the shell weight but using the skirt height and thickness.

The column diameters were calculated using the sizing method of the ProSimPlus "Distillation column" unit operations.

For heat exchangers, the exchange area is consistent with the FMM values and estimated as follows:

$$A = \frac{Q}{U \, . \, TML}$$

Where A: exchanger surface (m²)

Q: heat duty (kcal/h)

U: overall transfer coefficient (kcal/h/m²/°C)

TML: log mean temperature (°C)

The following table gathers the base prices calculated using the PEM:

UNIT OPERATION NAME	EQUIPMENT /SUB-EQUIPMENT	BASE PRICE (€)
C1	Compressor	630 416.25
	Centrifugal compressor (driver included) (PEM)	630 416.25
E1	Cooler/Heater	1 132 299.05
	Heating furnace (PEM)	1 132 299.05
E2	Cooler/Heater	87 564.68
	Air-cooler (PEM)	87 564.68
E3	Cooler/Heater	4 416.86
	Tube-type exchanger (PEM)	4 416.86
E4	Cooler/Heater	10 225.17
	Tube-type exchanger (PEM)	10 225.17
P1	Centrifugal pump	54 491.96
	Centrifugal pump (driver included) (PEM)	54 491.96
R1	Simple reactor	97 126.06
	Reactor shell (PEM)	43 293.85
	Reactor bottoms (PEM)	12 357.15
	Reactor accessories (PEM)	41 475.05
T1 condenser	Cooler/Heater	35 247.85
	Tube-type exchanger (PEM)	35 247.85
T1 reboiler	Cooler/Heater	44 264.88
	Tube-type exchanger (PEM)	44 264.88
T1	Distillation column	30 431.31
	Column shell (PEM)	7 303.22
	Column bottoms (PEM)	1 310.71
	Column skirt (PEM)	3 088.11
	Column accessories (PEM)	16 952.39
	Column trays (PEM)	1 776.89
T2 condenser	Cooler/Heater	13 790.49
	Tube-type exchanger (PEM)	13 790.49
T2 reboiler	Cooler/Heater	37 134.59
	Tube-type exchanger (PEM)	37 134.59
T2	Distillation column (total condenser)	80 314.30
	Column shell (PEM)	17 200.95
	Column bottoms (PEM)	836.32
	Column skirt (PEM)	5 431.38
	Column accessories (PEM)	22 273.85
	Column packing (PEM)	34 571.80
T3 condenser	Cooler/Heater	10 989.02
	Tube-type exchanger (PEM)	10 989.02
T3 reboiler	Cooler/Heater	22 603.27
	Tube-type exchanger (PEM)	22 603.27
T3	Distillation column (total condenser)	14 754.17
	Column shell (PEM)	988.98
	Column bottoms (PEM)	195.62
	Column skirt (PEM)	2 255.08
	Column accessories (PEM)	10 512.10
	Column trays (PEM)	802.39
X1	Liquid-vapor separator	53 520.40
	Drum shell (PEM)	28 789.98
	Drum bottoms (PEM)	6 909.42
	Drum accessories (PEM)	17 821.00

The unassembled real prices are gathered in the table below:

UNIT OPERATION NAME	EQUIPMENT /SUB-EQUIPMENT	UNASSEMBLED REAL PRICE (€)
C1	Compressor	630 416.25
	Centrifugal compressor (driver included) (PEM)	630 416.25
E1	Cooler/Heater	1 415 373.82
	Heating furnace (PEM)	1 415 373.82
E2	Cooler/Heater	96 321.15
	Air-cooler (PEM)	96 321.15
E3	Cooler/Heater	4 608.84
	Tube-type exchanger (PEM)	4 608.84
E4	Cooler/Heater	10 669.60
	Tube-type exchanger (PEM)	10 669.60
P1	Centrifugal pump	54 491.96
	Centrifugal pump (driver included) (PEM)	54 491.96
R1	Simple reactor	269 872.02
	Reactor shell (PEM)	95 891.54
	Reactor bottoms (PEM)	54 739.71
	Reactor accessories (PEM)	119 240.77
T1 condenser	Cooler/Heater	39 354.46
	Tube-type exchanger (PEM)	39 354.46
T1 reboiler	Cooler/Heater	64 664.34
	Tube-type exchanger (PEM)	64 664.34
T1	Distillation column	36 413.44
	Column shell (PEM)	7 425.80
	Column bottoms (PEM)	3 331.77
	Column skirt (PEM)	3 606.35
	Column accessories (PEM)	19 495.24
	Column trays (PEM)	2 554.28
T2 condenser	Cooler/Heater	14 389.88
	Tube-type exchanger (PEM)	14 389.88
T2 reboiler	Cooler/Heater	48 435.77
	Tube-type exchanger (PEM)	48 435.77
T2	Distillation column (total condenser)	97 778.50
	Column shell (PEM)	23 829.72
	Column bottoms (PEM)	2 896.54
	Column skirt (PEM)	5 679.76
	Column accessories (PEM)	25 614.92
	Column packing (PEM)	39 757.56
T3 condenser	Cooler/Heater	11 466.65
	Tube-type exchanger (PEM)	11 466.65
T3 reboiler	Cooler/Heater	53 362.66
	Tube-type exchanger (PEM)	53 362.66
T3	Distillation column (total condenser)	18 416.54
	Column shell (PEM)	1 635.08
	Column bottoms (PEM)	905.58
	Column skirt (PEM)	2 633.53
	Column accessories (PEM)	12 088.91
	Column trays (PEM)	1 153.44
X1	Liquid-vapor separator	57 237.91
	Drum shell (PEM)	25 429.14
	Drum bottoms (PEM)	12 205.68
	Drum accessories (PEM)	19 603.10

The calculation of the assembled real price from the unassembled real price is more complex in the case of the PEM than in the case of the FMM. Indeed, an assembly factor is taken into account but also a size factor. This size factor represents a decrease or an increase of the equipment depending on the “size” of the ordered batch: for instance, ordering a batch of 10 heat exchangers allows to save money on the total assembled real price instead of ordering the 10 heat exchangers separately.

