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Area-Based Retrofit and Operational Optimization of Existing Crude Oil Heat Exchanger Networks

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Retrofit and operational optimization projects are frequently implemented in crude oil heat exchanger networks (HENs) to reduce operating costs. However, it is a challenge to optimize these HENs because of their complexity and the many practical constraints to be considered (e.g. plant layout, installed area, limited budget, pressure drop limitations).
This work presents an optimization approach for industrial crude oil preheat HENs. The approach identifies the retrofit modifications and/or operating conditions that minimize operating and retrofit capital costs. Retrofit modifications considered include adding, deleting and relocating an exchanger, and adding and deleting a stream splitter. Operational optimization variables include stream split fractions and heat transfer area.
The main feature of this practical approach is the specification of heat exchangers in terms of heat transfer area. With area-based models, it is easier to monitor and constrain the heat transfer area of individual exchangers during optimization, compared to duty-based models. Furthermore, this consideration significantly simplifies the optimization, while capturing the details of the existing HEN. Temperature-dependent heat capacities are also considered. Practical constraints are implemented to ensure that industrially-relevant solutions can be achieved. These constraints include existing heat transfer area, maximum number of modifications, and forbidden relocations and matches. A case study on an industrial HEN demonstrates how the approach identifies opportunities to reduce energy consumption with minimal structural modifications.

1. Introduction

The configuration of crude oil preheat trains is very complex. Installations can range from, for example, networks with 20 exchangers and 10 process streams to installations with more than 60 exchangers and 30 process streams intricately interconnected. Moreover, when attempting to improve the energy performance of these HENs, one must also consider the practical constraints related to the existing design, such as space and budget available for structural modifications, installed heat transfer area, pressure drop restrictions, acceptable inlet and outlet temperatures to the distillation units, etc. The complexity of these HENs and the considerable economic savings that can be accomplished when implementing retrofit and operational optimization projects motivate the development of methodologies aimed at increasing energy recovery with minimal capital investment.
Various approaches have been developed over the years to optimize heat exchanger networks. These approaches can be classified into methodologies that employ pinch analysis (e.g. Varga and Danics, 2013), methodologies that employ optimization algorithms, and methodologies that combine both. Typically, optimization-based approaches either use a pre-formulated HEN superstructure and apply deterministic optimization (e.g. Koraviyotin and Siemanond, 2015), or perform a stochastic search of HEN configurations (e.g. Smith et al., 2010). Here, deterministic optimization refers to algorithms that use gradients to find optimal solutions, while stochastic search refers to applying optimization algorithms that use random numbers to find optimal solutions. Recent developments (Smith et al., 2010) account for temperature-dependence of fluid thermal properties, but generally the dependence of heat transfer coefficients on flow rate is neglected.

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Each of these HEN optimization approaches has advantages and limitations that should be considered in retrofit or operational optimization studies. It is a challenge to develop and apply optimization approaches that can accurately model crude oil HENs, accommodate the considerable number of practical constraints involved in the existing design and find acceptable solutions in reasonable computation times. Stochastic optimization offers advantages over deterministic optimization when dealing with highly combinatorial problems such as the retrofit of crude oil HENs (Dolan et al., 1989). Another benefit is that stochastic optimization is able to escape local optima due to the random search. On the other hand, deterministic optimization requires fewer function evaluations to find a solution and is more accurate than stochastic optimization (Cavazzuti, 2013). These features of deterministic optimization are particularly useful when performing operational optimization.

This work presents a methodology that employs both stochastic and deterministic optimization, where appropriate, to optimize existing crude oil heat exchanger networks. The methodology is suitable for retrofit and operational optimization. The proposed approach extends the work of Ochoa-Estopier et al. (2015) to explicitly consider installed and additional heat transfer areas as optimization variables. Thus, practical constraints related to heat transfer area (e.g. lower and upper bounds on additional heat transfer area, plant layout restrictions, etc.) can be captured and implemented more easily than in duty-based HEN models. New types of splitters and mixers are also introduced in this work. The new mixer model allows two streams that enter the HEN to be mixed and leave the HEN as a single stream. In the new splitter, a single process stream that enters the HEN can leave the HEN as two separate process streams. These new mixing and splitting models have been developed to account for configurations applied in practice in petroleum refineries.

All the above new features facilitate a more realistic representation of the existing HEN, help to find practicable solutions and simplify the formulation of the optimization problem. Other extensions of the approach of Ochoa-Estopier et al. (2015) include the reformulation of the retrofit algorithm to better identify additional area requirements and to model the dependence of heat transfer coefficients on flow rates.

