Article

Energy Savings in the Heat Exchanger Network of an Oil Refinery Pre-Heat Train Unit Using a Path's Combination at Different HRAT Values

Abdelbagi Osman *[ID] **and Mousab Salaheldeen Mirghani**

Department of Chemical Engineering, College of Engineering, Najran University, P.O. Box 1988, Najran 11001, Saudi Arabia
* Correspondence: aomustafa@nu.edu.sa

Abstract: Conservation of energy usage is essential in chemical process plants due to the expanded energy users and demands alongside the carry-on hike of energy prices. This study analyzed the performance of energy savings in a heat exchanger network (HEN). It is based on decreasing utility usage while increasing process-to-process heat exchange in HEN using a path combination approach at different heat recovery approach temperatures (HRATs). The approach generates different combined path options for heat shifting from utilities to exchangers in a HEN. In terms of cost targeting, the optimal HRAT in a HEN is determined for each path's combination option. The study focused on the HEN of crude oil preheat trains. Shifting heat load between utilities implies adding and subtracting loads to and from exchangers in a HEN. Therefore, a minor retrofit to compensate for the heat transfer area is required for some HEN exchangers. The optimum HRAT corresponding to the lowest total cost was determined for each option and ranged between 8 °C and 14 °C. Moreover, two out of five options in HEN with low capital investment and a short payback period were found to be promising.

Keywords: HEN retrofit; utility paths; energy savings; thermo-economic analysis

1. Introduction

The intake of energy should always be considered in terms of cost and environmental sustainability. On the other hand, industrial and commercial users are always looking to increase productivity, operability, efficiency, and profitability while sparingly consuming energy [1]. Energy conservation can be achieved by efficient energy use in conjunction with decreased energy consumption and/or reduced consumption from conventional energy sources.

Energy consumption is a critical issue in many ways and especially in chemical processes because energy costs occupy an important share of the overall production cost of chemical processes. Therefore, heat integration studies are to be undertaken for chemical processes to keep the level of energy cost at a minimum.

Currently, and as stated from the concept of pinch technology, a heat exchanger network (HEN) that often results in a trade-off between equipment and operation cost can represent the best design for energy efficiency in a chemical process plant. This is dependent on the choice of the minimum temperature difference between hot and cold streams of the process, which is denoted by ΔT_{min} [2]. However, incorporating optimal heat exchanger networks into the original plant design or a retrofit design of an existing plant to reduce energy consumption is a difficult engineering problem [3]. The same concept can be further investigated by considering innovative ideas for optimizing an existing HEN of a chemical process plant for further increasing energy efficiency.

The current study adopted the concept of pinch technology for optimizing energy usage in an existing HEN for a pre-heat train of a crude oil distillation unit while generating

different options of cost trade-off. The study resulted in different optimal heat recovery approach temperatures (HRATs).

Historical Review

The subject of heat exchanger networks (HENs) has been plentifully investigated during the last decades due to its impacts on energy conservation in chemical process plants. Different methods were developed for the synthesis and retrofit of HENs. The most well-known method is the pinch technology approach. The grass-roots design (synthesis) of HEN is concerned with defining the best exchanger matching between hot and cold streams, in other words, looking for the best matching among process streams with a trade-off between utility and equipment costs. For better management of energy usage in process plants, a number of studies have been employed for the designing of new HENs [1,2].

Aside from the new HEN design, it is sometimes needed to revamp the existing running HEN for what is called HEN retrofit. The drive for HEN retrofit is to increase plant capacity, allow for more feed or product specifications, decrease utility costs, and improve safety or decrease environmental emissions. Conducting a HEN retrofit implies heat loads within the network being altered [4]. In a HEN retrofit, the trade-off between operational utility cost and capital investment cost should be applied to yield the optimum heat transfer driving force, which is the heat recovery approach temperature (HRAT). In chemical processes, crude distillation units (CDUs) are considered major energy consumption units and require broad energy management from time to time. Heat transfer from hot products' streams to the cold crude feed occurs through the application of HEN to reduce external energy requirements in coolers and furnaces. As a result, while the operating utility cost is reduced, the capital cost for installing a greater exchanger area is increased. Therefore, HEN retrofit is more likely preferred rather than designing new costly HEN for oil refineries [5].

Ahmad and Linnhoff introduced the principle of minimum temperature difference (ΔT_{min}) ahead of HEN design [6].

A sequential synthesis approach was proposed by *Zhu* et al., wherein they suggested the partitioning of HENs problems into "blocks" or sets of enthalpy intervals. Moreover, the problem for each set of the network evolved individually [7].

A retrofit potential program was developed by *Siemanond* and *Kosol* in 2012 to optimize an existing HEN with thermodynamic property considerations. Operational and capital cost trade-off is applied to obtain optimum heat recovery approach temperature (HRAT). The study was conducted using Visual Basic for Applications (VBA) to obtain the optimum pinch temperature automatically [8].

Ahmad et al. proposed a vertical heat exchange technique to estimate the contribution of each stream to the overall HEN area instead of equally distributing the area between the computed minimum numbers of exchangers. This method allows us to consider the available area for each stream and to manage the fact that some streams may not be active during some periods of operation [6,9].

An approach of path combination was developed by *Osman* et al. to generate several retrofit options to optimize energy consumption in an existing HEN. The options are sets of combined utility paths in a HEN. The same method of path combination is used to investigate heat recovery enhancement in HEN of variable streams' temperature. Recently, they applied the same approach to investigate the environmental energy-saving in HEN along with the impact of CO_2 emission [10–12].

For enhancing the energy recovery system, an energy-area parameter was introduced by *Al Hagri* et al. [13]. The HEN generated by considering this parameter was found to have less heat transfer area and energy consumption compared with an automated one. Moreover, for enhancing energy recovery in HEN systems, a new idea of mixing HEN streams of azeotrope formation was considered and introduced recently by *Zhang* et al. [14]. Moreover, *Li* et al. studied and analyzed heat transfer enhancement and better energy recovery by introducing a target evaluation method for HEN retrofit [15].

Further, and for maximum energy recovery and a minimum number of units in HEN with enhanced mass integration, *Ong* et al. used different methods to develop HEN for the hydrothermal liquefaction process [16]. The number of exchanger units was shown to be reduced by 50% in their new proposed methods compared to classical ones.

For generating the n-best HEN, *Orosz* et al. recently considered the P-graph framework to synthesize multiple-solution HEN depending on predefined structural constraints [17]. *Alhajri* et al. considered the graphical approach of the Pinch analysis method for optimizing an existing real HEN of the crude oil distillation operation to perform energy analysis and retrofit the network [18]. A recent approach that also considered the graphical tool of the pinch technology was proposed by *Fu* et al. to avoid crossing the pinch point in HENs of different minimum temperature differences. They proposed a shifted temperature driving force plot for retrofitting such kinds of HENs [19].

2. Methodology

The method used to carry out this study was conducted on the basis of utility path and path combination in the heat exchanger network developed by *Osman* et al. [10]. To prove the approach, it was applied to an existing common example taken from the literature, namely, the HEN of a pre-heat train unit in an industrial refinery [20].

