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Simulation Driven Decision Framework for Heat Exchanger Retrofits: A Case Study of a Multi Pass Naphtha Cooler

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***Abstract*: A modular decision framework that integrates process simulation, fouling uncertainty quantification, and lifecycle economics is presented for prioritizing heat exchanger retrofits in petrochemical plants. A multi pass shell and tube cooler used to cool a C_6–C_{12} naphtha stream was modelled in Aspen HYSYS Exchanger Design and Rating and optimized over tube count, baffle spacing, and cooling water flow to minimize total annual cost subject to hydraulic and mechanical constraints. Fouling was modelled with a combined resistance and a Monte Carlo ±5% sampling quantified economic sensitivity. The optimized retrofit (220 tubes, 0.45 m baffle spacing, 28,000 kg·hr⁻¹ cooling water) increased heat duty from 2,205 kW to 3,150 kW (+42.7%), raised LMTD from 42.3 °C to 58.1 °C (+37.4%), and reduced shell and tube side pressure drops to 0.70 bar and 1.00 bar, respectively. Despite a 6.8% CapEx increase, TAC fell by 10.2% to $115,000/yr, yielding a 2.1 year payback under base economic assumptions. Fouling uncertainty produced a TAC sensitivity of ≈4.8%, shifting payback by ±0.3 years. The framework is transferable across plant exchanger inventories and supports data driven retrofit prioritization.**

***Keywords*: Retrofit, heat exchanger, total annual cost, payback, naphtha cooling, fouling uncertainty.**

1. Introduction

Heat exchangers are central to energy management in petrochemical plants. Many installed shell-and-tube units were designed for historical process conditions and now operate sub-optimally due to fouling, conservative sizing, or mismatched operating regimes. Retrofitting existing exchangers can deliver rapid energy and cost savings, but plant decision makers require a reproducible method that links technical performance, operational risk, and lifecycle economics.

This paper presents a practical decision framework that couples steady-state process simulation, constrained optimization, fouling uncertainty quantification, and lifecycle costing. The framework is demonstrated on a multi-pass shell-and-tube naphtha cooler typical of petrochemical service. The study focuses on three retrofit levers—tube count, baffle spacing, and cooling-water flow—and quantifies trade-offs among heat duty, pressure drop, fouling risk, and economics.

2. Methods

A. Case Definition and Baseline Data

System description: shell-and-tube, multi-pass exchanger cooling a C_6–C_{12} naphtha stream with water. Baseline geometry: 200 tubes; shell diameter 0.50 m; four tube passes.

Baseline performance:
heat duty $Q = 2{,}205$ kW;
LMTD = 42.3 °C;
Overall $U \approx$ 450–500 $\mathrm{W \cdot m^{-2} \cdot K^{-1}}$;
Shell ΔP = 0.80 bar;
Tube ΔP = 1.20 bar.

B. Simulation and Thermal Method

Software: Aspen HYSYS Exchanger Design and Rating.

Thermal approach: ε-NTU method to handle variable heat capacities and unknown outlet temperatures.

Fouling model: combined shell- and tube-side fouling resistance.

$$R_f = 0.0002 + 0.0001\ \mathrm{m^2 \cdot K \cdot W^{-1}}$$

C. Decision Variables and Constraints

Variables: tube count N_t(180–260), baffle spacing S_b(0.30–0.60 m), cooling-water mass flow $\dot{m}_w$(±30% baseline).

Constraints: maximum allowable shell and tube pressure drops, mechanical compatibility with existing shell, and utility capacity limits.

D. Optimization and Economic Model

Optimizer: Constrained non-linear optimization using Sequential Quadratic Programming style.

Objective: minimize total annual cost

TAC = annualized CapEx + annual OpEx.

Annualized CapEx computed via capital recovery factor. OpEx includes pumping energy and incremental utility costs. Economic assumptions are summarized in Table 3.

E. Uncertainty and Scenario Analysis

Fouling uncertainty: Monte Carlo sampling of combined fouling resistance ±5% around nominal; 1,000 samples.

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Operational scenarios: base 8,000 h/yr, low-use 4,000 h/yr, high-use 10,000 h/yr. Anti-fouling scenarios model additional CapEx for coatings or cleaning that reduce fouling by 10–25%.

F. Validation

Thermal and hydraulic outputs were benchmarked against TEMA guidance and literature ranges for hydrocarbon–water service to ensure plausibility.