2. Methodology

The methodology presented in this work is based on the approach of Ochoa-Estopier et al. (2015). This methodology is formulated as a two-level optimization problem. In the first level, a retrofit algorithm performs random structural modifications to the HEN. Then the modified HEN is passed to the second level, where a 'repair' algorithm ensures that HEN constraints are met (e.g. stream enthalpy balances, minimum approach temperatures). To assess any violation of constraints and to calculate operating and capital costs, a HEN simulation model is employed. Changes to the operating conditions of the distillation units can also be considered in Level 1 of the methodology (Ochoa-Estopier and Jobson, 2015), as illustrated in Section 3.

The first level of the methodology employs stochastic optimization, namely simulated annealing (SA), to select and accept/reject HEN structural modifications. The second level employs deterministic optimization, namely the interior-point method, to calculate heat transfer areas and split fractions that meet HEN constraints and minimize energy consumption. A flowchart of the methodology presented in this work is shown in Figure 1. This methodology can be applied for retrofit and operational optimization. HEN stream information (e.g. supply and target temperatures, heat capacities, mass flow rates) can also be updated in Level 1 of the methodology. For example, stream information changes if the operating conditions of the distillation units are modified, as is the case when the distillation units and HEN are optimized together (Section 3).

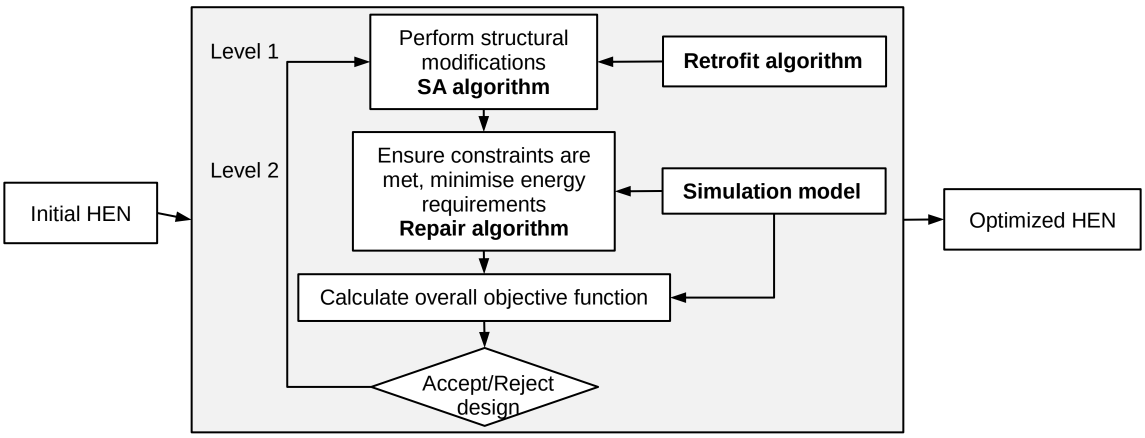

Figure 1: Two-level HEN optimization framework used in this work.

2.1 Simulation model

The simulation model used in this work calculates the outlet temperatures and mass flow rates of each heat exchanger, splitter, mixer and simple unit operation for a HEN with fixed structure and specifications (e.g. stream supply temperatures, heat capacities, heat transfer area, split fractions). This simulation model is used to check whether constraints are met and to calculate the overall objective function (e.g. utility consumption, total annualized costs) to be minimized, as shown in Figure 1.

The main feature of this simulation model is that exchangers are specified in terms of heat transfer area (instead of heat loads), which facilitates the monitoring and control of heat transfer area requirements during optimization. Another important feature of the simulation model used in this work is the consideration of temperature-dependent heat capacities.

Mass and energy balances are solved to calculate HEN temperatures and flow rates. In this model, the mass and energy balance equations are formulated based on the matrix approach of de Oliveira Filho et al. (2007). This matrix approach is extended in this work to consider:

- *New type of stream splitters and mixers*. These HEN elements are illustrated in Figure 2(a), namely mixer M1 and splitter S1. Mixer M1 mixes streams from the distillation process H1 and H2 into a single stream. This type of mixer accounts for when two distillation products (e.g. diesel and gas oil) are combined into a single product stream that further exchanges heat in the HEN, as shown in Figure 2(b). In this example, the exchanger minimum approach temperature (EMAT) of exchanger 3b is below the acceptable value $EMAT_{min}$ due to the poor representation of installed exchanger 3. The optimizer then unnecessarily attempts to reach an acceptable EMAT value for exchanger 3b, so as to meet constraints. Furthermore, heat transfer areas, outlet temperatures and potential retrofit modifications for exchanger 3 cannot be accurately represented using a model that treats the single exchanger 3 as two heat exchangers (3a and 3b).