The most critical data needed to conduct the approach involves stream heating and cooling information, as shown on the HEN grid diagram in Figure 1. The HEN includes six hot streams, as shown at the top of the figure running from left to right. The network has only one cold stream running from right to left at the bottom of the figure. Hot and cold streams exchange heat using six heat exchangers (E1–E6). In addition, one heater (H) and five coolers (C1–C5) are shown in the HEN with their heat loads. The temperature profile (°C) along the streams and heat capacity flow rates CP (kW/°C) are shown, as well as the heat load (kW) for each heat exchanger in HEN. The minimum heat transfer driving force between hot and cold streams in the HEN is 35 °C, which is called the heat recovery approach temperature (HRAT).
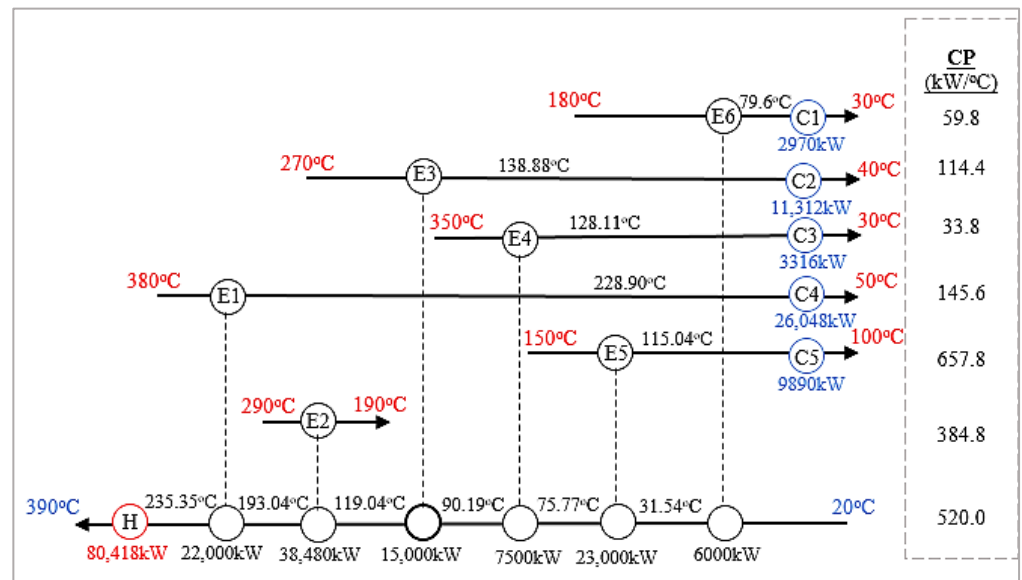
Figure 1. Existing HEN of refinery pre-heat train.

2.1. Exchangers and Utility Data

All exchangers in the HEN case study were shell-and-tube heat exchangers where cold and hot fluids are allocated in shell side and tube sides, respectively. Table 1 shows the existing HEN stream's data such as type of fluid, exchanger' side, exchangers' area (A_E), existing exchangers' heat loads (Q_E), and heat transfer coefficients for tube and shell sides

(h_T and h_S). Table 2 shows the existing heater and cooler (Q_H *and* Q_C) heat loads in addition to hot and cold utility prices (HU_{price} and CU_{price}). It is worth mentioning that the same case study was previously studied by *Ibrahim* [21] using the same data in Tables 1 and 2, in which the case was studied for only one moderate HRAT value.

Table 1. Existing HEN steams' data.

Stream	Fluid	Exchanger's Side	A_E (m^2)	Q_E (kW)	h_T (kW/m$^2 \cdot {}^\circ$C)	h_S (kW/m$^2 \cdot {}^\circ$C)
1	Kerosene	E6, Shell side	280	6000	-	0.4922
2	LGO	E3, Shell side	800	15,000	-	0.4778
3	HGO	E4, Shell side	280	7500	-	0.4389
4	ATB	E1, Shell side	1360	22,000	-	0.4704
5	Naphtha	E5, Shell side	1480	23,000	-	0.5615
6	BPA	E2, Shell side	2760	38,480	-	0.4922
7	Crude	E1-E6, Tube side	-	-	0.343	-

Table 2. Existing HEN utility data.

Utility Device	Q_H and Q_C (kW)	HU_{price} and CU_{price} ($/kW)
H	80,418	107
C1	2970	10.7
C2	11,312	21.04
C3	3316	21.04
C4	26,048	21.04
C5	9890	10.7

2.2. Utility Path Identification and Combination for Existing HEN

Logically, a path is a sequence of connected distinct lines. According to pinch technology, utility paths are an imaginary connection between two different utilities in HEN. It is used to shift heat from utilities to increase process-to-process heat exchange on the basis of the (+/−) principle, where the heat load is subtracted and added to and from devices on the path alternatively [2].

In the existing case of HEN, there were 11 utility paths, as defined in the following Table 3. Such individual paths were combined using the math combination Equation (1) as conducted by *Elsiddig* to describe the diverse ways by which the available utility paths could be grouped for generating different options of the heat shifting process in HEN [22].

$$C(n,r) = \frac{n!}{(n-r)! \cdot r!} \tag{1}$$

where *C* is combination, and *n*, *r* are non-negative integers, and ($r \leq n$). *n* is the number of available utility paths in HEN, where r stands for the set of combined paths beside the options of single paths.

Table 3. Individual utility paths in the existing HEN case.

Path No.	Path Name	Path Description
1	A	H → E6 → C1
2	B	H → E5 → C5
3	C	H → E4 → C3
4	D	H → E3 → C2
5	E	H → E1 → C4
6	F	C2 → E3 → E6 → C1
7	G	C2 → E3 → E5 → C5
8	H	C3 → E4 → E6 → C1
9	I	C3 → E4 → E5 → C5
10	J	C4 → E1 → E6 → C1
11	K	C4 → E1 → E5 → C5

The options of all combined paths are defined according to Equation (2) below:

$$Options = \sum_{r=1}^{n} C(n, r) \tag{2}$$

The heat-shifting options must be evaluated for feasibility on the basis of the only parameter that limits the heat-shifting process, i.e., the HRAT value.

Referring to an earlier work conducted by *Ibrahim* [21] that considered only one moderate value for the HRAT, the total number of options for the same case of HEN investigated in that study was found to be 10 options. Five out of those 10 were found to be economically promising according to energy-area trade-off. The five options were carried out in the present work by considering a wide range of HRAT values from which the optimum can be selected and analyzed.

2.3. Heat Load Shifting Using Combined Paths

Before starting the process of heat shifting, different values of HRAT were set to be from 2.0 °C to 30 °C, instead of one HRAT value for the sake of selecting the most optimum. The process of heat shifting by subtraction and addition (+/−) of heat along the paths for the five options of combined utility paths is detailed in Table 4 below.

To ensure thermodynamic equilibrium, energy balance in the shell and tube sides for each affected device was calculated continuously with any shifted heat load segment using a simple energy balance Equation (3). Since the process was repetitive and applied for different HRAT values, it was conducted using Dev C++ code to simplify the calculation and avoid mistakes. The heat-shifting process continued for each path until the designated HRAT value was reached.

$$Q = CP(T1 - T2) \tag{3}$$

where Q is heat duty (kW) for exchangers, heater and cooler, i.e., Q_E, Q_H, and Q_C. CP is heat capacity flow rate (kw/°C). $T1$ and $T2$ are exchanger input and output temperatures (°C), respectively, for either hot or cold stream.

Table 4. The selected combined paths in the HEN case.

