

Retrofit of Crude Units Preheating Trains: Mathematical Programming versus Pinch Technology

Miguel Bagajewicz,^{*,†,‡} Gary Valtinson,[‡] and DuyQuang Nguyen Thanh[‡]

[†]University of Oklahoma, 100 E. Boyd Street, T335, Norman, Oklahoma 73072, United States

[‡]OK-Solutions, 4017 Hatterly Lane, Norman, Oklahoma 73072, United States

ABSTRACT: This paper presents a comparison of two heat exchanger network retrofit methods as they are applied to crude units: the well-known and widely used Pinch Design Method (PDM) and a recently developed Heat Integration Transportation Model (HIT), a recently developed mathematical programming-based MILP model [Nguyen et al. *Ind. Chem. Eng. Res.* **2010**, *49*, 13]. We show that the three-step procedure (targeting, design, and evolution) used by Pinch Technology renders solutions with excessive and unrealistic splitting of streams as well as visibly less profit compared to the results of HIT.

1. INTRODUCTION

Pinch Technology was first introduced by B. Linnhoff^{1,2} for grassroots design. The method is based on a targeting phase where the minimum utility is calculated as a function of a minimum temperature approximation, originally called minimum approximation temperature difference (ΔT_{Min}), later named Heat Recovery Approximation Temperature (HRAT). The minimum utility is therefore a floating number that depends on the aforementioned HRAT parameter. Once the minimum utility is fixed, one must design the network using the Pinch Design Method (PDM)² according to certain rules (design the system above and below the pinch; use a tick-off rule and certain guidelines for picking matches). Smith³ nicely presents the method in detail.

In the case of mathematical programming, several approaches exist. Yee and Grossmann⁴ provide a review of the existing retrofit techniques in 1987. Ciric and Floudas⁵ proposed a retrofit strategy using a decomposition method. Asante and Zhu⁶ introduced an automated approach for HEN retrofit featuring minimal topology modifications. Finally, Briones and Kokossis⁷ used the hypertargets or conceptual programming approach for retrofitting industrial heat exchanger networks. Unlike the previous approaches that are nonlinear and hard to solve globally, our own work⁸ consists of a mathematical linear programming model that economically optimizes a network by appropriate selection of heat transferred between hot and cold intervals and provides a globally optimal solution. This method is currently used commercially.

Tjoe and Linnhoff⁹ extended the Pinch Design Method to retrofit using targeting procedures for energy-area trade-offs which subsequently translate into investment savings plots, followed by a retrofit design procedure that accounts for existing area. The method has been and is being used for years by many consulting and engineering companies for the retrofit of heat exchanger networks despite the high volume of mathematical programming methods developed in the last 40 years. It has also been heralded as the most simple and effective way to solve problems for crude units (see for example Rossiter¹⁰). The Pinch Technology-based retrofit method consists of three steps:⁹ (1) A targeting step where energy saving are computed and capital

investment is roughly estimated based on vertical heat transfer, (2) a design step based on Pinch Technology grassroots design analogies, and (3) an evolutionary step that includes a rearranging phase using loops and paths aiming at a better new area distribution (often forced to reduce the energy savings predicted in the targeting phase). This is also based on the grassroots principles of Pinch Technology.

While the estimation of capital investment in grassroots design using Pinch Technology is straightforward, this is not the case in retrofit design. The literature is vague in agreeing on a systematic methodology in the targeting phase. More specifically, a means to compute precisely the amount of additional area, the number of new exchangers and/or new shells, and the amount of repiping required in retrofitting the network are presented much more as a holistic procedure that requires experience in trial and error than a systematic algorithm with concrete steps. In other words, several alternatives are left to the discretion of the designer. Some suggest using only the added area, but there is the possibility of counting added shells. In addition, the method may miss the area needed for each HRAT because it relies on the computation of vertical heat transfer multiplied by a fixed factor called area efficiency. The selection of this area efficiency factor is of critical importance. The optimum is also found using different options (net present value, payback time, etc.). It is only in the design/retrofit phase of Pinch Technology, where details of network configuration and exchanger areas are available, that it is possible to compute the needed capital investment. Thus, capital investment could be significantly miscalculated in the targeting phase, which leads to nonoptimal solutions.

In addition, in the design/retrofit phase of Pinch Technology as applied to crude units some specific problems arise: (i) Having typically one cold stream versus many hot streams at the pinch, the method requires the cold stream to be split below the pinch, merge, and split again in a different fashion above the pinch, rendering unrealistic designs as we shall see later in our example

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for light crudes in atmospheric fractionation units. (ii) Sometimes, there is almost a second pinch, which adds additional complexity (i.e., merging and splitting at the pinch twice). (iii) crude units handling light crudes many times exhibit “extended pinch” or “continuous pinch”. Although one can formally encounter a pinch point, the reality is that from the practical point of view several values can be picked. (iv) The tick-off rule assumes a minimum number of units above and below the pinch separately, which leads to an excessive number of units. (v) The number of different options to explore is sometimes daunting for anybody that wants to explore them by hand. We will illustrate this issue.

In this work, we show that HIT is capable of handling the retrofit more efficiently in one single computer run, as opposed to the trial and error pinch method. In addition, we will show that the results are more reasonable (no splitting and merging at a pinch), and appreciably more profitable.

2. PINCH METHOD RETROFIT GUIDELINES

Retrofit design using Pinch Technology follows the same principle as that of grassroots design: targeting first, followed by network design. These are briefly described next:

Retrofit targeting: This task sets targets for energy saving and capital investment that maximizes the benefit (e.g., maximal net present value, return on investment, or minimal payback time). Consider the energy versus area plot shown in Figure 1:

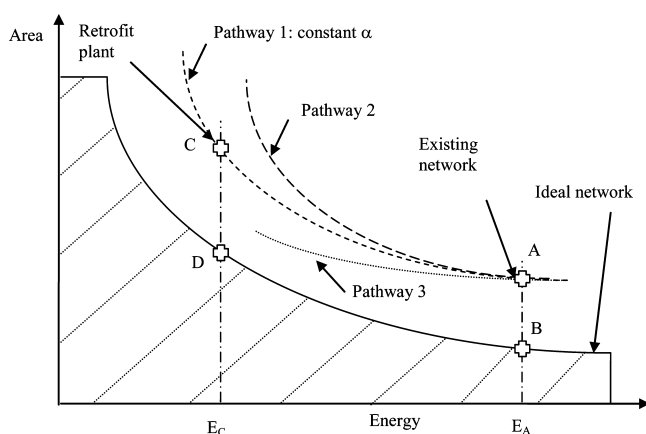


Figure 1. Energy versus area curves indicating (A) the existing network, (B) the minimum area needed for energy E_A , (C) the retrofit network, and (D) the minimum area needed for energy E_C .

point A refers to the existing network (which usually has some heat crossing the pinch), while point B refers to a “minimum area” network (obtained using vertical heat transfer; also called “ideal network”). This network has the same energy consumption as the existing network. In addition, the “minimum area” network points are such that there is no heat crossing the pinch. The ratio of the minimum area network divided by the area of the existing network is termed “area efficiency.” It is given by

$$\alpha_e = \left(\frac{A_{\text{minimum area}}}{A_{\text{existing}}} \right)_{\text{same energy}} = \left(\frac{A_A}{A_B} \right)_{E_A} \quad (1)$$

The value of α_e is less than 1. In Figure 1, point C refers to a candidate retrofitted plant with reduced energy consumption (E_C). In turn, point D refers to minimum area network with the

same energy consumption. The target area of the retrofitted network is therefore

$$A_C = \left(\frac{A_D}{\alpha_r} \right)_{E_C} \quad (2)$$

Figure 1 also shows three different scenarios: $\alpha_r = \alpha_e$ (pathway 1), $\alpha_r < \alpha_e$ (pathway 2), $\alpha_r > \alpha_e$ (pathway 3). A constant α pathway (pathway 1) is the most popular assumption in retrofit studies, and while pathway 3 is desired (smaller area), it may call for a greater degree of network modifications (area adjustment, repiping), and hence greater capital investment. Assuming a constant α pathway allows acquisition of A_D and E_C (pinch calculations), from which A_C can be readily calculated using pathway 2. Then, the energy saving ($E_A - E_C$) can be calculated and the capital investment can be estimated (e.g., purchase cost for new area can be obtained knowing A_A and A_C). Finally, optimal values for energy saving and capital investment can be found.

As one moves on a constant α pathway, the estimated capital investment increases (more area is added) and the energy savings increase. At some point, the investment is larger than the savings, which indicates the optimal point has been reached. To evaluate this tradeoff, a profitability measure (we use net present value) is used.

It has been suggested that this procedure should only be used if α_e is greater than 0.9.¹¹ In the event that α_e is less than 0.9, instead of equation (2), the new area ought to be calculated using the difference of vertical areas; that is,

$$A_C = A_A + (A_D - A_B) \quad (3)$$

Retrofit Design. While retrofit targeting is quite straightforward, retrofit design is a challenging task. No method of retrofit design has gained recognition as the “best” method. Successful retrofit design relies on a mixture of user expertise/experience, insightful knowledge about the process, and some inspired guesses. Kemp¹² describes three different retrofit design methodologies. We summarize them as follows: (1) Obtain a grassroots design for the targeted energy consumption. Where a choice exists, favor matches which already exist in the current network. (2) Start with the existing network and work toward the grassroots design for the targeted energy consumption. To do this, identify and partially remove exchangers that cross the pinch, and complete the network so the pinch matches are restored. If the area does not match the existing exchangers, use loops and paths to move heat. (3) Start with the existing network and identify the most critical changes required in the network structure to give a substantial energy reduction. This method will be appropriate if the “ideal” grassroots design is so different in configuration from the existing layout that they are virtually incompatible.