  On the other hand, splitter S1 in Figure 2(a), divides process stream C2 into two streams that can have different target temperatures. Examples of this type of splitter can be typically found in the vacuum distillation unit, when a single stream is drawn from a stage, cooled down, and then divided into a distillation product and a recirculation stream (pump-around) for further cooling to two different target temperatures. The implementation of these new types of splitters and mixers in the simulation model also reduces the number of variables and constraints to be handled during optimization, which decreases the computational burden of the optimizers.

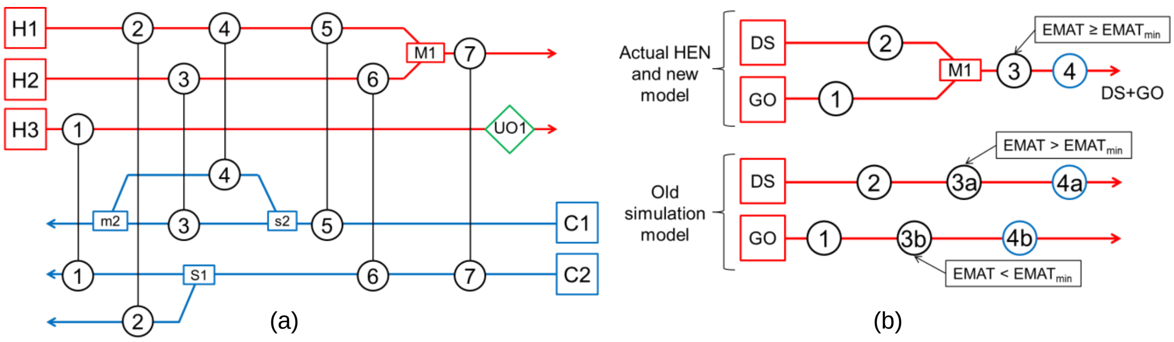

Figure 2: New types of splitters (S1) and mixers (M1) are considered in this work. s2, conventional splitter; m2, conventional mixer; UO1, simple unit operation; DS, diesel stream; GO, gas oil stream; EMAT, exchanger minimum approach temperature; $EMAT_{min}$, minimum allowed EMAT for the heat exchanger network.

- Correction of overall heat transfer coefficient, U. The simulation model is extended to represent the dependence of U on flow rate variations (Smith, 2005, Chap.15.6). Flow rates change if the splitter split fractions are modified during HEN optimization and if flow rates of process streams from the distillation unit (CDU) change when CDU and HEN are optimized together. The optimized HEN can be better represented if the dependence of U on flow rate is considered.

- Simple unit operations. Examples of simple unit operations in distillation systems include desalters and heat recovery steam generation units. This type of HEN element has already been considered by Ochoa-Estopier et al. (2015). However, in the new formulation, these unit operations can also be specified in terms of enthalpy change or temperature change. This element is identified as UO1 in Figure 2a.

2.2 Retrofit algorithm

The retrofit algorithm implements structural changes to the HEN at random potentially-feasible locations. Here, feasible refers to HEN structures that meet constraints, for example, constraints related to the maximum number of new heat exchangers and splitters in the HEN and per stream, the maximum additional heat transfer area in the HEN or per exchanger, forbidden matches and minimum approach temperatures.

Structural modifications are selected at random by the SA algorithm based on user-defined probabilities for each type of modification. The structural modifications considered are: add a new heat exchanger or splitter; remove or relocate a heat exchanger; add new area to an existing heat exchanger, remove a stream splitter and change the split fraction of a stream splitter. Similarly, the retrofit algorithm selects at random which exchanger or splitter to modify and where to place new and relocated exchangers or splitters from a list of potentially-feasible candidates and positions.

The retrofit algorithm of Ochoa-Estopier et al. (2015) is modified to use the area-based simulation model. The new retrofit algorithm easily allows or forbids additional area to be installed on each heat exchanger by using integer variables. A threshold on minimum additional area is included to avoid addition of very small areas. For example, if an exchanger is allowed to have additional area, this additional area should be greater than 50 m^2; a lower area would not be accepted as it is unlikely to be cost-effective or practical to install.