Options	Combined Paths	HEN Devices (Exchangers, Heaters, Coolers)											
		H_1	E_1	E_2	E_3	E_4	E_5	E_6	C_1	C_2	C_3	C_4	C_5
Opt 1	D	-			+				-				
	E	-	+									-	
Opt 2	A	-						+	-				
	B	-					+						-
	C	-			+						-		
Opt 3	A	-						+	-				
	B	-					+						-
	J		+					-		+		-	
	K		+				-					-	+
Opt 4	A	-						+	-				
	B	-					+						-
	C	-				+					-		
	D	-			+					-			
	E	-	+									-	
Opt 5	A	-						+	-				
	F				+			-		+	-		
	B	-					+						-
	C	-				+					-		
	D	-			+					-			
	E	-	+									-	

2.4. Pinch Technology Targeting

Due to the heat shifting process, thermodynamic data for all affecting exchangers in HEN were subjected to changes in terms of heat duties and temperatures. The heat transfer area (A) for each exchanger was to be re-found using the area targeting Equation (4). As reported by *Smith* [4], the targeting stage in HEN retrofit and optimization does not deal with precise area. Instead, it is concerned mostly with area targeting, for which the overall heat transfer coefficient should assumed as $U = (1/h_S + 1/h_T)^{-1}$.

$$A = \left(\frac{1}{h_S} + \frac{1}{h_T} \right) \times \frac{Q}{LMTD} \tag{4}$$

where h_S and h_T are the heat transfer coefficients for shell and tube sides, respectively. *LMTD* is the logarithmic mean temperature difference for each exchanger in HEN, which is calculated according to Equations (5)–(7).

$$LMTD = \frac{\Delta T1 - \Delta T2}{ln \frac{\Delta T1}{\Delta T2}} \tag{5}$$

$$\Delta T1 = T_{H,in} - T_{C,out} \tag{6}$$

$$\Delta T2 = T_{H,out} - T_{C,in} \tag{7}$$

where $T_{H,in}$, $T_{H,out}$, $T_{C,in}$, and $T_{C,out}$ are in and out temperatures for hot and cold sides, respectively, for each exchanger in HEN.

The total heat transfer area for the HEN (A_{HEN}) is calculated as in Equation (8) before or after the heat-shifting process.

$$A_{HEN} = \sum_i^n A_E \tag{8}$$

The difference between A_{HEN} before ($A_{HEN,ex}$) and after shifting heat loads ($A_{HEN,new}$) is denoted as ΔA_{HEN}, which is the added area penalty due to load distribution and relocation.

After estimating the overall HEN area requirement to overcome the relocation of heat loads, cost targeting was conducted to define the optimality of HRAT. Therefore, annual operating and capital investment costs were calculated in addition to the total cost for each option separately according to pinch technology targeting.

Operating cost is the cost of external heating and cooling utilities that are affected by the heat shifting process while increasing the heat recovery. Operating cost was calculated using a set of Equations (9) to (14).

$$Cost_{operating} = Cost_{existing} - Cost_{saving} \tag{9}$$

$$Cost_{saving} = \left(\sum HU_{cost,ex} + \sum CU_{cost,ex} \right) - \left(\sum HU_{cost,new} + \sum CU_{cost,new} \right) \tag{10}$$

$$HU_{cost,ex} = Q_{H,ex} \times HU_{price} \tag{11}$$

$$CU_{cost,ex} = Q_{C,ex} \times CU_{price} \tag{12}$$

$$HU_{cost,new} = Q_{H,new} \times HU_{price} \tag{13}$$

$$CU_{cost,new} = Q_{C,new} \times CU_{price} \tag{14}$$

where $HU_{cost,ex}$ and $CU_{cost,ex}$ are hot and cold utility cost ($/yr) of the existing case before heat shifting, respectively. $Q_{H,ex}$, $Q_{C,ex}$, $Q_{H,new}$, and $Q_{C,new}$ are hot and cold utility heat duty (kW) for the existing and new cases (before and after heat shifting), respectively.

The capital cost to be invested for the added area requirement in the whole HEN was calculated using Equation (15).

$$Cost_{capital} = \Delta N \left(a + b \left(\frac{\Delta A_{HEN}}{\Delta N} \right)^c \right) \tag{15}$$

According to *Al-Riyami* et al. [23], it is assumed that all HEN exchangers are made of carbon steel. The values of cost coefficients *a*, *b*, and *c* were 33,422, 814, and 0.81, respectively. ΔN is the number of required extra shells, which was found in Equations (16) and (17).

$$\Delta N = \frac{\Delta A_{HEN}}{av_{shell}} \tag{16}$$

$$av_{shell} = \frac{A_{HEN,ex}}{N_{shell}} \tag{17}$$

where av_{shell} and N_{shell} are average size of exchangers shell and number of exchanger shells, respectively. N_{shell} is the same as the number of exchangers in HEN, which is 6.

The capital investment cost and according to *Smith* [4] can be expressed on an annual basis. We assumed that the capital was borrowed over a fixed period (*n*) ranging from 5 to 10 years at a fixed rate of interest (*i*). Therefore, the annualized capital cost can be calculated using Equation (18), where *n* is taken to be 5 years and interest *i* to be 0.05 for the current study.

$$Cost_{Annual} = Cost_{capital} \times \frac{i(1+i)^n}{(1+i)^n - 1} \tag{18}$$

To determine the optimum HRAT value for each path's combination option, the total cost profile was to be defined for the lowest cost along with the range of HRAT vales.

The total cost was the summation of both operating and annualized costs, as shown in Equation (19) below.

$$Cost_{Total} = Cost_{operating} + Cost_{Annual} \tag{19}$$

Economic Assessment

Overall, HEN profitability and the comparison between combined paths options were needed for making the right decision. Economic assessment of saving ($/year) and capital investment ($) were calculated as in Equations (10) and (15), respectively. The payback period (year) was calculated using Equation (20). Economic calculations were assessed on the basis of the following hypothesizes:

- Investment was considered only for the required added area.
- No piping or other costs were considered.

$$Payback = \frac{Cost_{capital}}{Cost_{saving}} \tag{20}$$

The overall method to describe the processes followed in this study can be summarized in the flow diagram shown in Figure 2 below.
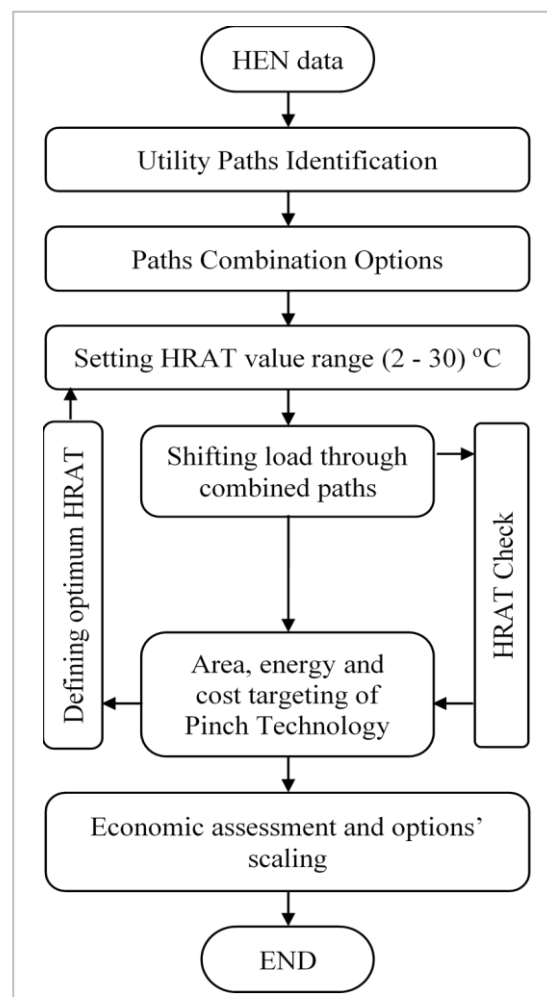

Figure 2. Method flow diagram.

3. Results and Analysis

The initial results of heat recovery and energy consumption due to the heat-shifting process in the case study are tabulated in Tables A1–A10 located in Appendices A and B. A graphical representation of important results is interpreted and analyzed in this section.