The first methodology is a bit vague and may produce networks that do not completely use the existing area. If there is more than one possible grassroots design (which is the case for crude units, where there are many as we will illustrate below), this method of enumeration may become an impractical task to produce the optimal retrofit design.

The second methodology is a little less vague, but it requires expertise to implement this method to do retrofit design. Even with that expertise, it may be quite difficult to obtain the energy target with the same area efficiency or better for a crude unit. Examples of retrofit network design using these guidelines can be found in Kemp.¹²

The third methodology is not systematic and it does not provide a recipe of actions to take (or even a list of issues to look at). It is so ad-hoc that it needs the use of intuition.

3. MATHEMATICAL PROGRAMMING MODEL (HIT)

Our Heat Integration Transportation Model (HIT) for grassroots design and retrofit of heat exchanger networks is based on mathematical programming. It was first developed for grassroots design,¹³ and it was then extended to perform retrofit study.⁸ It uses the concept of transportation of heat from hot streams to cold streams. Indeed, the hot and cold streams are divided into several small temperature intervals. Heat from a hot stream interval can only be transferred to a cold stream interval if the temperature difference allows it. The model “transports” heat from each hot interval to possibly more than one cold interval so that the economic objective is optimized. So far, these are the details of an old idea (see Cerda et al.¹⁴). Indeed, heat from a hot interval can only be transferred to a cold stream interval if the temperature difference allows it. Figure 2 depicts a generic hot

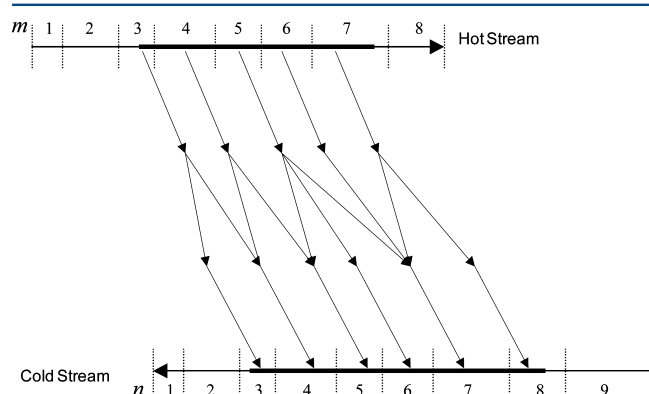


Figure 2. Transportation model concept with hot stream *m* transporting energy to cold stream *n*.

stream *m* divided into eight small temperature intervals and a generic cold stream *n* divided into nine small temperature intervals. Thus, a temperature interval (e.g., temperature interval “*m*₁”) represents a specific temperature interval of the process streams under consideration. For example, if the temperature span of the hot stream is 90–10 °C (inlet *T* = 90 °C, outlet *T* = 10 °C) then the temperature interval “*m*₁” represents temperature interval 90–80 °C while the temperature interval “*m*₈” represents

temperature interval 20–10 °C, etc. In Figure 2, we see that from hot stream *m*, interval 3, a small portion of its heat content is transferred to cold stream *n*’s intervals 3 and 4. The same happens with interval 4, which sends heat to intervals 4 and 5. In turn, interval 5 sends heat to intervals 5, 6, and 7. One can also note that in Figure 2 intervals 1, 2, and a portion of interval 3 for stream *m*, do not show any heat transferred. This is because this heat will eventually transfer to some other cold stream. We refer the reader to our older work¹³ for more explanation. The temperature difference between hot and cold intervals has to be positive and larger than any imposed exchanger minimum approach temperature (EMAT).

Our contribution to this old transportation model idea is a set of equations that can count exchangers, count shells, determine splitting, and even consider nonisothermal mixing, all in a linear model that does not need to consider a pinch. This is important because in cases like crude plants the Pinch Design Method presents problems: as we pointed out above it may exhibit a second pinch, a continuous (or extended) pinch and, it requires an important merge and split of the single cold stream (the crude) at the pinch. For retrofit cases, HIT can

- add exchangers
- add shells to existing exchangers
- add area to existing shells
- relocate existing exchangers
- split or merge streams in any pattern
- perform nonisothermal mixing
- consider an exchanger minimum approach temperature (EMAT) for each pair of streams
- avoid usage of a heat recovery approximation temperature (HRAT)
- avoid resorting to designs “above” or “below” any pinch temperature, which in crude units is a problem.

Moreover, unlike Pinch Technology, HIT does not rely on a sequence of targeting followed by design. Rather, it automatically takes into account the balance between savings and capital costs. In addition, it can automatically generate second best, third best solutions, etc. so it is ideal for exploring options in decreasing order of profitability and in a systematic manner. Finally, the model is linear, yet rigorous, which is important because it can take advantage of existing very powerful methods. Because it is linear, powerful (and reliable) linear solvers can be used. We use GAMS/CPLEX.

Table 1. Comparison of our HIT Model and the Pinch Method

	HIT model	Pinch Design method
approach	Simultaneous optimization of utility consumption and network configuration	Three-stage approach: (1) minimum utility targeting; (2) network design for minimum number of units; (3) use loops and paths to evolve.
design criterion	Simultaneous minimization of utility cost and capital investment	Same criterion but in a hierarchical manner: optimize utility consumption first, then the network configuration
design principle	The whole network is designed in one single model run. Heat can transfer across the pinch.	Design starts from the pinch point, sections above and below the pinch are designed separately.
retrofit targeting	HIT does not use a targeting step	Performed using an estimation of the cost of total area added.
retrofit design	The whole network is retrofitted in one single model run. Heat can transfer across the pinch. The model can compute new shells, new units, new splits, etc.	Typically the grassroots design is used as a starting point.
special cases	Automatically handles streams with varied heat capacity, the case of multiple utilities and even nonisothermal mixing.	Need special treatments for special cases like streams with varied heat capacity, multiple utilities or multiple pinches
usability	The program is user-friendly and requires no expertise from the users. The users can control network structure by using appropriate parameter values. It can solve industrial scale problems on a PC within a day	Require expertise of the user to make all the right decisions on splitting of stream, etc. according to the pinch design rules. The design process is time-consuming, especially for large scale problems and presents multiple alternatives.

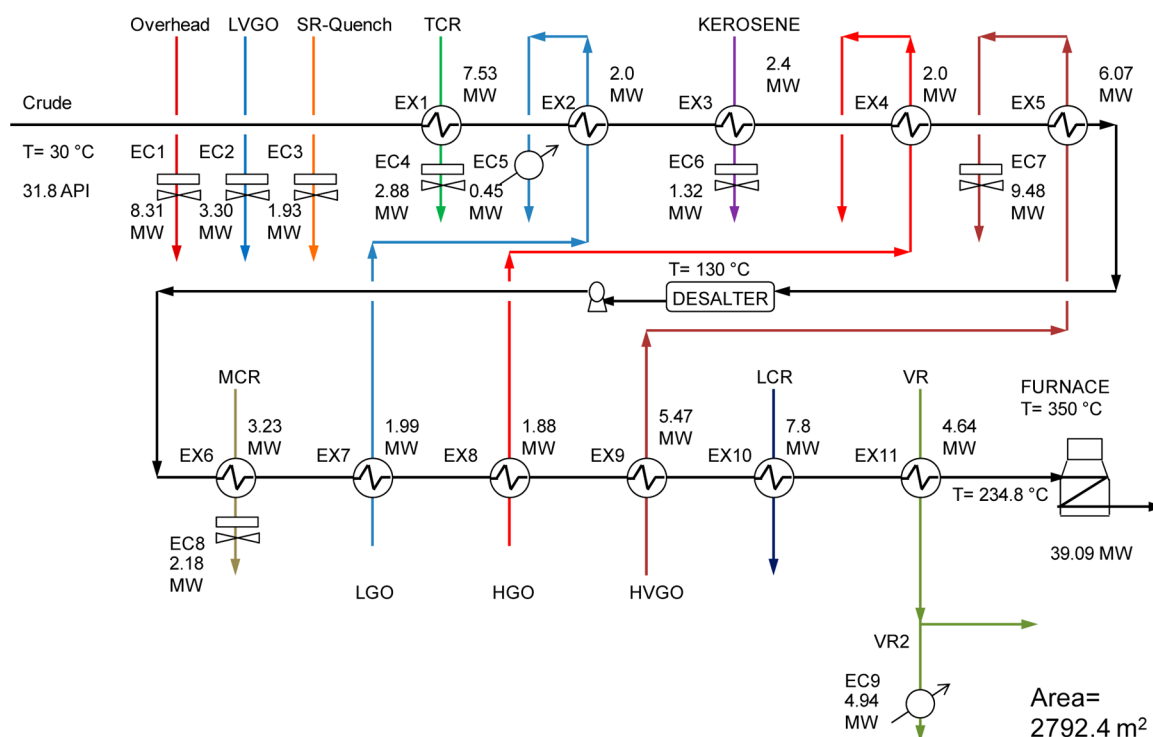


Figure 3. Existing network design for a crude at 31.8 API and 10 hot streams.

