

# **Heat Exchanger Network Retrofit Comparison**

*Trevor Hallberg and Sarah Scribner*

# Table of Contents

Executive Summary.....	4
Introduction .....	5
Paper Overview.....	6
Example 1.....	7
Example 2.....	9
1. Mixed Integer Linear Programming.....	12
1.1 Exchanger Location .....	12
1.2 Area Restrictions.....	13
1.3 Cost Analysis .....	13
1.3.1 Area Reduction .....	14
1.3.2 Area Addition .....	14
1.3.3 New Exchanger .....	14
1.3.4 Exchanger Relocation.....	14
1.3.5 Stream Splitting.....	14
1.4 Objective Function .....	14
2. Process Pinch Technology .....	16
2.1 Introduction .....	16
2.2 Stream Data .....	16
2.3 Composite Curves and $\Delta T_{\min}$ .....	17
2.4 Supertargeting .....	22
2.4.1 Area Targeting.....	22
2.4.2 Vertical Heat Transfer .....	24
2.4.3 Area Efficiency .....	26
2.4.4 Optimum $\Delta T_{\min}$ value .....	31
2.5 Heat Exchanger Matches .....	35
2.6 Heat Exchanger Area.....	39
2.7 Cost Comparisons.....	43
3. Pinch Improvement.....	45
3.1 Relocation .....	45
3.2 Pro-II.....	45
3.2.1 Controllers .....	46
3.2.1 Calculator.....	46
3.2.1 Optimizer .....	47
4. Discussion.....	48
4.1 No Relocation (Example 1).....	48
4.1.1 MILP Results.....	48
4.1.2 Process Pinch Results.....	49
4.1.3 Pro-II Results .....	50
4.1.4 Cost Comparison.....	51
4.2 Allow Relocation (Example 1) .....	53
4.2.1 MILP Results.....	53
4.2.2 Process Pinch Results.....	55
4.2.3 Pro-II Results .....	56
4.2.4 Cost Comparison.....	56
4.3 No Relocation (Example 2).....	58

4.3.1 MILP Results.....	58
4.3.2 Process Pinch Results.....	59
4.3.3 Pro-II Results .....	60
4.3.4 Cost Comparison.....	61
4.4 Allow Relocation (Example 2) .....	63
4.4.1 MILP Results.....	63
4.4.2 Process Pinch Results.....	64
4.4.3 Pro-II Results .....	64
4.4.4 Cost Analysis .....	65
5. Recommendations .....	67
Appendix .....	69

## List of Figures and Tables

Table 1. Stream Properties for Example 1 .....	7
Figure 1. Original heat exchanger network for Example 1. ....	8
Table 2. Existing heat exchanger areas for Example 1.....	8
Table 3. Stream Properties for Example 2 .....	9
Figure 2. Original heat exchanger network for Example 2. ....	10
Table 4. Existing heat exchanger areas for Example 2.....	11
Table 5. Amount and cost of each utility for the original HEN of Example 2.....	11
Figure 3. MILP models.....	12
Figure 4. Possible locations for new exchangers .....	13
Figure 5. Typical process flow-sheet of an HEN.....	16
Figure 6. Composite curve generation.....	17
Table 6. Data to create hot composite curve for Example 1. ....	18
Table 7. Data to create cold composite curve for Example 1. ....	18
Figure 7. Composite curve for Example 1. ....	19
Figure 8. Process separation by pinch. ....	20
Figure 9. $\alpha$ units of cross-pinch heat transfer.....	20
Table 8. Data to calculate the pinch temperature for Example 1.....	21
Figure 10. Grand composite curve for Example 1.....	22
Figure 11. Area vs. Energy plot. ....	23
Figure 12. Area vs. Energy plot for retrofitting.....	23
Figure 13. Vertical heat transfer. ....	24
Table 9. Data to calculate the target area. ....	26
Figure 14. Retrofit Curve.....	26
Figure 15. Retrofit curve areas.....	27
Table 10. Area results for Example 1. ....	29
Figure 16. Optimum area efficiency.....	29
Table 11. Area results for Example 2. ....	30
Figure 17. Area vs. Energy diagram for Example 1. ....	30
Figure 18. Area vs. Energy diagram for Example 2. ....	31
Figure 19. A typical Total Annualized Cost (TAC) vs. $\Delta T_{\min}$ diagram.....	32
Figure 20. TAC vs. $\Delta T_{\min}$ plot for Example 1. ....	34
Figure 21. TAC vs. $\Delta T_{\min}$ plot for Example 1. ....	34
Figure 22. Grid diagram for the original heat exchanger network for Example 1. ....	35
Figure 23. Grid diagram for the retrofitted heat exchanger network for Example 1. ....	37
Figure 24. Grid diagram for the retrofitted heat exchanger network for Example 1. ....	39
Table 12. Results for the streamwise area distribution, $A_j$ .....	40
Table 13. Results for the matchwise area distribution, $A_m$ .....	41

Table 14. Process pinch Example 1 area results. ....	42
Figure 25. Pro-II simulation. ....	46
Figure 26. Retrofitted HEN from the MILP methodology ....	49
Figure 27. Retrofitted HEN from the process pinch methodology. ....	50
Table 15. Final network areas and $\Delta T_{min}$ values for Example 1 disallowing relocation. ....	51
Figure 28. Retrofitted HEN from the Pro-II simulation ....	51
Table 16. Cost comparison data for Example 1, disallowing relocation. ....	52
Figure 29. Comparison between various methodologies, disallowing relocation.....	52
Table 17. Results of ROI calculations for Example 1, disallowing exchanger relocation. ....	53
Figure 30. Retrofitted HEN from the MILP methodology. ....	54
Figure 31. Retrofitted HEN from the process pinch methodology. ....	55
Table 18. Final network areas and $\Delta T_{min}$ values for Example 1 allowing relocation. ....	56
Figure 32. Retrofitted HEN from the Pro-II methodology.....	56
Table 19. Results of cost comparison for Example 1, allowing exchanger relocation.....	57
Figure 33. Comparison between various methodologies, allowing relocation ....	57
Table 20. Results of ROI calculations for Example 1, allowing exchanger relocation.....	58
Figure 34. Retrofitted HEN for the MILP for Example 2, disallowing relocation ....	59
Figure 35. Retrofitted HEN for the process pinch methodology for Example 2, disallowing relocation....	60
Figure 36. Retrofitted HEN for the Pro-II simulation for Example 2, disallowing relocation.....	61
Table 21. Final network areas and $\Delta T_{min}$ values for Example 2 disallowing relocation. ....	61
Table 22. Fixed capital investment results and cost analysis for Example 2 ....	62
Figure 37. Cost and profit analysis for Example 2 for a project life of 7.5 years ....	62
Table 23. Fixed capital investment results and cost analysis for Example 2 ....	62
Figure 37. Cost and profit analysis for Example 2.....	62
Figure 38. Retrofitted HEN for MILP, allowing exchanger relocation.....	63
Figure 39. Retrofitted HEN for process pinch methodology, allowing exchanger relocation ....	64
Figure 40. Retrofitted HEN for the Pro-II simulation, allowing exchanger relocation ....	65
Table 24. Final network areas and $\Delta T_{min}$ values for Example 2 allowing relocation. ....	65
Table 25. Fixed capital investment results and cost analysis for Example 2 ....	66
Figure 41. Cost and profit analysis for Example 2.....	66
Table 26. Fixed capital investment results and cost analysis for Example 2 ....	66
Figure 41. Cost and profit analysis for Example 2.....	66
Table 26. Computation time and user-involvement comparison between retrofit methodologies.....	67
Figure A1. Result Comparisons for a project life of 5 years.....	69
Figure A2. Result Comparisons for a project life of 10 years.....	70
Figure A3. Result Comparisons for a project life of 15 years.....	70

# Executive Summary

## Heat Exchanger Network Retrofit

The retrofit of heat exchanger networks (HEN) is a complicated process to design and implement. Several solutions to the retrofit problem have been suggested. This paper will compare two specific approaches and evaluate the most effective and useful methodology. Also, this paper will attempt to improve process pinch technology by incorporating optimization software and other techniques.

## Mixed Integer Linear Programming

The Mixed Integer Linear Programming (MILP) methodology allows the user to tailor the program for very specific scenarios. This is beneficial for the retrofit application because industrial retrofit problems are numerous and varied. The MILP maintains the intricateness of the retrofit problem by not making any of the classical simplifying assumptions. Another benefit of the MILP is the ability to easily change the objective function, which allows the user to optimize a variety of cost functions.

## Process Pinch

The process pinch methodology is based on thermodynamic principles that set energy savings and cost targets prior to the design of a HEN. The goal of pinch analysis is to maximize the process-to-process heat recovery and minimize the utility requirements of a system. The pinch method allows the engineer to locate specific regions within the current network where process change will result in a reduction of the overall energy consumption of the system.

## Process Pinch Improvements

This work presents improvements to the process pinch methodology which include allowing the relocation of existing heat exchangers and the incorporation of software optimization. The relocation of existing heat exchangers has an associated fixed cost which, in some cases, may be less than the costs associated with the addition of a new heat exchanger. Also, the incorporation of software optimization with the process pinch methodology allows Pro-II to optimize heat exchanger areas while maintaining stream target temperatures. This optimization procedure was applied to the optimal HEN exchanger location generated from the process pinch methodology.

## Discussion

From the comparison of the above listed technologies, it was found that the MILP was the superior methodology based on ease and timeliness of use, as well as the ability to tailor the program to solve a wide range of retrofit problems. The limitations of the pinch technology, even with the addition of the improvement methods, make it the less preferred method in an industrial setting.

## Introduction

Energy conservation became a priority for the oil and gas industry during the energy crisis of the late 1970's. Now, due to the current economic situation, energy integration has once again become an important concern. One of the most direct approaches for energy savings is the retrofit of existing heat exchanger networks. Various technologies and approaches have been applied to the HEN retrofit problem.

For many years the standard of energy integration was pinch technology. Pinch technology optimizes a HEN through the incorporation of thermodynamic properties of the process streams. Recent improvements to pinch technology include the development of the network pinch<sup>1</sup>. The network pinch incorporates HEN topology along with process stream data into its analysis. This advantage allows the user to optimize exchanger location as well as exchanger area. The network pinch methodology requires the user to have in depth knowledge of the HEN capabilities and model formulation.

A mixed integer linear programming (MILP) model has been proposed by Barbaro and Nguyen. The MILP is capable of many real-world optimizing scenarios, such as non-isothermal mixing, exchanger relocation, repiping costs, and incorporating various costs for exchanger area manipulation. The scenarios for the manipulation of exchanger area include area added to an existing shell, area added as a new shell, area reduced by plugging tubes, and area reduced by bypassing exchangers. Another benefit of the MILP is the ability to manipulate the objective function. This allows the user to optimize a variety of cost and profit variables to generate an optimal solution for various design constraints.

Another HEN retrofit methodology includes the use of genetic algorithms (GA). Due to the use of binary variables, GAs can easily become complicated formulas which require extensive computational time. One approach to this problem is presented by Bochenek and Jezowski<sup>2</sup>. This methodology includes splitting the optimization into two levels which separately optimize structural changes and parameter changes. However, implementation of this methodology includes limiting the search space by finding process and network pinches. Additionally, GAs commonly locate a local optimum instead of the global optimum.

Additional retrofit methodologies include the use of simulated annealing (SA) and a nonlinear programming (NLP) algorithm as master and slave problems, respectively<sup>3</sup>. The use of a SA procedure is not as effective as a GA because of the limited search procedure of the SA. SA is best used to find suitable answers in a small amount of time and not necessarily the global optimum. Also, the use of a NLP algorithm allows for the opportunity for the problem to fail to converge. Although non-convergence is only reported to exist in approximately 10% of the problems, the use of a NLP algorithm is viewed as a non-ideal methodology. Stochastic mathematical optimization is used in a Random search method<sup>4</sup>. This method allows for topological changes in the HEN as well as the introduction of stream splitting. However, this mathematical approach is limited to medium-scale industrial tasks. Another retrofit procedure is to optimize the HEN based on pressure drop constraints<sup>5</sup>. This method ensures that HEN designs meet the system pressure requirements by individually designing heat exchanger shell arrangements. The benefits of this procedure include an effective use of existing area as well as heat-transfer enhancement. However, this method cannot guarantee a global optimum due to the

problem's strong nonlinearity and high nonconvexity. A simultaneous approach for changes in stream parameters and HEN topology has been suggested<sup>6</sup>. This method allows for changes in the process streams of a crude distillation unit. Varying cut point temperatures and flow rates relaxes some of the constraints on the HEN design. This model bridges the gap between single-system and entire-process optimization. Although this approach is novel and extremely useful for real world scenarios, a generic model has yet to be developed that would allow users to quickly and easily apply this technique.

## Paper Overview

The goal of this paper is to compare the methodologies and results of two HEN retrofit procedures including process pinch and MILP. The attributes and shortcomings of each methodology will be analyzed in an effort to determine the best method for a specific HEN retrofit problem. Additionally, this paper will present improvements to the process pinch methodology in an effort to obtain an optimal design while decreasing computation time.

Each methodology will be applied to two specific retrofit situations. The first is a problem adapted from Ciric and Floudas<sup>7</sup> and will be named Example 1. The methodology of the paper will be based on Example 1. The second problem is adapted from Barbaro *et. al*<sup>8</sup> and will be named Example 2. The results for Example 1 and Example 2 presented in the Discussion section.



## Example 1

This problem consists of three hot and two cold process streams and one hot and one cold utility stream. The current design has 2 coolers and 1 heater in the process. The stream data is shown in Table 1. The existing exchanger network configuration is shown in Figure 1. The existing network does not have splitters. For this example we will separately compare the results of allowing and disallowing heat exchanger relocation. For the case that disallows heat exchanger relocation, alterations in the HEN may only include new exchanger addition and area addition or reduction to existing exchangers, as well as the introduction of split streams. Since it is desirable to reduce the use of utilities, no additional utility exchangers are considered. The original HEN consumes 17,759 kW of hot utility at \$0.0113/MJ and 15,510 kW of cold utility at \$0.00238/MJ. Table 2 identifies the existing heat exchangers' original areas, which were calculated using the log mean temperature difference. The results will be compared for a project life of 5, 10, and 15 years. 350 working days per year is assumed.

**Table 1. Stream Properties for Example 1**

Stream	F kg/s	Cp kJ/kg.C	Tin °C	Tout °C	H kW/m <sup>2</sup> .°C
H1	228.5	1	159	77	0.4
H2	20.4	1	267	88	0.3
H3	53.8	1	343	90	0.25
HU (hot utility)		1	500	499	0.53
C1	93.3	1	26	127	0.15
C2	196.1	1	118	265	0.5
CU (cold utility)		1	20	40	0.53

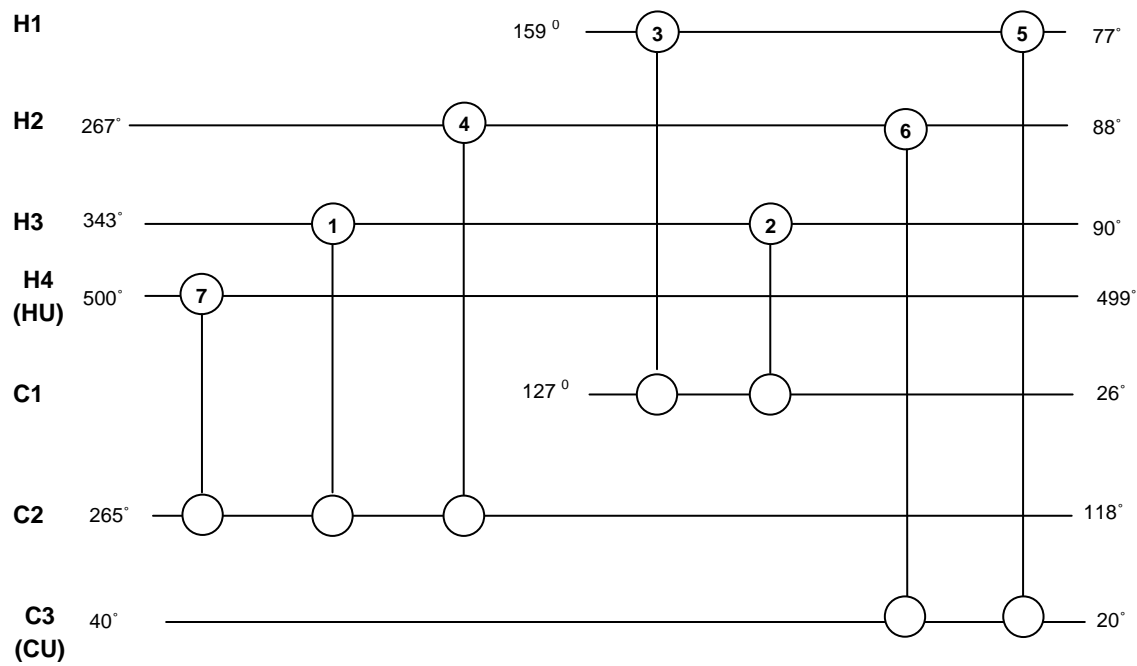


Figure 1. Original heat exchanger network for Example 1.

Table 2. Existing heat exchanger areas for Example 1

Exchanger	Existing Area (m <sup>2</sup> )
1	609.7
2	579.2
3	1,008.5
4	117.96
5	787.5
6	104.6
7	246.75

## Example 2

This problem is the retrofitting of a crude distillation unit. The network consists of 18 streams and 18 exchangers. The current design uses two hot utilities and three cold utilities. The stream data is shown in Table 3. The existing exchanger network configuration is shown in Figure 2. The existing network does not have splitters. For this example we will compare the results of allowing and disallowing heat exchanger relocation. For the case that disallows heat exchanger relocation, alterations in the HEN may only include new exchanger addition and area addition or reduction to existing exchangers. The original HEN consumes 67,964 kW of hot utility and 75,051 kW of cold utility. Table 4 identifies the existing exchangers' original areas, which were calculated using the log mean temperature difference. The amount and costs of each utility used is shown in Table 5. The results will be compared for a project life of 7.5 and 15 years and presented in the Discussion section. 350 working days per year is assumed.