This size factor is defined for each equipment category (in the PEM sense) and depends on the sum of the unassembled real prices of the equipment belonging to the category.

The following table shows the assembled real price of each piece of equipment and its respective category (in the PEM sense):

NOM DU MODULE	EQUIPEMENT SOUS-EQUIPEMENT	PRIX REEL NON MONTE (€)	PRIX REEL MONTE (€)
C1	Compresseur	630 416.25	1 929 868.61
	Centrifugal compressor (driver included) (PEM)	630 416.25	
Condenseur T1	Consignateur de température	36 779.87	132 200.80
	Tube-type exchanger (PEM)	36 779.87	
Condenseur T2	Consignateur de température	14 389.88	51 722.69
	Tube-type exchanger (PEM)	14 389.88	
Condenseur T3	Consignateur de température	11 466.65	41 215.50
	Tube-type exchanger (PEM)	11 466.65	
E1	Consignateur de température	1 415 373.82	3 170 112.36
	Heating furnace (PEM)	1 415 373.82	
E2	Consignateur de température	96 321.15	260 886.56
	Air-cooler (PEM)	96 321.15	
E3	Consignateur de température	4 608.84	16 565.92
	Tube-type exchanger (PEM)	4 608.84	
E4	Consignateur de température	10 669.60	38 350.59
	Tube-type exchanger (PEM)	10 669.60	
P1	Pompe centrifuge	54 491.96	187 651.86
	Centrifugal pump (driver included) (PEM)	54 491.96	
R1	Réacteur simple	269 872.02	605 802.46
	Reactor shell (PEM)	95 891.54	
	Reactor bottoms (PEM)	54 739.71	
	Reactor accessories (PEM)	119 240.77	
Rebouilleur T1	Consignateur de température	46 188.82	166 020.11
	Tube-type exchanger (PEM)	46 188.82	
Rebouilleur T2	Consignateur de température	38 748.62	139 277.21
	Tube-type exchanger (PEM)	38 748.62	
Rebouilleur T3	Consignateur de température	23 585.71	84 775.97
	Tube-type exchanger (PEM)	23 585.71	
T1	Colonne à distiller	35 174.53	140 286.76
	Column shell (PEM)	7 225.39	
	Column bottoms (PEM)	1 874.62	
	Column skirt (PEM)	3 512.66	
	Column accessories (PEM)	19 275.74	
	Column trays (PEM)	3 286.11	
T2	Colonne à distiller avec condenseur total	144 832.86	565 984.77
	Column shell (PEM)	23 598.09	
	Column bottoms (PEM)	1 632.43	
	Column skirt (PEM)	4 189.41	
	Column accessories (PEM)	24 772.82	
	Column packing (PEM)	90 640.12	
T3	Colonne à distiller avec condenseur total	18 901.95	72 061.57
	Column shell (PEM)	1 875.64	
	Column bottoms (PEM)	541.13	
	Column skirt (PEM)	2 595.66	
	Column accessories (PEM)	12 260.08	
	Column trays (PEM)	1 629.45	
X1	Séparateur diphasique liquide-vapeur	53 592.88	182 557.95
	Drum shell (PEM)	25 429.57	
	Drum bottoms (PEM)	8 957.01	
	Drum accessories (PEM)	19 206.30	

To calculate the total price of an equipment category, the sum of the assembled real prices of the equipment belonging to the category is done. The results are gathered in the table below:

Category (PEM)	**Category price (€)**
Air-coolers	260 886
Drums	191 689
Columns and reactors	1 194 131
Centrifugal compressors and drivings	1 929 869
Tubular heat exchangers	728 527
Heating furnaces	3 170 112
Pumps and drivings	187 652
Total (Process)	**7 662 866**

4.2.3. Results comparison (FMM and PEM)

The following table contains the initial investment costs of the operations evaluated by the FMM and the PEM (that is why the P1 pump is not present):

		Unassembled real price (€)		Assembled real price (€)	
Module	**Nature de l'équipement**	**FMM**	**PEM**	**FMM**	**PEM**
C1	Compressor	393 288	630 416	1 144 467	1 929 869
E1	Heating furnace	768 220	1 415 374	984 718	3 170 112
E2	Heat exchanger	45 346	96 321	107 151	260 887
E3	Heat exchanger	1 109	4 609	3 150	16 514
E4	Heat exchanger	5 503	10 670	15 629	38 230
P1	Pump	-	54 491	-	187 652
R1 + R2	Reactor	230 000	269 872	1 886 000	606 524
T1*	Distillation column (partial condenser)	11 546	140 432	39 140	460 222
T2*	Distillation column (total condenser)	85 527	160 604	289 937	756 242
T3*	Distillation column (total condenser)	13 109	83 246	44 438	224 927
X1	Separation drum	719 491	57 237	1 957 017	182 557
Total		**2 273 139**	**2 923 272**	**6 471 647**	**7 833 736**

*: in this table, the prices of the columns take into account the prices of the reboilers and of the condensers for the PEM

**: the pumps prices are taken into account into the equipment prices for the FMM method

It can be noticed that the prices of some operations are noticeably different for the two methods. The FMM and the PEM are indeed two distinct cost evaluation methods: the first one is mainly based on operating parameters and estimates the price of a functional unit (distillation, reaction…) whereas the second one takes equipment sizing aspects into account.