Table 2. Exchanger Information for Example

Exchanger	EX1		EX2		EX3		EX4		EX5		Desalter Crude T=130°C	
Cold Stream	CRUDE		CRUDE		CRUDE		CRUDE		CRUDE			
Flow (ton/day)	8330.3		8330.3		8330.3		8330.3		8330.3			
	In	Out	In	Out	In	Out	In	Out	In	Out		
Temperature (°C)	30.0	70.0	70.0	80.0	80.0	91.9	91.9	101.6	101.6	130.0		
Hot Stream	TCR		LGO		KEROSENE		HGO		HVGO			
Flow (ton/day)	4000.0		1100.0		1273.6		850.0		4760.6			
	In	Out	In	Out	In	Out	In	Out	In	Out		
Temperature (°C)	140.2	69.3	190.0	125.4	170.1	101.5	206.0	121.9	212.6	167.6		
DUTY (MW)	7.53		2.00		2.40		2.00		6.07			
Exchanger	EX6		EX7		EX8		EX9		EX10		EX11	
Cold Stream	CRUDE		CRUDE		CRUDE		CRUDE		CRUDE		CRUDE	
Flow (tonm/day)	8350.2		8350.2		8350.2		8350.2		8350.2		8350.2	
	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
Temperature (°C)	130.0	145.0	145.0	153.7	153.7	161.9	161.9	185.0	185.0	216.7	216.7	234.8
Hot Stream	MCR		LGO		HGO		HVGO		LCR		VR	
Flow (tonnm/day)	4000.0		1100.0		850.0		4760.6		7000		2023.5	
	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
Temperature (°C)	210.0	181.9	248.8	190.0	277.0	206.0	250.6	212.6	303.6	270.2	360.0	290.0
DUTY (MW)	3.36		1.99		1.88		5.47		7.80		4.64	

In our second paper,⁸ we describe the extension of the grassroots model to retrofit. We presented two models, one that considers adding shells to existing and new units and another that also considers unit relocation.

To summarize the differences between the HIT model and the Pinch Design Method, HIT requires a single model run to optimize the utility consumption and network design (configuration, shells, units, splits, etc.) as per provided economic parameters. It does not require a targeting step and does not have heat transfer restrictions associated to a pinch. A versatile approach, HIT does not have difficulty handling special circumstances like varying heat capacities,

multiple utilities, nonisothermal mixing, or phenomena in the composite curves. HIT only requires implementation of network parameters to the model, thus it is very user-friendly. In turn, the Pinch Method requires a targeting step to determine the optimal utility followed by designing a network. Design starts at the pinch with a network developed separately above and below the pinch. Even when retrofitting, the grassroots design is typically the starting point. The method requires special treatment for special circumstances like those listed above. It is not a very user-friendly method and requires expertise to make the right decisions. It can also be very time-consuming if there are many possibilities for the network.

Table 3. Heater/Cooler's information for Example

Heater/Cooler	EC1		EC2		EC3		EC4		EC5		EC6	
Stream	Overhead		LVGO		SR-Quench		TCR		LGO		KEROSENE	
Flow (tonm/day)	994.3		1653.7		662.4		4000.0		1100.0		1273.6	
	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
Temperature (°C)	117.7	50.0	178.6	108.9	359.6	280.0	69.3	39.5	125.4	110.0	101.5	60.0
DUTY (MW)	8.31		3.30		1.93		2.88		0.45		1.32	
Heater/Cooler	EC7		EC8		EC9		FURNACE					
Stream	HVGO		MCR		VR2		CRUDE AD					
Flow (tonm/day)	4760.6		4000.0		2023.5		8350.2					
	In	Out	In	Out	In	Out	In	Out				
Temperature (°C)	167.6	90.0	181.9	163.0	290.0	115.0	234.8	350.0				
DUTY (MW)	9.48		2.18		4.94		39.09					

Table 4. Overall Heat Transfer Coefficients and Areas for Exchangers in Example

	EX1	EX2	EX3	EX4	EX5	EX6	EX7	EX8	EX9	EX10	EX11
U (kW/(m ² ·K))	0.2	0.4	0.3	0.35	0.2	0.2	0.4	0.35	0.2	0.28	0.31
area (m ²)	707	63	182	96	411	240	74	68	473	324	154

The characteristics of the HIT model, as compared against the pinch design method, are summarized in Table 1.

4. EXAMPLE

Consider an existing network (Figure 3), which uses one crude oil with an API of 31.8 at 8330 ton/day. Currently, the furnace heats the crude from 234.8 to 350 °C, with a furnace utility of 39.09 MW. Table 2 provides exchanger information for the flow rates of each stream, the temperatures of the streams in and out of the exchanger, and the duty of each exchanger. Table 3 provides the same information for the heaters and coolers. Table 4 provides the overall heat transfer coefficients and areas of each exchanger.

Assumptions. In developing and economically analyzing the Pinch Technology and HIT networks, we required a few assumptions regarding the design decisions and economic parameters. First, we assumed that exchangers did not have to stay in a particular order. If the model called for a change then we permitted it without considering additional piping costs. Although alternative heat exchangers may be applicable to a given network, and probably have a higher benefit, this study is only looking at the use of standard S&T heat exchanger units. We priced the exchangers on the basis of a fixed cost per shell, a variable cost per area, and installation costs at 50% of the equipment costs. The maximum area for a given shell is assumed to be 500 m². We assumed the cost of energy to heat the furnace is \$100 per kW-year. The furnace runs at 80% efficiency. We only consider the exchanger investment and the energy savings. Costs due to splitting and cooling are not considered in the capital costs as they have a much smaller impact. Table 5 summarizes all of our economic assumptions.

We also develop simulations matching measured values using PRO/II (Invensys) to see how the network actually performs. This is essential as a simulation can show possible problems with both model results. This is so because, especially for Pinch Technology, assumptions of average heat capacity are usually taken.

Using the defined data from this simulation, composite curves are constructed. These composite curves are developed using the average FCP values across a given stream and the initial and final temperatures of each stream. The crude stream is divided into

Table 5. Assumptions Made for This Analysis

furnace utility costs (\$/(Kw·yr))	100.00
area addition costs (\$/m ²)	271.20
fixed exchanger cost (\$)	127,129
maximum area per shell (m ²)	500
installation cost as a percent of equipment cost	50%
interest rate	10%
furnace efficiency	80%

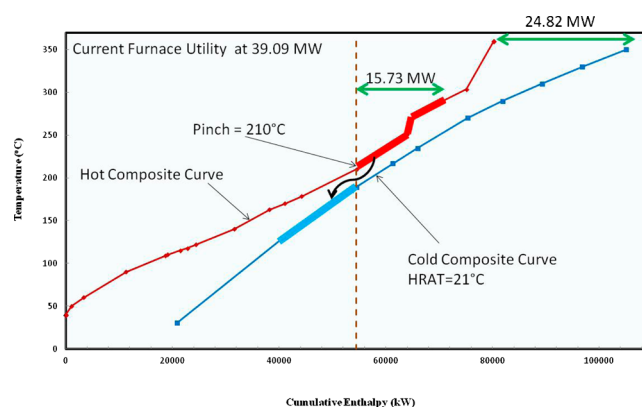


Figure 4. Example network composite curves showing energy crossing the pinch at 210 °C.

multiple intervals after the desalter to account for FCP changes, which gives rise to the curved cold composite. We also note that no vaporization occurs. Figure 4 shows the composite curve for the example network. The HRAT selected for these curves is the minimum temperature difference between the hot and cold side of all exchangers in the existing network (21 °C at exchanger EX3). We also show the amount of heat crossing the pinch.

The pinch occurs at 210 °C for the hot composite curve. At this HRAT, a minimum utility of 24.82 MW is possible. No problematic phenomena such as a second pinch or continuous/extended pinch occur in this example, meaning that Pinch Technology should have no trouble producing a network. The network has 15.73 MW crossing the pinch, something that needs

fixing. This is the difference between the current furnace utility and the minimum utility at an HRAT of 21 °C. In the network, it relates to the exchangers that experience pinch crossing: EX5, EX7, EX8, and EX9. It also includes any energy above the pinch that dumped into the cold utility: SR-Q and VR2.