**Table 3. Stream Properties for Example 2**

Stream	F Ton/hr	T in °C	T out °C	Cp kJ/kg·°C	H MJ/hr·m <sup>2</sup> ·°C
H1	155.1	319.4	244.1	3.161	4.653
H2	5.695	73.24	30	4.325	18.211
H3	251.2	347.3	202.7	3.02	3.210
		202.7	45	2.573	2.278
H4	151.2	263.5	180.2	2.930	4.894
H5	26.03	297.4	203.2	3.041	4.674
		203.2	110	2.689	3.952
H6	86.14	248	147.3	2.831	4.835
		147.3	50	2.442	3.800
H7	91.81	73.24	40	2.262	4.605
H8	63.99	231.8	176	2.854	5.023
		176	120	2.606	4.846
H9	239.1	167.1	116.1	2.595	4.995
		116.1	69.55	2.372	4.880
H10	133.8	146.7	126.7	6.074	1.807
		126.7	99.94	4.745	3.373
		99.94	73.24	9.464	6.878
HU1		250	249		21.600
HU2		1000	500		0.400
C1	519	30	108.1	2.314	1.858
		108.1	211.3	2.645	2.356
		211.3	232.2	3.34	2.212
C2	496.4	232.2	343.3	3.540	2.835
C3	96.87	226.2	228.7	13.076	11.971

		228.7	231.8	15.808	11.075
CU1		20	25		13.500
CU2		124	125		21.600
CU3		174	175		21.600

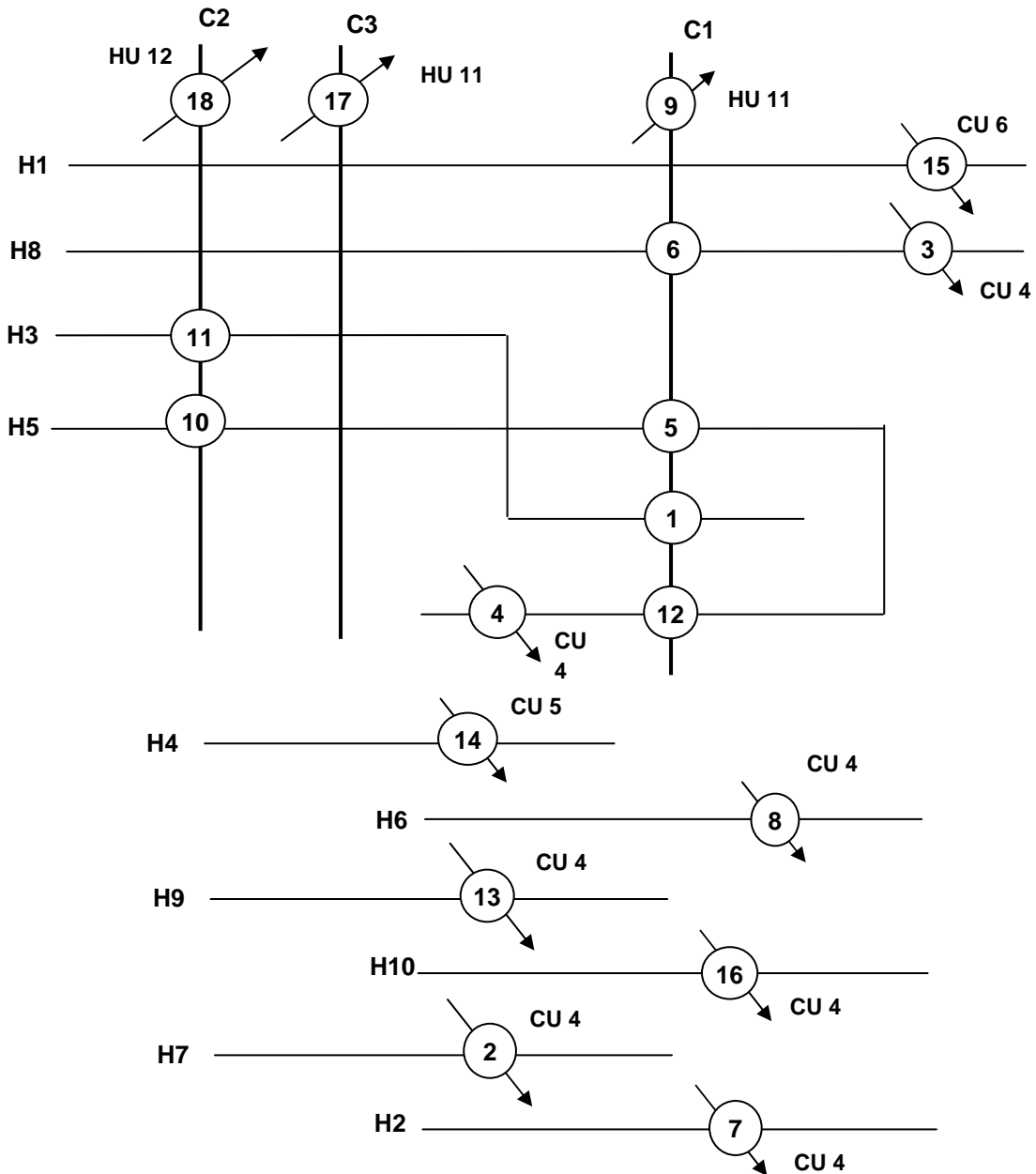


Figure 2. Original heat exchanger network for Example 2.

**Table 4. Existing heat exchanger areas for Example 2**

Exchanger	Area (m <sup>2</sup> )	Heat load (MJ/hr)	Exchanger	Area (m <sup>2</sup> )	Heat load (MJ/hr)
1	4303.20	159491.5	10	93.70	3998.7
2	63.80	6903.1	11	685.70	55438.0
3	33.17	17083.8	12	40.00	6293.8
4	4.07	1192.5	13	182.39	58042.3
5	26.30	2554.7	14	101.47	36903.2
6	19.55	2446.9	15	93.87	36917.4
7	5.87	1065.0	16	288.97	67053.1
8	146.59	45024.5	17	52.24	7913.8
9	1211.22	100960.4	18	979.62	135794.5

**Table 5. Amount and cost of each utility for the original HEN of Example 2.**

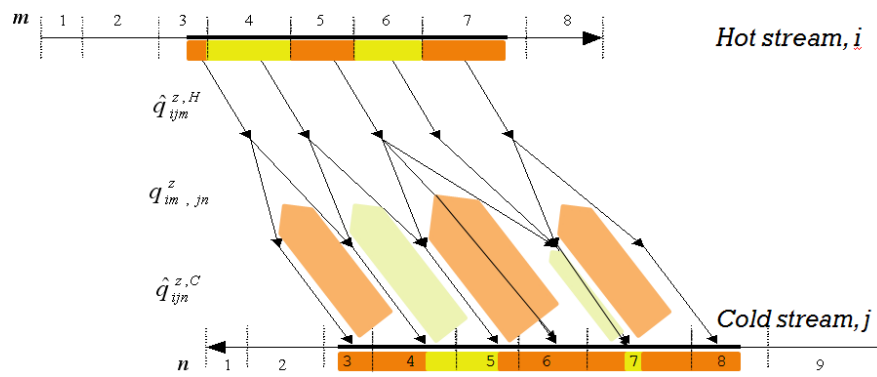
Hot utility	Cost (cent/MJ)	Amount (MJ/hr)	Cold utility	Cost (cent/MJ)	Amount (MJ/hr)
H11	0.2351	108874.21	C4	0.0222	196364.3
H12	0.4431	135794.5	C5	0.0773	36903.2
			C6	0.1518	36917.4
Total hot utilities (MJ/hr)		244,668.7	Total cold utilities (MJ/hr)		270,184.9

# 1. Mixed Integer Linear Programming

The MILP procedure for a HEN retrofit is based on a grassroots application<sup>9</sup> that does not include any of the classical simplifying assumptions, while also considering stream splitting and non-isothermal mixing. The application of the grassroots MILP to the retrofit case maintains the basic structure of the original MILP, but also includes additional constraints to account for retrofit requirements. An in depth presentation of the MILP procedure and its associated equations is presented in the paper by Barbaro and Quang, titled “MILP Formulation for the Retrofit of Heat Exchanger Networks”, which is awaiting publication. In the following work an overview of the MILP is presented which highlights the intricacies of the procedure.

This retrofit MILP model is based on transportation and transshipment models, which allow the model to quickly and effectively distribute heat between hot and cold streams. This approach is shown below in Figure 3. The use of preexisting models as well as the linearization of the HEN retrofit problem ensures that the MILP will generate a feasible solution. The MILP is capable of considering heat exchanger relocation, as well as repiping costs. The cases of allowing and disallowing heat exchanger relocation are separately compared. However, both cases allow the addition of new exchangers, amending existing exchangers’ area, and allowing stream splitting.

The implementation of the MILP includes the user inputting specified parameters. The MILP allows for many parameters to be limited by maximum values determined by the user. This allows the program to be tailored to generate feasible solutions for a variety of scenarios.

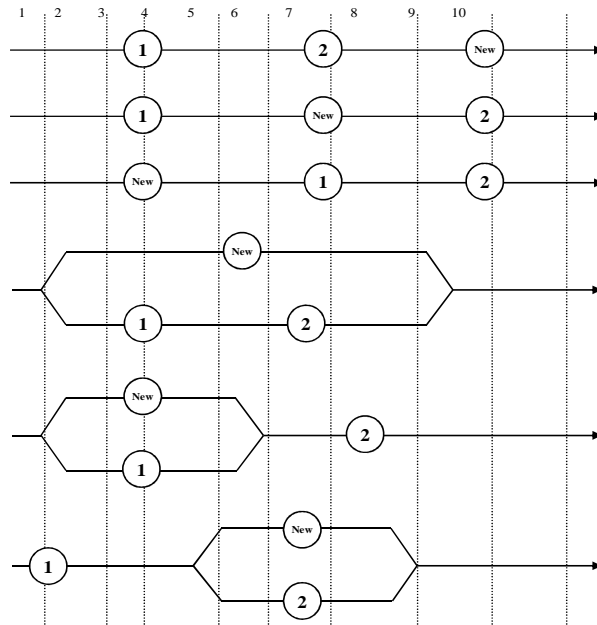


**Figure 3. MILP models.**

Representation of transshipment and transportation models as applied to heat transfer.

## 1.1 Exchanger Location

The MILP allows new exchangers to be placed in series or parallel to any of the existing heat exchangers. Figure 4 illustrates some of the possible locations for new exchangers, where **1** and **2** represent existing exchangers. Should the addition of new exchangers require the splitting of existing streams, the MILP accounts for additional repiping costs.



**Figure 4. Possible locations for new exchangers**

The MILP also allows the user to limit the number of new exchangers added to the existing HEN.

### **1.2 Area Restrictions**

The MILP allows the user to restrict the solution to realistic exchanger sizes, as well as practical changes in existing exchanger areas. In the case of Example 1, the maximum area per shell is set to 5,000 m<sup>2</sup> and each exchanger is limited to a maximum of 4 shells. This generates a maximum exchanger area of 20,000 m<sup>2</sup>. The addition of area to existing exchangers is limited to 20% of the existing area. The addition of area to existing exchangers is defined as increasing the area of existing shells or adding new shells to an existing exchanger. The reduction of area is limited to 50% of the existing area. The MILP analyzes multiple cases for area reduction, including plugging existing tubes or bypassing exchangers via new or existing piping.

### **1.3 Cost Analysis**

The MILP accounts for fixed and variable costs that are associated with specific scenarios of altering the size of existing exchangers and installing new exchangers. The user-defined cost functions allow the user to penalize certain adjustments to the HEN that would be undesirable. This approach generates retrofitted designs that meet the needs of various financial and situational scenarios. The application of each cost function is described below.

### **1.3.1 Area Reduction**

The cost equation associated with area reduction includes a fixed cost term (\$8,650) that is dominant for the reduction of area through tube plugging or bypassing through new piping. However, in the case that area is reduced by bypassing through existing piping the fixed cost term is zero. Area reduction also contains a variable cost term (\$5 per m<sup>2</sup>) which accounts for the amount of area reduced.

### **1.3.2 Area Addition**

The cost equation associated with the addition of area to existing exchangers accounts for two options of increasing area; area may be increased to existing shells or by adding new shells. The fixed cost for increasing the area of *existing shells* is \$8,650 per unit, while the fixed cost for increasing area by adding *new shells* is \$17,300 per unit, per shell. The variable cost for area addition to existing exchangers is \$857 per m<sup>2</sup>.

### **1.3.3 New Exchanger**

It is expected that the addition of an entire heat exchanger would have a higher fixed cost than the addition of area to existing exchangers. This insight is validated in the following cost analysis. The cost equation associated with new exchangers is similar to that of area addition. The variable cost associated with the amount of new area is \$857; however, the fixed cost for a new exchanger is \$34,600.

### **1.3.4 Exchanger Relocation**

For the case that allows the relocation of existing heat exchangers a fixed cost is applied to the relocated exchangers. The fixed cost for relocation is \$15,000, which accounts for the disassembly and reassembly of the heat exchanger, as well as changes to the existing HEN infrastructure to facilitate exchanger relocation. The fixed cost for exchanger relocation can represent a large penalty for networks that cannot easily allow exchanger relocation, or a smaller penalty for networks that have the necessary space for exchanger relocation.

### **1.3.5 Stream Splitting**

The MILP accounts for costs associated with repiping by assigning a fixed cost to stream splits. The model allows split stream costs to be input separately for hot and cold streams. This procedure allows the user to easily penalize the repiping of networks that house volatile liquids or networks that do not have room for additional piping requirements. For the case of Example 1, the fixed cost of splitting hot or cold streams is \$10,000 per split.

## **1.4 Objective Function**

The MILP allows the user to optimize a variety of cost functions. This allows users to easily find an optimal retrofitted network for a variety of design constraints. One instance is the case where the amount of available capital is the limiting design constraint. For this case the user could maximize the



amount of projected savings while limiting the amount of the fixed capital investment. The objective function can be easily manipulated to optimize numerous design scenarios with varying design constraints. The most commonly used objective functions include maximizing savings, the net present value, and the return on investment. Each of these objective functions is described below.

**Savings** = Utility Cost Annual Savings – Annualized Capital Cost

**Net Present Value** =  $\sum(\text{Discount Factor}_i * \text{Utility Cost Savings}_i)$  – Total Capital Cost

**Return on Investment** = Utility Cost Annual Savings / Total Capital Cost

## 2. Process Pinch Technology

### 2.1 Introduction

The second technology researched for the retrofitting of heat exchanger networks (HENs) is pinch technology. It is a technology based on thermodynamic principles that sets energy savings and cost targets prior to the design of an HEN. The goal of pinch analysis is to maximize the process-to-process heat recovery and minimize the utility requirements of a system.<sup>10</sup> The methodology locates specific regions within an existing network where process change will result in a reduction of the overall energy requirements of the system. Locating these regions prior to actual retrofit design allows the engineer to apply the physical constraints of the system with the theoretical targets to design the most economical solution.

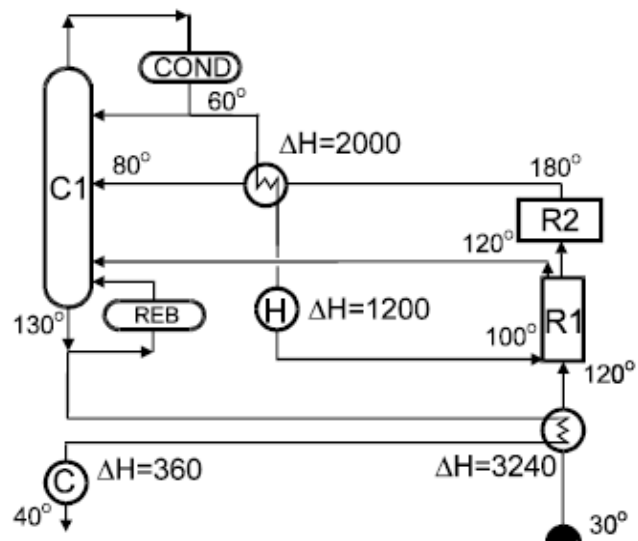
### 2.2 Stream Data

Often the original process will be illustrated in a process flow-sheet such as in Figure 5. However, the methodology is better applied if the streams are arranged into a grid diagram. In this diagram, the hot streams cool from left to right while the cold streams heat from right to left. Exchanger matches are illustrated between specific hot and cold streams. The hot utility exchangers (heaters) are located on the far left of the cold streams, and the cold utility exchangers (coolers) are located on the far right of the hot streams. The utilities exchange heat with the process streams when heat transfer between process streams is not possible or not economic.<sup>11</sup> The streams are arranged into this type of diagram because it will be useful later in the methodology. The grid diagram for Example 1 is illustrated in Figure 1.

Specific thermodynamic data is required from the streams to perform the pinch methodology. These include the supply temperature of each stream ( $T_S$ ) in °C, the target temperature of each stream ( $T_T$ ) in °C, the mass flow rate ( $F$ ) in kg/s, and the specific heat ( $C_p$ ) in kJ/kg·°C. The first property that needs to be calculated is the heat capacity flow rate ( $CP$ ) in kW/°C; it is the product of the mass flow rate and the specific heat and is given by Equation 1. The second property that needs to be calculated is the enthalpy change of each stream given by Equation 2.

$$CP = F \cdot C_p \quad (\text{Equation 1})^{12}$$

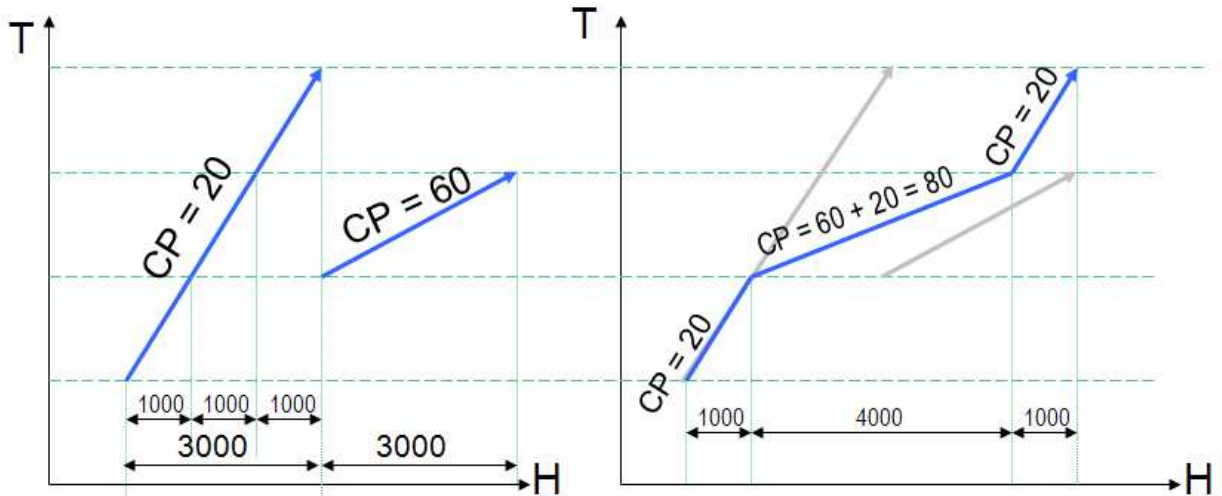
$$\Delta H = CP \cdot (T_S - T_T) \quad (\text{Equation 2})^{13}$$



SOURCE: Linnhoff March. "Introduction to Pinch Technology." 1998: 5.

Figure 5. Typical process flow-sheet of an HEN.

Once the enthalpy change is calculated, every stream can be plotted on a temperature-enthalpy diagram. Each stream will be a combination of straight-line segments with slopes being the reciprocal of the heat capacity flow rate;<sup>14</sup> the hot stream segments represent the hot stream temperature intervals and the cold stream segments represent the cold stream temperature intervals. Hot streams will then be combined to create one curve called the hot composite curve; similarly, a cold composite curve will be developed. Figure 6 demonstrates how a hot composite curve is developed from the straight line segments of each hot stream in a network.