3.1. Area Targeting

Due to the heat load shifting using combined paths, the obtained results of area targeting are showing the HEN area profile with HRAT values for the five options, as illustrated in Figure 3. The profile showed the total HEN area increasing step-wisely with shrinking HRAT values for each path combination option. Compared with the existing case, all options performed in a prime way, with option 3 taking the least and best area performance along the descending HRAT. Options 2 and 4 showed a typical performance, although they were made of different combinations of utility paths, with a short profile from 10 to 30 °C of HRAT. Before 10 °C, these two options showed excessive heat shifting that resulted in –ve values of utility duties that were not considered logically.
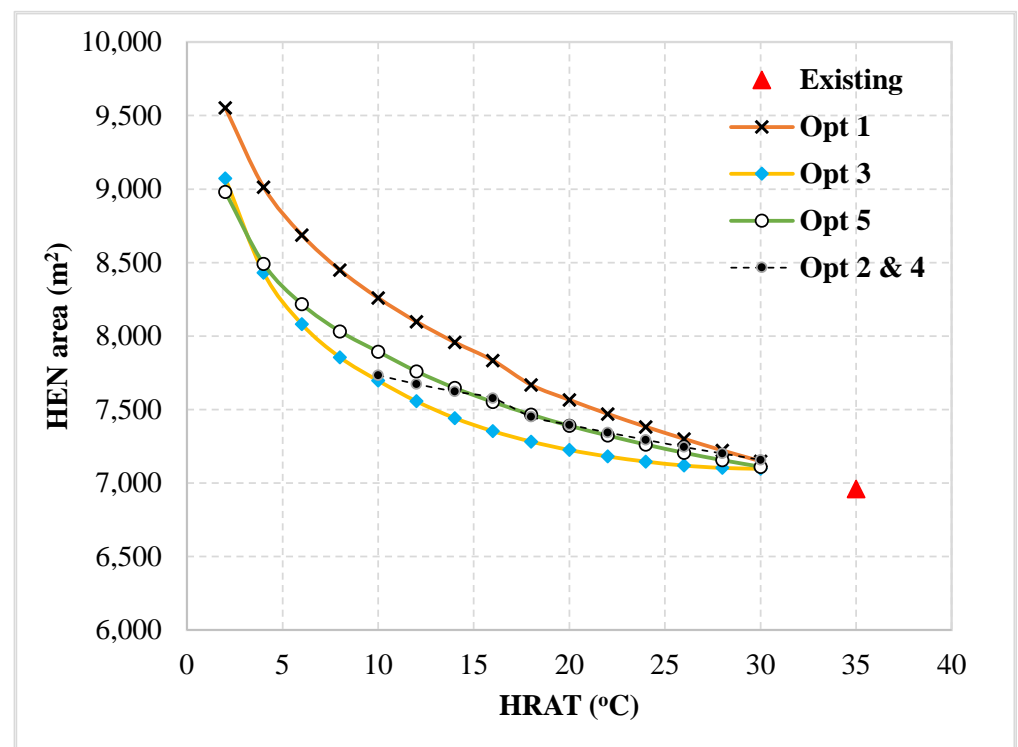
Figure 3. Total HEN area based on HRAT for path combination options.

For the sake of comparison, Table 5 shows the difference in area targeting between the previous work of *Ibrahim* [21] and the present work. It is illustrated that the previous work for the same case study suggested only one value for the HRAT that would not reflect the optimality of the required additional area in the HEN and consequently the total investment cost. The high value of HRAT (27 °C) looked attractive for the heat transfer process, less area, and cost requirement in a HEN retrofit. However, it would not reflect the optimum operation of HEN compared to screening a wide range of HRAT and selecting the optimum on the basis of the trade-off between total cost and operating cost, as presented in the current study.

**Table 5.** Comparison between previous and present work for area targeting in a HEN.

Options of Combined Paths	HRAT Value		Area Targeting, A_{HEN} (m^2)	
	Previous Work	Present Work (Optimum HRAT)	Previous Work	Present Work
DE	Assumed one value for all options, 27 °C	8	7300	8449
ABC		14	7210	7623
ABJK		10	7100	7696
ABCDE		14	7210	7623
AFBCDE		10	7180	7894

3.2. Cost Targeting

Optimum design or retrofit of HEN can be achieved by setting a perfect trade-off between capital investment and energy uses that defines optimum heat recovery approach temperature (HRAT). On the other hand, the lower the values of HRAT of HEN, the greater the possible setting for targets of capital and energy costs ahead of HEN retrofit and optimization design.

Figure 4 shows the cost targeting for operating and annual and capital cost profiles as regards path combination option (1). The optimum HRAT was shown to be 8 °C as a minimum heat transfer deriving force between hot and cold streams in a HEN, corresponding to a total cost of 16.1 × 10^6 $/y.
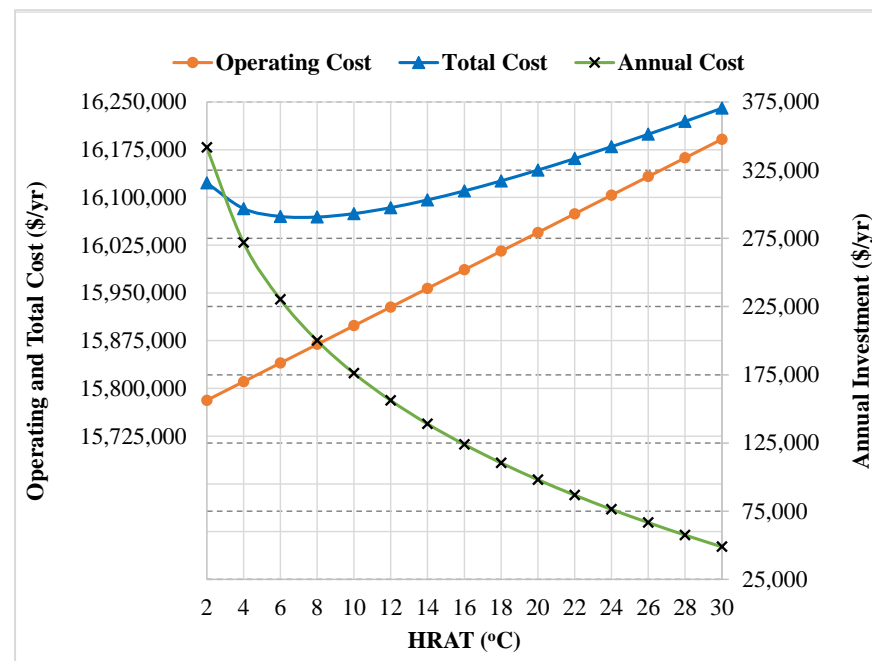
Figure 4. Economic profile of the optimized HEN using option (1).