Pinch Technology Retrofit Targeting. For retrofit targeting using Pinch Technology, we sought the optimal net present value of savings over 10 years minus the investment (additional cost of new exchangers and new shells for existing exchangers). It is not clearly stated in the different pinch retrofit procedures that fixed costs per shell ought to be added, but because HIT actually considered them, we added to the cost per area the cost of new shells. To obtain the optimal NPV, we varied the utility usage based on an area efficiency of 0.68, the existing network value. As this value is smaller than 0.9, we used eq 3 to calculate the targeted retrofit area. When the piecewise FCP is used for the crude, the maximum NPV is obtained for HRAT = 30 °C (see Figure 5), which has a minimum utility of 27 MW with

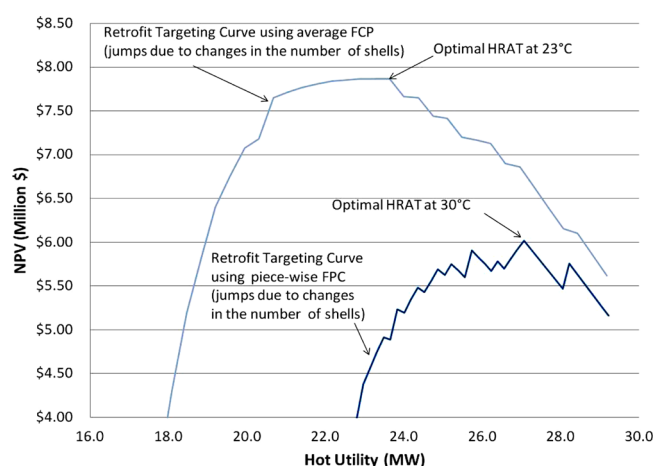


Figure 5. Results from the targeting phase (NPV) for average and piecewise FCPs.

the pinch remaining at 210 °C. This amounts to a total savings of 12.09 MW of energy. The discontinuities in the NPV curves correspond to changes in the number of shells. Figure 5 also shows the NPV curve corresponding to retrofit targeting using average FCP. Notice how the NPV curve based on average FCP shows a much more optimistic NPV with the optimum to be around a hot utility value of 23.5 MW (this corresponds to an HRAT = 28 °C). This difference arises because the average FCP of the cold composite underestimates the minimum utility. The cold composite consists of two streams, a stream before the desalter and a stream after the desalter. The average FCP of the stream after the desalter includes the energy before the pinch and after the pinch. Thus, using the average FCP above the pinch underestimates the minimum utility and overestimates the energy required to reach the pinch. Figure 6 shows the composite curves for each case, that is, piecewise and average FCP. The area below the pinch increases when using average FCP, but it also decreases above the pinch. In addition, we found that the total area does not differ significantly between the two cases. The minimum utility of the average FCP case for HRAT = 30 °C is approximately 24 MW, rendering a difference between the two methods of approximately 3 MW. As we want to utilize pinch in a way that obtains the best network possible, we base our analysis on the piecewise retrofit targeting.

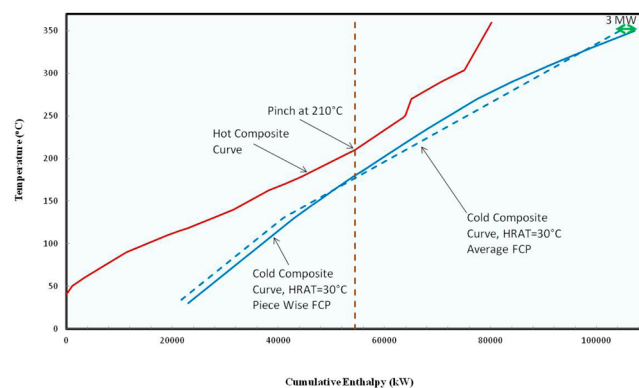


Figure 6. Comparison of composite curves for average and piecewise FCP.

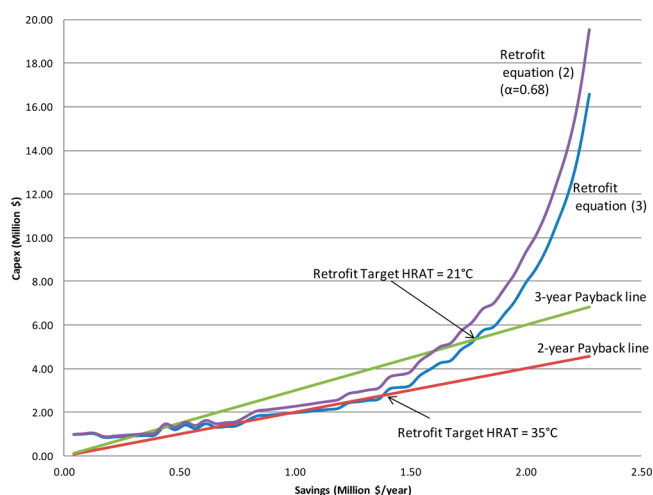


Figure 7. Results from the targeting phase indicating the payback for $\alpha = 1$ (suggested when $\alpha < 0.9$) and $\alpha = 0.68$ (current network efficiency).

Similarly, if we use paybacks of 2 or 3 years (see Figure 7), for the piecewise FCP case only, which is the one we use from now on, the answer is different. In the same figure, we also provide a comparison of the savings versus the investment if the current efficiency of 0.68 was used in equation 2.

Pinch Technology Network Design. We start using the NPV criterion, by identifying which exchangers cross the pinch (Figure 8). As we indicated earlier, no vaporization occurs for the cold streams before the furnace. We still use piecewise FCPs for the crude after the desalter to account for adjustments in FCP in our analysis. In Figure 8, we mark all exchangers that cross the pinch and indicate the energy crossing the pinch with parentheses. The FCP of the crude stream into the furnace ranges between 224 and 328 kW per °C. We indicate only the average FCP of 288 kW per degree °C for the crude after the desalter.

Above the pinch, there is only one possible pinch design, but below the pinch, the number of different networks is too large for any pinch expert to perform by hand in a reasonable amount of time. Indeed, we found that 23 possible networks are possible using only 11 exchangers below the pinch (the predicted minimum number). Of the 23, only one solution uses all the exchangers present in the original network and does not add new matches before the desalter (Figure 9). In Figure 9, dotted lines indicate new exchangers and solid lines indicate existing exchangers. If new area is to be added, a +A sign is located close to the exchanger. All splits are new.

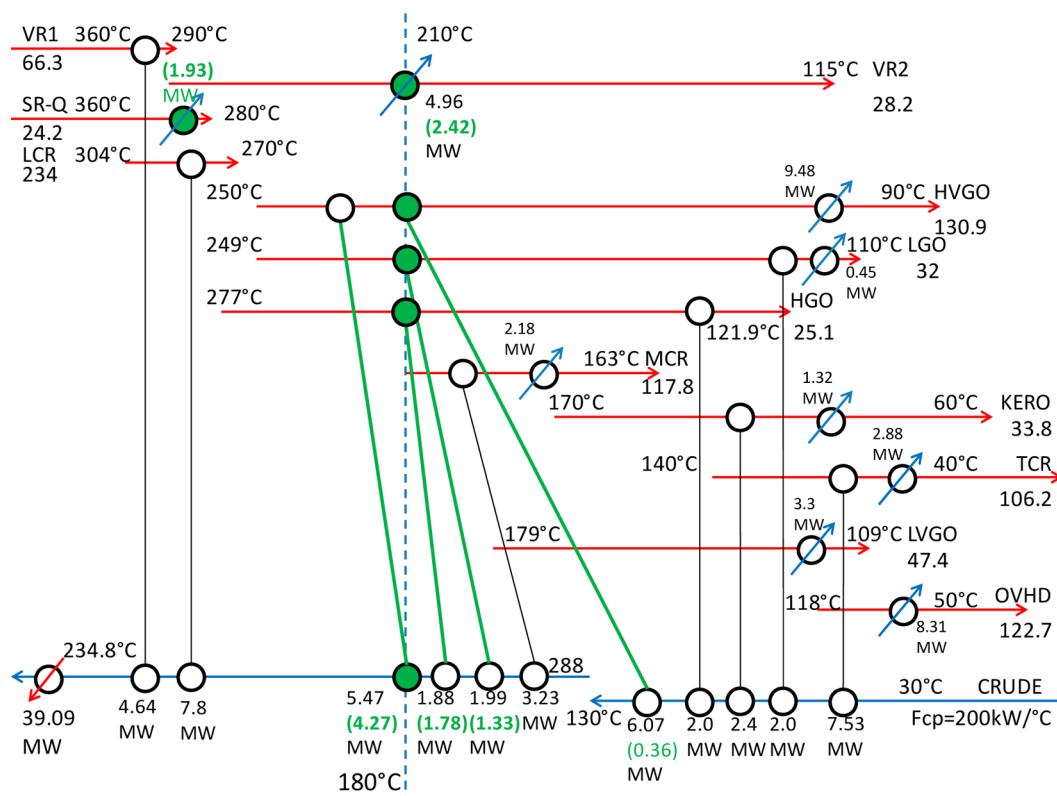


Figure 8. Original network. Energy crossing the pinch is in parentheses and is represented by shaded exchangers; stream connections represent existing exchangers.