**Figure 6. Composite curve generation.**

The combination of straight-line segments of each hot stream in a typical heat exchanger network. The slope of each segment is the reciprocal of the heat capacity flow rate. The heat capacity flow rates of overlapping streams are added and the reciprocal taken to create the hot composite curve.

### 2.3 Composite Curves and $\Delta T_{min}$

The hot and cold composite curves (HCC and CCC, respectively) provide the minimum energy targets for a process.<sup>15</sup> The hot composite curve is created by first arranging all of the hot stream temperatures in ascending order and then calculating the sum of the CP values in each interval accordingly. The heat requirement for each interval ( $Q_{int}$ ) is calculated based on Equation 3. The cumulative enthalpy for each interval ( $CumQ_{h,i}$ ) is calculated using Equation 4. The composite curve is a plot of the cumulative enthalpy versus the temperature intervals. The cold composite curve is developed in an identical manner. For heat transfer to occur from the hot streams to the cold streams, the hot composite curve must lie above the cold composite curve.<sup>16</sup> The enthalpy region where the hot and cold composite curves overlap is where process-to-process heat exchange can occur; the regions that do not overlap will require utility streams to satisfy the necessary heat exchange. Thus, the goal of pinch technology is to maximize this process-to-process heat exchange and minimize the utility requirements. Calculations for the creation of the hot and cold composite curves for Example 1 are displayed in Table 6 and Table 7, respectively. The hot and cold composite curves for Example 1 are displayed in Figure 7.

$$Q_{int} = CP_{int} \cdot (T_{in,int} - T_{out,int}) \quad \text{(Equation 3)}^{17}$$

$$CumQ_i = CumQ_{i-1} + Q_i \quad \text{(Equation 4)}^{18}$$

**Table 6. Data to create hot composite curve for Example 1.**

Hot stream data is indicated in red.

Interval i				Th	Sum CP,h	Qint,h	CumQh
0			x	77	0	0	0
1		x	x	88	229	2,514	2,514
2	x	x	x	90	249	498	3,011
3	x	x	x	159	303	20,886	23,898
4	x	x		267	74	8,014	31,911
5	x			343	54	4,089	36,000
stream	H3	H2	H1				
CP	53.8	20.4	228.5				

\*T in °C, CP in kW/°C, Q in kW

**Table 7. Data to create cold composite curve for Example 1.**

Cold stream data is indicated in blue.

Interval i			Tc	Sum CP,c	Qint,c	CumQc
6		x	26	0	0	8395.2
7	x	x	118	93.3	8583.6	16978.8
8	x	x	127	289.4	2604.6	19583.4
9	x		265	196.1	27061.8	46645.2
stream	C2	C1				
CP	196.1	93.3				

\*T in °C, CP in kW/°C, Q in kW

The point between the hot and cold composite curves that has the shortest vertical distance is the minimum temperature difference,  $\Delta T_{min}$ , and is called the pinch point. The significance of the pinch is that different  $\Delta T_{min}$  values correspond to different process-to-process heat transfer amounts in the system; at a certain  $\Delta T_{min}$ , a maximum process-to-process heat exchange will occur and thus decrease the amount of excess heating and cooling utility that must be incorporated to satisfy the system. It also demonstrates how close the two curves can get without violating the second law of thermodynamics;<sup>19</sup> in a heat exchanger network, the output temperature of a cold stream in an enthalpy interval or exchanger cannot be hotter than the input temperature of the hot stream, and the output temperature of the hot stream cannot be cooler than the input temperature of the cold stream.

The pinch separates the process into two sections. Above the pinch there is a heat sink which requires heat from a hot utility and a heat source below the pinch that rejects heat to a cold utility, as can be seen in Figure 8. These sections must be analyzed separately in the pinch methodology.

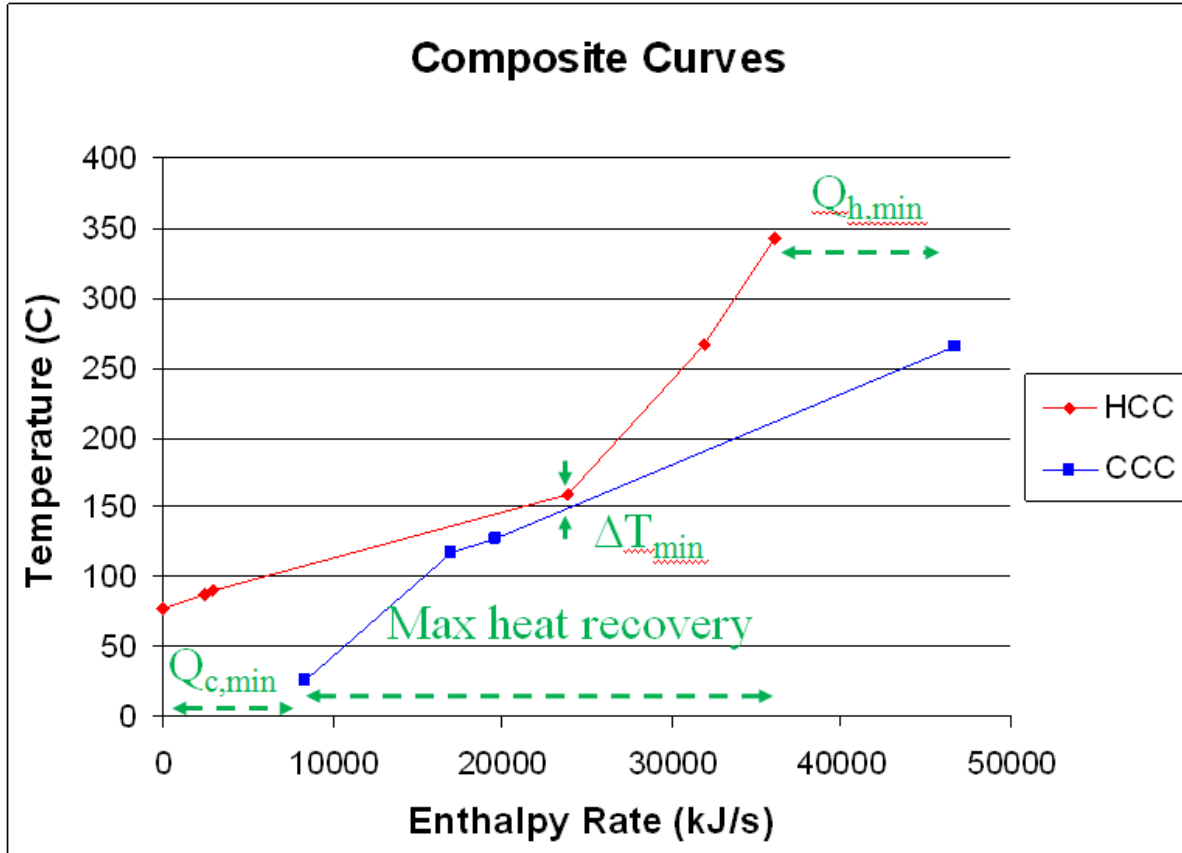


Figure 7. Composite curve for Example 1.

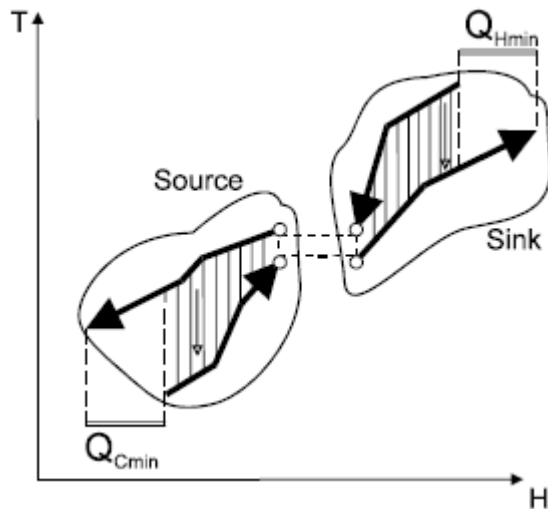
Composite curves,  $\Delta T_{\min}$ , maximum heat recovery, and minimum utility requirements for Example 1.

If  $\alpha$  amount of heat is transferred from above the pinch to below the pinch, thus increasing the heat in the source  $\alpha$  units, then the sink above the pinch must add  $\alpha$  units of heat to restore balance in the system. This situation is illustrated in Figure 9. This heat transfer across the pinch is called cross-pinch heat transfer and results in an increase in both the hot and cold utilities by the amount of heat transferred across the pinch. To avoid excess utilities, three rules must be satisfied to ensure minimum energy targets for the process:

- 1) Heat cannot be transferred across the pinch.
- 2) There can be no external cooling above the pinch (only hot utility can be used).
- 3) There can be no external heating below the pinch (only cold utility can be used).

If any of these rules are disobeyed, then cross-pinch heat transfer will occur, thus requiring an amount of energy that surpasses the process target. In a retrofit situation, obeying these rules corrects any exchangers that currently undergo cross-pinch heat transfer.<sup>20</sup> Avoiding this cross-pinch heat transfer is the reason for analyzing the section above the pinch separately from that below the pinch.

The table used to calculate the pinch temperature for Example 1 is located in Table 8. For the composite curves in Example 1, the  $\Delta T_{\min}$  is given to be 10°C. To locate the pinch temperature, the  $\Delta T_{\min}$



SOURCE: Linnhoff March. "Introduction to Pinch Technology." 1998: 9.

**Figure 8. Process separation by pinch.**

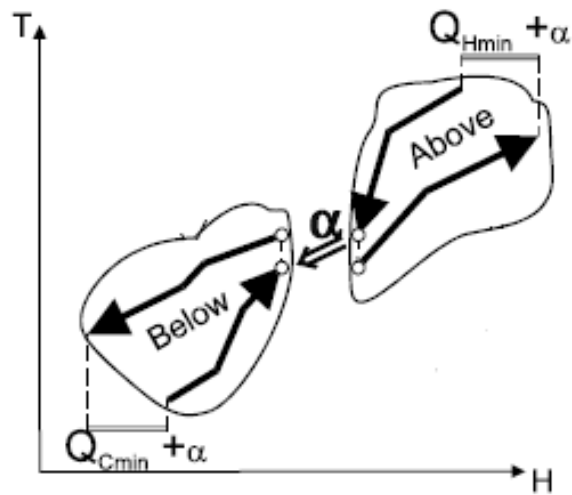
The pinch separates the process into a heat sink (above the pinch) and a heat source (below the pinch).

must be added to every cold stream temperature and then arranged in descending order with the hot stream temperatures. Then the sum of all CP values for the hot streams within a given interval is subtracted from the sum of all CP values for the cold streams within the same interval. The heat requirement for each interval ( $Q_{int}$ ) is calculated based on Equation 5. Next, the cascaded heat ( $Q_{cas}$ ) for each interval is the net enthalpy in the previous interval minus the net enthalpy in an interval as in Equation 5. Finally, the revised cascaded heat ( $R_{cas}$ ) is the cascaded heat in an interval minus the most negative cascaded heat as in Equation 6.

$$Q_{cas,i} = Q_{cas,i-1} - Q_{int,i} \quad \text{(Equation 5)}^{21}$$

$$R_{cas,i} = Q_{cas,i} - \min(Q_{cas}) \quad \text{(Equation 6)}^{22}$$

The pinch is located at the temperature where  $R_{cas}$  is zero. For Example 1, this occurs at a hot stream temperature of 159°C; for the cold streams it occurs at 149°C. As expected, the difference between the hot and cold composite curves at the pinch is the  $\Delta T_{min}$ . The minimum hot utility ( $Q_{h,min}$ ) is equivalent to the revised cascaded heat of the first temperature interval; similarly, the minimum cold utility ( $Q_{c,min}$ ) is equivalent to the revised cascaded heat of the last temperature interval. For Example 1,  $Q_{h,min}$  is 10,645 kW and  $Q_{c,min}$  is 8,395 kW. In Table 5, the pinch location,  $Q_{h,min}$ , and  $Q_{c,min}$  are highlighted in green.



SOURCE: Linnhoff March. "Introduction to Pinch Technology." 1998: 9.

**Figure 9.  $\alpha$  units of cross-pinch heat transfer.**

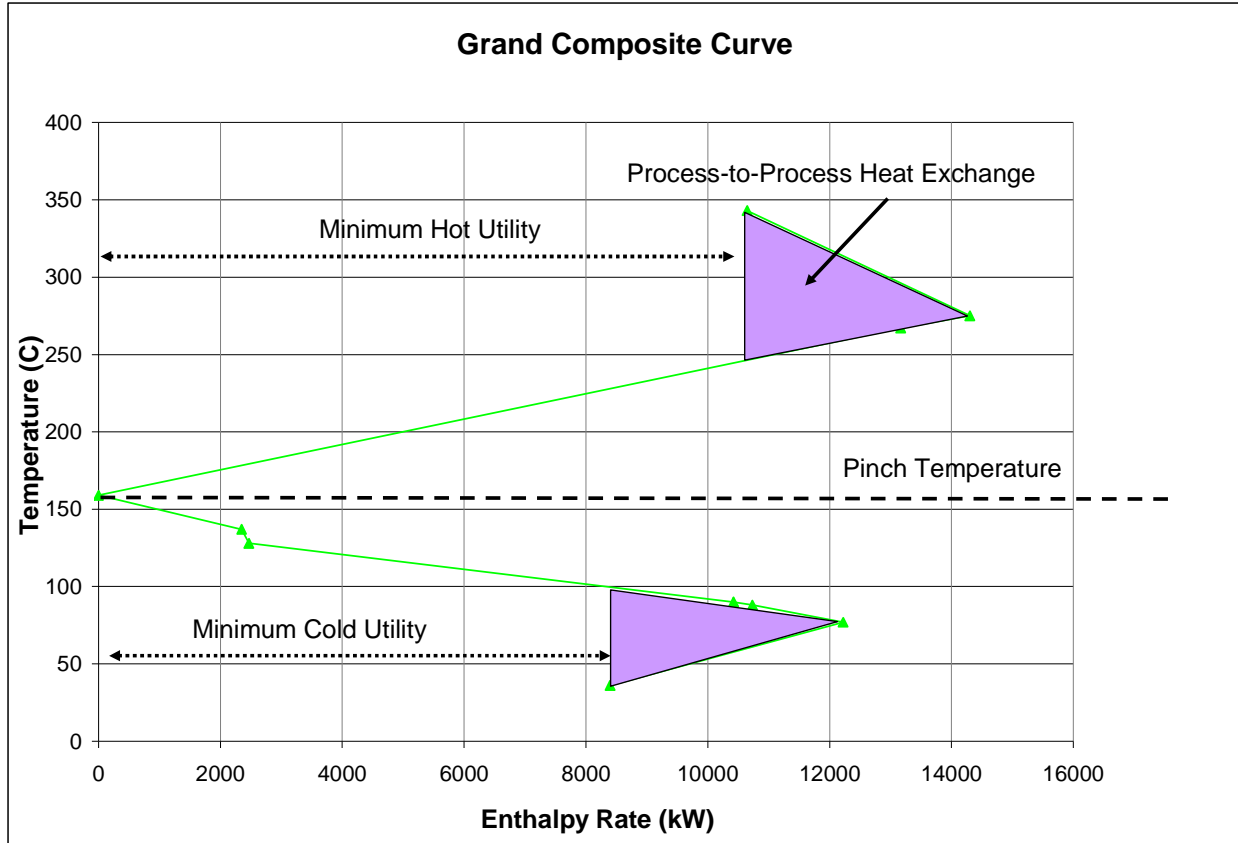
**Table 8. Data to calculate the pinch temperature for Example 1.**

Hot stream data are indicated in red and cold stream data are indicated in blue.  $Q_{h,min}$ , the pinch location, and  $Q_{c,min}$  (from top to bottom) are highlighted in green.

Tint	Interval i						Tint	CPint	Qint	Qcas	Rcas
343	0	x					343	0	0	0	10,645
275	1	x				x	275	-54	-3,658	3,658	14,304
267	2	x	x			x	267	142	1,138	2,520	13,165
159	3	x	x	x		x	159	122	13,165	-10,645	0
137	4	x	x	x	x	x	137	-107	-2,345	-8,300	2,345
128	5	x	x	x	x	x	128	-13	-120	-8,180	2,465
90	6	x	x	x		x	90	-209	-7,957	-223	10,422
88	7		x	x		x	88	-156	-311	88	10,733
77	8			x		x	77	-135	-1,487	1,575	12,221
36	9					x	36	93	3,825	-2,250	8,395
	stream	H3	H2	H1	C2	C1					
	CP	-53.8	-20.4	-229	196.1	93.3					

\*T in °C, CP in kW/°C, Q and R in kW

From the hot and cold composite curves, a grand composite curve (GCC) is developed. It illustrates the temperature intervals in which heat supply and demand of the process above and below the pinch occur. Moreover, it shows the locations of the process-to-process heat transfer, the process sinks, and the process sources.<sup>23</sup> It is created by shifting the cold composite curve towards the hot composite curve by an increment equal to the  $\Delta T_{min}$  and then plotting the difference between the heat flows of both curves versus temperature. Figure 10 is the grand composite curve for Example 1 and illustrates the minimum hot and cold utilities, the pinch temperature, and the process-to-process heat exchange locations.



**Figure 10. Grand composite curve for Example 1.**

Illustrates the minimum hot and cold utilities, the pinch temperature, and the process-to-process heat exchange locations.

## 2.4 Supertargeting

The next step in the retrofit process after the composite curves have been created is to calculate the optimum  $\Delta T_{\min}$  value based on which value provides the most economical design. To do this, the total network area and the utility requirements for the retrofit network are calculated for each  $\Delta T_{\min}$  value. Then the costs of the area and energy requirements are calculated and the optimum value is determined. This section describes in detail the supertargeting process.

### 2.4.1 Area Targeting

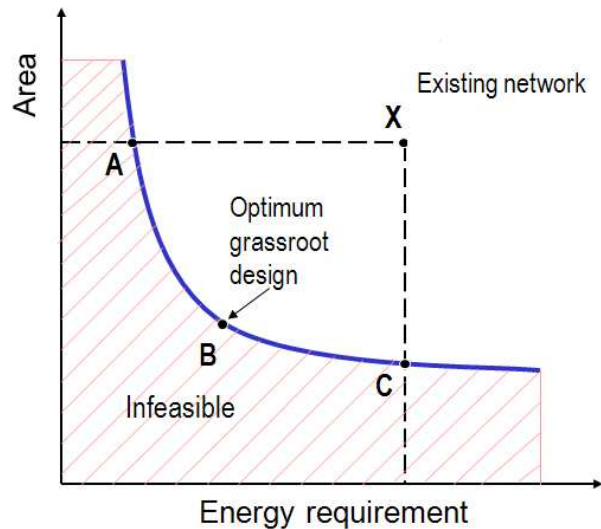
In order to determine the total network retrofit area for various  $\Delta T_{\min}$  values, it is necessary to understand the theory behind how pinch technology calculates the area. Figure 11 illustrates the energy versus area plot for a typical HEN retrofit process. Point X represents the current heat exchanger area for the total system as well as the energy requirements. The curve represents the optimum design curve for the HEN if it were developed for a grassroots situation. Had our existing network been



designed for a grassroots situation with the same energy requirements, point C would correspond to the required area; likewise, if our existing network were a grassroots design and had the same amount of area, point A would correspond to the required energy. The optimum grassroots design would minimize the costs of both area and energy and would thus have a location near point B.<sup>24</sup>

The goal of the retrofit process is to increase energy savings and decrease total cost by moving X towards the target curve. As the  $\Delta T_{min}$  is decreased, the energy requirements will decrease while the required area for the system will increase. Going below the curve is not feasible because a retrofit cannot be better than the targeted grassroots design. If possible, the retrofitted design should reuse and try to improve on the use of existing area; however, if this is not feasible or not economic, area addition to the network will be considered to decrease the total energy requirements and find the optimum solution.