3. Results – Base Performance

Table 1
Baseline performance

Metric	Value	Units
Heat duty	2205	kW
LMTD	42.3	C
Overall U	450-500	W/m2/K
Shell dP	0.80	bar
Tube dP	1.20	bar
TAC	128000	USD/yr

Source: Aspen Hysys v14

A. Optimized Retrofit

Optimization converged to$N_t = 220$, $S_b = 0.45$ m, $\dot{m}_w = 28{,}000$ kg\cdotphr^{-1}.

Key outcomes: $Q = 3{,}150$ kW (+42.7%), LMTD = 58.1 °C (+37.4%), shell/tube ΔP = 0.70/1.00 bar, CapEx +6.8%, TAC = \$115,000/yr (−10.2%), payback = 2.1 years.

Table 2
Optimized performance

Metric	Value	Units
Tube count	220	-
Baffle spacing	0.45	m
Cooling-water flow	28000	kg/hr
Heat duty	3150	kW
LMTD	58.1	C
Shell dP	0.70	bar
Tube dP	1.00	bar
CapEx change	6.8	percent
TAC	115000	USD/yr
Payback	2.1	yr

Source: Aspen Hysys v14

B. Fouling Uncertainty and Sensitivity

Monte Carlo ±5% fouling sampling produced TAC distribution with standard deviation ≈ 4.8% of optimized TAC. Payback varied by approximately ±0.3 years. Tornado analysis identified fouling resistance and cooling-water flow as dominant TAC drivers.

C. Scenario Analysis

Low-use (4,000 h/yr) payback ≈ 4.8 years; high-use (10,000 h/yr) payback ≈ 1.6 years. Anti-fouling CapEx reducing fouling by 10% shortens payback by ≈0.4 years under base hours; 25% reduction yields payback <1.5 years in high-use scenarios.

D. Validation Checks

Predicted $U$and ΔP values align with TEMA Class B ranges for hydrocarbon–water service. Mechanical compatibility with the existing shell was confirmed for the recommended tube count and baffle spacing.

4. Discussion

A. Technical Interpretation

Increasing tube count increased heat-transfer area and improved velocity distribution. Reduced baffle spacing increased crossflow and LMTD without excessive shell-side pressure penalty. Increased cooling-water flow improved convective coefficients on the water side, driving the large heat-duty increase.

B. Economic Interpretation

Modest CapEx increase is offset by improved heat recovery and lower pumping energy per unit heat removed. Short payback under continuous operation supports prioritizing such retrofits for high-hour exchangers.

Table 3
Economics

Parameter	Value	Units
Discount rate	10	percent
Equipment life	10	yr
Electricity price	0.12	USD/kWh
Operating hours base	8000	hr/yr
Operating hours low	4000	hr/yr
Operating hours high	10000	hr/yr

Source: Aspen Hysys v14

C. Fouling Management Implications

Fouling uncertainty materially affects TAC and payback. Quantitative Monte Carlo results justify anti-fouling investments when operating hours and utility costs make the incremental CapEx recoverable.

Table 4
Monte carlo

Statistic	Value	Units
TAC mean	115000	USD/yr
TAC std	5520	USD/yr
TAC 5th	106000	USD/yr
TAC 95th	124500	USD/yr
Samples	1000	-

Source: Aspen Hysys v14

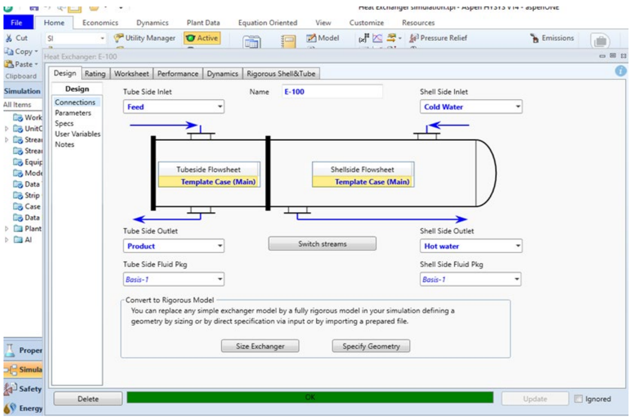
Table 5
Antifouling

Fouling reduction	Additional CapEx	Payback change (yr)
10%	2000	0.4
25%	5000	0.9

Source: Aspen Hysys v14

D. Framework Applicability and Limitations

The framework is modular and transferable across exchanger inventories. Limitations include steady-state modelling (no fouling growth dynamics), site-specific cost uncertainty, and assumptions about feasible mechanical modifications. Prior to execution, vendor quotes and transient fouling studies are recommended.