Considering the total initial investment costs, the results are nevertheless of the same order of magnitude with a deviation of about 22% on the total unassembled real price and 17% on the total assembled real price.

4.3. Secondary investment cost and residual value

For each unit operation for which the initial investment cost was defined, it is necessary to specify a life time. As soon as the life time of a piece of equipment is reached, this piece needs to be replaced. The secondary investment cost of a piece of equipment is then defined as the sum of the rebuy costs of this piece on the time horizon.

The life time also allows to determine the residual value of a piece of equipment, i.e. the resale price of this piece every year. In the economic evaluation unit operation, we consider that the decreasing of the residual value of a piece of equipment is linear with time.

If the rebuy year of a piece of equipment occurs the last year of the time horizon, then the piece is not rebought this year and its residual value is null.

The equipment life times considered in this example are gathered in the table hereafter:

Unit operation	Life time (year)
C1	10
E1	10
E2	10
E3	10
E4	10
P1	10
R1 + R2	15
T1	15
T1 condenser	15
T1 reboiler	15
T2	15
T2 condenser	15
T2 reboiler	15
T3	15
T3 condenser	15
T3 reboiler	15
X1	15

*: only defined for the PEM

The following tables indicate for each unit operation the number of equipment changes, the total secondary investment cost and the residual value at the end of the time horizon:

Functional Modules Method (FMM):

UNIT OPERATION NAME	CATEGORY	NUMBER OF EQUIPMENT CHANGES	TOTAL SECONDARY INVESTMENT (€)	RESIDUAL VALUE (€)
C1	Centrifugal compressions (FMM)	1	773 160.77	0
E1	Heating furnaces (FMM)	1	665 240.05	0
E2	Heat exchangers (FMM)	1	72 387.49	0
E3	Heat exchangers (FMM)	1	2 127.88	0
E4	Heat exchangers (FMM)	1	10 558.28	0
R1	Homogeneous fixed bed reactors with external pump system with shell and without quench (FMM)	1	1 047 228.64	573 830.41
T1	Distillations (FMM)	1	21 732.84	11 908.54
T2	Distillations (FMM)	1	160 991.93	88 215.75
T3	Distillations (FMM)	1	24 674.87	13 520.63
X1	Expansion or separation drums (FMM)	1	1 086 662.09	595 438.02

Pré-Estime method (PEM):

UNIT OPERATION NAME	CATEGORY	NUMBER OF EQUIPMENT CHANGES	TOTAL SECONDARY INVESTMENT (€)	RESIDUAL VALUE (€)
C1	Centrifugal compressors and drivings (PEM)	1	1 303 750.09	0
E1	Heating furnaces (PEM)	1	2 141 614.32	0
E2	Air-coolers (PEM)	1	176 245.61	0
E3	Tubular heat exchangers (PEM)	1	11 156.01	0
E4	Tubular heat exchangers (PEM)	1	25 826.48	0
P1	Pumps and drivings (PEM)	1	126 770.87	0
R1	Columns and reactors (PEM)	1	336 781.13	184 539.69
T1 condenser	Tubular heat exchangers (PEM)	1	74 604.22	40 879.49
T1 reboiler	Tubular heat exchangers (PEM)	1	102 152.82	55 974.78
T1	Columns and reactors (PEM)	1	78 787.81	43 171.89
T2 condenser	Tubular heat exchangers (PEM)	1	28 629.10	15 687.36
T2 reboiler	Tubular heat exchangers (PEM)	1	82 470.45	45 189.80
T2	Columns and reactors (PEM)	1	208 867.45	114 449.21
T3 condenser	Tubular heat exchangers (PEM)	1	22 813.25	12 500.55
T3 reboiler	Tubular heat exchangers (PEM)	1	63 458.55	34 772.20
T3	Columns and reactors (PEM)	1	38 622.22	21 163.10
X1	Drums (PEM)	1	106 438.09	58 322.90

4.4. Maintenance cost

The annual maintenance cost of each piece of equipment (in €/year) can be either defined as a constant, be calculated as a percentage of the investment cost (unassembled or assembled real price) or be calculated by a user formula.

In this example we have considered that the annual maintenance cost of the equipment corresponds to 5% percent of their assembled real price.

The annual maintenance cost of each piece of equipment is indicated in the following tables.

Functional Modules Method (FMM):

UNIT OPERATION NAME	MAINTENANCE COST (€/YR)
C1	57 223.34
E1	49 235.89
E2	5 357.56
E3	157.49
E4	781.44
R1	94 299.98
T1	1 956.98
T2	14 496.87
T3	2 221.90
X1	97 850.85
TOTAL	323 582.30

Pré-Estime Method (PEM):

UNIT OPERATION NAME	MAINTENANCE COST (€/YR)
C1	96 493.43
E1	158 505.62
E2	13 044.33
E3	825.68
E4	1 911.48
P1	9 382.59
R1	30 326.19
T1 condenser	6 717.90
T1 reboiler	9 198.57
T1	7 094.62
T2 condenser	2 577.97
T2 reboiler	7 426.23
T2	18 807.92
T3 condenser	2 054.27
T3 reboiler	5 714.26
T3	3 477.82
X1	9 584.45
TOTAL	383 143.33

4.5. Operating gains and costs

The operating gains and costs include the following elements:

- gains and costs of the process inlets and outlets
- costs of the utilities defined in the unit operations
- production gains and consumption costs of electricity

The following table gathers the data used to calculate the operating gains and costs of the example.