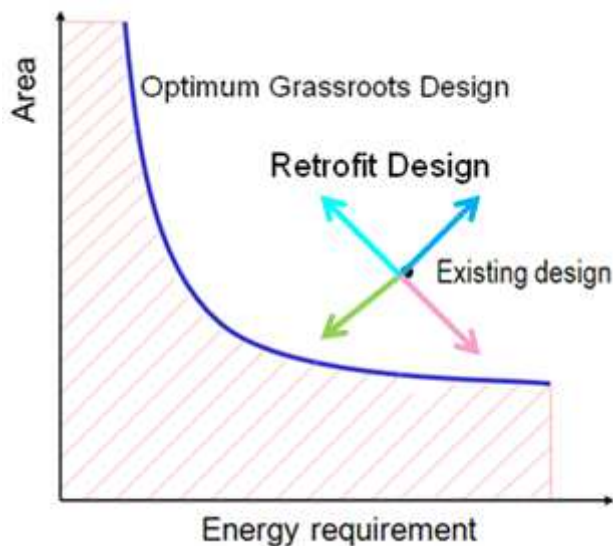
As a result, a retrofit design theoretically has four possible options to consider (Figure 12). If the existing design moves in the direction of the dark blue arrow (up and to the right), then the energy and area requirements will both increase; finding a more economical solution in this manner is highly unlikely. If the existing design follows the pink arrow (down and to the right), then we will be decreasing area but increasing energy; theoretically, a more optimal design could be located here but the purpose of pinch technology is to reduce energy requirements and increase the use of area. Therefore, this region will be rejected. Thus, we have the two arrows pointing to the left to consider. Pinch technology recommends not ignoring area that has already been invested and so assumes that the green



SOURCE: Texas A&M University. "Network Pinch Analysis." 123.

**Figure 11. Area vs. Energy plot.**

Illustrates the relationship between area requirements and energy requirements for a current process relative to the grassroots design curve.



SOURCE: Texas A&M University. "Network Pinch Analysis." 123.

**Figure 12. Area vs. Energy plot for retrofitting.**

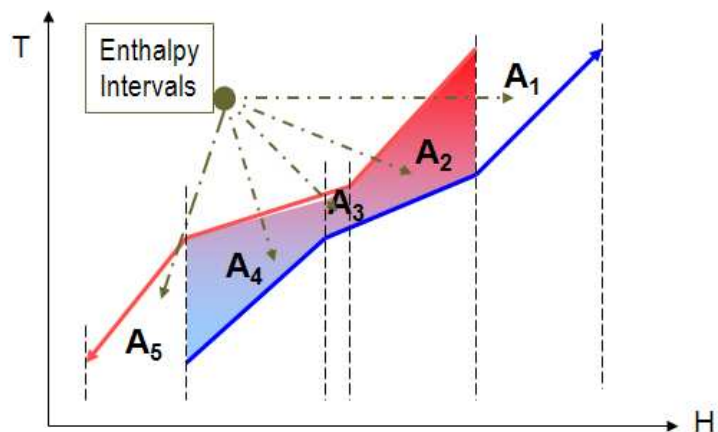
Illustrates the possible HEN changes that a current process could undergo for a retrofit to increase energy savings and decrease total cost.

arrow (down and to the left) will not be economical. For now, we will follow this recommendation and assume pinch technology is correct. However, this is a limitation of pinch and we will try to improve upon it later. Therefore, we will assume that the light blue arrow (up and to the left) will be the direction we move to retrofit the HEN.

Section 3 will discuss improvements to pinch technology. These improvements will not ignore the area in Figure 12 represented by the green arrow (down and to the left). The results for these improvements will fall somewhere in the figure that is to the left of the existing design. However, the specifics as to whether the optimum solution will lie above or below the existing design will be a result of the specifics of each retrofit case.

### 2.4.2 Vertical Heat Transfer

Before we can determine the most economical trade-off between energy and area requirements, we need to actually develop the grassroots design curve. This curve will be the basis for our retrofitted design. To do this, we use something called vertical heat transfer. Essentially, for each  $\Delta T_{\min}$  value that we choose to analyze for our current process, we will have an ideal minimum hot and cold utility requirement. Using the same technique from section 2.3 and Table 5, these utility requirements can be calculated for various  $\Delta T_{\min}$  values. For each  $\Delta T_{\min}$  value, a new composite curve can be created. Using this composite curve, the total network area will be calculated assuming that heat is transferred vertically from the hot composite curve to the cold composite. By assuming that there is no heat transfer across vertical enthalpy regions, we can determine  $A_{\text{ideal}}$  by calculating the area required for each separate enthalpy region and summing them as in Figure 13. The enthalpy regions where the hot and cold composite curves overlap represent process-to-process heat exchangers; conversely, the regions of no overlap correspond to utility exchangers. The areas for the utility exchangers will not be calculated at this stage of the retrofitting process because their duties are going to be reduced later when the overall network changes are made. Furthermore, because we do not know the specifics of the retrofitted design, we must assume that each exchanger in our network will have an equal area. This will allow us to determine our optimum  $\Delta T_{\min}$  by estimating the total cost.



SOURCE: Texas A&M University. "Network Pinch Analysis." 123.

**Figure 13. Vertical heat transfer.**

This allows us to calculate the network area for vertical enthalpy intervals. Summing the areas for each interval gives us the ideal area,  $A_{\text{ideal}}$ , for the grassroots design of a given process for a particular  $\Delta T_{\min}$  value.

As mentioned above,  $A_{ideal}$  for a given  $\Delta T_{min}$  value is calculated using the utility consumption of that particular process. To demonstrate how to calculate  $A_{ideal}$ , we will use the original process for Example 1 given the original  $\Delta T_{min}$  value. The original network consumes 17,759 kW of hot utility and 15,510 kW of cold utility. The  $CumQ_i$  values for the temperature intervals of the all the hot and cold streams are taken from Tables 6 and 7 and arranged in ascending order into a pinch tableau table as in Table 8. The temperature intervals are then placed in the table; the hot temperatures correspond to the  $CumQ_h$  values and the cold temperatures correspond to the  $CumQ_c$  values. Cells that do not have a temperature are calculated using linear interpolation. In the table, these values are highlighted in pink. The ideal area for the process is calculated using Equation 7 where LMTD is the logarithmic mean temperature difference for the temperature interval,  $Q_j$  is the enthalpy change of the j-th stream,  $h_j$  is the heat transfer coefficient of the j-th stream,  $i$  is the i-th enthalpy interval, and  $j$  is the j-th stream. Equation 8 splits the summation over the streams existing in each enthalpy interval into two summations that were used in the calculations of  $A_{ideal}$  where  $h$  denotes a hot stream, and  $c$  denotes a cold stream. Equation 9 is the logarithmic mean temperature difference for each interval. The interval areas and  $A_{ideal}$  for Example 1 for the original process are shown in Table 9. For the current process,  $A_{ideal}$  is 2,047 m<sup>2</sup>.

$$A = \sum_i \left( \frac{1}{LMTD} \right)_i \sum_j \left( \frac{Q_j}{h_j} \right)_i \quad \text{(Equation 7)}^{25}$$

$$\sum_j \left( \frac{Q_j}{h_j} \right)_i = (dT_h)_i \cdot \sum_{jh} \left( \frac{CP}{h} \right)_{jh} + (dT_c)_i \cdot \sum_{jc} \left( \frac{CP}{h} \right)_{jc} \quad \text{(Equation 8)}^{26}$$

$$LMTD_i = \frac{(T_{h,i} - T_{c,i}) - (T_{h,i-1} - T_{c,i-1})}{\ln \left( \frac{T_{h,i} - T_{c,i}}{T_{h,i-1} - T_{c,i-1}} \right)} \quad \text{Equation 9)}^{27}$$

**Table 9. Data to calculate the target area.**

Target area,  $A_{ideal}$ , is for the current process and is based on the area in each interval for the original heat exchanger network. Temperatures calculated by assuming linear interpolation are highlighted in pink. Areas calculated are highlighted in green.

Interval i						CumQi	Th,i	Tc,i	sum(Q/h)	LMTDi	Ai	
0						0	77					
1			x			2,514	88					
2	x		x			3,011	90					
3	x		x			15,510	131	26				
4	x		x		x	23,898	159	116	79,594	70	1,143	
5	x		x		x	24,094	162	118	2,055	43	47	
6	x		x		x	26,698	197	127	19,069	56	342	
7	x		x		x	31,911	267	154	30,323	90	338	
8	x				x	36,000	343	174	24,533	139	176	
9					x	53,760		265				
stream	H3	H2	H1	C2	C1						<b>Total</b>	<b>2,047</b>
CP	53.80	20.40	228.50	196.10	93.30							
h	0.25	0.30	0.40	0.50	0.15							

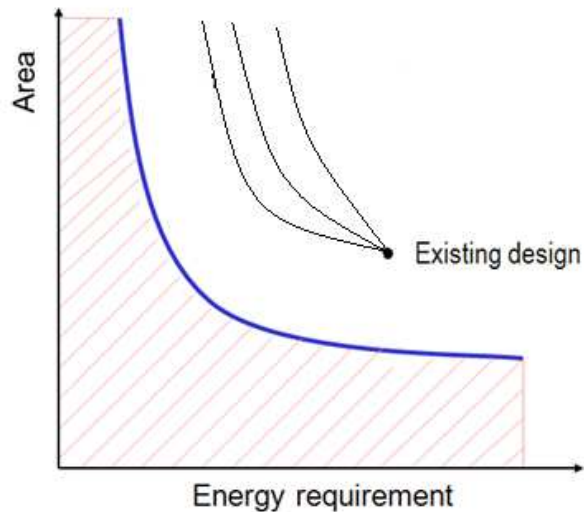
\*T and LMTD in °C, CP in kW/°C, Q in kW, A in m<sup>2</sup>

### 2.4.3 Area Efficiency

Now that we have developed the grassroots design curve by calculating the ideal area for various  $\Delta T_{min}$  values, we need a way to determine the most optimum retrofit design. To do this, we want to develop a curve similar to the grassroots design curve but that begins at our existing location point on the area-energy diagram. However, there are an infinite number of curves that we could use as shown in Figure 14. To determine our retrofit curve, we will use something called area efficiency.

Area efficiency,  $\alpha$ , is a factor used to quantify how close an existing network is to the predicted targets of the grassroots design. The closer  $\alpha$  is to unity signifies a network with more vertical heat transfer; a value of unity signifies that the existing design is located on the grassroots curve. Area efficiency is defined in Equation 10.

$$\alpha = \frac{A_{ideal}}{A_{existing}} \quad \text{(Equation 10)}^{28}$$



SOURCE: Texas A&M University. "Network Pinch Analysis." 123.

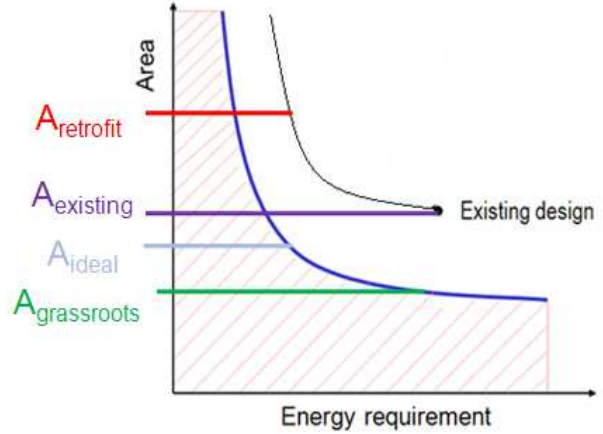
**Figure 14. Retrofit Curve.**

We need to develop a curve from the existing design point that is similar to the grassroots design curve (blue) in order to determine the optimal combination of area and energy requirements.

Thus, for Example 1 for the current process,  $A_{ideal}$  is 2,047 m<sup>2</sup> as calculated above and  $A_{existing}$  is 2,315 m<sup>2</sup>. This corresponds to an  $\alpha_{current}$  value of 0.884.

So how does this  $\alpha$  factor help us determine the retrofit curve? Using Figure 15, we will use area efficiency along with  $A_{retrofit}$ ,  $A_{existing}$ ,  $A_{ideal}$ , and  $A_{grassroots}$  to determine the retrofit curve.  $A_{grassroots}$  is the ideal area that our current process would have if the network were designed from scratch with its current utility usage and current  $\Delta T_{min}$  value.  $A_{ideal}$  is the grassroots area for the current process after we have altered the  $\Delta T_{min}$  value and correspondingly determined the new utility requirements.  $A_{existing}$  is the original network area and  $A_{retrofit}$  is the new retrofit area.

At this point we are going to introduce a new area efficiency factor,  $\beta$ , which will be a ratio between  $A_{ideal}$  and  $A_{retrofit}$  as indicated by Equation 11.



SOURCE: Texas A&M University. "Network Pinch Analysis." 123.

**Figure 15. Retrofit curve areas.**

The four areas demonstrated in this curve, along with the current area efficiency value, will allow us to develop a retrofit curve (black curve) that is similar to the grassroots design curve (blue curve).

$$\beta = \frac{A_{ideal}}{A_{retrofit}} \quad (\text{Equation 11})$$

With this new  $\beta$  value, we are going to assume that  $(A_{retrofit} - A_{existing})$  and  $(A_{ideal} - A_{grassroots})$  vary by a constant value  $x$  as in Equation 12.

$$(A_{retrofit} - A_{existing}) \cdot x = (A_{ideal} - A_{grassroots}) \quad (\text{Equation 12})$$

Rearranging and dividing each term by  $A_{ideal}$  and  $A_{grassroots}$ , we get Equations 13 and 14.

$$x = \frac{(A_{ideal} - A_{grassroots})}{(A_{retrofit} - A_{existing})} \quad (\text{Equation 13})$$

$$x = \frac{\left( \frac{1}{A_{grassroots}} - \frac{1}{A_{ideal}} \right)}{\left( \frac{A_{retrofit}}{A_{ideal} \cdot A_{grassroots}} - \frac{A_{existing}}{A_{ideal} \cdot A_{grassroots}} \right)} \quad (\text{Equation 14})$$

Using the definitions of  $\alpha$  and  $\beta$  from Equations 10 and 11, we obtain Equation 15.

$$x = \frac{\left( \frac{1}{A_{grassroots}} - \frac{1}{A_{ideal}} \right)}{\left( \frac{1}{\beta \cdot A_{grassroots}} - \frac{1}{\alpha \cdot A_{ideal}} \right)} \quad (\text{Equation 15})$$

The next step in the derivation is to assume that  $\alpha = \beta$ . This is a valid assumption because we want our retrofit network to have at least the same area efficiency as the original network. Doing this, we obtain Equation 16.

$$x = \alpha \quad (\text{Equation 16})$$

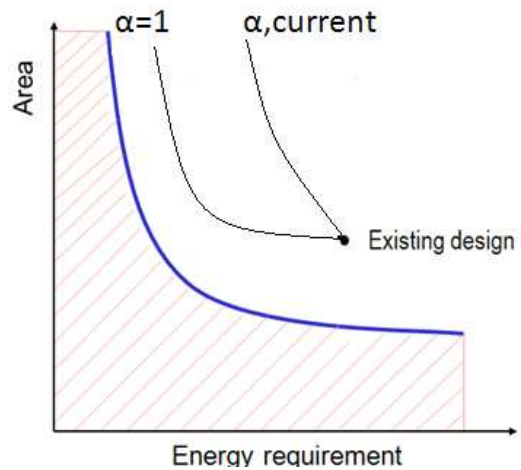
Therefore, we obtain Equation 17. Assuming we know the value of  $\alpha$ ,  $A_{retrofit}$  is the only variable in the equation that we do not know. Thus, by rearranging we obtain Equation 18 which allows us to calculate  $A_{retrofit}$ .

$$\alpha = \frac{(A_{ideal} - A_{grassroots})}{(A_{retrofit} - A_{existing})} \quad (\text{Equation 17})$$

$$A_{retrofit} = \frac{A_{ideal} - A_{grassroots}}{\alpha} + A_{existing} \quad (\text{Equation 18})^{29}$$

Because one of the goals of retrofitting is to improve the use of area, the area efficiency  $\alpha$  should be greater than or equal to  $\alpha_{current}$ . As  $\alpha$  increases, the retrofit area will decrease assuming that the utility consumption stays constant. This means that a higher  $\alpha$  value corresponds to a lower total area and thus lower area costs. Because we are trying to increase energy savings and decrease total costs, we want the highest  $\alpha$  possible. As can be seen by Figure 16, there are an infinite number of  $\alpha$  values that can be chosen for the retrofit design even we look only between an  $\alpha$  of unity and our current  $\alpha$  value. Therefore, because we want the highest  $\alpha$  possible, we will follow another of Shenoy's recommendations; when  $\alpha$  is less than 0.9, it is recommended to use an  $\alpha$  value of 1. For both Example 1 and Example 2, this recommendation was assumed.

Finally, a retrofit curve can be developed. By changing the  $\Delta T_{\min}$  value of the process, we obtained a unique composite curve. From this composite curve, we were able to calculate the utility requirements of the process using Equation 5, Equation 6, and producing tables similar to Table 8. With the utility requirements we used vertical heat transfer within enthalpy intervals to calculate the ideal area had the network been a grassroots design; this was done using Equation 7, Equation 8, Equation 9, and producing tables similar to Table 9. With these ideal areas we generated an area vs. energy diagram with the grassroots design curve present. By using the ideal area for the original process with its original  $\Delta T_{\min}$  value, we calculated the area efficiency according to Equation 10. Then by assuming a constant value of  $\alpha$  we generated a retrofit curve to calculate the retrofit area for various  $\Delta T_{\min}$  values.



SOURCE: Texas A&M University. "Network Pinch Analysis." 123.

**Figure 16. Optimum area efficiency.**

The optimum area efficiency,  $\alpha$ , value is unity. As  $\alpha$  is increased, the retrofit area decreases which decreases the overall cost of the retrofit process.

The ideal areas, retrofit areas, and retrofit area addition for Examples 1 and 2 are displayed in Tables 10 and 11, respectively. The retrofit area addition is merely the difference between the retrofit area and the original network area. The area vs. energy diagrams for Example 1 and 2 are illustrated in Figures 17 and 18, respectively. These diagrams include the grassroots curves as well as the retrofitted curves for a constant  $\alpha$  value of unity. These diagrams were generated using the retrofit area of the new process and the hot utility consumption for each process with various  $\Delta T_{\min}$  values.