Although options (2) and (3) consist of different path combinations, they show a cost targeting of a typical profile, as illustrated in Figure 5. Since HRAT values ranged only between 10 and 30 °C, these options showed a semi-horizontal profile for the total cost. However, the minimum optimum HRAT value seemed to be more operable, namely, 14 °C at a higher total cost of 16.3 × 10^6 $/y.
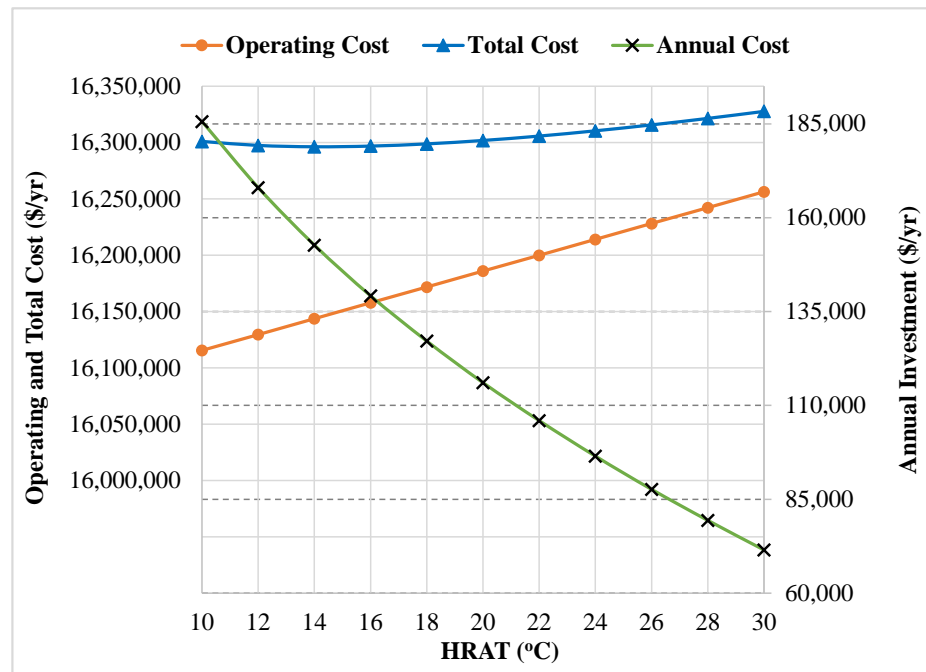
Figure 5. Economic profile of the optimized HEN using options (2) and (4).

Option (3), as illustrated in Figure 6, showed a clear cost targeting profile summing with a minimum total cost of 16.15×10^6 \$/y at an optimum HRAT of 10 °C.
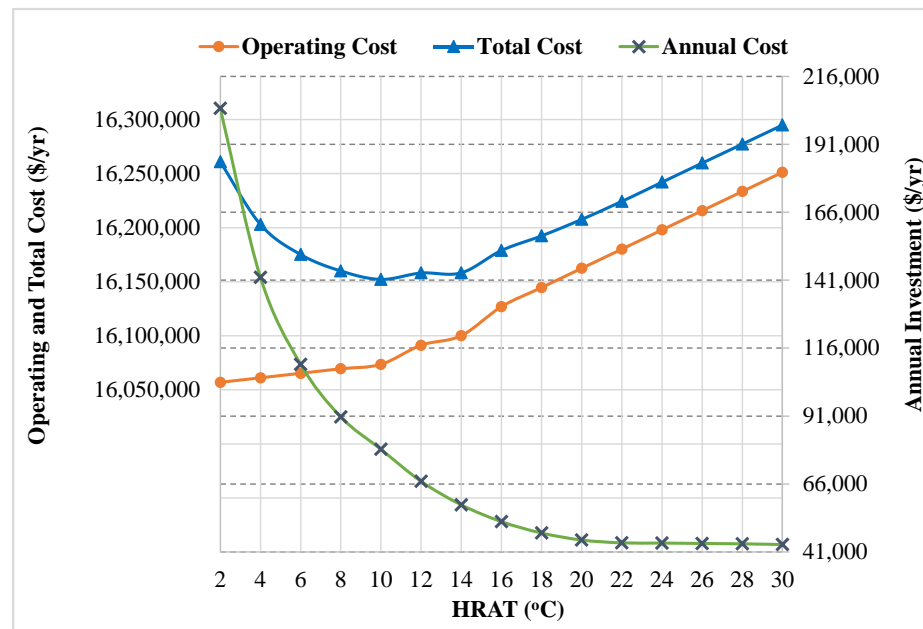
Figure 6. Economic profile of the optimized HEN using option (3).

Figure 7 also shows a perfect cost profile for option (5), somewhat similar to option (3). The minimum total was 16.18×10^6 \$/y at a HRAT of 10 °C.
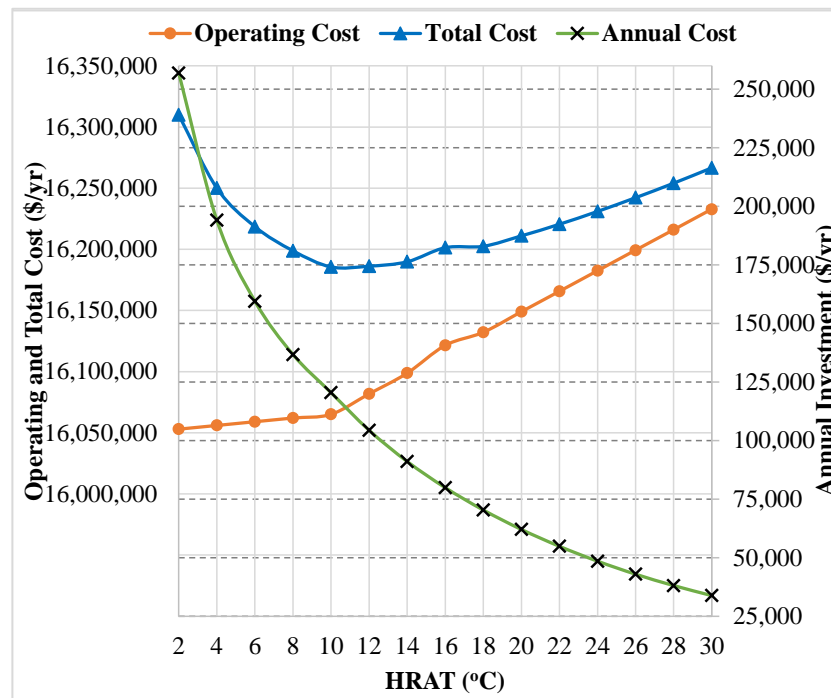
Figure 7. Economic profile of the optimized HEN using option (5).

For the sake of cost targeting comparison, all path combination options are presented by a single illustration in Figure 8. Option (1) revealed the lowest total cost to be invested for revamping the HEN by adding the surface area to existing exchangers in the network; however, the HRAT was shown to be weak as a heat transfer driving force. Options (2) and (4) exposed stronger HRATs at the high optimum total cost. Options (3) and (5) showed similar optimum HRAT values at different total costs, wherein option (3) is presented to be the best among them all.
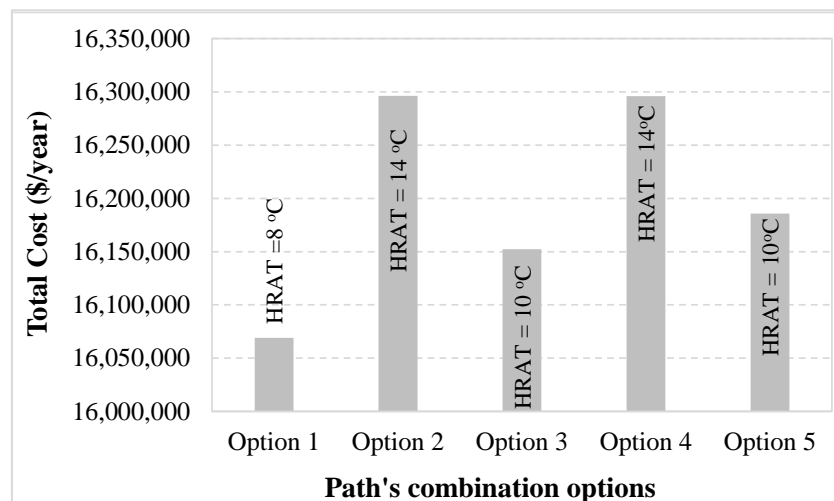
Figure 8. Comparison between total cost profile and optimum HRAT.

Cost-Effective Analysis

For a more thorough economic analysis, a trade-off must be made between the capital cost of investment and the expected profit from energy savings for each option with the best HRAT.

This could simply be single-minded by taking the investment–savings ratio to obtain the payback period. The lower the payback, the better the expected cost-effective design or retrofit of the HEN.