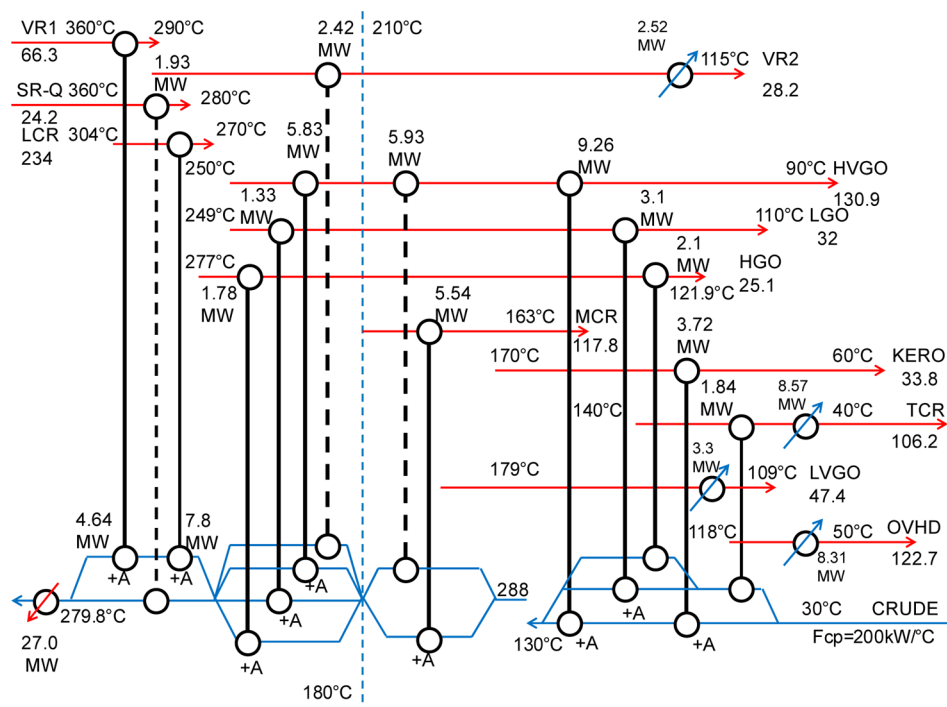


Figure 9. Pinch Design Network: Solid connections are existing exchangers, dash connections are new exchangers, +A represents area addition.

Once we designed the network of Figure 9, we found that the number of splits is characteristically high in addition to the problematic merging and resplitting at the pinch (the pinch is located after the exchangers in two branches after the desalter, namely MCR and HVGO). All networks with 11 exchangers

below the pinch and 8 above (the minimum possible) exhibit this problem of splitting and remerging at the pinch. All other splits are made to keep the network at an HRAT of 30 °C.

As per the network before the desalter, it also exhibits an undesired splitting complexity that if explored further may

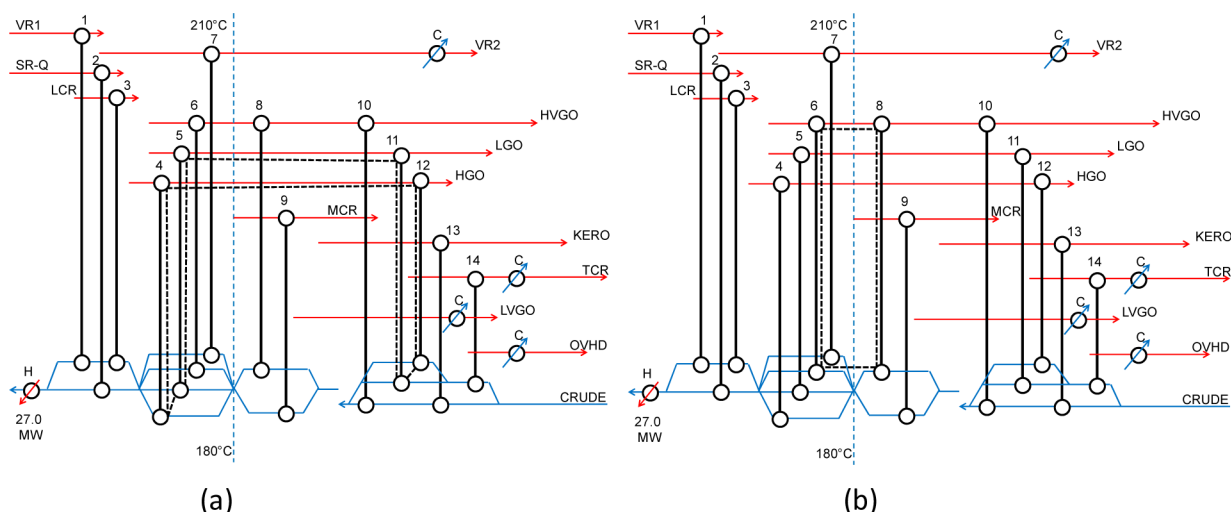


Figure 10. Pinch design network detailing loops: (a) loop starts at exchanger 4 and proceeds as follows 4–5–11–12–4; (b) loop starts at exchanger 6 and proceeds as follows 6–8–6.

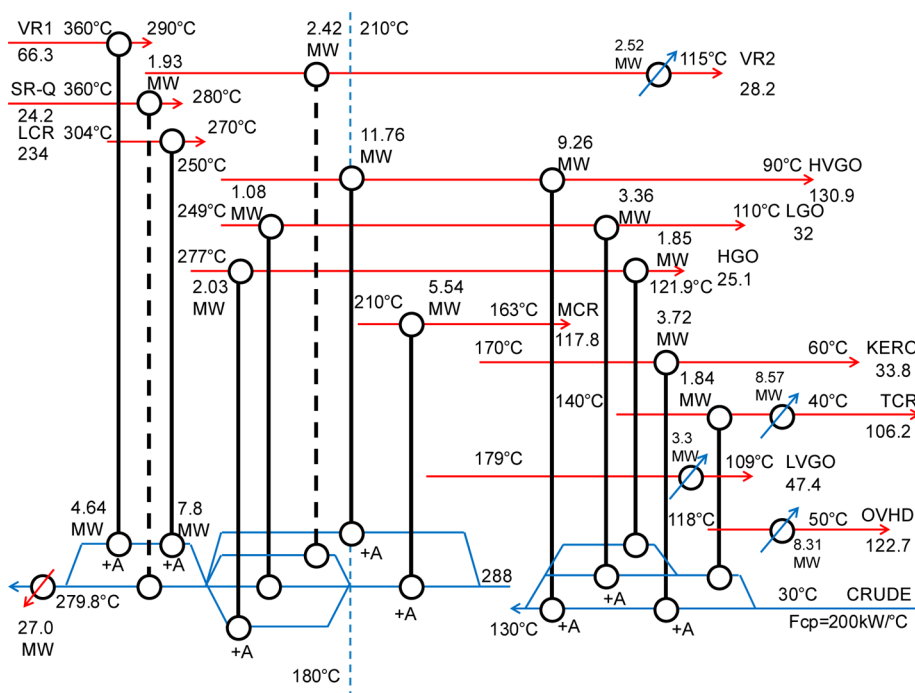


Figure 11. Pinch Design Network after loops: solid connections are existing exchangers, dash connections are new exchangers, +A represents area addition.

be simplified. Other networks of the 23 found could exhibit more simplicity (more coolers with fewer splits). We omit discussing all the alternatives as they share the same complexity problem.

Pinch Technology Evolution. The next step suggested in the Pinch Design Method is to use loops to simplify the network, mostly to reduce the area addition to existing exchangers and replace it with area added to new exchangers. After this, one can use paths to restore HRAT if needed and/or desired. The network has 22 observable loops. Figure 10 indicates the specific loops used to transfer area. The resulting network shown in Figure 11 is the PDM network design after loops only. The network is feasible with an $\text{EMAT} = 20^\circ\text{C}$. We notice that aside from transferring area, one major concern is to reduce the splitting, which was partially accomplished.

Figure 12 depicts the paths used to restore the retrofit target of $\text{HRAT} = 30^\circ\text{C}$. We determined that there are five possible paths in the network. If the minimum temperature difference in the network is reasonable (which it is with an $\text{EMAT} = 20^\circ\text{C}$), it may be advisable to keep the network as is with an EMAT smaller than the HRAT selected and not use a path. If the reduction in energy does not reduce a sufficient amount of area, then the network in Figure 11 would be more desirable. The optimal trade-off can be determined through economic analysis of the networks. Figure 13 shows the network after paths have been explored. Any further changes would be allowing for pinch crossing methods or knowledgeable guesses.

Although the network of Figure 13 improves the area slightly, the economics will show that it is not enough to overcome the reduction in savings of 1 MW. Thus, the best network design

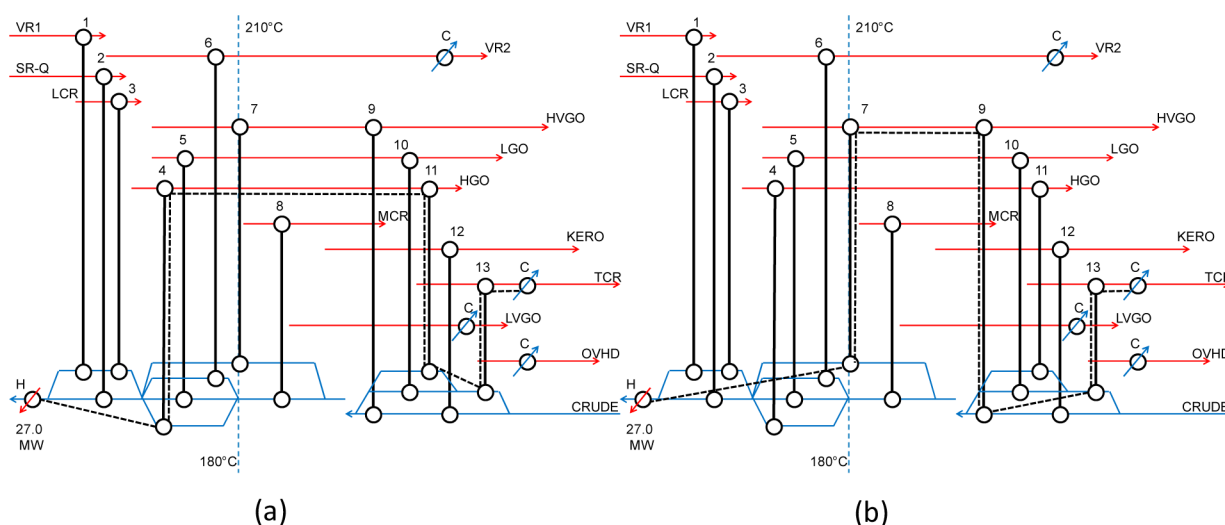


Figure 12. Pinch design network detailing paths: (a) path starts at hot utility and proceeds as follows H-4-11-13-C; (b) path starts at hot utility and proceeds as follows H-7-9-13-C.