**Table 10. Area results for Example 1.**

Results for the ideal area, retrofit area, and retrofit area addition. The  $\Delta T_{\min}$  values were varied from 2°C to 35°C. The results are calculated for an  $\alpha$  value of unity.

$\Delta T_{\min}$	Aideal	Aretrofit	Aaddition,retrofit
2	11,221	11,490	9,175
5	8,215	8,483	6,168
10	6,045	6,313	3,998
15	4,856	5,124	2,809
20	4,064	4,332	2,017
25	3,485	3,753	1,438
30	3,037	3,306	990
35	2,300	2,569	253

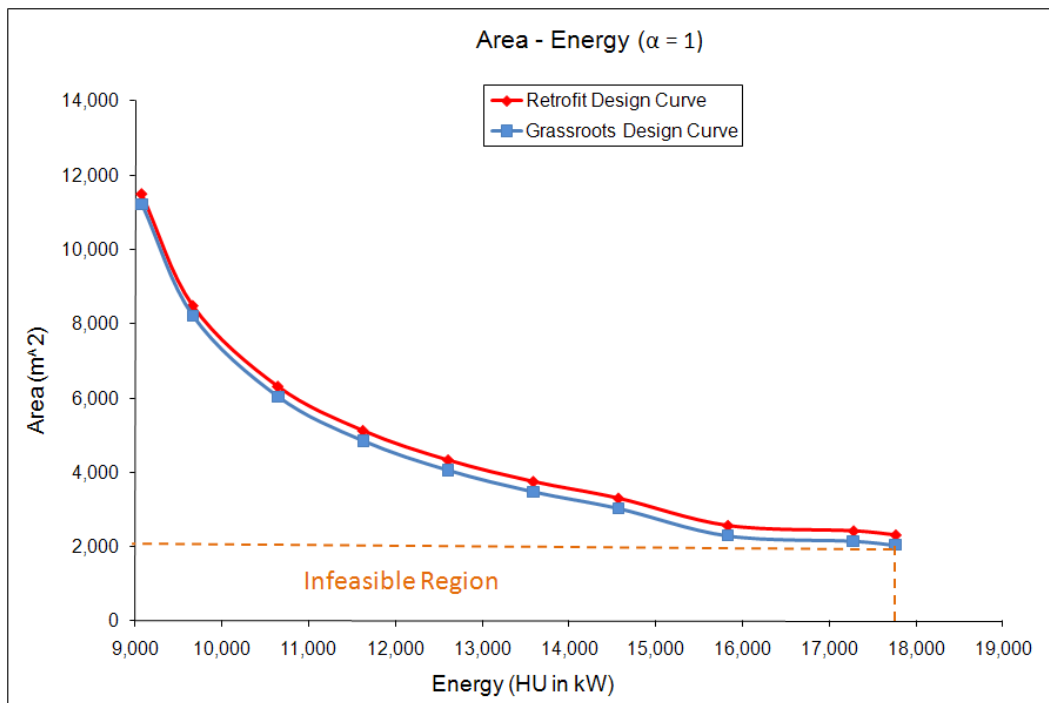
\* $\Delta T$  in °C, A in m<sup>2</sup>

**Table 11. Area results for Example 2.**

Results for the ideal area, retrofit area, and retrofit area addition. The  $\Delta T_{min}$  values were varied from 5°C to 40°C. The results are calculated for an  $\alpha$  value of unity.

$\Delta T_{min}$	Aideal	Aretrofit	Aaddition,retrofit
5.0	21,486.3	28,571.4	20,239.6
10.0	14,073.2	21,158.2	12,826.5
15.0	10,628.7	17,713.7	9,382.0
20.0	8,550.9	15,635.9	7,304.2
25.0	7,255.6	14,340.7	6,008.9
30.0	6,204.3	13,289.3	4,957.6
35.0	5,384.5	12,469.6	4,137.9
40.0	4,733.1	11,818.1	3,486.4

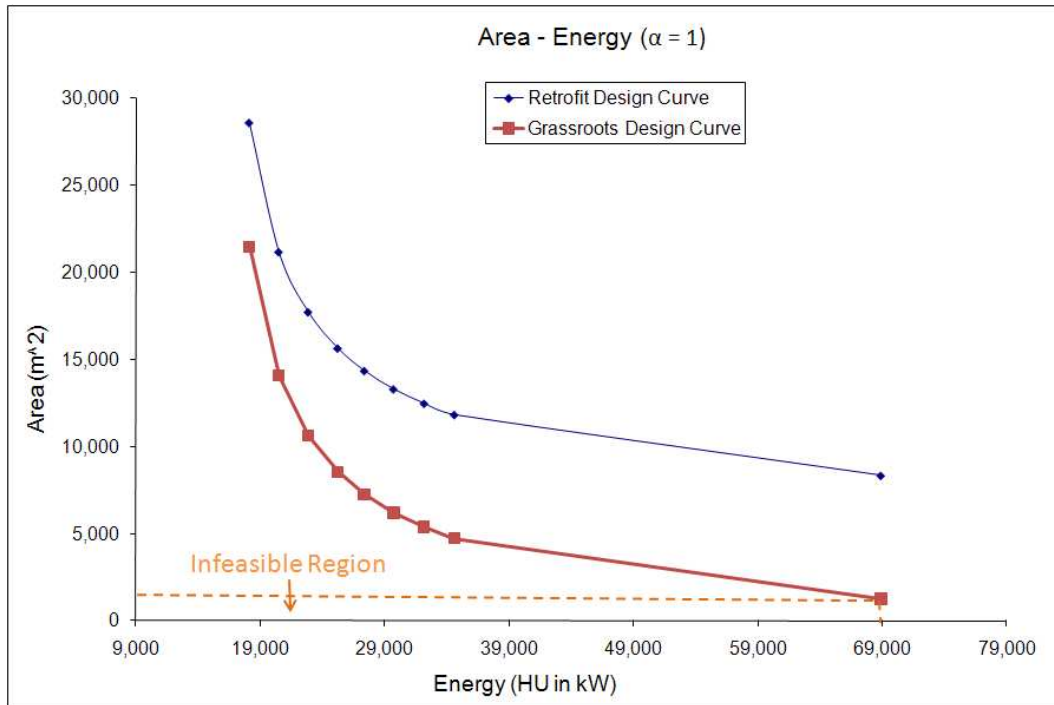
\* $\Delta T$  in °C, A in m<sup>2</sup>



**Figure 17. Area vs. Energy diagram for Example 1.**

The blue curve represents the grassroots design curve and the red curve represents the retrofit design curve. These curves were generated assuming a constant  $\alpha$  value of unity.





**Figure 18. Area vs. Energy diagram for Example 2.**

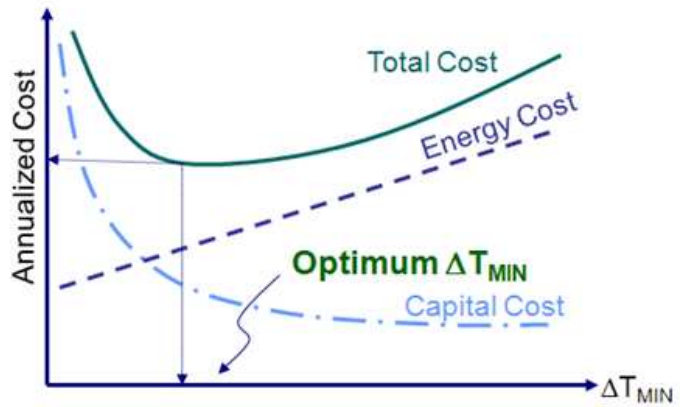
The blue curve represents the grassroots design curve and the red curve represents the retrofit design curve. These curves were generated assuming a constant  $\alpha$  value of unity.

Now that we have developed the grassroots design curve by calculating the ideal area for In Example 1, relocation is not allowed and heat exchanger area addition is only allowed by means of adding shells to existing exchangers. Furthermore, only two new heat exchangers can be added. To try to optimize this network, a  $\Delta\alpha = 1$  will be used to calculate the maximum retrofitted area allowed for various  $\Delta T_{\min}$  values ranging from 2°C to 35°C. The ideal areas and interval areas for each  $\Delta T_{\min}$  were calculated as in Table 6 for the current process. Table 7 displays this information for  $\Delta T_{\min} = 20^\circ\text{C}$ .

#### 2.4.4 Optimum $\Delta T_{\min}$ value

Now that we have developed a retrofit curve for our heat exchanger network, we must determine the optimum  $\Delta T_{\min}$  value prior to the design of the new process. To determine this value, we will use a Total Annualized Cost (TAC) vs.  $\Delta T_{\min}$  diagram for a constant  $\alpha$  value of 1. Figure 19 illustrates a typical TAC vs.  $\Delta T_{\min}$  diagram. The minimum on the TAC curve corresponds to the optimum value. Total annualized cost (TAC) is a function of the operating cost and the capital cost according to Equation 19.

Because the operating costs and the capital costs are both a function of  $\Delta T_{\min}$ , a compromise must be made when a network design is to be retrofitted. As  $\Delta T_{\min}$  increases, the energy requirements will increase while the area requirements will decrease. Thus, the operating costs will increase. However, as  $\Delta T_{\min}$  decreases, the energy requirements will decrease while the area requirements increase. Thus, the capital costs will increase. As a result of how each cost curve behaves with  $\Delta T_{\min}$ , it is expected that the TAC curve when plotted with  $\Delta T_{\min}$  will have a minimum value. This value correlates to the optimum  $\Delta T_{\min}$ .<sup>30</sup>



SOURCE: Texas A&M University. "Network Pinch Analysis." 40.

**Figure 19. A typical Total Annualized Cost (TAC) vs.  $\Delta T_{\min}$  diagram.**

The minimum on the total cost curve corresponds to the optimum  $\Delta T_{\min}$  value.

The operating cost (OC) (in \$/year) is a function of the hot utility cost ( $C_{HU}$ ), the cold utility cost ( $C_{CU}$ ), and a discount factor according to Equations 20, 21, and 22, respectively. The utility cost factors in Equations 20 and 21 are the values for Example 1; Example 2 has similar cost factors as displayed in Table 5. Operating costs are an expense that must be paid every year. The discount factor for the operating cost (in \$) is  $1/(1.1)^{n-1}$  for year  $n$ .

$$TAC = OC + CC \quad (\text{Equation 19})^{31}$$

$$C_{HU} = Q_{HU,\min} \cdot \left( \frac{\$26.4/\text{year}}{MJ/\text{hr}} \right) \cdot \left( \frac{3600\text{ s}}{1\text{ hr}} \right) \quad (\text{Equation 20})$$

$$C_{CU} = Q_{CU,\min} \cdot \left( \frac{\$5.55/\text{year}}{MJ/\text{hr}} \right) \cdot \left( \frac{3600\text{ s}}{1\text{ hr}} \right) \quad (\text{Equation 21})$$

$$OC = (C_{HU} + C_{CU}) \cdot \left( \frac{1}{1.1^{t-1}} \right) \quad (\text{Equation 22})^{32}$$

The capital cost (CC) is a function of the number of heat exchangers in a network and the area distribution for each exchanger as in Equation 23; furthermore, it is paid only once, not yearly like the operating costs. Because the optimum  $\Delta T_{\min}$  value is still unknown at this point, the area distribution for each exchanger is not known. Therefore, it is still assumed here that each individual exchanger in the network has the same area.

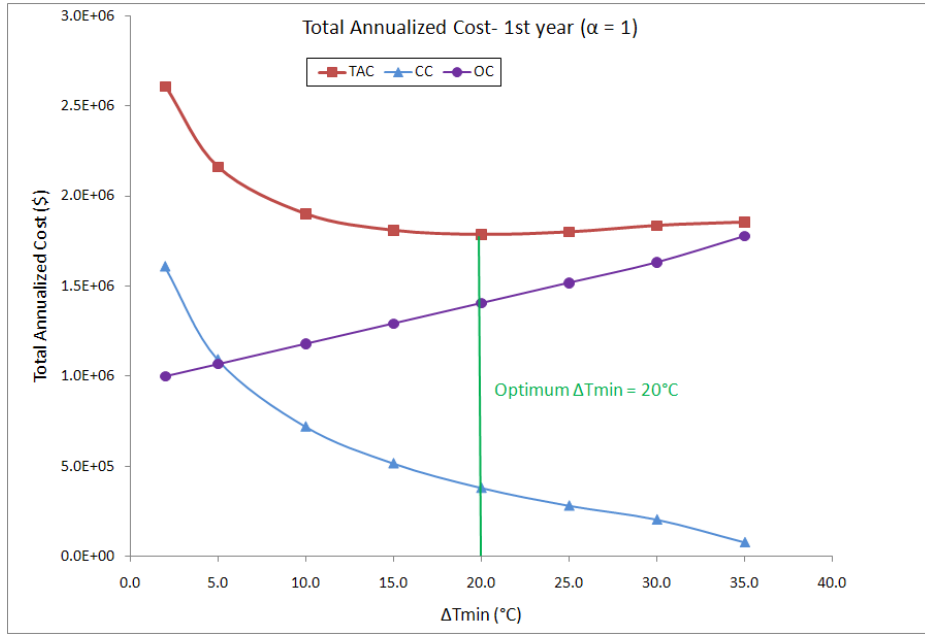
In Equation 23,  $N_{\min}$  is the minimum number of exchangers in the network,  $A_{\text{retrofit}}$  is the retrofitted area for the new network, and  $a$ ,  $b$ , and  $c$  are cost law coefficients that depend on the network itself. This equation assumes the retrofit network is constructed of only countercurrent heat

exchangers and that each exchanger uses the same cost coefficients.<sup>33</sup> The cost law coefficients used were taken from Barbaro *et. al* for Example 1 and Example 2. Because the retrofit design is still unknown,  $N_{\min}$  is calculated according to Equation 24.  $N_h$  is the number of hot streams,  $N_c$  is the number of cold streams,  $N_u$  is the number of utility streams, AP is above the pinch, and BP is below the pinch.

$$CC = N_{\min} \cdot \left[ a + b \cdot \left( \frac{A_{\text{retrofit}}}{N_{\min}} \right)^c \right] \quad (\text{Equation 23})^{34}$$

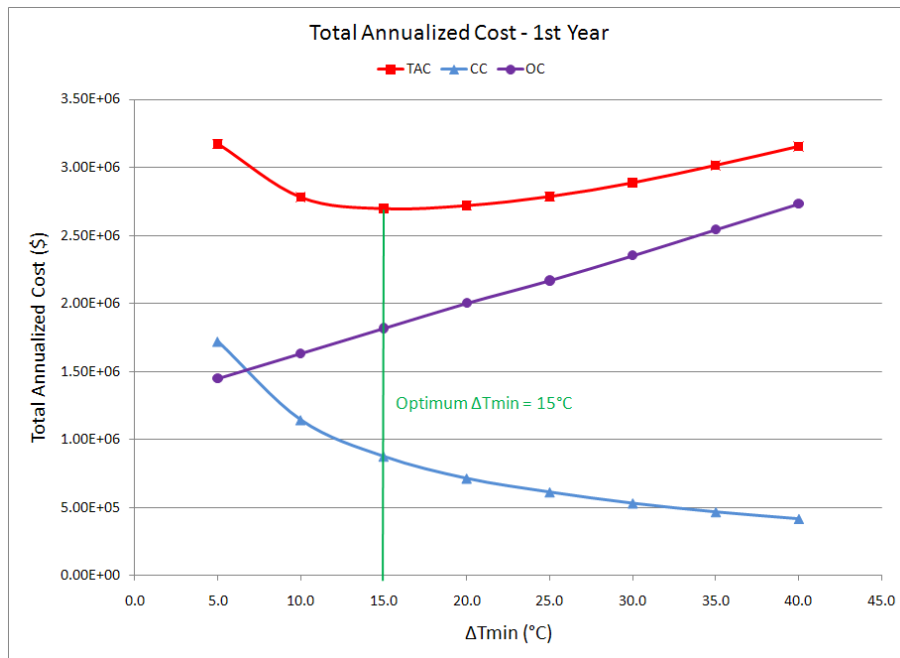
$$N_{\min} = [N_h + N_c + N_u - 1]_{AP} + [N_h + N_c + N_u - 1]_{BP} \quad (\text{Equation 23})^{35}$$

The TAC versus  $\Delta T_{\min}$  diagrams for Example 1 and Example 2 are displayed in Figures 20 and 21, respectively. For Example 1, the optimum  $\Delta T_{\min}$  value is 20°C. For Example 2, the optimum  $\Delta T_{\min}$  value is 15°C. These values represent an economic compromise between heat exchanger areas and utility requirements for the retrofitted networks.



**Figure 20. TAC vs.  $\Delta T_{min}$  plot for Example 1.**

It describes the optimum  $\Delta T_{min}$  value with a vertical green line. This  $\Delta T_{min}$  value represents an economic compromise between heat exchanger area and utility requirements.

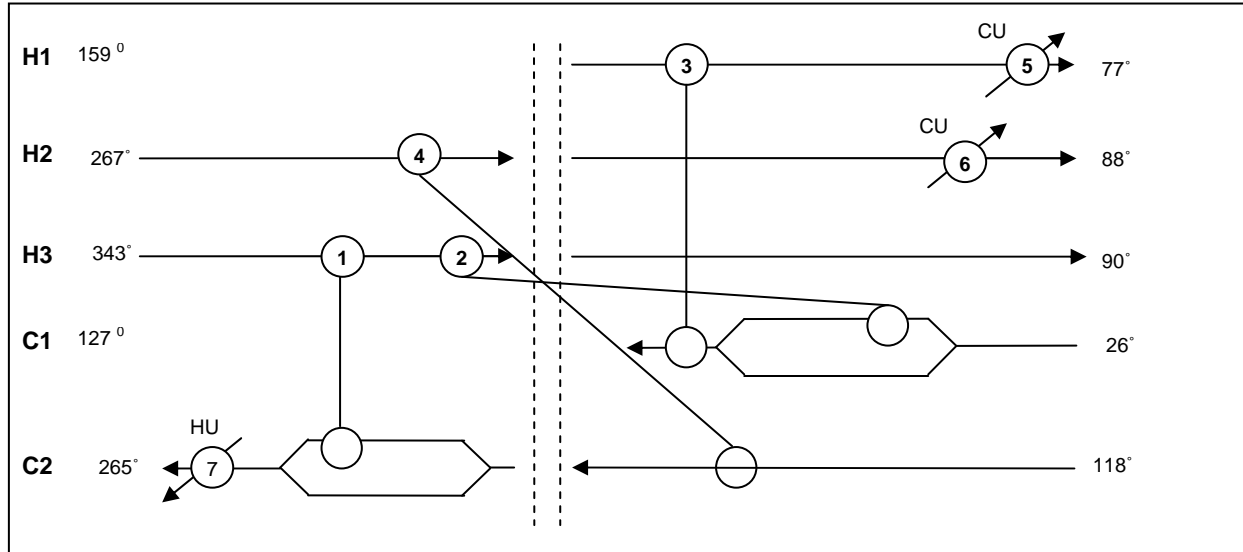


**Figure 21. TAC vs.  $\Delta T_{min}$  plot for Example 1.**

It describes the optimum  $\Delta T_{min}$  value with a vertical green line. This  $\Delta T_{min}$  value represents an economic compromise between heat exchanger area and utility requirements.