Tube Side Inlet: Feed

Name: E-100

Shell Side Inlet: Cold Water

Tube Side Outlet: Product

Shell Side Outlet: Hot water

Tube Side Fluid Pkg: Basis-1

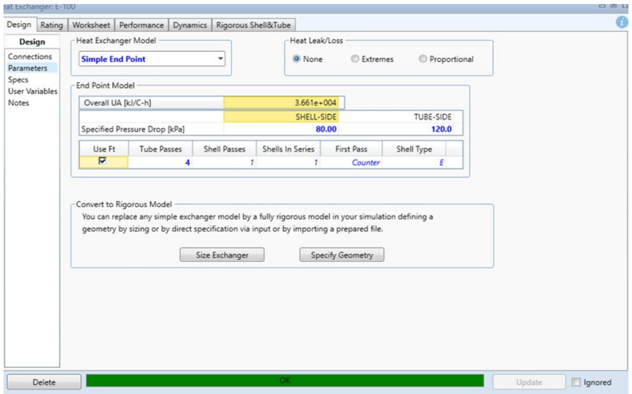
Shell Side Fluid Pkg: Basis-1

Convert to Rigorous Model

You can replace any simple exchanger model by a fully rigorous model in your simulation defining a geometry by sizing or by direct specification via input or by importing a prepared file.

☐ Ignored

Fig. 1. Process schematic — Shell and tube naphtha cooler process schematic showing naphtha feed, tube passes and cooling water flow
(source: Aspen Hysys v14)



Heat Exchanger Model: Simple End Point

Heat Leak/Loss: ● None ○ Extremes ○ Proportional

End Point Model

	SHELL-SIDE	TUBE-SIDE
Overall UA [kJ/C-h]	3.661e+004	
Specified Pressure Drop [kPa]	80.00	120.0

Use Ft	Tube Passes	Shell Passes	Shells In Series	First Pass	Shell Type
☑	4	1	1	Counter	E

Convert to Rigorous Model

You can replace any simple exchanger model by a fully rigorous model in your simulation defining a geometry by sizing or by direct specification via input or by importing a prepared file.

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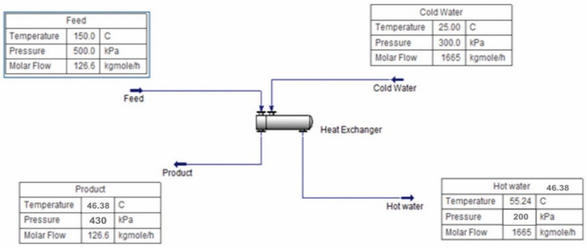
Fig. 2. Workflow diagram — Simulation–optimizer–economic workflow used to generate retrofit recommendations
(source: Aspen Hysys v14)



Feed		
Temperature	150.0	C
Pressure	500.0	kPa
Molar Flow	126.6	kgmole/h

Cold Water		
Temperature	25.00	C
Pressure	300.0	kPa
Molar Flow	1665	kgmole/h

Product		
Temperature	46.38	C
Pressure	430	kPa
Molar Flow	126.6	kgmole/h

Hot water	46.38	
Temperature	55.24	C
Pressure	200	kPa
Molar Flow	1665	kgmole/h

Fig. 3. Simulated case after optimization
(source: Aspen Hysys v14)

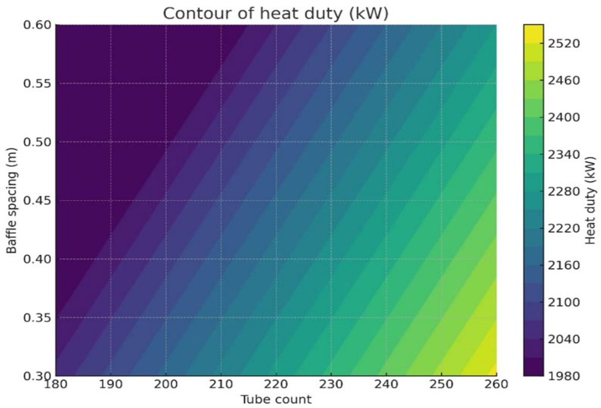


Fig. 4. Visualization - Contour plot of heat duty (kW) as a function of tube count and baffle spacing at fixed cooling water flow