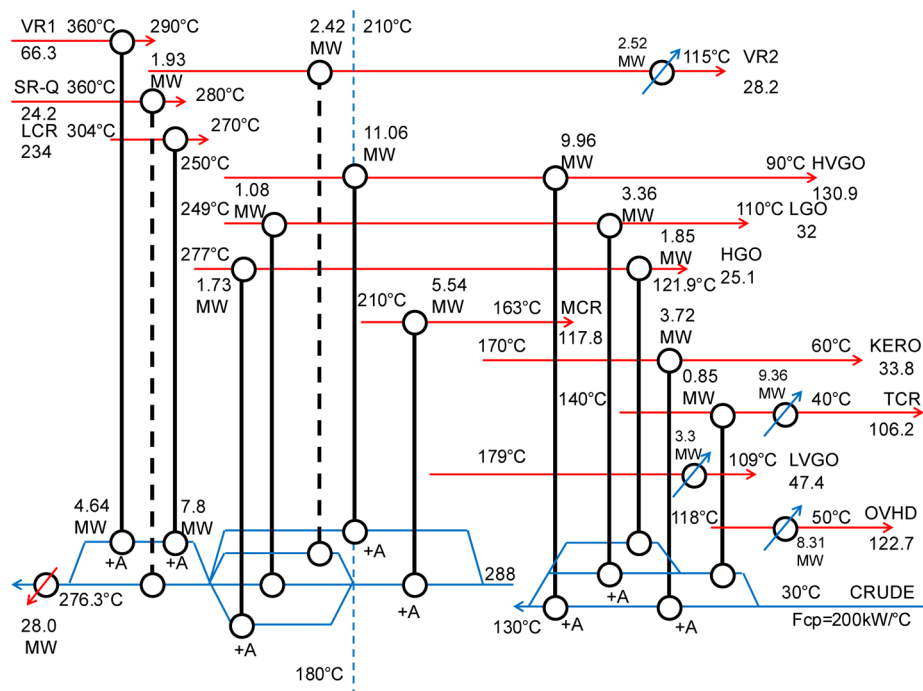


Figure 13. Pinch Design Network after loops and paths: solid connections are existing exchangers, dash connections are new exchangers, +A represents area addition.

corresponds to Figure 11 where an EMAT of 20 °C is used. The network uses 5889 m² across 13 exchangers requiring the addition of only 13 shells. Its furnace utility is 27 MW with an outlet temperature of 279.8 °C. A process flow diagram of Figure 11 is provided in Figure 14.

Something to consider is that the network area of the pinch retrofit design does not completely use the existing area. The only way of fixing this is to break the tick-off rule and allow the energy to be shifted around so that the existing area is completely used. The existing network has pre-existing coolers that would allow for this. The only other issue that we would like to examine further with pinch is the number of splits.

Analysis beyond Pinch Technology. While pinch retrofit recipes suggest that loops and paths be used to move new area around, preferably to a new exchanger, the network may still

remain overly complex due to splits. The pinch design for our example has too many splits, a total of five with one using multiple branches. To reduce the number of splits while keeping the same utility usage, we took the network after loops and then looked at the possibility of allowing some matches to crisscross the pinch. We considered the HRAT to be fixed; therefore, the minimum utility would not be reduced, and we used an EMAT of 20 °C.

Through analysis of the location of each exchanger, we determined that the Crude2-LGO match could be before the Crude2-HVGO match. We then removed the split after the pinch and moved the Crude2-HGO match onto another branch. This resulted in a simple structure around the pinch but with issues in the temperature difference. By reusing the loops and adjusting the FCP of the crude between the branches,

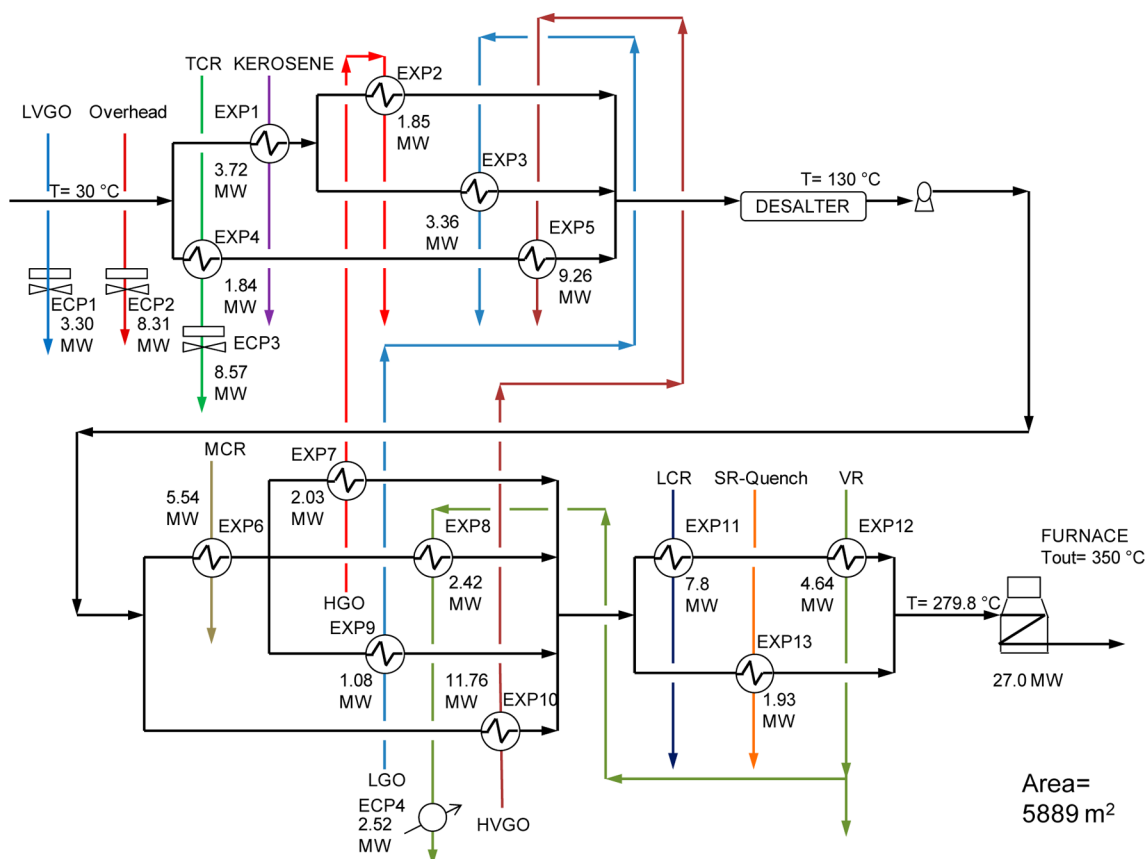


Figure 14. Pinch Network process flow diagram: design based on the pinch design network after loops (see Figure 11).

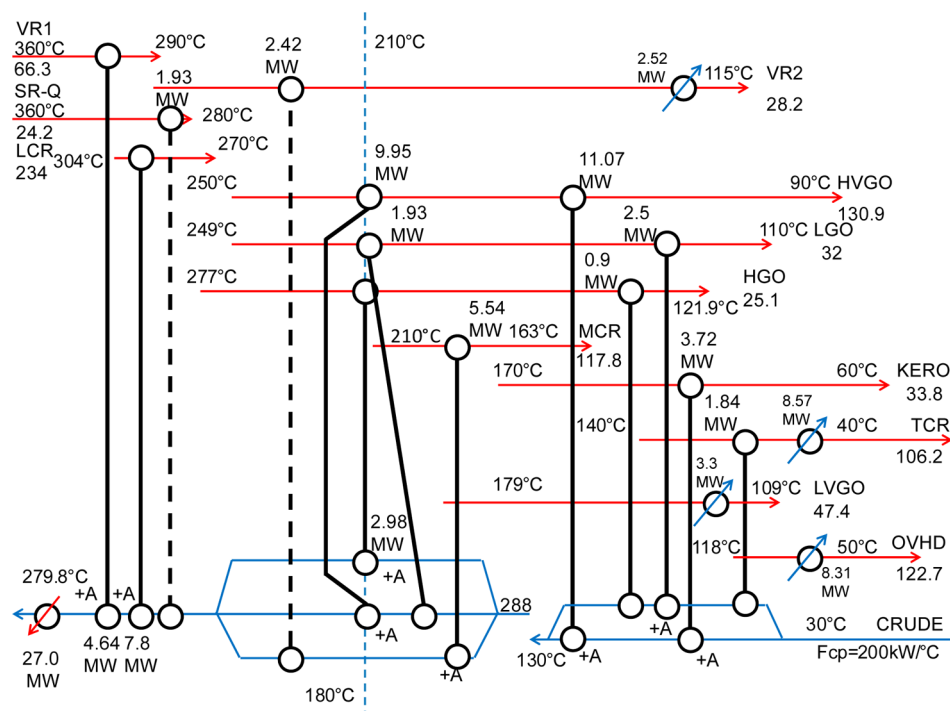


Figure 15. Pinch Design network modified for reduced splitting: solid connections are existing exchangers, dash connections are new exchangers, +A represents area addition.

the network EMAT was restored to 20 °C. With the allowable temperature difference that low, we also removed some of the splits away from the pinch. In particular, we removed the second

split before the desalter and placed the Crude1–LGO match in series with the Crude1–HGO match. Energy was transferred around a loop once again to keep temperature differences above 20 °C.