Gains and costs of the process inlets and outlets:

Unit operation	Consumption / production type	Price (€/t)
Hydrogen feed	Raw material	34
Toluene feed	Raw material	291
Benzene outlet	Product	383
Biphenyl outlet	Product	250
Light gas outlet	Product	308
Purge	Product	308
CU-1	Utility	0
CU-3	Utility	0
CU-5	Utility	0
HU-1	Utility	20
HU-3	Utility	15
HU-5	Utility	25

Costs of the utilities defined in the unit operations:

Unit operation	Utility type of use	Utility description	Price (€/MWh)
E1	Heat duty	Natural gas	20
E2	Heat duty	Air (20°C)	0
E3	Heat duty	Cold water (15°C)	0
E4	Heat duty	Cold water (15°C)	0
R1	Heat duty	Cold water (15°C)	0
R2	Heat duty	Cold water (15°C)	0
X1	Heat duty	Natural gas	20

Remarks:

- Cold water and air costs are neglected
- Natural gas has been chosen to feed the E1 furnace and to heat the heat transfer fluid in the X1 drum (the heat transfer losses have been neglected)
- The utility consumption in the reactor is the sum of the consumptions in the R1 and R2 unit operations
- The row “Utility description” does not appear in the economic evaluation unit operation but is present in this document to precise the hypothesis of the example

Production gains and consumption costs of electricity:

Unit operation	Electricity	Price (€/MWh)
C1	Consumption	40
P1	Consumption	40

Results:

Operating gains:

UNIT OPERATION NAME	OPERATING GAIN (€/YR)			
	PRODUCT	REMUNERATIVE INPUT	PRODUCED ELECTRICITY	TOTAL
Benzene outlet	31 499 065.32	0.00	0.00	31 499 065.32
Biphenyl outlet	1 043 463.85	0.00	0.00	1 043 463.85
Light gas outlet	386 545.79	0.00	0.00	386 545.79
Purge	6 288 026.33	0.00	0.00	6 288 026.33
TOTAL	39 217 101.29	0.00	0.00	39 217 101.29

Operating expenses:

UNIT OPERATION NAME	OPERATING EXPENSE (€/YR)				
	RAW MATERIAL	UTILITY	CONSUMED ELECTRICITY	WASTE (REPROCESSING)	TOTAL
C1	0.00	0.00	126 684.42	0.00	126 684.42
E1	0.00	4 475 278.78	0.00	0.00	4 475 278.78
HU-1	0.00	367 210.23	0.00	0.00	367 210.23
HU-3	0.00	373 397.93	0.00	0.00	373 397.93
HU-5	0.00	206 633.40	0.00	0.00	206 633.40
Hydrogen feed	161 613.14	0.00	0.00	0.00	161 613.14
P1	0.00	0.00	2 643.05	0.00	2 643.05
Toluene feed	30 070 261.98	0.00	0.00	0.00	30 070 261.98
X1	0.00	2 931.89	0.00	0.00	2 931.89
TOTAL	30 231 875.12	5 425 452.22	129 327.46	0.00	35 786 654.81

The **operating balance** (difference between operating gains and cost) is equal to **3.4** M**€/year**.

4.6. Schedule

The economic evaluation unit provides a schedule on the time horizon specified by user. The actualization is taken into account. The definitions of the results given in the schedule are available in the ProSimPlus Online Help. For instance, we can have access to the depreciation, the cumulative discounted cash flow or the net discounted value.

The following pages contain the schedules obtained for this example with the FMM and the PEM.

Schedule (FMM)

YEAR	INVESTMENT COST (€)	MAINTENANCE COST (€)	OPERATING GAIN (€)	OPERATING EXPENSE (€)	DEPRECIATION (€)	OPERATING COST (€)	NET INCOME (€)
0	7 471 646.05	0	0	0	0	0	0
1	0	323 582.30	39 217 100.96	35 786 654.51	506 613.55	36 293 268.05	1 754 299.74
2	0	323 582.30	39 217 100.96	35 786 654.51	506 613.55	36 293 268.05	1 754 299.74
3	0	323 582.30	39 217 100.96	35 786 654.51	506 613.55	36 293 268.05	1 754 299.74
4	0	323 582.30	39 217 100.96	35 786 654.51	506 613.55	36 293 268.05	1 754 299.74
5	0	323 582.30	39 217 100.96	35 786 654.51	506 613.55	36 293 268.05	1 754 299.74
6	0	323 582.30	39 217 100.96	35 786 654.51	506 613.55	36 293 268.05	1 754 299.74
7	0	323 582.30	39 217 100.96	35 786 654.51	506 613.55	36 293 268.05	1 754 299.74
8	0	323 582.30	39 217 100.96	35 786 654.51	506 613.55	36 293 268.05	1 754 299.74
9	0	323 582.30	39 217 100.96	35 786 654.51	506 613.55	36 293 268.05	1 754 299.74
10	2 255 114.36	323 582.30	39 217 100.96	35 786 654.51	506 613.55	36 293 268.05	1 754 299.74
11	0	323 582.30	39 217 100.96	35 786 654.51	506 613.55	36 293 268.05	1 754 299.74
12	0	323 582.30	39 217 100.96	35 786 654.51	506 613.55	36 293 268.05	1 754 299.74
13	0	323 582.30	39 217 100.96	35 786 654.51	506 613.55	36 293 268.05	1 754 299.74
14	0	323 582.30	39 217 100.96	35 786 654.51	506 613.55	36 293 268.05	1 754 299.74
15	4 216 531.69	323 582.30	39 217 100.96	35 786 654.51	506 613.55	36 293 268.05	1 754 299.74
16	0	323 582.30	39 217 100.96	35 786 654.51	506 613.55	36 293 268.05	1 754 299.74
17	0	323 582.30	39 217 100.96	35 786 654.51	506 613.55	36 293 268.05	1 754 299.74
18	0	323 582.30	39 217 100.96	35 786 654.51	506 613.55	36 293 268.05	1 754 299.74
19	0	323 582.30	39 217 100.96	35 786 654.51	506 613.55	36 293 268.05	1 754 299.74
20	-3 811 021.13	323 582.30	39 217 100.96	35 786 654.51	506 613.55	36 293 268.05	1 754 299.74