A new criterion to select candidates for the "additional area" modification type is also developed. The simulation model calculates the number of transfer units (NTU) of each exchanger. Exchangers with NTU values greater than 4 (approximately) are discarded as candidates, as increasing the area of these exchangers would not significantly increase heat transfer. The remaining exchangers are sorted according to their NTU value and installed area. Then, a probability is assigned to each exchanger according to its weighted contribution to the overall NTU and installed area values. Finally, a candidate for modification is selected at random using these probabilities. The maximum additional area for the selected exchanger is set to be the lowest number between a user-defined value and the area that renders a NTU value of 4.

2.3 Repair algorithm

The role of the repair algorithm is to reduce energy requirements and to ensure that the operational constraints of the HEN are met. The repair algorithm is formulated as an optimization problem and considers heat transfer areas and split fractions as optimization variables. The constraints included in this algorithm consider the available heat transfer area, EMAT values and stream energy balances.

The formulation of this algorithm is very similar to that of Ochoa-Estopier et al. (2015) — modifications have been made to simplify the optimization problem. The main modification is that utility heat exchangers located at the end of process streams are excluded from the optimization. However, the algorithm still checks that the excluded exchangers do not violate any constraints when the full HEN is simulated again (e.g. that target temperatures are met and EMAT values are acceptable). To make these checks, the algorithm calculates the maximum temperature change (ΔT) that the area of the excluded utility exchanger can provide on the process stream side and the corresponding temperature ($T_x = T_T - \Delta T$), which represents the bound for the end temperature of the process streams with utility exchangers excluded. Previously, the target temperature (T_T) constraint had to be considered. For the remaining process streams, the target temperature constraint is retained. Figure 3 illustrates this simplification: for stream H1, utility heat exchanger 3 is excluded from the repair algorithm. The new target temperature for this stream becomes $T_{x,1}$, instead of $T_{T,1}$. For stream H2, the target temperature remains equal to $T_{T,2}$, as this stream does not have any utility exchangers at the end.

The benefit of this formulation is that the number of optimization variables and constraints is reduced, compared to when the utility heat exchangers are included in the optimization. Weights can be added to these constraints to account for utility costs in order to minimize operating costs. The application of this feasibility solver, the retrofit algorithm and the simulation model is illustrated in the following case study.

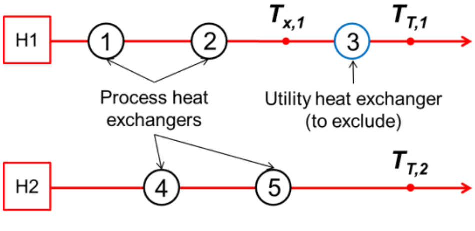

Figure 3: Example of the new features of the repair algorithm: utility exchanger 3 can be excluded from the formulation. The target temperature constraint for stream H1, $T_{T,1}$, is replaced by $T_{x,1}$.

3. Case Study

This section shows the results of a retrofit study developed for a medium-size refinery with a preflash unit (PF), an atmospheric distillation unit (ADU) and a vacuum distillation unit (VDU). However, the scope of the retrofit study only covers the PF and ADU. In this case, the streams from the VDU are not heat-integrated with PF and ADU streams, so can be studied separately. Note that this is not the case for all refineries.

The crude oil is heated by hot ADU product streams before entering a desalter. Then, the heated crude oil is fed to the flash drum, where the lightest components are separated. The crude oil is further heated before entering the furnace, where it reaches the temperature required by the ADU.

The ADU consists of 50 stages, two pump-arounds, one condenser, three side strippers and 5 distillation products. The HEN for the PF and ADU consists of 13 process-to-process heat exchangers, 6 coolers, one furnace, a heat recovery steam generation unit, 3 conventional stream splitters and one mixer (as in Figure 2b). The total installed heat transfer area is 30,000 m^2.

For this study, the desalter, PF and ADU inlet temperatures were constrained to the design values. These constraints ensure the structural integrity and operability of the equipment. Due to pressure drop constraints, the condenser stream is forbidden to have any more heat exchangers installed.

Constraints are also considered for the type and number of structural modifications that can be performed. Due to limited budget and downtime for retrofit, no more than 2 new heat exchangers are allowed, no more than 2 exchangers with additional area are permitted, and only one new splitter and one relocated exchanger are allowed. The total new area (in new and existing exchangers) should be less than 1,300 m^2.

In this case study, the CDU and HEN are optimized together, as described in Ochoa-Estopier and Jobson (2015). The proposed HEN approach is applied for retrofit and operational optimization. The objective function in both cases is to minimize the furnace duty.