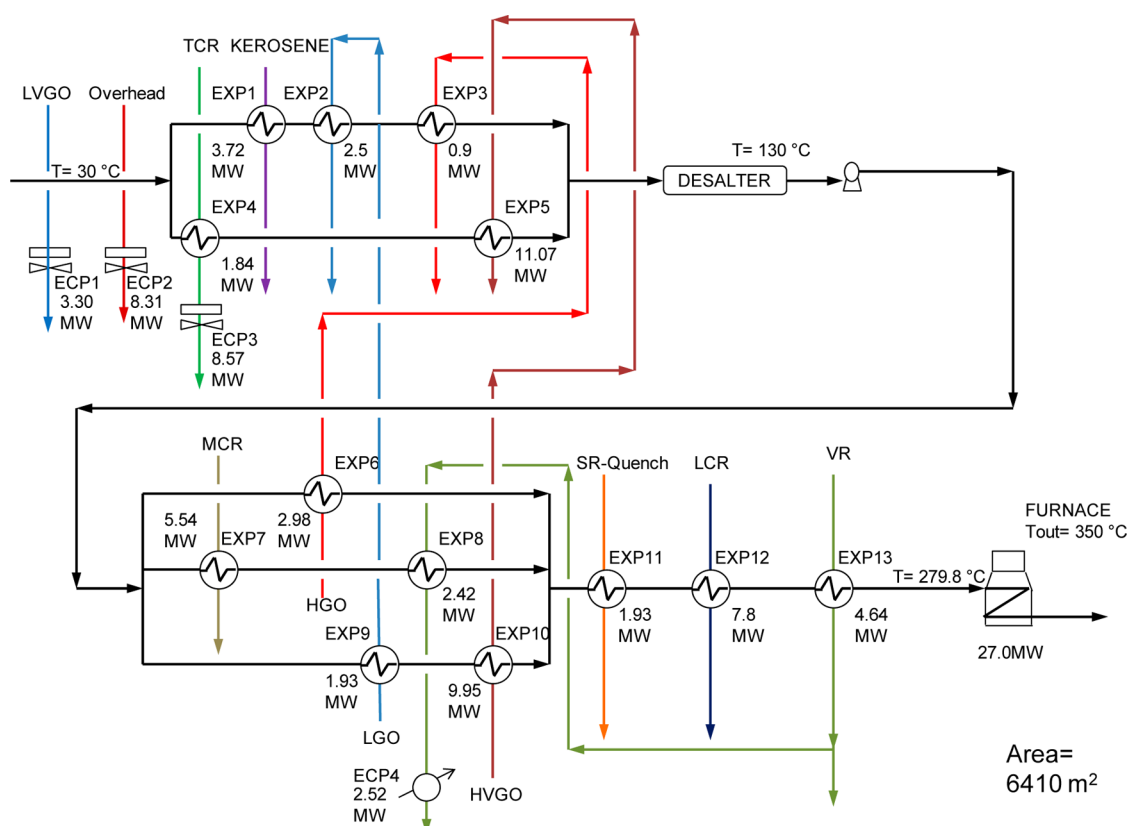


Figure 16. Modified Pinch Network process flow diagram: design based on reduction of splits by allowing crisscrossing at the pinch (see Figure 15).

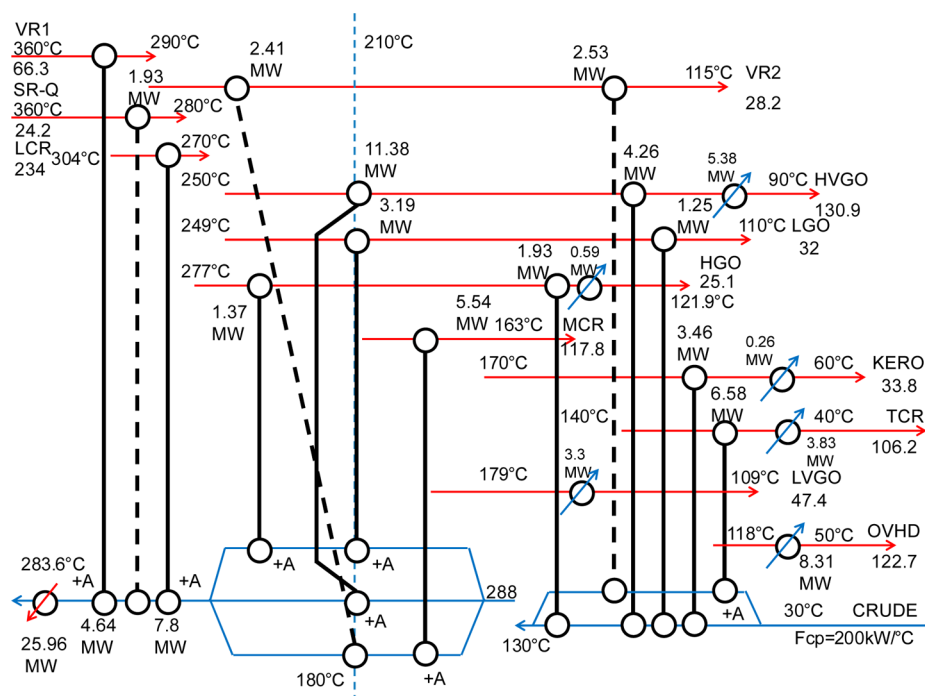


Figure 17. HIT retrofit design: solid connections are existing exchangers, dash connections are new exchangers, +A represents area addition.

Finally, the last three exchangers are placed in series. The temperature difference was adequate so no paths were required to keep above the EMAT of 20 °C. This produces a far simpler network with only one split before the desalter and one split after the desalter with three branches. The resulting design detailing the matches is depicted in Figure 15, the network process flow diagram is in Figure 16.

HIT Results. As indicated, HIT uses temperature intervals of heat transfer to determine the design, not the pinch. All that we obtained from Pinch Technology is the minimum utility at various HRATs. The method can also have constraints added, like for instance, the maximum number of splits for each individual stream. With these details, the software determines the

Table 6. Comparison of HIT and Pinch Technology Results and Simulated Result

	HIT			pinch				
	result	simulation result	error	result using average FCP	result using piecewise FCP	result from simulation	error for average FCP	error for piecewise FCP
new area (m ²)	4077.4	3881.8	−5.0%	3152.2	3791.8	3638.6	13.4%	−4.2%
new shells	12	13	7.7%	15	14	14	−7.1%	0.0%
furnace utility (MW)	25.96	25.98	0.1%	26.32	26.96	27.0	2.5%	0.1%