YEAR	CASH FLOW (€)	RESIDUAL VALUE (€)	DISCOUNT FACTOR	DISCOUNTED CASH FLOW (€)	CUMULATIVE DISCOUNTED CASH FLOW (€)	DISCOUNTED RESIDUAL VALUE (€)	NET DISCOUNTED VALUE (€)
0	-7 471 646.05	6 471 646.05	1.000	-7 471 646.05	-7 471 646.05	6 471 646.05	0
1	1 937 330.99	5 965 032.51	0.962	1 862 818.26	-5 608 827.80	5 735 608.18	1 088 318.84
2	1 937 330.99	5 458 418.96	0.925	1 791 171.40	-3 817 656.39	5 046 615.16	2 153 514.98
3	1 937 330.99	4 951 805.41	0.889	1 722 280.19	-2 095 376.20	4 402 136.98	3 195 757.13
4	1 937 330.99	4 445 191.86	0.855	1 656 038.65	-439 337.55	3 799 768.63	4 215 235.27
5	1 937 330.99	3 938 578.31	0.822	1 592 344.85	1 153 007.30	3 237 224.27	5 212 158.68
6	1 937 330.99	3 431 964.76	0.790	1 531 100.82	2 684 108.12	2 712 331.60	6 186 754.25
7	1 937 330.99	2 925 351.21	0.760	1 472 212.33	4 156 320.45	2 223 026.50	7 139 264.76
8	1 937 330.99	2 418 737.66	0.731	1 415 588.78	5 571 909.23	1 767 347.92	8 069 947.35
9	1 937 330.99	1 912 124.11	0.703	1 361 143.05	6 933 052.28	1 343 433.04	8 979 072.06
10	-317 783.37	3 660 624.93	0.676	-214 683.06	6 718 369.22	2 472 987.04	9 866 920.43
11	1 937 330.99	3 154 011.38	0.650	1 258 453.27	7 976 822.49	2 048 785.65	10 675 189.07
12	1 937 330.99	2 647 397.83	0.625	1 210 051.22	9 186 873.71	1 653 556.87	11 465 027.63
13	1 937 330.99	2 140 784.28	0.601	1 163 510.79	10 350 384.50	1 285 699.56	12 236 658.15
14	1 937 330.99	1 634 170.73	0.577	1 118 760.37	11 469 144.87	943 692.88	12 990 312.83
15	-2 279 200.70	5 344 088.87	0.555	-1 265 559.25	10 203 585.62	2 967 382.85	13 726 232.98
16	1 937 330.99	4 837 475.32	0.534	1 034 356.85	11 237 942.48	2 582 767.63	14 354 618.28
17	1 937 330.99	4 330 861.78	0.513	994 573.90	12 232 516.38	2 223 348.57	14 969 238.19
18	1 937 330.99	3 824 248.23	0.494	956 321.06	13 188 837.43	1 887 756.47	15 570 222.02
19	1 937 330.99	3 317 634.68	0.475	919 539.48	14 108 376.91	1 574 690.17	16 157 709.50
20	5 748 352.12	2 811 021.13	0.456	2 623 472.87	16 731 849.78	1 282 913.35	16 731 849.78

Schedule (PEM)

YEAR	INVESTMENT COST (€)	MAINTENANCE COST (€)	OPERATING GAIN (€)	OPERATING EXPENSE (€)	DEPRECIATION (€)	OPERATING COST (€)	NET INCOME (€)
0	8 662 866.70	0	0	0	0	0	0
1	0	383 143.33	39 217 101.29	35 786 654.81	697 633.20	36 484 288.00	1 639 687.97
2	0	383 143.33	39 217 101.29	35 786 654.81	697 633.20	36 484 288.00	1 639 687.97
3	0	383 143.33	39 217 101.29	35 786 654.81	697 633.20	36 484 288.00	1 639 687.97
4	0	383 143.33	39 217 101.29	35 786 654.81	697 633.20	36 484 288.00	1 639 687.97
5	0	383 143.33	39 217 101.29	35 786 654.81	697 633.20	36 484 288.00	1 639 687.97
6	0	383 143.33	39 217 101.29	35 786 654.81	697 633.20	36 484 288.00	1 639 687.97
7	0	383 143.33	39 217 101.29	35 786 654.81	697 633.20	36 484 288.00	1 639 687.97
8	0	383 143.33	39 217 101.29	35 786 654.81	697 633.20	36 484 288.00	1 639 687.97
9	0	383 143.33	39 217 101.29	35 786 654.81	697 633.20	36 484 288.00	1 639 687.97
10	5 603 262.52	383 143.33	39 217 101.29	35 786 654.81	697 633.20	36 484 288.00	1 639 687.97
11	0	383 143.33	39 217 101.29	35 786 654.81	697 633.20	36 484 288.00	1 639 687.97
12	0	383 143.33	39 217 101.29	35 786 654.81	697 633.20	36 484 288.00	1 639 687.97
13	0	383 143.33	39 217 101.29	35 786 654.81	697 633.20	36 484 288.00	1 639 687.97
14	0	383 143.33	39 217 101.29	35 786 654.81	697 633.20	36 484 288.00	1 639 687.97
15	2 059 604.18	383 143.33	39 217 101.29	35 786 654.81	697 633.20	36 484 288.00	1 639 687.97
16	0	383 143.33	39 217 101.29	35 786 654.81	697 633.20	36 484 288.00	1 639 687.97
17	0	383 143.33	39 217 101.29	35 786 654.81	697 633.20	36 484 288.00	1 639 687.97
18	0	383 143.33	39 217 101.29	35 786 654.81	697 633.20	36 484 288.00	1 639 687.97
19	0	383 143.33	39 217 101.29	35 786 654.81	697 633.20	36 484 288.00	1 639 687.97
20	-2 373 069.46	383 143.33	39 217 101.29	35 786 654.81	697 633.20	36 484 288.00	1 639 687.97