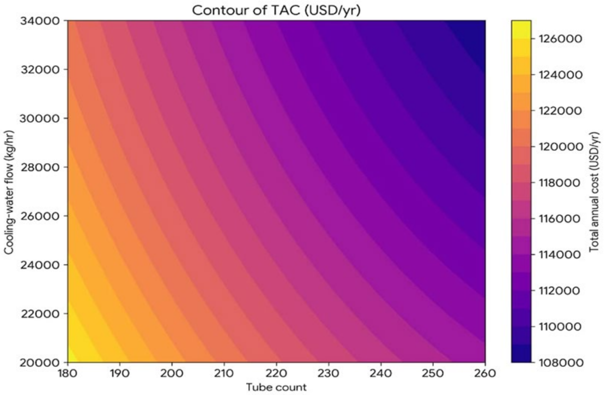


Fig. 5. Contour TAC Visualization — Contour plot of total annual cost ($/yr) as a function of tube count and cooling water flow

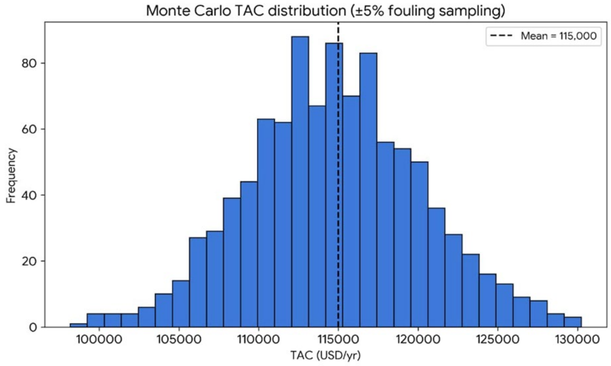


Fig. 6. Monte Carlo TAC histogram Visualization — Distribution of TAC outcomes from Monte Carlo ±5% fouling sampling for the optimized design

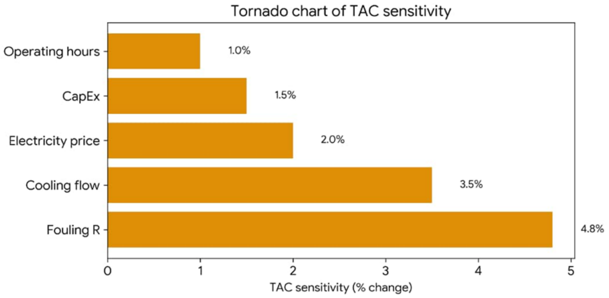


Fig. 7. Tornado sensitivity chart Visualization — Sensitivity of TAC to fouling resistance, cooling water flow, and electricity price

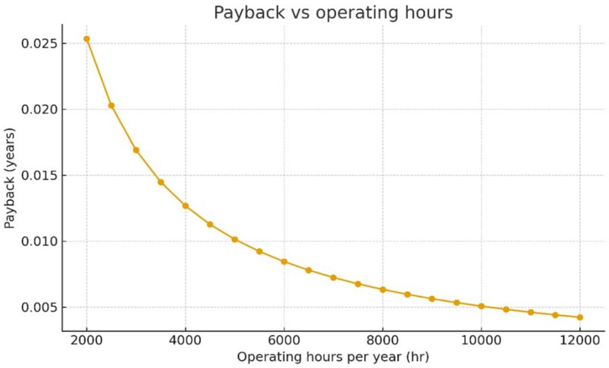


Fig. 8. Payback vs Operating hours Visualization — Payback period as a function of annual operating hours for baseline, optimized, and anti-fouling scenarios

5. Conclusion

A simulation-driven decision framework that integrates fouling uncertainty and lifecycle economics enables robust prioritization of heat-exchanger retrofits. For the studied naphtha cooler, the recommended retrofit increased heat duty by 42.7%, reduced TAC by 10.2%, and achieved a 2.1-year payback. Fouling uncertainty is a key economic risk and should be explicitly modelled.

6. Recommendations

This framework can be applied to plant exchanger inventories, obtain vendor quotes before execution, implement post-retrofit fouling monitoring, and extend the framework to transient fouling models.

Nomenclature

Q - Heat duty kW
LMTD - Log mean temperature difference °C
U - Overall heat-transfer coefficient $W\cdot m^{-2}\cdot K^{-1}$
ΔP - Pressure drop bar
Nt - Tube count –
Sb - Baffle spacing m
$\dot{m}w$ - Cooling-water mass flow $kg\cdot hr^{-1}$
TAC - Total annual cost $/yr

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