Comparison and analysis in terms of investment cost and expected savings for each path combination option in a HEN were made on the basis of the payback period as depicted in Figure 9.
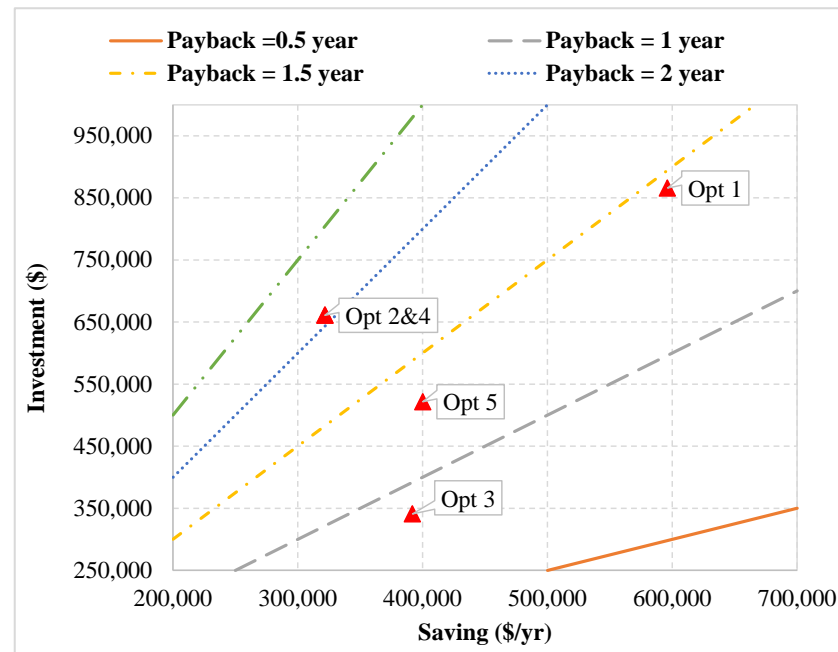
Figure 9. Investment, saving, and payback at optimum HRAT for retrofit options.

From the figure, option (1) showed the highest savings at the expense of investing USD 850,000 with a 1.45-year payback period. It is worth mentioning that the HRAT for this option was the smallest among the rest of the other options, which restricted the heat transfer operation somewhere in the HEN. Therefore, option (1) will not be considered as an energy-saving option.

The typical readings for options (2) and (4) showed the lowest saving among others, with moderate capital investment and higher payback of more than 2 years.

Options (3) and (5) showed the same energy savings but with different capital investments (USD 341,000 for option (3) and USD 522,000 for option (5)). Therefore, option (3) was preferred and considered the best among others, especially for the payback period of only 0.87 years (about 10 and a half months).

4. Conclusions

A minor retrofit for energy optimization in an existing HEN can be accomplished using the path combination approach within the pinch technology method for minimizing utility consumption at optimum HRAT. The minor retrofit could feature only area addition to the existing exchangers in a HEN.

When using utility paths for energy optimization in a HEN, the related previous work in the literature shows that utility paths are used to shift the heat load between utility devices through considering single paths individually. The idea of using the available utility paths in HEN as clusters to shift the heat load in a simultaneous way makes the heat-shifting process tighter, resulting in a compact, optimized HEN. Moreover, considering the area and energy targeting of pinch technology, together with the idea of combined utility paths, adds new value to the heat integration and optimization process.

On the basis of the suggested method, an excessive heat load shifting process can be conducted in a HEN using different options at different heat recovery approach temperatures (HRATs). Using cost targeting analysis, the optimum HRAT for each option can be defined separately. The cost-effective analysis is a great tool to compare the options for choosing the best for energy optimization in a HEN when making the right decision.

The huge number of repetitions is a drawback that can be resolved if the related software packages are considered.

It is recommended that future work consider sensitivity analysis by applying the same idea to the HEN of variable stream flows and fluctuating utility prices with time.

Appendix A

Heat recovery data: The obtained results for heat duty for exchangers in HEN are tabulated for the five heat shifting options in Tables A1–A5.

Table A1. Heat loads at different HRAT values for option (1).

HRAT (°C)	Q_{E1} (kW)	Q_{E2} (kW)	Q_{E3} (kW)	Q_{E4} (kW)	Q_{E5} (kW)	Q_{E6} (kW)	Total (kW)
Existing	22,000	38,480	15,000	7500	23,000	6000	111,980
2	22,001	38,480	20,341	7500	23,000	6000	117,322
4	22,001	38,480	20,112	7500	23,000	6000	117,093
6	22,001	38,480	19,884	7500	23,000	6000	116,865
8	22,001	38,480	19,655	7500	23,000	6000	116,636
10	22,001	38,480	19,426	7500	23,000	6000	116,407
12	22,001	38,480	19,197	7500	23,000	6000	116,178
14	22,001	38,480	18,968	7500	23,000	6000	115,949
16	22,001	38,480	18,740	7500	23,000	6000	115,721
18	22,001	38,480	18,511	7500	23,000	6000	115,492
20	22,001	38,480	18,282	7500	23,000	6000	115,263
22	22,001	38,480	18,053	7500	23,000	6000	115,034
24	22,001	38,480	17,824	7500	23,000	6000	114,805
26	22,001	38,480	17,594	7500	23,000	6000	114,575
28	22,001	38,480	17,367	7500	23,000	6000	114,348
30	22,001	38,480	17,138	7500	23,000	6000	114,119

Table A2. Heat loads at different HRAT values for option (2).

HRAT (°C)	Q_{E1} (kW)	Q_{E2} (kW)	Q_{E3} (kW)	Q_{E4} (kW)	Q_{E5} (kW)	Q_{E6} (kW)	Total (kW)
Existing	22,000	38,480	15,000	7500	23,000	6000	111,980
2	22,000	38,480	15,000	7500	23,000	9449	115,429
4	22,000	38,480	15,000	7500	23,000	9329	115,309
6	22,000	38,480	15,000	7500	23,000	9209	115,189
8	22,000	38,480	15,000	7500	23,000	9090	115,070
10	22,000	38,480	15,000	7500	23,000	8970	114,950
12	22,000	38,480	15,000	7500	23,000	8851	114,831
14	22,000	38,480	15,000	7500	23,000	8731	114,711
16	22,000	38,480	15,000	7501	23,001	8611	114,593
18	22,000	38,480	15,000	7501	23,001	8492	114,474
20	22,000	38,480	15,000	7501	23,001	8372	114,354
22	22,000	38,480	15,000	7501	23,001	8253	114,235
24	22,000	38,480	15,000	7501	23,001	8133	114,115
26	22,000	38,480	15,000	7501	23,001	8013	113,995
28	22,000	38,480	15,000	7501	23,001	7894	113,876
30	22,000	38,480	15,000	7501	23,001	7774	113,756

Table A3. Heat loads at different HRAT values for option (3).

HRAT (°C)	Q_{E1} (kW)	Q_{E2} (kW)	Q_{E3} (kW)	Q_{E4} (kW)	Q_{E5} (kW)	Q_{E6} (kW)	Total (kW)
Existing	22,000	38,480	15,000	7500	23,000	6000	111,980
2	27,693	38,480	15,000	7500	22,999	3279	114,951
4	27,289	38,480	15,000	7500	22,999	3683	114,951
6	26,885	38,480	15,000	7500	22,999	4047	114,911
8	26,480	38,480	15,000	7500	22,999	4492	114,951
10	26,075	38,480	15,000	7500	23,000	4896	114,951
12	25,717	38,480	15,000	7500	23,000	5135	114,832
14	25,359	38,480	15,000	7500	23,000	5373	114,712
16	25,002	38,480	15,000	7500	23,000	5610	114,592
18	24,643	38,480	15,000	7500	23,000	5850	114,473
20	24,286	38,480	15,000	7500	23,000	6087	114,353
22	23,927	38,480	15,000	7500	23,000	6327	114,234
24	23,575	38,480	15,000	7500	23,000	6564	114,119
26	23,212	38,480	15,000	7500	23,000	6802	113,994
28	22,854	38,480	15,000	7500	23,000	7041	113,875
30	22,496	38,480	15,000	7500	23,000	7279	113,755

Table A4. Heat loads at different HRAT values for option (4).