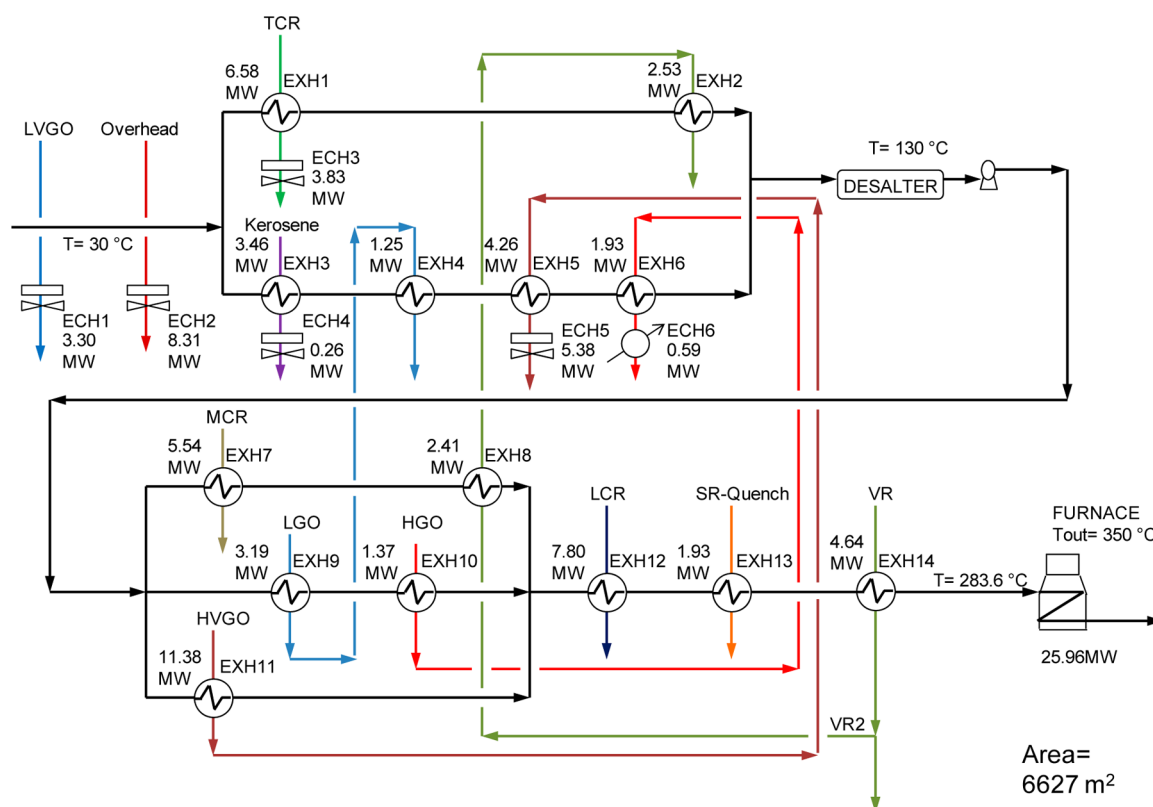


Figure 18. HIT network process flow diagram: based on HIT retrofit result.

optimal network that meets the constraints and uses the optimal area and heating utility. While costs of splitting are not considered (as in the case of Pinch Technology), we did limit the network to only one split before the desalter and three splits after. Although it is possible to restrict the location of a particular match, we did not place this restriction on our HIT run.

We ran HIT with $EMAT > 5$ °C as a constraint (no limitations on the utility used), maximizing NPV, and it produced the network seen in Figure 17. We then simulated the network using only the locations and duties of each exchanger obtained by the software results. Although the split flow rates are also provided by HIT, we usually see if adjusting the flow rates can minimize the area further in the simulation, just as we did with the results of Pinch Technology. The area determined by the software is not without error, the severity of which is dependent on the number of temperature intervals used and the FCP associated to each interval. For this network, we found that using 140 temperature intervals in HIT overestimated the area by 5%. It should be noted that we only used 52 different FCP values (25 FCPs for the 11 hot streams, 25 FCPs for the 2 cold streams, and 1 FCP each for the hot and cold utility) across all 140 intervals, which is where most of the error may arise. HIT predicted one less shell than what simulation indicates is required. Using more intervals is

possible and it would reduce the error at a larger computational cost, but as we show later, the difference in NPV is small enough to accept the result. To compare HIT to pinch, if we obtained the area using the average FCPs and temperatures in pinch for the initial pinch result (Figure 8), we would find that it underestimates the area by 13.4% compared to the simulation of the pinch network. In addition, it overestimates the possible energy savings. In turn, the deviations are smaller when the piecewise FCP is used. The disparities between the expected result and simulated results for HIT and Pinch are provided in Table 6.

The HIT design of Figure 17 is simple, with only one split before the desalter and one split with three branches after the desalter. The network reaches a furnace utility of 25.96 MW, with a furnace inlet temperature of 283.6 °C. The required network area is approximately 6627 m² across 14 heat exchangers. This area required only 13 new shells across the network. This means that as far as design goes, the network is much more feasible, but uses roughly 750 m² more and the same number of shells as the Pinch Technology design. The HIT network has 1 MW of savings more than the Pinch Technology network. Figure 17 shows the HIT design using matches while Figure 18 shows the HIT design process flow diagram.

The HIT network has fewer splits and branches than the pinch design. It is more comparable to the design after analysis beyond PT. This HIT network is a simple network with higher savings and comparable area requirements.

The economics are detailed in Figure 19, showing a comparison of the net present values of all the solutions. First, we

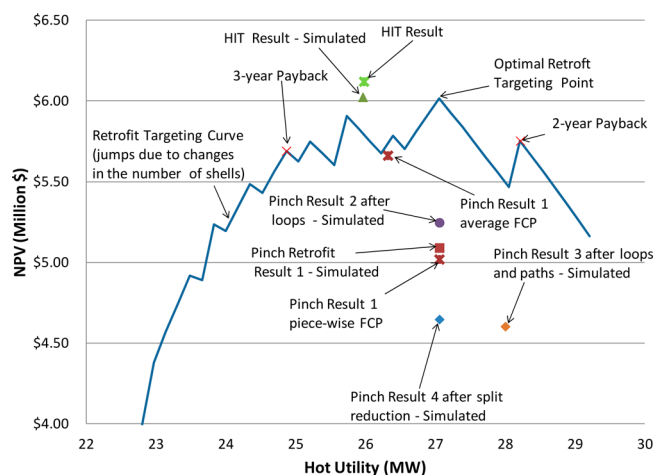


Figure 19. Economics of HIT and Pinch Technology indicating the NPV for the HIT result: all points in the development of the pinch network, and the corresponding simulations.

note that pinch targeting (the curve on top) is very optimistic because it underestimates the area needed. Once the network was simulated, we calculated the areas and obtained the point labeled “Pinch Retrofit Result 1 Simulated”. The network corresponding to Figure 11 (labeled “Pinch Retrofit Result 2 after loops”) has the best NPV for Pinch Technology. The use of paths to restore the minimum temperature difference, as in Figure 13, results in a poor NPV.

A few critical details can be noticed from Figure 19. First, the use of average FCP can lead to results that are not realistic. This disparity is indicated by the smaller hot utility and larger NPV when using average FCP compared to piecewise or simulated pinch results. The NPV is larger because of the difference in area from the network and minimum utility. Second, the pinch simulated result is close to the piecewise calculation, but for the use of average FCP the result is quite different. The simulated design of pinch performs better than the piecewise design because the simulation has very small intervals of FCP. The use of average FCP gets both the furnace utility and the area wrong as indicated earlier. The HIT result performs slightly better than the HIT result simulated. This is an issue with the number, size, and FCP of intervals used. In this case, HIT did not see the area that needed to be added to one of the exchangers, while simulation indicates that a new area, and thus a new shell, must be added.

Table 7 summarizes our findings for the HIT result and the pinch result for the best pinch network and a simplified pinch network. We notice that the results from HIT and from Pinch Technology differ from their corresponding simulated results. Simulations are done in such a way that the energy consumption is the same. Thus, the area is adjusted and therefore the NPV changes a little. The results of this analysis indicate that HIT produces (a) a more reasonable network, and (b) a more profitable network than pinch technology.

HIT found an optimal furnace utility (26 MW) smaller than the utility retrofit targeting predicts (27 MW). We made all effort

Table 7. Summary of HIT and Pinch Results

	HIT	pinch after loops	pinch after reducing splits
energy savings (MW)	25.96	27.0	27.0
new area (m ²)	3881.8	3722.8	4258.4
no. of new shells	13	13	15
no. of new units	3	2	2
savings (\$ million/year)	\$1.64	\$1.51	\$1.51
investment (\$ million)	\$4.06	\$4.00	\$4.59
NPV (\$ million)	\$6.02	\$5.29	\$4.69

possible to make the pinch retrofit method succeed in proving its best. We even went farther from its recommendations to simplify the network, one of the biggest problems. Indeed, pinch renders two splits before the desalter and three splits after the desalter with as many as four branches when only loops and paths were considered. The HIT network, in contrast, requires one split before and one after the desalter. Finally, HIT obtains an NPV over 10 years of \$6.02 million, while pinch does not exceed an NPV \$5.29 million.

5. CONCLUSIONS

We pointed out the difficulties one can have using the pinch design method in crude units. These difficulties are rooted in the fact that it requires starting the designs at the pinch, which leads to branching above and below the pinch utilizing a lot more exchangers than needed, and especial expertise on the subject to “evolve” the design. Our HIT model provides more reasonable and more profitable designs, without the need of user built-in expertise in one single run. Specifically:

- The strict pinch retrofit result is overly complex from the operational point of view. Even when loops are used to simplify it, the network is still complex, albeit a bit better economically. Usage of paths makes matters worse.
- HIT predicts a network with larger savings (1 MW more) than the pinch targeting predicts. This has an impact on the NPV. The network also exhibits a more reasonable crude split.
- HIT largely outperforms the pinch result rendering a simpler network and a higher NPV (~15% better in this example).
- The roots of the problems for Pinch Technology are (a) bad targeting (pessimistic in this case; 1 MW difference with HIT) and, (b) complex networks, that is, too many splits.
- After one attempts to fix the splitting problems using analysis beyond pinch technology, the economics actually deteriorates further.

Finally, we point out the need for simulations (we used Pro II) to provide a realistic analysis of the networks. Because of these simulations, both HIT and Pinch Technology exhibit adjustments in area calculations, and the economics is adjusted accordingly.

AUTHOR INFORMATION

Corresponding Author

*E-mail: bagajewicz@ou.edu.

Notes

The authors declare no competing financial interest.

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To perform our simulations we used Pro/II from Simsci/Invensys.

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