For retrofit, Level 1 of the optimization algorithm (shown in Figure 1) changes the operating conditions of the CDU (pump-around duties and PF and ADU inlet temperatures), simulates the CDU to update the HEN stream information, and applies the HEN retrofit algorithm. For operational optimization, the HEN retrofit algorithm is not applied. In both cases, Level 2 of the proposed methodology is applied to minimize energy requirements and to ensure that the HEN constraints are met. Considering the CDU and HEN together creates more chances of finding cost-effective solutions, compared to optimizing the HEN alone, as the synergy between CDU and HEN is exploited.

Tables 1 and 2 show results for the retrofit and operational optimization studies. For space saving and confidentiality, sensitive client information is removed from the case data. Table 1 shows the changes of some important variables of the distillation system with respect to the base case values. Table 2 lists the retrofit modifications suggested by the optimization framework. It can be seen in Table 1 that, for both studies, the duty of Pump-around 1 is increased while the duty of Pump-around 2 is reduced. However, the total pump-around duty in both studies is practically the same as in the base case. This result concurs with sensitivity studies carried out prior to the optimization. Optimized split fractions and PF and ADU inlet temperatures are also similar in both studies. The existing heat transfer area is used fully for almost all heat exchangers and additional heat transfer area is added to the maximum extent.

Table 1: Optimization results

Description	Change compared to base case	
	Operational optimization	Retrofit
Pump-around 1 duty	+ 24 %	+ 14 %
Pump-around 2 duty	- 13 %	- 7 %
PF inlet temperature (°C)	- 0.7	- 0.6
Furnace inlet temperature, CIT (°C)	+ 1.6	+ 2.7
Furnace outlet temperature, COT (°C)	- 2.7	- 3.0
Cold utility demand	- 7 %	- 34 %
Furnace duty	- 5 %	- 10 %

Table 2: Proposed structural modifications for the retrofit study

Description	Value	Upper bound
Resequenced exchangers	1	1
Exchangers with additional area	2	2
Total additional area (m^2)	1,300	1,300

The furnace duty is reduced by 5 % and 10 % for operational optimization and retrofit, respectively. These reductions are indicated by an increase in the coil inlet temperature (CIT) and a decrease in the coil outlet temperature (COT). A lower furnace duty is observed in the retrofit case, compared to operational optimization, mainly due to a higher CIT. As more area is available for heat transfer in the retrofit case, more energy can be recovered and the CIT is increased.

Table 2 shows that just a few structural modifications are needed in the retrofitted HEN. Only one heat exchanger is relocated and only 2 exchangers require additional heat transfer area. The resequenced exchanger is one of those that require additional area. This heat exchanger is only “swapped” with its upstream heat exchanger, suggesting that little repiping work may be needed. The additional area requirement for each exchanger is similar to its existing area per shell, which means that the new shells may have a similar configuration as the existing shells.

In both studies, the optimization framework is able to find a significant reduction in the furnace duty, which is directly related to fuel oil consumption and operating costs. For operational optimization, results can be readily implemented at no cost as no capital investment is needed. For retrofit, greater savings in operating costs can be achieved by investing capital in performing only a few structural modifications.

4. Conclusions

This work presents a new procedure for practicable retrofit and operational optimization of existing crude oil heat exchanger networks. The main feature of this approach is that heat exchangers are specified in terms of area rather than duty. This consideration facilitates the addition of heat transfer area to a limited number of heat exchangers for reduced cost and downtime. Another important feature is the introduction of a new type of process splitters and mixers, which account for the mixing of two or more distillation products and side-draw splitting. The specification of heat transfer areas and the introduction of these new features (splitters and mixers) help to provide a realistic representation of existing HENs and also to reduce the number of optimization variables and constraints. Additional features include the prediction of heat transfer coefficients as a function of flow rate and the consideration of temperature-dependent heat capacities.

Practical constraints specified by the designer can be easily incorporated, such as maximum additional area, maximum number of new splitters, acceptable inlet temperatures to the desalter, preflash unit and ADU, acceptable exchanger minimum approach temperature, etc. The capability of incorporating these practical constraints allows more realizable design solutions to be identified. Operational optimization and retrofit studies were carried out for an existing crude oil distillation unit and its associated HEN. Results from these studies showed that the proposed methodology is able to find solutions with reduced furnace duty that are applicable and industrially-relevant. For retrofit, minimal structural modifications to the HEN were proposed.

Acknowledgments

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