YEAR	CASH FLOW (€)	RESIDUAL VALUE (€)	DISCOUNT FACTOR	DISCOUNTED CASH FLOW (€)	CUMULATIVE DISCOUNTED CASH FLOW (€)	DISCOUNTED RESIDUAL VALUE (€)	NET DISCOUNTED VALUE (€)
0	-8 662 866.70	7 662 866.70	1.000	-8 662 866.70	-8 662 866.70	7 662 866.70	0
1	1 954 177.83	6 965 233.50	0.962	1 879 017.15	-6 783 849.55	6 697 339.91	875 028.81
2	1 954 177.83	6 267 600.31	0.925	1 806 747.26	-4 977 102.30	5 794 748.80	1 742 202.72
3	1 954 177.83	5 569 967.11	0.889	1 737 256.98	-3 239 845.32	4 951 680.48	2 600 831.51
4	1 954 177.83	4 872 333.91	0.855	1 670 439.40	-1 569 405.92	4 164 891.45	3 450 289.72
5	1 954 177.83	4 174 700.71	0.822	1 606 191.73	36 785.81	3 431 299.68	4 290 012.60
6	1 954 177.83	3 477 067.52	0.790	1 544 415.13	1 581 200.94	2 747 976.97	5 119 492.43
7	1 954 177.83	2 779 434.32	0.760	1 485 014.54	3 066 215.48	2 112 141.65	5 938 274.94
8	1 954 177.83	2 081 801.12	0.731	1 427 898.60	4 494 114.08	1 521 151.69	6 745 955.97
9	1 954 177.83	1 384 167.92	0.703	1 372 979.42	5 867 093.50	972 498.02	7 542 178.26
10	-3 649 084.68	6 289 797.24	0.676	-2 465 190.86	3 401 902.64	4 249 161.65	8 326 628.46
11	1 954 177.83	5 592 164.05	0.650	1 269 396.66	4 671 299.30	3 632 563.13	8 953 443.36
12	1 954 177.83	4 894 530.85	0.625	1 220 573.71	5 891 873.00	3 057 109.53	9 573 579.58
13	1 954 177.83	4 196 897.65	0.601	1 173 628.57	7 065 501.57	2 520 547.97	10 186 623.63
14	1 954 177.83	3 499 264.46	0.577	1 128 489.01	8 193 990.58	2 020 738.03	10 792 203.69
15	-105 426.35	4 861 235.44	0.555	-58 539.51	8 135 451.06	2 699 271.48	11 389 987.05
16	1 954 177.83	4 163 602.24	0.534	1 043 351.52	9 178 802.59	2 222 981.28	11 935 692.04
17	1 954 177.83	3 465 969.05	0.513	1 003 222.62	10 182 025.20	1 779 335.78	12 474 734.23
18	1 954 177.83	2 768 335.85	0.494	964 637.13	11 146 662.33	1 366 528.42	13 006 818.88
19	1 954 177.83	2 070 702.65	0.475	927 535.70	12 074 198.04	982 843.33	13 531 683.79
20	4 327 247.29	1 373 069.46	0.456	1 974 899.17	14 049 097.21	626 650.98	14 049 097.21

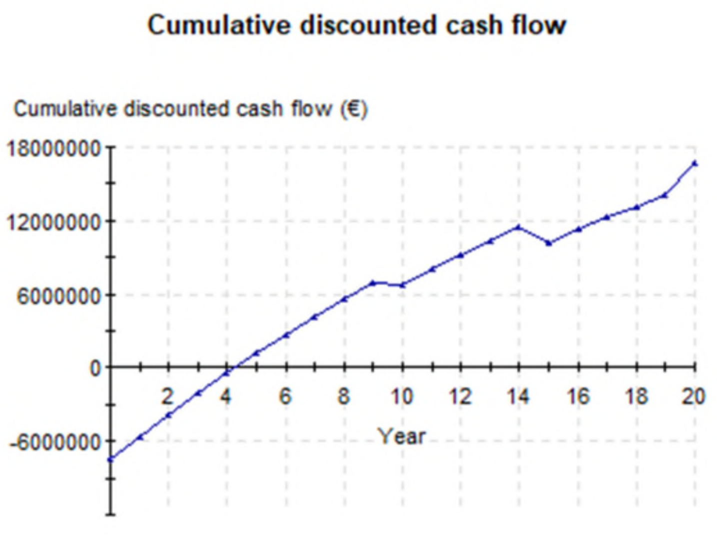
4.7. Profiles supplied by the economic evaluation unit operation

The economic evaluation unit operation supplies the following profiles:

- cumulative discounted cash flow function of time
- net discounted cash flow function of time
- discounted residual value of the process function of time
- cumulative discounted cash flow function of discount rate

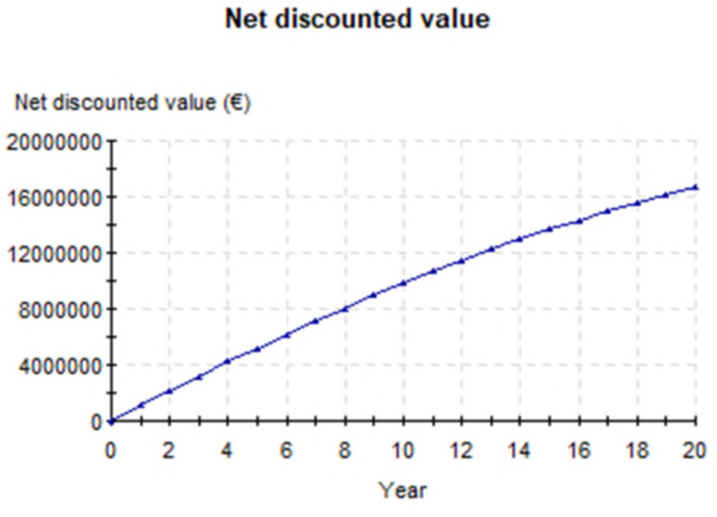
The following shows the profiles obtained in the example with the FMM and the PEM.