## 2.5 Heat Exchanger Matches

Now that the retrofit area has been calculated for each  $\Delta T_{\min}$  and the optimum  $\Delta T_{\min}$  value has been determined, the next step is to generate the stream matches for heat exchange in the new network. To do this, a grid diagram of the process is analyzed with the pinch temperature represented as two vertical lines through the middle of the grid. For this section, Example 1 will be used to demonstrate how to match streams to exchangers. The grid diagram for the retrofitted network of Example 1 is illustrated in Figure 22.



\*T in °C

**Figure 22. Grid diagram for the original heat exchanger network for Example 1.**

The diagram illustrates which exchangers currently transfer heat across the pinch (exchangers 2 and 4). Our goal is to eliminate these exchangers and reuse them elsewhere.

The first step to designing the new network is to locate the existing exchangers that transfer heat across the pinch. For Example 1, exchangers 2 and 4 transfer heat across the pinch. Because pinch technology does not allow cross-pinch heat transfer, we must eliminate these exchangers and essentially reuse them. We do this by moving each exchanger to one side of the pinch and then altering the input and target temperatures to ensure that no cross-pinch heat transfer occurs in the new design. As a reminder, the sections above and below the pinch must be analyzed separately.

Once we have located the exchangers that transfer heat across the pinch, we need to begin matching one hot stream and one cold stream to each exchanger. We want to reuse as many, if not all, existing exchangers as possible to minimize our capital costs. Furthermore, to ensure that our retrofitted network has the minimum number of heat exchangers possible, we want to maximize the heat transfer of every exchanger between its two matched streams.

To match two streams to an exchanger, we need to look at the heat capacity flow rate (CP) values. For streams above the pinch (to the left of the dashed line in the grid diagram),  $CP_{\text{HOT}} \leq CP_{\text{COLD}}$ .

Matches below the pinch are made in a similar fashion except  $CP_{\text{COLD}} \leq CP_{\text{HOT}}$ . These two matching rules ensure that if a stream's target temperatures are not satisfied by process-to-process heat exchange, then the addition of a utility exchanger will satisfy the stream. Moreover, matching should begin at the pinch. As matches move away from the pinch, these rules become less critical to follow.

After an exchanger has been matched, the heat load must be determined. To do this, we use something called the "Tick-Off" rule which states that we want to satisfy the heat requirements of at least one of the streams connected by each exchanger. This will ensure the minimum number of heat exchangers for the network.<sup>36</sup> The heat requirements for each stream are calculated according to Equation 24. This equation only works for one side of the pinch at a time (the temperature change cannot occur over the pinch) and must be applied for both streams that an exchanger matches. The duty for an exchanger is chosen as the smallest heat requirement of the two streams that are matched.

$$q = (T_{in} - T_{target}) \cdot CP \quad (\text{Equation 24})^{37}$$

Let us take a look at exchanger 4 (E4), which is one of the exchangers that we had to eliminate and reuse because it transferred heat across the pinch. We will begin the matching of our network by moving E4 above the pinch and keeping the match between H2 and C2. Pinch technology does not allow us to relocate the exchanger to match two different streams; however, relocation is one of the improvements we will try to make on pinch technology later. Because the CP of H2 is less than the CP of C2, we can match these two streams. Next, we need to calculate the duty for E4. By using equation 24, we calculate the heat requirements for H2 and C2, but the  $T_{\text{out}}$  for H2 and the  $T_{\text{in}}$  for C2 are the temperatures of the pinch for the hot streams and cold streams, respectively. Doing this, we obtain a heat requirement for H2 of 2,203 kW and a heat requirement for C2 of 24,709 kW. Therefore, the duty for E4 becomes 2,203 and the heat transfer requirement of C2 is now (24,709 kW – 2,203 kW) = 22,506 kW. Thus, the heat requirement for H2 is completely satisfied because the heat transfer between the two streams allows H2 to reach its target pinch temperature.

Because C2 is the only cold stream that can be matched with streams H2 and H3 due to the CP rule, a split must occur in C2 for both hot streams to transfer heat. The duty for E1 is calculated the same way as for E4. Because the duty requirement for H3 is less than the revised duty for C2 after the duty of E4 has been subtracted, all of the duty from H3 is transferred to C2. This results in H3 reaching its target temperature above the pinch and the final duty of C3 is its original duty minus the duties of E4 and E1. Because C3 does not have any more hot streams that it can gain heat from to reach its target temperature, a heater (cold utility) must be added at the end of the stream. The duty of this heater is the final duty of the stream after all heat transfer is completed.

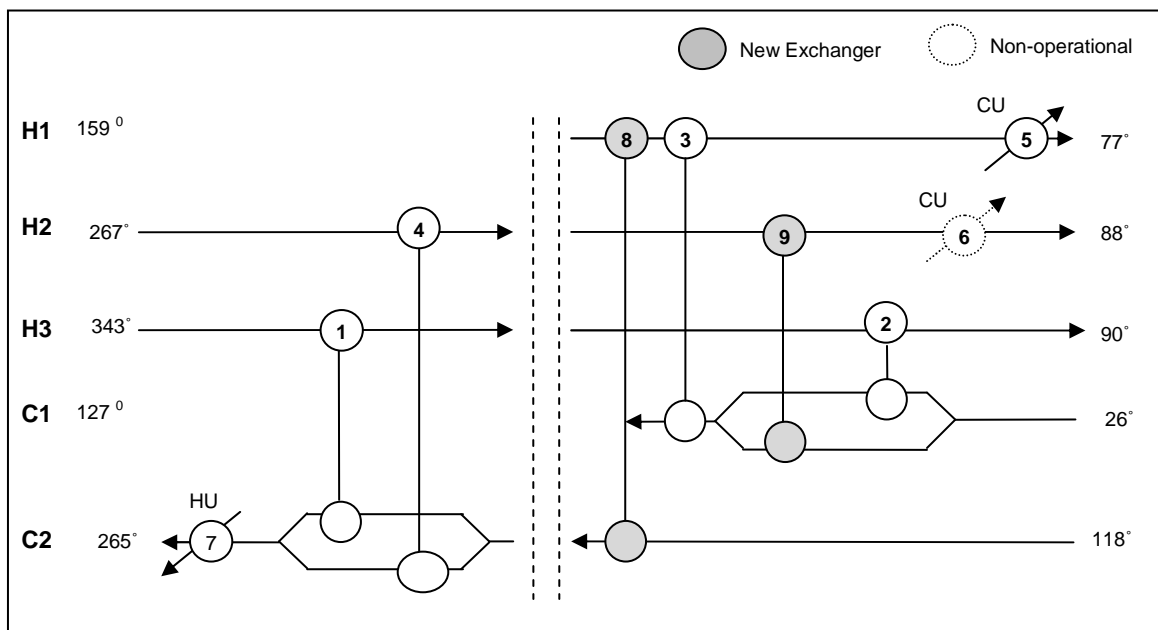
All other exchanger matches above and below the pinch are calculated in the same manner. For Example 1, the retrofitted network has 8 operational heat exchangers. 8 is the minimum number of units possible for the design of this network. All of the original exchanger locations stay the same, but exchanger 6 becomes non-operational. Exchangers 8 and 9 are added to the network to satisfy all of system requirements. E6 is non-operation because E9 on H2 satisfies all of the heat requirements and

results in H2 not needing any utilities. The final retrofitted design for Example 1 is illustrated in Figure 23.

The last step to complete the grid diagram is to calculate the outlet temperatures on the cold side of exchangers for streams that have more than one exchanger. These temperatures are needed later to calculate the logarithmic mean temperature difference for each exchanger. The outlet temperature is determined using Equation 25 where  $i$  is the number of exchangers on a stream split.

$$T_{outlet} = T_{inlet} - \sum_i q_i \cdot CP \quad (\text{Equation 25})^{38}$$

If there is not a stream split, then use only the duty of the one exchanger to calculate the outlet temperature. However, if there is a split, then sum the duties of each exchanger on the split to calculate the outlet temperature. This is done because isothermal mixing is assumed (thus the outlet temperature for each exchanger in a split is the same).



\*T in °C

**Figure 23. Grid diagram for the retrofitted heat exchanger network for Example 1.**

The diagram illustrates which exchangers were added (E8 and E9) and which became non-operational (E6).

The final aspect of heat exchanger matching that needs to be considered is the presence of heat loops and paths. Essentially these loops and paths introduce flexibility into the design. A heat loop is a closed connection through streams and exchangers that starts and ends at the same point. Likewise, a heat path is a connection through streams and exchangers between two utilities. Incorporating paths and loops can increase the process-to-process heat exchange in a network and possibly even decrease the number of exchangers needed in a network.<sup>39</sup> One possible heat loop is illustrated in Figure 24 by an orange dashed line. The loop illustrates what even a slight change on the duty of a single exchanger

can do to a relatively simple example. If we add  $X$  units of duty to  $E4$ , then a web of effects will result:  $E1$  will decrease by  $X$  units,  $E2$  will increase by  $X$ , and  $E9$  will decrease by  $X$ . Assuming the target temperatures and overall heat transfer coefficients of each exchanger stay constant, altering the duty of a heat exchanger will change its required area. This allows us one more way to optimize our retrofit network; by including heat loops and paths we can reduce the area and energy costs of our system.

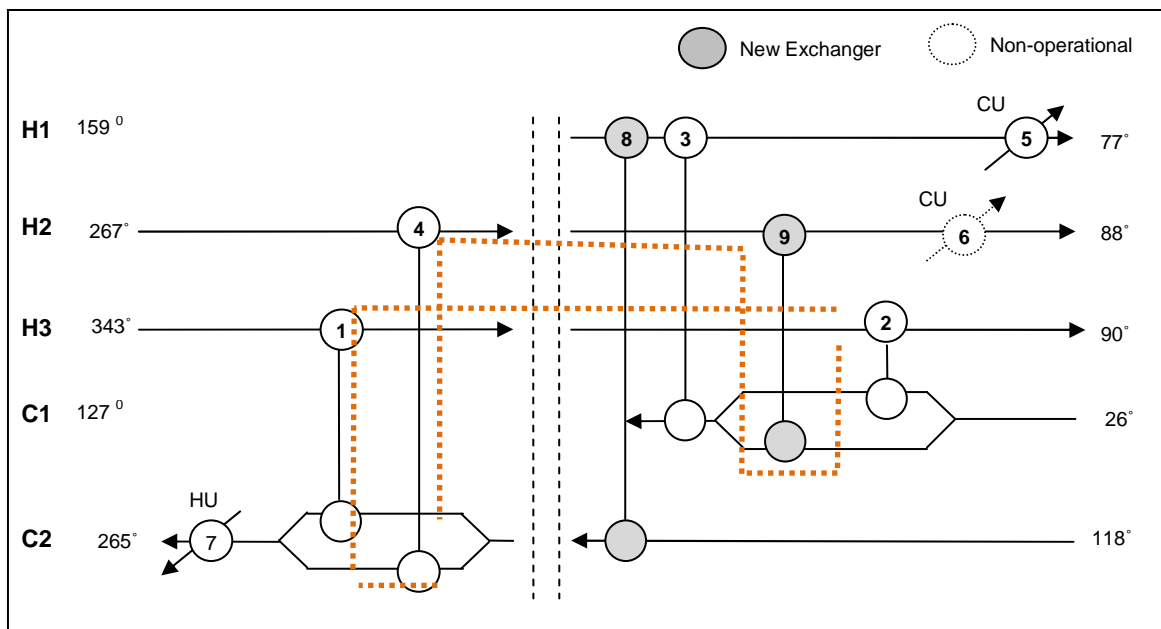
However, one of pinch technology's limitations is the time it takes to analyze the possibilities for heat loops and paths. Altering the duty, and thus the area, of one exchanger can cause a web of effects that may add hours to the manual computation time of this methodology. Because of this limitation, we will later try to incorporate another improvement to pinch technology that can consider all of the heat loops and paths in a retrofitted network.



\*T in °C

**Figure 24. Grid diagram for the retrofitted heat exchanger network for Example 1.**

The orange lines represents a heat loop which can increase the process-to-process heat exchange, decrease utility requirements, and even minimize the number of exchanger units required for a retrofitted design.



## 2.6 Heat Exchanger Area

Now that the minimum number of heat exchangers for the network has been found and the exchangers have been matched, the next step is to determine how the new area is split among the exchangers in the new network. Heat exchanger area dispersion via addition of extra shells, area

reduction by plugging tubes, and addition of new exchangers must all be considered. The area dispersion is determined using a streamwise area distribution matrix and a matchwise area distribution matrix.<sup>40</sup> The streamwise area distribution shows how the total area is split among each stream and is calculated for each stream based on the CumQ<sub>i</sub> intervals from Table 9. Streamwise area is calculated according to Equation 26. The terms in this equation are defined as in Equations 7-9.

$$A_j = \frac{CP_j}{h_j} \sum_i \left( \frac{dT_j}{LMTD} \right)_i \quad (\text{Equation 26})^{41}$$

The calculations for the streamwise and matchwise distributions will be demonstrated for Example 1. Example 2 procedure is performed identically. For Example 1, the streamwise area for ΔT<sub>min</sub> = 20°C is displayed in Table 12. The summation of the A<sub>j</sub> areas is slightly larger than the summation of the A<sub>i</sub>, but this is because A<sub>j</sub> is based on the cumulative enthalpy intervals. However, when the streamwise areas are turned into matchwise areas between heat exchangers, the total area of the network will once again be equivalent to A<sub>p</sub>.

**Table 12. Results for the streamwise area distribution, A<sub>j</sub>.**

A<sub>j</sub> is for ΔT<sub>min</sub> = 20°C and is highlighted in green.

Interval i						CumQi	Th,i	Tc,i	LMTDi	Ai
0	x					0.0	77.0			
1	x		x			2,513.5	88.0			
2	x	x	x			3,011.3	90.0			
3	x	x	x		x	10,356.2	114.3			
4	122.4	38.7	325.0	x	1472.4	18,939.8	142.6	118.0	49.8	1,634.0
5	75.8	24.0	201.3	144.5	229.2	21,544.4	151.2	127.0	24.4	674.8
6	75.9	24.0	201.4	213.5		23,897.6	159.0	139.0	22.0	514.8
7	509.5	161.0		351.3		31,911.2	267.0	179.9	45.6	1,021.8
8	145.4			72.7		36,000.0	343.0	200.7	112.5	218.1
9						48,606.2				
A <sub>j</sub>	929	247.6	727.7	782.1	1702					4,063.5
stream	H3	H2	H1	C2	C1					
CP	53.8	20.4	228.5	196.1	93.3					
h	0.25	0.30	0.40	0.50	0.15					

\*T and LMTD in °C, CP in kW/°C, Q in kW, h in kW/m<sup>2</sup>·°C, A in m<sup>2</sup>

The matchwise area distribution determines the area for each heat exchanger based on the streamwise area distribution. Matchwise area is calculated according to Equation 27. The matchwise distribution for ΔT<sub>min</sub> = 20°C is displayed in Table 13.

$$A_m = A_j \cdot h_{jh} \cdot \left( \frac{1}{h_{jh}} + \frac{1}{h_{jc}} \right) \cdot \frac{CP_{jc}}{\sum_{jc} CP_{jc}} \quad (\text{Equation 27})^{42}$$

The exchanger areas calculated thus far have not included the areas of the exchangers matched with the hot and cold utility streams. The duties were changed from the original values when the exchangers in the new retrofitted network were matched. Equation 28 is used to calculate the new utility heat exchangers using the duty of the exchanger, the inlet and outlet temperatures of the hot and cold sides of the exchanger for each stream it matches, and the heat transfer coefficients for the hot and cold streams.

$$A_U = \frac{Q}{\left( \frac{1}{\frac{1}{h_h} + \frac{1}{h_c}} \right) \cdot LMTD} \quad (\text{Equation 28})^{43}$$

**Table 13. Results for the matchwise area distribution,  $A_m$ .**

$A_m$  is for  $\Delta T_{\min} = 20^\circ\text{C}$  and is highlighted in green.

Interval i	H3-C2	H3-C1	H2-C2	H2-C1	H1-C2	H1-C1
0						
1						
2						
3						
4		326.4		116.0		1191.5
5	77.1	65.2	26.0	23.2	245.5	237.9
6	113.8		38.4		362.6	
7	764.2		257.6			
8	218.1					
9						
<b>Am</b>	<b>1173.3</b>	<b>391.6</b>	<b>321.9</b>	<b>139.2</b>	<b>608.1</b>	<b>1429.4</b>
stream	H3	H2	H1	C2	C1	<b>4063.5</b>
CP	53.8	20.4	228.5	196.1	93.3	
h	0.25	0.30	0.40	0.50	0.15	

\* CP in kW/°C, h in kW/m<sup>2</sup>-°C, A in m<sup>2</sup>

The final heat exchanger area results for Example 1 with a  $\Delta T_{\min}$  of  $20^\circ\text{C}$  are displayed in Table 14. These areas exclude the heat exchangers used on the utility streams (exchangers 5 and 7) because

the retrofit area using an  $\alpha$  of unity was calculated ignoring the utility exchangers.  $A_{\text{retrofit}}$  was calculated according to Equation 18 and the other areas are calculated according to Equation 29, Equation 30, and Equation 31.

$$A_{\text{addition,retrofit}} = A_{\text{retrofit}} - A_{\text{original}} \quad (\text{Equation 29})$$

$$A_{\text{actual}} = A_m \quad (\text{Equation 30})$$

$$A_{\text{addition,actual}} = A_{\text{actual}} - A_{\text{original}} \quad (\text{Equation 31})$$

Table 14 illustrates that the actual retrofitted HEN area is less than what was predicted using the area efficiency method. However, the actual areas vary from the area efficiency estimates by only 7%. Therefore, we determine that the area efficiency method is a valid method to estimate the retrofit area of a heat exchanger network.

**Table 14. Process pinch Example 1 area results.**

These are for the heat exchanger area distribution for the retrofitted network with  $\Delta T_{\text{min}} = 20^\circ\text{C}$ . The retrofit areas for each exchanger and the area change from the original are highlighted in green.

Aretrofit	Addition,retrofit	Actual	Addition,actual
4,332	2,017	4,064	1,936

\* A in  $\text{m}^2$

Pinch technology has one more limitation that was uncovered during the process of retrofitting Example 1 and Example 2. The optimum  $\Delta T_{\text{min}}$  value calculated using the pinch methodology from Shenoy ensured that there was no temperature cross between the enthalpy intervals of the design. However, these  $\Delta T_{\text{min}}$  values did not account for temperature cross within the exchanger units. To account for this, the areas calculated using the streamwise and matchwise distributions needed to be adjusted to disallow temperature cross in the exchangers. This was performed using Equations 32-34. Q is the heat duty on the exchanger, U is overall heat transfer coefficient which is a function of the heat transfer coefficients for the hot and cold streams to which the exchanger is matched, and LMTD is the log mean temperature difference of the exchanger.

$$A = \frac{Q}{U \cdot LMTD} \quad (\text{Equation 32})$$

$$U = \frac{1}{\frac{1}{h_h} + \frac{1}{h_c}} \quad (\text{Equation 33})$$

$$LMTD_i = \frac{(T_{h,i} - T_{c,i}) - (T_{h,i-1} - T_{c,i-1})}{\ln\left(\frac{T_{h,i} - T_{c,i}}{T_{h,i-1} - T_{c,i-1}}\right)} \quad (\text{Equation 34})$$

Revising each exchanger's specific area to account for temperature cross resulted in an increase in the optimum  $\Delta T_{\min}$  value. Because the target temperatures and pinch temperatures are constant for given  $\Delta T_{\min}$  values, the only way to eliminate the temperature cross and thus validate the denominator of LMTD equation is to increase the  $\Delta T_{\min}$  value.