HRAT (°C)	Q_{E1} (kW)	Q_{E2} (kW)	Q_{E3} (kW)	Q_{E4} (kW)	Q_{E5} (kW)	Q_{E6} (kW)	Total (kW)
Existing	22,000	38,480	15,000	7500	23,000	6000	111,980
2	22,000	38,480	15,000	7500	23,000	9449	115,429
4	22,000	38,480	15,000	7500	23,000	9329	115,309
6	22,000	38,480	15,000	7500	23,000	9209	115,189
8	22,000	38,480	15,000	7500	23,000	9090	115,070
10	22,001	38,480	15,001	7501	23,001	8970	114,950
12	22,001	38,480	15,001	7501	23,001	8851	114,831
14	22,001	38,480	15,001	7501	23,001	8731	114,711
16	22,001	38,480	15,001	7501	23,001	8611	114,595
18	22,001	38,480	15,001	7501	23,001	8492	114,476
20	22,001	38,480	15,001	7501	23,001	8372	114,356
22	22,001	38,480	15,001	7501	23,001	8253	114,237
24	22,001	38,480	15,001	7501	23,001	8133	114,117
26	22,001	38,480	15,001	7501	23,001	8013	113,997
28	22,001	38,480	15,001	7501	23,001	7894	113,878
30	22,001	38,480	15,001	7501	23,001	7774	113,758

Table A5. Heat loads at different HRAT values for option (5).

HRAT (°C)	Q_{E1} (kW)	Q_{E2} (kW)	Q_{E3} (kW)	Q_{E4} (kW)	Q_{E5} (kW)	Q_{E6} (kW)	Total (kW)
Existing	22,000	38,480	15,000	7500	23,000	6000	111,980
2	22,001	38,480	21,011	7501	23,001	2961	114,955
4	22,001	38,480	20,718	7501	23,001	3254	114,955
6	22,001	38,480	20,424	7501	23,001	3548	114,955
8	22,001	38,480	20,131	7501	23,001	3841	114,955
10	22,001	38,480	19,837	7500	23,000	4133	114,951
12	22,001	38,480	19,598	7501	23,001	4274	114,955
14	22,001	38,480	19,318	7501	23,001	4414	114,715
16	22,001	38,480	19,059	7501	23,001	4553	114,595
18	22,001	38,480	18,799	7501	23,001	4694	114,476
20	22,001	38,480	18,540	7501	23,001	4833	114,356
22	22,001	38,480	18,280	7501	23,001	4974	114,237
24	22,001	38,480	18,020	7501	23,001	5114	114,117
26	22,001	38,480	17,761	7501	23,001	5253	113,997
28	22,001	38,480	17501	7501	23,001	5394	113,878
30	22,001	38,480	17,242	7501	23,001	5533	113,758

Appendix B

Energy consumption data: Heat duties of utility devices (heater and coolers) in the case of the HEN example are tabulated in Tables A6–A10. This involves external energy requirements for the heat-shifting options before and after the heat-shifting process.

Table A6. External energy consumption at different HRAT values for option (1).

HRAT (°C)	Q_{C1} (kW)	Q_{C2} (kW)	Q_{C3} (kW)	Q_{C4} (kW)	Q_{C5} (kW)	Q_H (kW)	Total (kW)
Existing	2970	11,312	3316	26,048	9890	80,418	133,954
2	2970	5971	3316	26,047	9890	75,076	123,272
4	2970	6200	3316	26,047	9890	75,305	123,728
6	2970	6428	3316	26,047	9890	75,533	124,184
8	2970	6657	3316	26,047	9890	75,762	124,642
10	2970	6886	3316	26,047	9890	75,991	125,100
12	2970	7115	3316	26,047	9890	76,220	125,558
14	2970	7344	3316	26,047	9890	76,449	126,016
16	2970	7572	3316	26,047	9890	76,677	126,472
18	2970	7801	3316	26,047	9890	76,906	126,930
20	2970	8030	3316	26,047	9890	77,135	127,388
22	2970	8259	3316	26,047	9890	77,364	127,846
24	2970	8488	3316	26,047	9890	77,593	128,304
26	2970	8716	3316	26,047	9890	77,821	128,760
28	2970	8945	3316	26,047	9890	78,050	129,218
30	2970	9174	3316	26,047	9890	78,279	129,676

Table A7. External energy consumption at different HRAT values for option (2).

HRAT (°C)	Q_{C1} (kW)	Q_{C2} (kW)	Q_{C3} (kW)	Q_{C4} (kW)	Q_{C5} (kW)	Q_H (kW)	Total (kW)
Existing	2970	11,312	3316	26,048	9890	80,418	133,954
2	−479	11,312	3316	26,048	9890	77,448	127,535
4	−359	11,312	3316	26,048	9890	77,448	127,655
6	−239	11,312	3316	26,048	9890	77,448	127,775
8	−120	11,312	3316	26,048	9890	77,448	127,894
10	0	11,312	3315	26,048	9889	77,446	128,010
12	119	11,312	3315	26,048	9889	77,565	128,248
14	239	11,312	3315	26,048	9889	77,685	128,488
16	359	11,312	3315	26,048	9889	77,805	128,728
18	478	11,312	3315	26,048	9889	77,924	128,966
20	598	11,312	3315	26,048	9889	78,044	129,206
22	717	11,312	3315	26,048	9889	78,163	129,444
24	837	11,312	3315	26,048	9889	78,283	129,684
26	957	11,312	3315	26,048	9889	78,403	129,924
28	1076	11,312	3315	26,048	9889	78,522	130,162
30	1196	11,312	3315	26,048	9889	78,642	130,402

Table A8. External energy consumption at different HRAT values for option (3).

HRAT (°C)	Q_{C1} (kW)	Q_{C2} (kW)	Q_{C3} (kW)	Q_{C4} (kW)	Q_{C5} (kW)	Q_H (kW)	Total (kW)
Existing	2970	11,312	3316	26,048	9890	80,418	133,954
2	5691	11,312	3316	20,356	9890	77,448	128,013
4	5287	11,312	3316	20,759	9891	77,448	128,013
6	4883	11,312	3316	21,163	9891	77,448	128,013
8	4478	11,312	3316	21,568	9891	77,448	128,013
10	4074	11,312	3316	21,973	9890	77,448	128,013
12	3835	11,312	3316	22,331	9890	77,566	128,250
14	3597	11,312	3316	22,689	9890	77,686	128,490
16	3360	11,312	3316	23,046	9890	77,806	128,730
18	3120	11,312	3316	23,405	9890	77,925	128,968
20	2883	11,312	3316	23,762	9890	78,045	129,208
22	2643	11,312	3316	24,121	9890	78,164	129,446
24	2406	11,312	3316	24,478	9890	78,284	129,686
26	2168	11,312	3316	24,836	9890	78,404	129,926
28	1929	11,312	3316	25,194	9890	78,523	130,164
30	1691	11,312	3316	25,552	9890	78,643	130,404

Table A9. External energy consumption at different HRAT values for option (4).