Profiles obtained with the FMM:

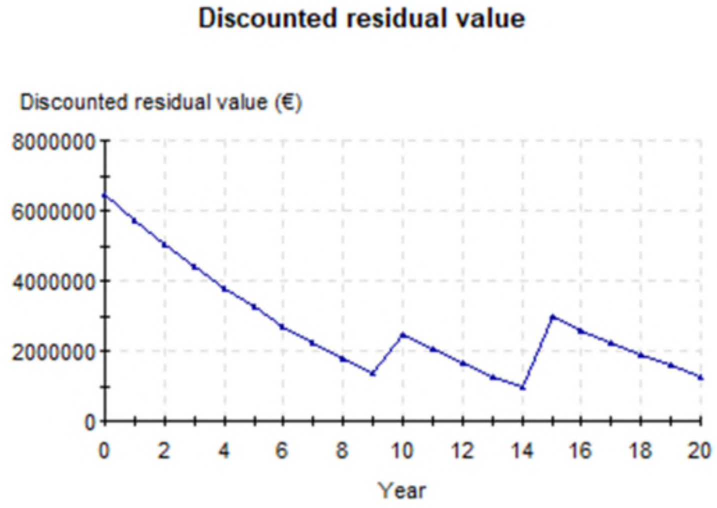


Cumulative discounted cash flow vs. Time

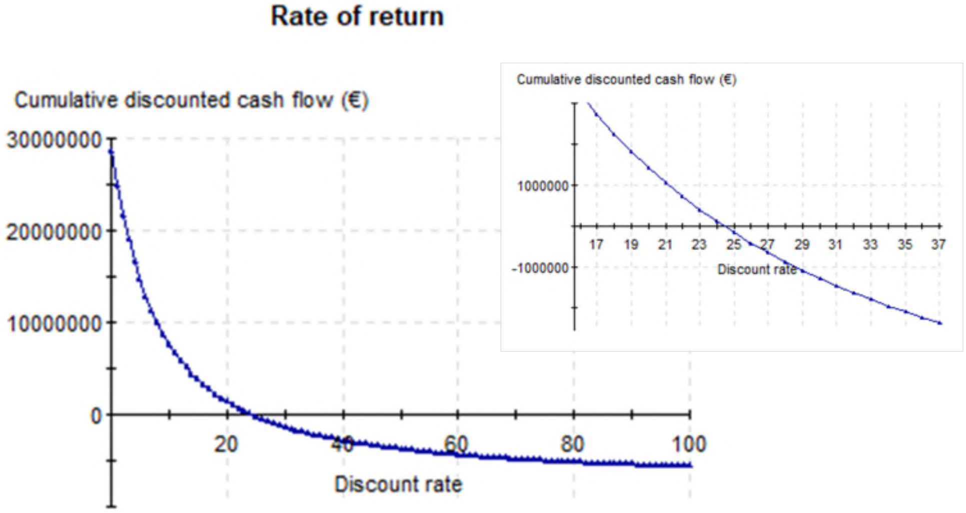
On this curve, we can remark that the payout time (time when the cumulative discounted cash flow becomes positive) is around 4.5 years.



Net discounted value vs. Time



Discounted residual value vs.Time

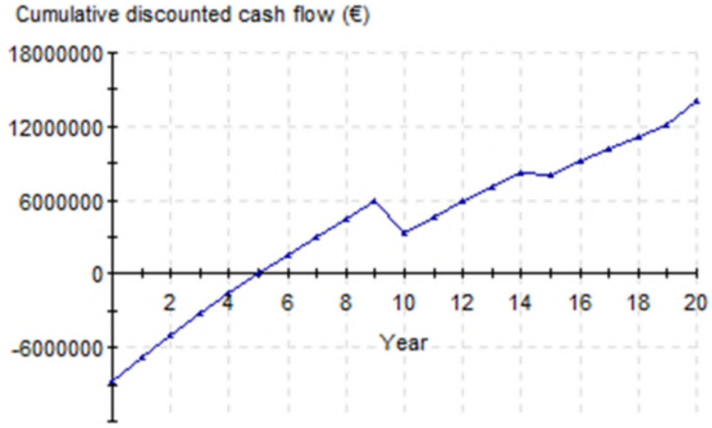


Cumulative discounted cash flow vs. Discount rate

On this last curve, we can notice that the rate of return (discount rate for which the cumulative discounted cash flow at the end of the time horizon is null) is around 25%.