## 2.7 Cost Comparisons

With the revised exchanger areas for the retrofitted networks and the new  $\Delta T_{\min}$  values, the actual cost calculations can be performed. Four cost calculations will be compared for this paper. These include the Fixed Capital Investment (FCI), the change in Total Annualized Cost ( $\Delta TAC$ ), the Net Present Value (NPV), and the Return on Investment (ROI).

The FCI is calculated for the project life. The actual capital cost will be calculated in a manner similar to Equation 23 but the assumption that all heat exchangers have the same area can now be ignored. The FCI (in \$) is calculated using Equation 35 where  $A_{\text{change}}$  is the absolute value of the difference of the exchanger area for the retrofitted network minus the original area for that exchanger. The first summation includes all heat exchangers that had area added to them in the retrofit process; for new exchangers,  $A_{\text{change}}$  is equal to the total exchanger area. The second summation includes all heat exchangers that had area reduced in the retrofit process. The variables a, b, c, and d are cost coefficients taken from Barbaro *et al.*

$$FCI = \sum_{\text{addition}} [a + b \cdot (A_{\text{change}})^c] + \sum_{\text{reduction}} [d + e \cdot (A_{\text{change}})^c] \quad (\text{Equation 35})$$

$\Delta TAC$  is an annualized cost that is a function of the energy savings and the FCI. The energy savings (ES) (in \$/yr) is calculated according to Equation 36 where U is the utility cost and i is the year of question within the project life. The  $\Delta TAC$  (in \$/yr) is calculated according to Equation 37 where n is the project life.

$$ES_i = (U_{\text{original}} - U_{\text{retrofit}}) \cdot \left(\frac{1}{1.1^{i-1}}\right) \quad (\text{Equation 36})^{44}$$

$$\Delta TAC_i = ES_i - \frac{FCI}{n} \quad (\text{Equation 37})$$

NPV is calculated for the project life and is a function of the total savings over the project life and the FCI. NPV (in \$) is calculated according to Equation 38.

$$NPV = \sum_i^n ES_i - FCI \quad (\text{Equation 38})$$

ROI is calculated for the project life and is a function of the energy savings and FCI. Percent ROI is calculated according to Equation 39 where n corresponds to the savings in the last year of the project life.

$$ROI = \frac{ES_n}{FCI} \quad (\text{Equation 39})$$

## **3. Pinch Improvement**

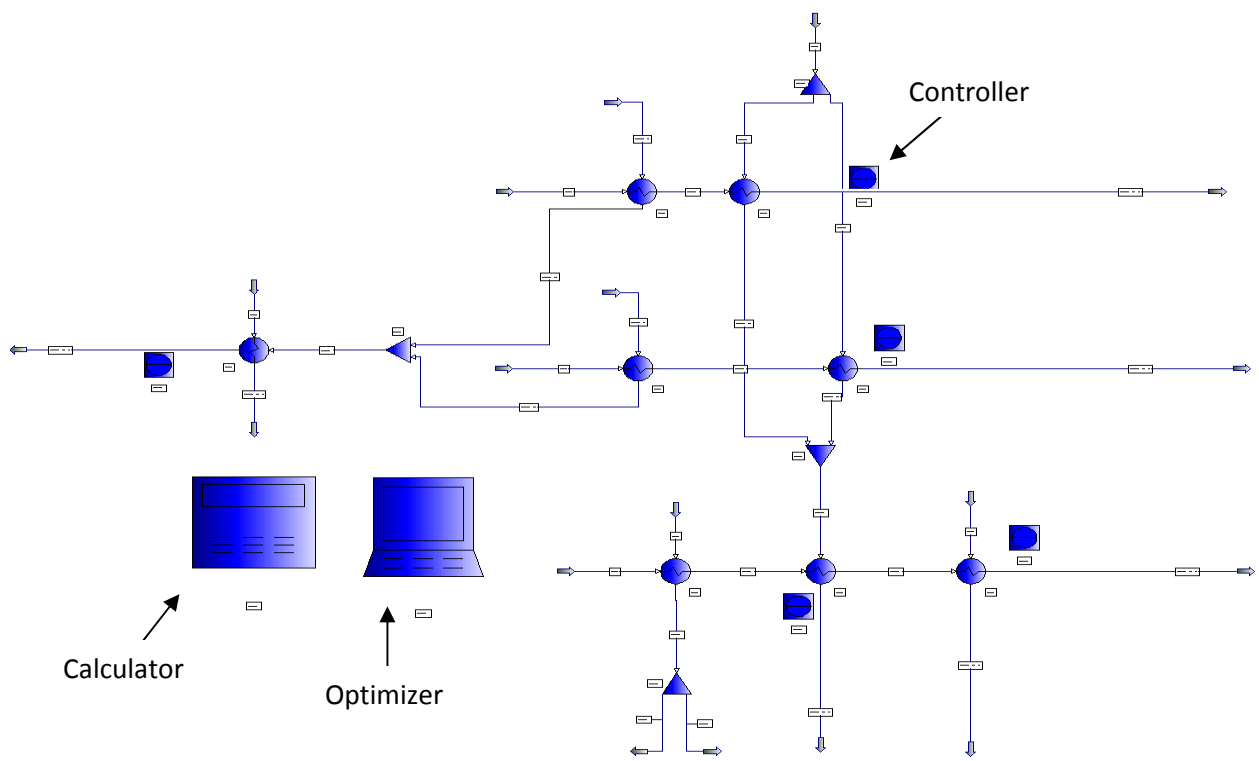
### ***3.1 Relocation***

One improvement for the process pinch methodology was the extension of HEN retrofit to include exchanger relocation. The relocation of existing heat exchangers incurs a fixed cost. However, the costs associated with relocating an existing heat exchanger may be less than that of purchasing and installing a new exchanger.

The process pinch methodology was amended to allow the relocation of existing heat exchangers. This process included analyzing the retrofitted network based on predefined process pinch methodology. Without relocation the process pinch retrofitted network includes the addition of new exchangers to both eliminate cross-pinch heat transfer and improve process to process heat transfer. One consequence of the process pinch retrofitted design is the existence of unused heat exchangers. For the examples which allow relocation, existing heat exchangers that were unused in the retrofitted design were relocated to positions of new heat exchangers. This procedure generated lower fixed costs while maintaining the integrity of the HEN.

### ***3.2 Pro-II***

Another improvement to the process pinch methodology was the use of Pro-II's optimization capabilities. The optimal location of heat exchangers in the retrofitted design, as determined by the process pinch methodology, was simulated in Pro-II. The Pro-II optimizer was allowed to vary heat exchanger areas while controllers maintained stream target temperatures in an effort to minimize the total cost for the system. Essentially, including Pro-II as an improvement to pinch technology allowed all of the possible heat loops and paths in a retrofitted network to be considered. Instead of manually calculating the effects of changing the areas and duties of exchangers like is need with the pinch technology, Pro-II uses a computer to optimize the area and energy requirements after the network has already been designed. This procedure is discussed in further detail in the following sections.



**Figure 25. Pro-II simulation.**  
HEN simulation including controllers, calculator, and optimizer.

### 3.2.1 Controllers

Controllers were used to maintain stream outlet temperatures by varying the area of the heat exchanger at the stream outlet. This technique ensures that the optimal network will meet the target temperatures for every stream.

### 3.2.1 Calculator

The calculator assigns applicable cost functions to area adjustments for existing exchangers (area addition or reduction) and area added by new exchangers. For existing exchangers, logic statements in the calculator calculations compare the retrofitted area of an exchanger to the original area. Based on the result (area increase or decrease from original area) the calculator assigns a cost (area addition or area reduction) for each existing exchanger. A simpler approach is used for cost calculations of new exchangers. The calculator assigns a cost function for area added to new exchangers based on the size of the exchanger.

The calculator also calculates the utility cost requirements of the retrofitted system. The utility cost functions are predetermined and are based on the duty of the utility exchangers. Since the utility exchangers are determined by the process pinch results, the assignment of hot and cold utility prices involves adding the hot and cold utility cost functions to the calculator.



### **3.2.1 Optimizer**

The optimizer minimizes the total cost function that is calculated by the calculator. The total cost function includes the fixed capital investment (FCI) and the cost of utilities for the retrofitted network. The FCI is the cost associated with adjustments to existing exchanger area as well as the cost of area for new exchangers. Separately, the cost of utilities is determined by the duty requirements of the utility exchangers. In order to minimize the objective function, the optimizer is allowed to vary the area of all heat exchangers that are not associated with controllers and the flow rates of split streams. This approach allows the Pro-II simulation to determine the optimal area and duty requirements for exchanger locations determined by the process pinch methodology.

## **4. Discussion**

In this section the results for the retrofitted design of the MILP, process pinch, and the improved process pinch (Pro-II simulation) are presented and compared. Each method was applied to the same HEN retrofit problem using the same constraints and cost functions to determine the optimal solution. First, the results of Example 1 will be presented and compared and then we will discuss the results of Example 2. Furthermore, we will separately discuss and compare the results of allowing and disallowing the relocation of existing heat exchangers.

### ***4.1 No Relocation (Example 1)***

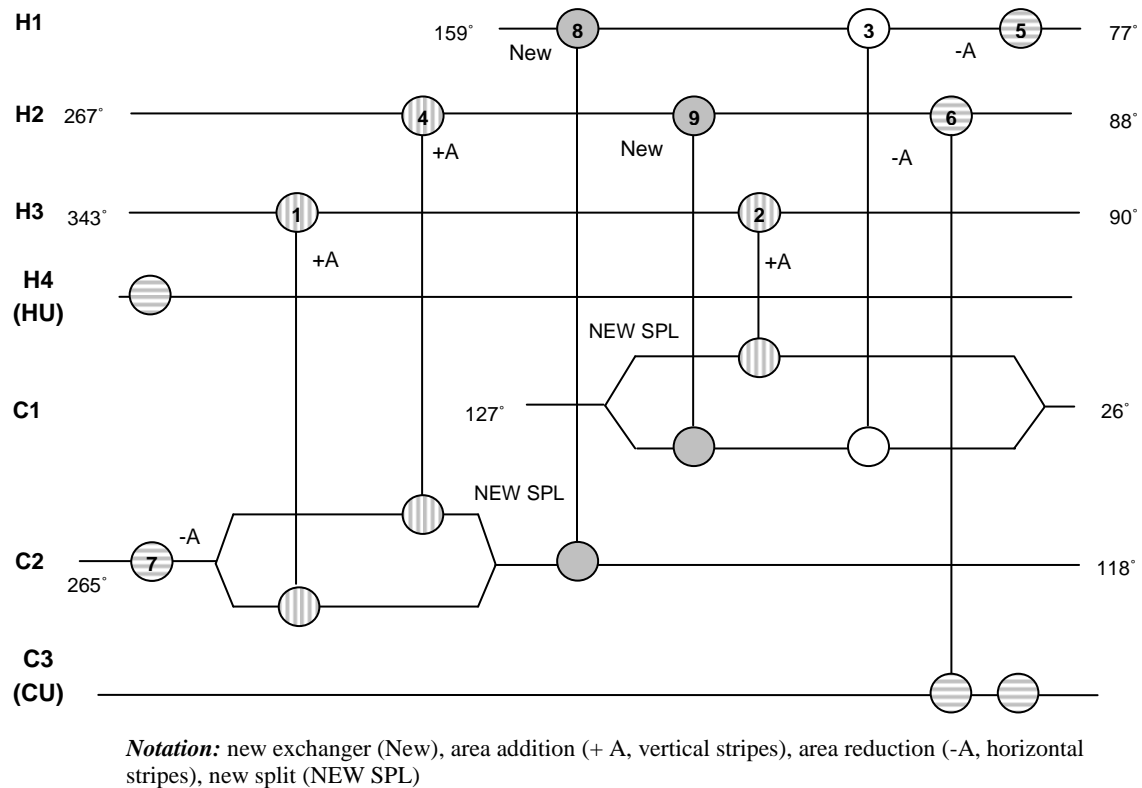
This scenario allows each methodology to manipulate the area of existing exchangers as well as adding new exchangers and introducing split streams. However, the methodologies are not allowed to relocate existing exchangers.

#### **4.1.1 MILP Results**

For the first analysis the results of MILP, process pinch, and the Pro-II simulation are presented for the retrofit of Example 1, disallowing heat exchanger relocation.

The retrofitted design for the MILP is shown below in Figure 26. The network includes two new exchangers (E8 and E9), an increase in existing exchanger area (E1, E2, and E4), and a reduction in existing exchanger area (E5, E6, and E7). Of the seven existing exchangers only one exchanger remained unchanged (E3). The increase in area to exchangers E8 and E9 was in the form of adding new shells. It is interesting to note that no additional area was added via increasing the area of existing shells.

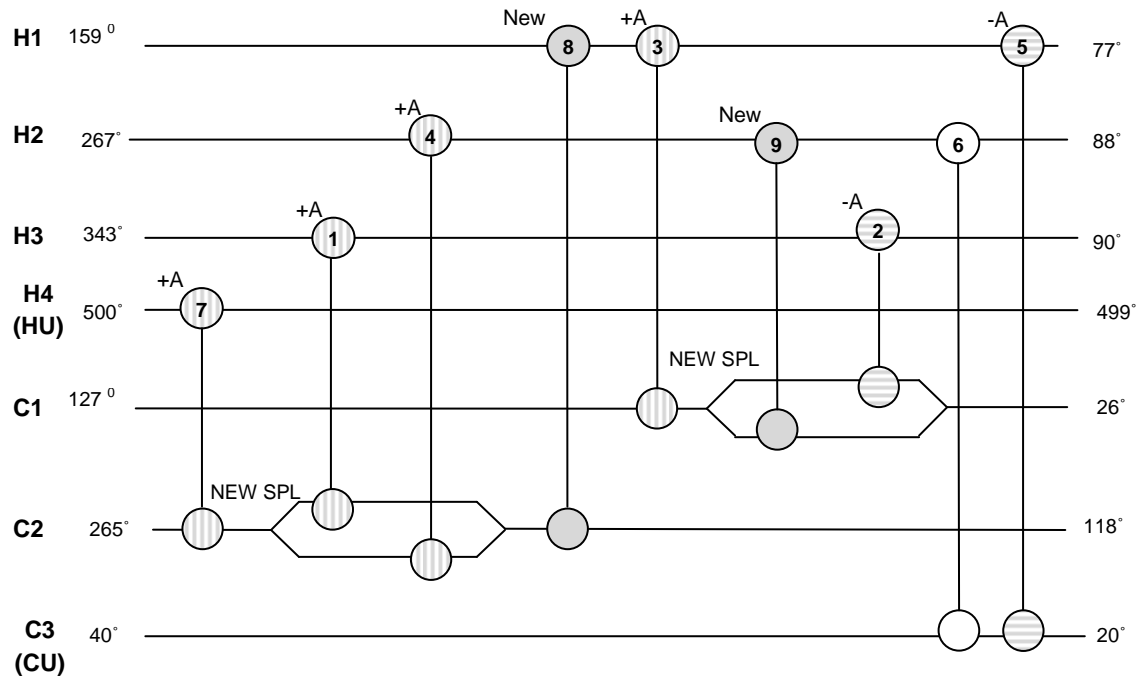
The existing heat exchangers that were increased in area represent heat exchange between process streams; while the heat exchangers that were reduced in area exchanged heat with utilities. These changes in area will produce a more energy efficient design by decreasing the amount of utilities required by the system.



**Figure 26. Retrofitted HEN from the MILP methodology**

### 4.1.2 Process Pinch Results

The retrofitted design for the process pinch is shown below in Figure 27. The optimal design from the process pinch method includes increasing the existing area of 4 exchangers (E1, E3, E4, and E7), reducing the existing area of 2 exchangers (E2 and E5), and adding two new exchangers (E8 and E9). As with the MILP, one of the exchangers remains unchanged (E6). However, in the process pinch network, the duty of E6 is zero. Instead of assigning a cost of removing the unused exchanger, it was decided to leave the exchanger in place to allow for future changes in operating parameters.

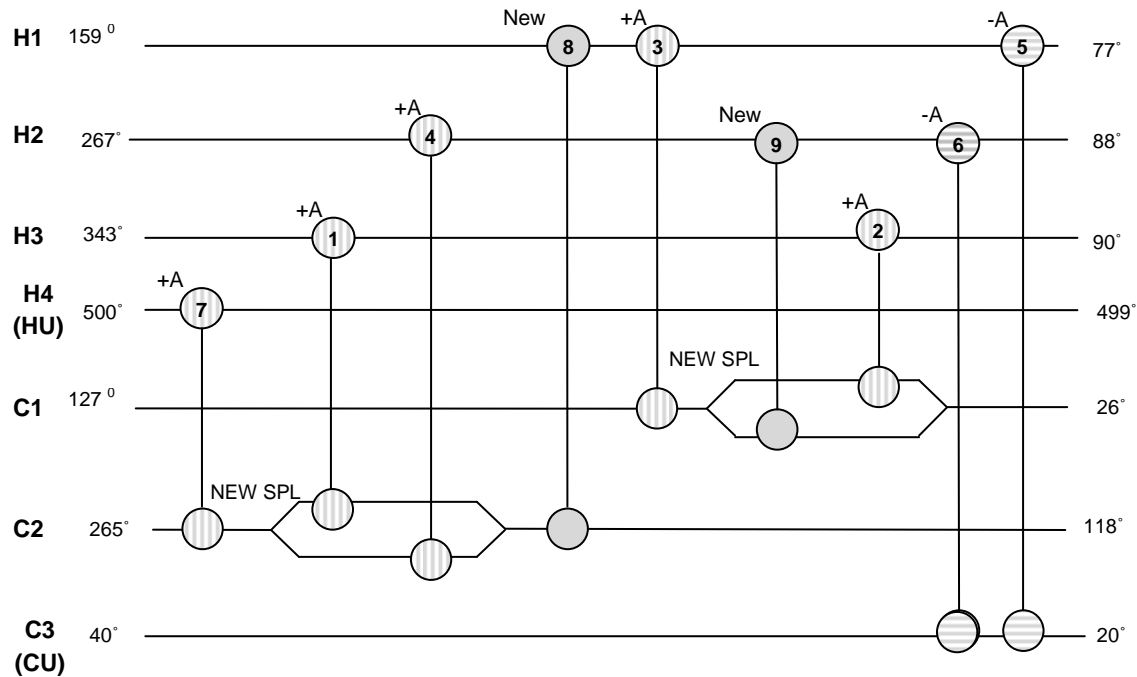


*Notation:* new exchanger (New), area addition (+ A, vertical stripes), area reduction (-A, horizontal stripes), new split (NEW SPL)

**Figure 27. Retrofitted HEN from the process pinch methodology.**  
Exchanger 6 becomes non-operational.

### 4.1.3 Pro-II Results

The retrofitted design for the Pro-II simulation is shown below in Figure 28. The optimal design from the process pinch method includes increasing the existing area of 5 exchangers (E1, E3, E4, and E7), reducing the existing area of 3 exchangers (E2, E6, and E5), and adding two new exchangers (E8 and E9). Since the location of the heat exchangers for the Pro-II simulation were determined by the process pinch methodology, the two methods have similar results.