HRAT (°C)	Q_{C1} (kW)	Q_{C2} (kW)	Q_{C3} (kW)	Q_{C4} (kW)	Q_{C5} (kW)	Q_H (kW)	Total (kW)
Existing	2970	11,312	3316	26,048	9890	80,418	133,954
2	−479	11,312	3316	26,048	9890	77,448	127,535
4	−359	11,312	3316	26,048	9890	77,448	127,655
6	−239	11,312	3316	26,048	9890	77,448	127,775
8	−120	11,312	3316	26,048	9890	77,448	127,894
10	0	11,312	3315	26,047	9889	77,444	128,007
12	119	11,312	3315	26,047	9889	77,563	128,245
14	239	11,312	3315	26,047	9889	77,683	128,485
16	359	11,312	3315	26,047	9889	77,803	128,725
18	478	11,312	3315	26,047	9889	77,922	128,963
20	598	11,312	3315	26,047	9889	78,042	129,203
22	717	11,312	3315	26,047	9889	78,161	129,441
24	837	11,312	3315	26,047	9889	78,281	129,681
26	957	11,312	3315	26,047	9889	78,401	129,921
28	1076	11,312	3315	26,047	9889	78,520	130,159
30	1196	11,312	3315	26,047	9889	78,640	130,399

Table A10. External energy consumption at different HRAT values for option (5).

HRAT (°C)	Q_{C1} (kW)	Q_{C2} (kW)	Q_{C3} (kW)	Q_{C4} (kW)	Q_{C5} (kW)	Q_H (kW)	Total (kW)
Existing	2970	11,312	3316	26,048	9890	80,418	133,954
2	6009	5301	3315	26,047	9889	77,444	128,005
4	5716	5594	3315	26,047	9889	77,444	128,005
6	5422	5888	3315	26,047	9889	77,444	128,005
8	5129	6181	3315	26,047	9889	77,444	128,005
10	4837	6475	3316	26,048	9890	77,448	128,014
12	4696	6734	3315	26,047	9889	77,563	128,244
14	4556	6994	3315	26,047	9889	77,683	128,484
16	4417	7253	3315	26,047	9889	77,803	128,724
18	4276	7513	3315	26,047	9889	77,922	128,962
20	4137	7772	3315	26,047	9889	78,042	129,202
22	3996	8032	3315	26,047	9889	78,161	129,440
24	3856	8292	3315	26,047	9889	78,281	129,680
26	3717	8551	3315	26,047	9889	78,401	129,920
28	3576	8811	3315	26,047	9889	78,520	130,158
30	3437	9070	3315	26,047	9889	78,640	130,398

References

1. Linnhoff, B.; Flower, J. Synthesis of heat exchanger networks: Synthesis of heat exchanger networks: II. Evolutionary generation of networks with various criteria of optimality. *AICHE J.* **1978**, *24*, 642–654. [CrossRef]
2. March, L. Introduction to pinch technology. In *Targeting House*; Targeting House: Cheshire, England, 1998.
3. Telang, K.; Knopf, F.C.; Pike, R.W. *The Heat Exchanger Network*; Mineral Processing Research Institute: Baton Rouge, LA, USA, 2001.
4. Smith, R. *Chemical Process: Design and Integration*; John Wiley & Sons: New York, NY, USA, 2005.
5. Pejpichestakula, W.; Siemanond, K. Retrofit of refinery heat exchanger network under different kinds of crude oil by pinch design method using mathematical programming. *Chem. Eng.* **2013**, *32*, 1332236.
6. Linnhoff, B.; Ahmad, S. Cost optimum heat exchanger networks—1: Minimum energy and capital using simple models for capital cost. *Comput. Chem. Eng.* **1990**, *14*, 729–750. [CrossRef]
7. Zhu, X.; O'Neill, B.; Roach, J.; Wood, R. A new method for heat exchanger network synthesis using area targeting procedures. *Comput. Chem. Eng.* **1995**, *19*, 197–222. [CrossRef]
8. Siemanond, K.; Kosol, S. Heat exchanger network retrofit by pinch design method using stage-model mathematical programming. *Chem. Eng. Trans.* **2012**, *29*, 367–372.
9. Ahmad, S.; Linnhoff, B.; Smith, R. Cost optimum heat exchanger networks—2: Targets and design for detailed capital cost models. *Comput. Chem. Eng.* **1990**, *14*, 751–767. [CrossRef]
10. Osman, A.; Mutalib, M.A.; Shuhaimi, M.; Amminudin, K. Paths combination for HENs retrofit. *Appl. Therm. Eng.* **2009**, *29*, 3103–3109. [CrossRef]
11. Osman, A.; Mutalib, M.A.; Shigidi, I. Heat recovery enhancement in HENs using a combinatorial approach of paths combination and process streams' temperature flexibility. *S. Afr. J. Chem. Eng.* **2016**, *21*, 37–48. [CrossRef]
12. Osman, A.; Eltayeb, M.; Rajab, F. Utility paths combination in HEN for energy saving and CO2 emission reduction. *Processes* **2019**, *7*, 425. [CrossRef]
13. Alhajri, I.H.; Gadalla, M.A.; Elazab, H.A. A conceptual efficient design of energy recovery systems using a new energy-area key parameter. *Energy Rep.* **2021**, *7*, 1079–1090. [CrossRef]
14. Zhang, D.; Li, Y.; Sun, H.; Liu, G. Energy recovery enhancement of heat exchanger network by mixing and azeotrope formation. *Chem. Eng. Sci.* **2020**, *228*, 115992. [CrossRef]
15. Li, N.; Wang, J.; Klemeš, J.J.; Wang, Q.; Varbanov, P.S.; Yang, W.; Liu, X.; Zeng, M. A target-evaluation method for heat exchanger network optimisation with heat transfer enhancement. *Energy Convers. Manag.* **2021**, *238*, 114154. [CrossRef]
16. Ong, B.H.; Walmsley, T.G.; Atkins, M.J.; Varbanov, P.S.; Walmsley, M.R. A heat-and mass-integrated design of hydrothermal liquefaction process co-located with a Kraft pulp mill. *Energy* **2019**, *189*, 116235. [CrossRef]
17. Orosz, Á.; How, B.S.; Friedler, F. Multiple-solution heat exchanger network synthesis using P-HENS solver. *J. Taiwan Inst. Chem. Eng.* **2021**, *130*, 103859. [CrossRef]

18. Alhajri, I.H.; Gadalla, M.A.; Abdelaziz, O.Y.; Ashour, F.H. Retrofit of heat exchanger networks by graphical Pinch Analysis–A case study of a crude oil refinery in Kuwait. *Case Stud. Therm. Eng.* **2021**, *26*, 101030. [CrossRef]
19. Fu, D.; Yu, Z.; Lai, Y. Linking pinch analysis and shifted temperature driving force plot for analysis and retrofit of heat exchanger network. *J. Clean. Prod.* **2021**, *315*, 128235. [CrossRef]
20. Panjeshahi, M.; Tahouni, N. Pressure drop optimisation in debottlenecking of heat exchanger networks. *Energy* **2008**, *33*, 942–951. [CrossRef]
21. Ibrahim, M.A.M. *Energy Optimization and Retrofit of Heat Exchanger Networks Case Study: Preheat-Train of the Crude Distillation Unit*; University of Gezira: Wad Madani, Sudan, 2013.
22. Elsiddig, A.O. Path Analysis for the Retrofit of Heat Exchanger Networks and the Utility System. Ph.D. Thesis, UTP, Seri Iskandar, Malaysia, 2011.
23. Al-Riyami, B.A.; Klemes, J.; Perry, S. Heat Integration Retrofit Analysis of a Heat Exchanges Network of a Fluid Catalytic Cracking Plant. *Appl. Therm. Eng.* **2001**, *21*, 449–1487. [CrossRef]