Profiles obtained with the PEM:

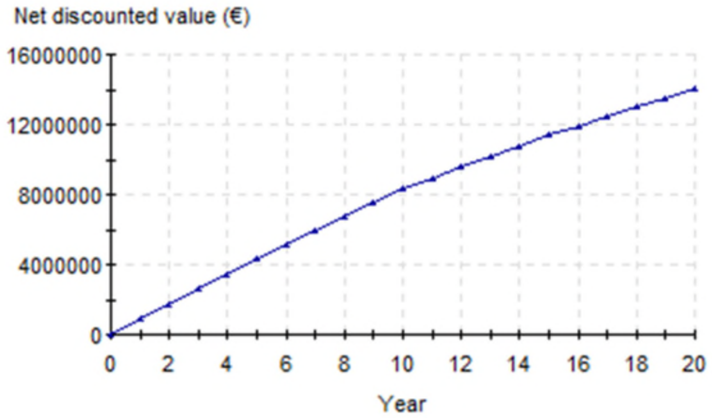
Cumulative discounted cash flow



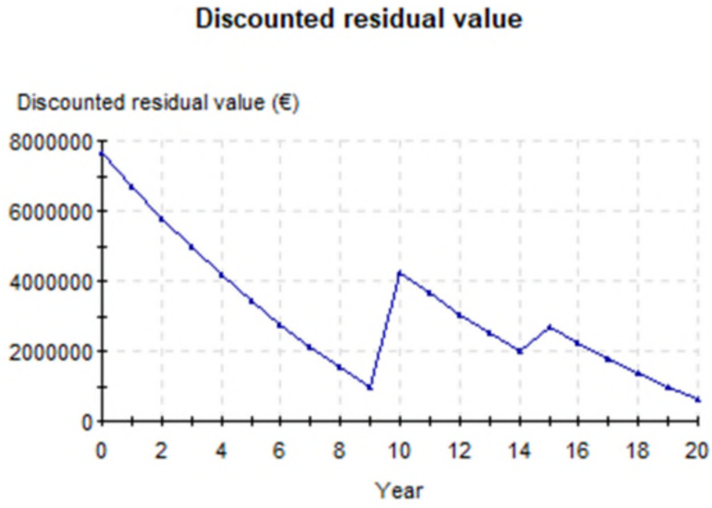
Cumulative discounted cash flow vs. Time

On this curve, we can remark that the payout time is around 5 years.

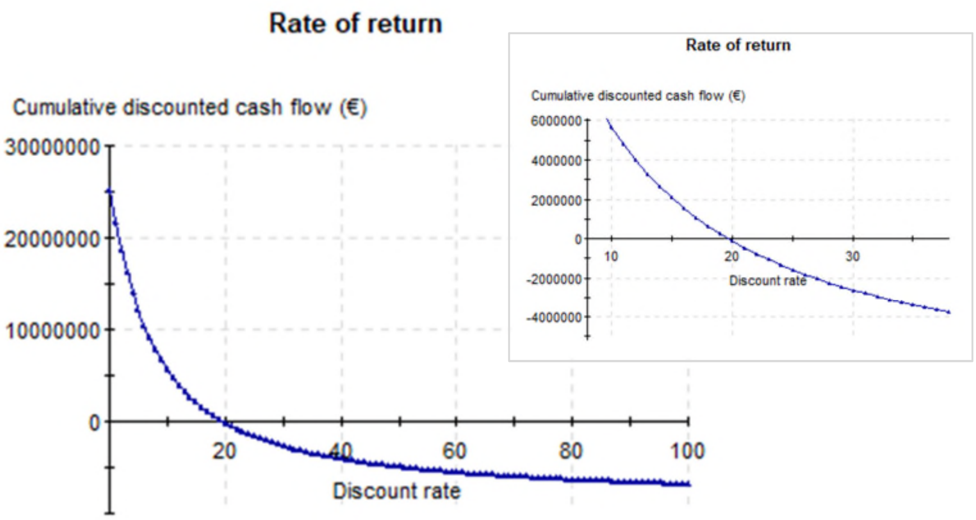
Net discounted value



Net discounted value vs. Time



Discounted residual value vs.Time



Cumulative discounted cash flow vs. Discount rate

On this last curve, we can remark that the rate of return is around 20%.

4.8. Summary of the economic evaluation results

The economic evaluation unit supplies a global economic balance of the process that summarizes the different results previously described.

The results obtained using the FMM are:

Initial investment cost	=	7 471 646.05	(€)
Total secondary investment cost	=	3 864 764.83	(€)
Residual value at the time horizon	=	1 282 913.35	(€)
Maintenance cost	=	323 582.30	(€/YR)
Operating balance	=	3 430 446.45	(€/YR)
Operating gain	=	39 217 100.96	(€/YR)
Products	=	39 217 100.96	(€/YR)
Remunerative inputs	=	0.00	(€/YR)
Produced electricity	=	0.00	(€/YR)
Operating expense	=	35 786 654.51	(€/YR)
Raw materials	=	30 231 874.86	(€/YR)
Utilities	=	5 425 452.18	(€/YR)
Consumed electricity	=	129 327.46	(€/YR)
Waste (reprocessing)	=	0.00	(€/YR)
Pay out time	=	4.28	(AN)
Rate of return	=	24.41	(%)

The results obtained using the PEM are:

Initial investment cost	=	8 662 866.70	(€)
Total secondary investment cost	=	4 928 988.48	(€)
Residual value at the time horizon	=	626 650.98	(€)
Maintenance cost	=	383 143.33	(€/YR)
Operating balance	=	3 430 446.48	(€/YR)
Operating gain	=	39 217 101.29	(€/YR)
Products	=	39 217 101.29	(€/YR)
Remunerative inputs	=	0.00	(€/YR)
Produced electricity	=	0.00	(€/YR)
Operating expense	=	35 786 654.81	(€/YR)
Raw materials	=	30 231 875.12	(€/YR)
Utilities	=	5 425 452.22	(€/YR)
Consumed electricity	=	129 327.46	(€/YR)
Waste (reprocessing)	=	0.00	(€/YR)
Pay out time	=	4.98	(AN)
Rate of return	=	19.65	(%)

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