*Notation:* new exchanger (New), area addition (+ A, vertical stripes), area reduction (-A, horizontal stripes), new split (NEW SPL)

**Figure 28. Retrofitted HEN from the Pro-II simulation**

#### 4.1.4 Cost Comparison

The final network areas and  $\Delta T_{\min}$  values for the MILP and process pinch methods are displayed in Table 15.

**Table 15. Final network areas and  $\Delta T_{\min}$  values for Example 1 disallowing relocation.**

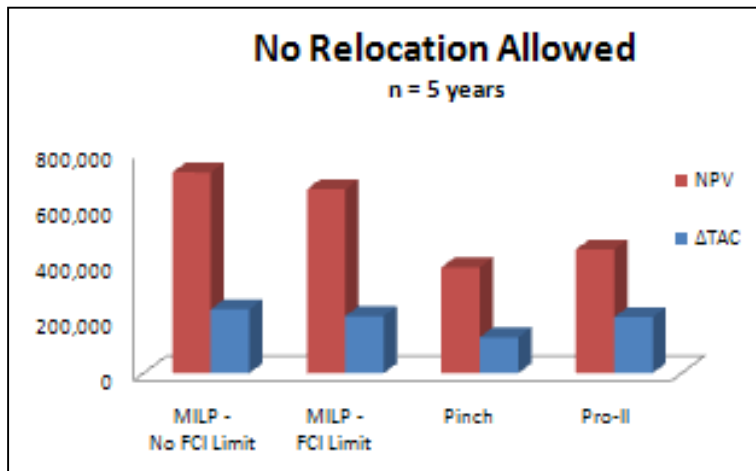
	Original HEN	Retrofitted HEN (No Relocation)		
		MILP	Process Pinch	Pro-II
$\Delta T_{\min}$	43.1	10.0	32.0	35.0
Network Area	3,739	5,088	4,212	3,792

\* T in °C, A in m<sup>2</sup>

The following tables represent the cost comparison between the three methodologies. The results are shown for a variety of objective functions for the MILP. The tables show the results of maximizing the savings ( $\Delta TAC$ ) separately from maximizing the net present value. Also, each objective function is shown with and without a limit on the fixed capital investment. Finally, a separate analysis of the return on investment (ROI) results is discussed.

**Table 16. Cost comparison data for Example 1, disallowing relocation.**

<b>Fixed Capital Investment (FCI) (\$) - No Relocation</b>				
MILP	MILP		Pinch	Pro-II
	No Limit	Limit		
	1,730,945	854,628	959,329	854,628
<b>ΔTAC (\$/yr) - No Relocation</b>				
n	MILP		Pinch	Pro-II
	No Limit	Limit		
5	231,002	206,442	130,085	202,646
10	450,560	301,569	226,018	288,108
15	558,508	324,124	257,995	316,596
<b>NPV (\$) - No Relocation</b>				
n	MILP		Pinch	Pro-II
	No Limit	Limit		
5	726,622	665,520	383,162	447,959
10	2,232,910	1,802,193	1,216,743	1,670,349
15	3,335,118	2,292,945	1,734,331	2,270,925



**Figure 29. Comparison between various methodologies, disallowing relocation.**

From Table 16 it can be seen that for certain cases in the MILP the fixed capital investment (FCI) is limited. It was decided to limit the FCI to the lowest capital investment generated from the pinch and Pro-II methodologies. In this case, the Pro-II simulation generated the lowest fixed capital investment. Also, from the graphical representation in Figure 29 it is clear that the MILP has the highest net present value as well as the highest ΔTAC for scenarios with and without a limit on the fixed capital investment. Since Example 1 represents a relatively smaller project, it was decided to show the graphical representation of the data for a project life of 5 years. Similar trends are shown for project lives of 10 and 15 years and these graphs can be found in the Appendix.

Another cost analysis that may be beneficial for industrial applications is the return on investment (ROI). Table 17 shows the calculated ROIs for Example 1 at project lifetimes of 5, 10, and 15

years. From these results it is clear that the MILP has a much larger ROI than the process pinch or Pro-II results.

**Table 17. Results of ROI calculations for Example 1, disallowing exchanger relocation.**

ROI (\$) - No Relocation				
n	MILP		Pinch	Pro-II
	No Limit	Limit		
5	37.0%	41.0%	22.9%	29.9%
10	30.0%	33.0%	14.2%	18.5%
15	27.0%	29.0%	8.8%	11.5%

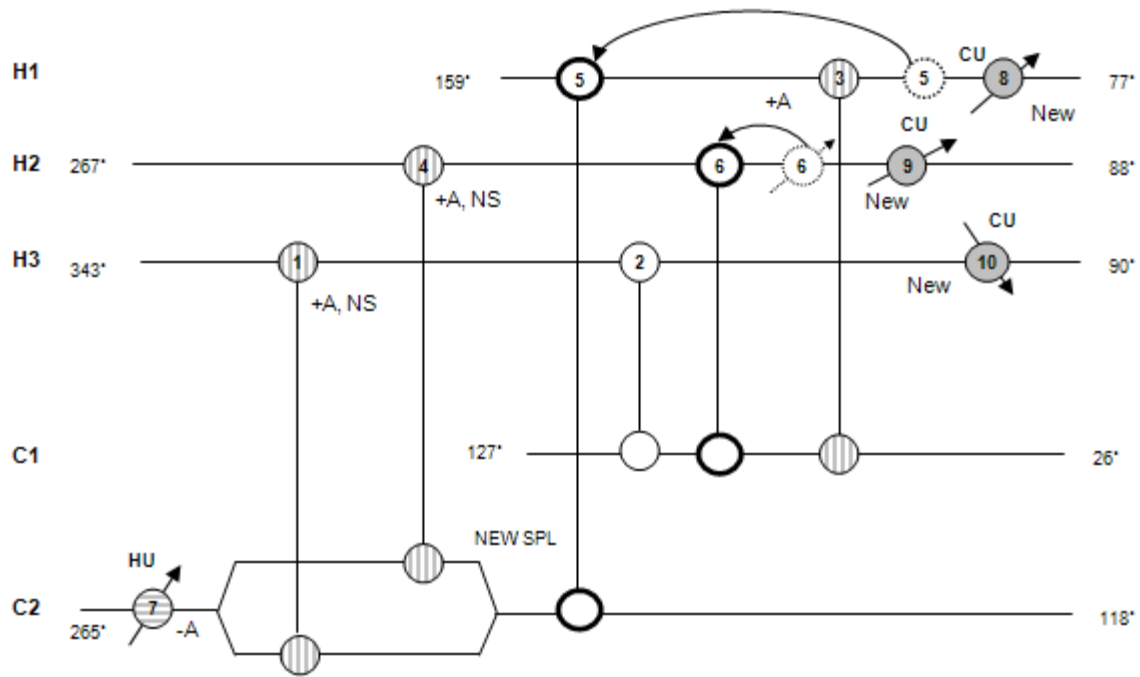
## ***4.2 Allow Relocation (Example 1)***

Allowing the relocation of existing heat exchangers enables each methodology to increase the number of feasible solutions. These additional solutions may represent networks which require a lower fixed capital investment while still meeting the target temperatures of each stream. This approach is an extension and improvement of the process pinch technology and is discussed below.

### **4.2.1 MILP Results**

For the following analysis the results of MILP, process pinch, and the Pro-II simulation are presented for the retrofit of Example 1, allowing heat exchanger relocation.

The retrofitted design for the MILP is shown below in Figure 30. The network includes three new exchangers (E8, E9, and E10), an increase in existing exchanger area (E1, E3, and E4), a reduction in existing exchanger area (E7), the relocation of 2 existing exchangers (E5 and E6), and the introduction of a splitter on cold stream 2.



**Notation:** new exchanger (New), area addition (+ A, vertical stripes), area reduction (-A, horizontal stripes), new split (NEW SPL)

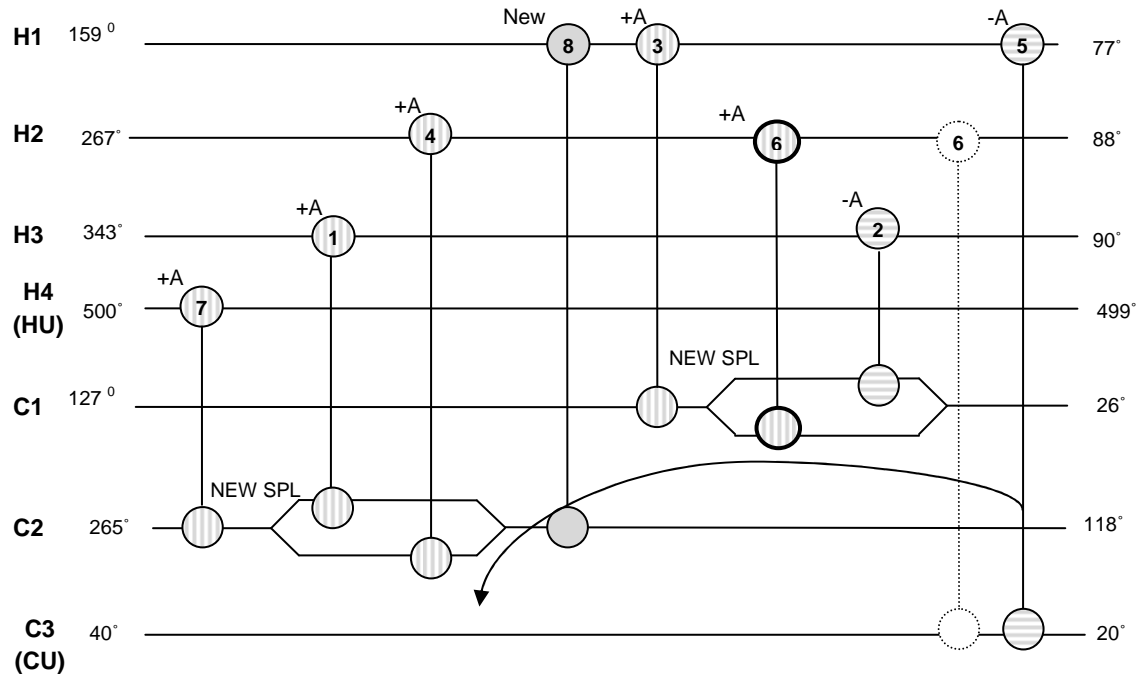
**Figure 30. Retrofitted HEN from the MILP methodology.**

E5 and E6 are relocated. E8, E9, and E10 are added.



## 4.2.2 Process Pinch Results

The retrofitted design for Example 1 includes the relocation of one exchanger (E6), the addition of one new exchanger (E8), the addition of exchanger area (E1, E3, E4, E6, and E7), the reduction of exchanger area (E2 and E5), and the introduction of two new splits (cold stream 1 and cold stream 2).

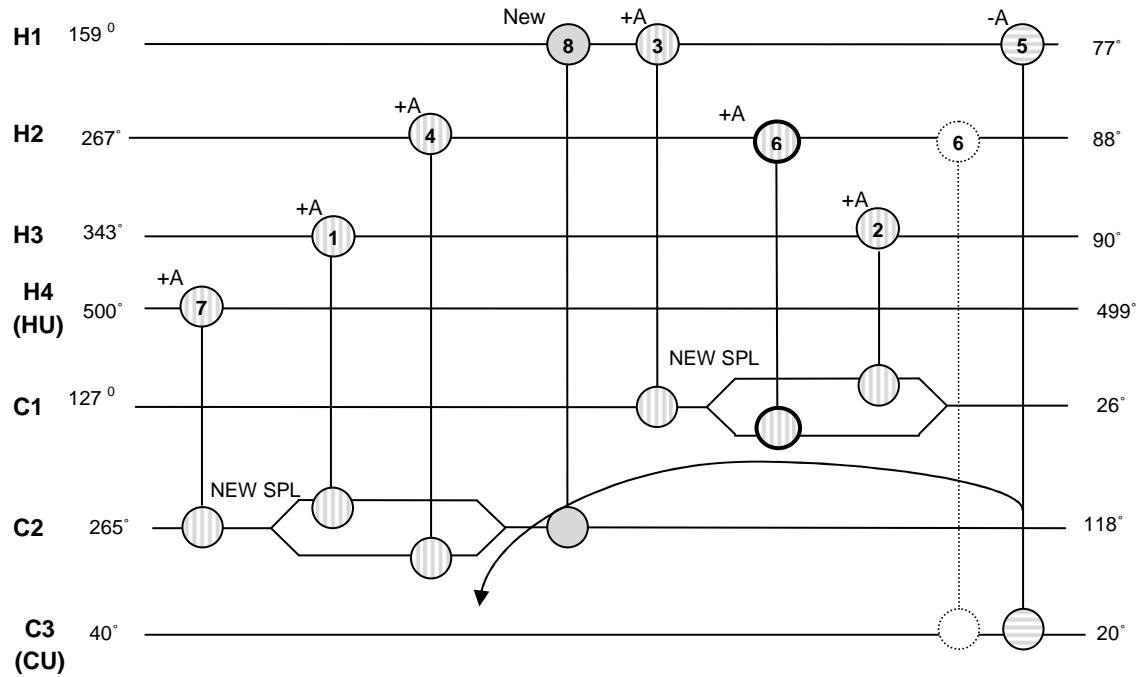


**Notation:** new exchanger (New), area addition (+ A, vertical stripes), area reduction (-A, horizontal stripes), new split (NEW SPL)

**Figure 31. Retrofitted HEN from the process pinch methodology.**  
E6 was relocated and E8 was added.

### 4.2.3 Pro-II Results

The retrofitted design for Example 1 includes the addition of one new exchanger (E8), the relocation of one existing exchanger (E6), an increase in existing area (E1, E2, E3, E4, E6, and E7), a reduction in existing area (E5), and the introduction of two new splits (cold stream 1 and cold stream 2).



**Notation:** new exchanger (New), area addition (+ A, vertical stripes), area reduction (-A, horizontal stripes), new split (NEW SPL)

**Figure 32. Retrofitted HEN from the Pro-II methodology.**  
E6 was relocated and E8 was added.

### 4.2.4 Cost Comparison

The final network areas and  $\Delta T_{\min}$  values for the MILP and process pinch methods are displayed in Table 18.

**Table 18. Final network areas and  $\Delta T_{\min}$  values for Example 1 allowing relocation.**

	Original HEN	Retrofitted HEN (Relocation Allowed)		
		MILP	Process Pinch	Pro-II
$\Delta T_{\min}$	43.1	10.0	32.0	35.0
Network Area	3,739	4,865	4,087	3,778

\* T in °C, A in m<sup>2</sup>

As with the previous cost comparison in which exchanger relocation was not considered, the results allowing relocation compare various objective functions for the MILP with and without limits on the FCI. These results are shown below in Table 19 and Figure 33.

**Table 19. Results of cost comparison for Example 1, allowing exchanger relocation.**

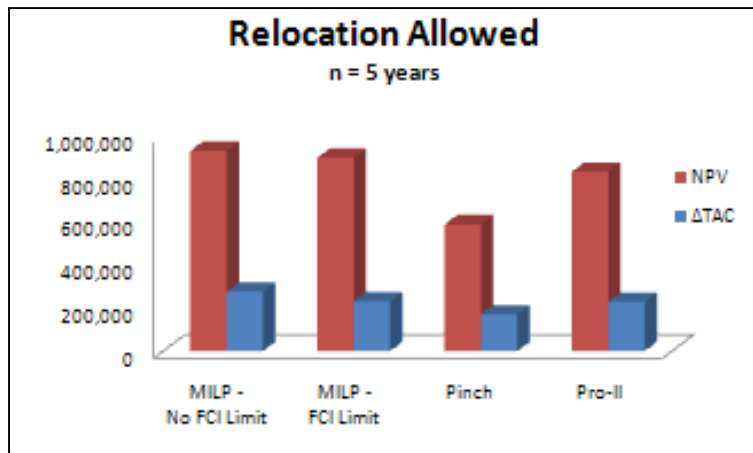
<b>Capital Costs (CC) (\$) - Relocation Allowed</b>				
Limit	MILP		Pinch	Pro-II
	No Limit	Limit		
720,136	1,346,855	751,137	720,136	

<b><math>\Delta</math>TAC (\$/yr) - Relocation Allowed</b>				
n	MILP		Pinch	Pro-II
	No Limit	Limit		
5	277,462	232,641	171,723	229,234
10	479,882	305,297	246,837	301,248
15	580,128	348,266	271,875	325,252

<b>NPV (\$) - Relocation Allowed</b>				
n	MILP		Pinch	Pro-II
	No Limit	Limit		
5	933,566	902,165	591,354	836,313
10	2,474,046	1,984,728	1,424,935	1,802,745
15	3,574,389	2,206,545	1,942,523	2,077,479



**Figure 33. Comparison between various methodologies, allowing relocation**

From Table 19 it is shown that the FCI for the MILP has a limit of the lowest FCI between the process pinch and Pro-II methodologies. As with the case which disallows the relocation of heat

exchangers, the lowest FCI is determined by the Pro-II results. It is also important to note that the MILP has the highest NPV and  $\Delta TAC$  for all cases, and for all project lives. The results for the scenario which allows relocation and a project life of 5 years is shown graphically in Figure 33. The graphs for project lives of 10 and 15 years can be found in the Appendix.

From the cost analysis presented in Table 19 it is possible to calculate the return on investment (ROI). In many project selections, the ROI plays a part in determining which projects are selected and which are neglected. In the instance of Example 1 and allowing the relocation of existing exchangers, the MILP has the largest ROI of any of the methodologies. This data is shown below in Table 20.

**Table 20. Results of ROI calculations for Example 1, allowing exchanger relocation**

ROI (\$) - Relocation Allowed				
n	MILP		Pinch	Pro-II
	No Limit	Limit		
5	43%	47%	29.3%	35.4%
10	32%	35%	18.2%	22.0%
15	30%	32%	11.3%	13.6%

### ***4.3 No Relocation (Example 2)***

Example 2 represents a heat exchanger network for a crude distillation unit. As such, Example 2 is much more involved than Example 1. The original design of Example 2 includes 18 streams, 18 exchangers, 2 hot utilities and 3 cold utilities. The first analysis of Example 2 will disallow the relocation of existing heat exchangers.

#### **4.3.1 MILP Results**

The MILP produced a retrofitted heat exchanger network which required the addition of 8 new exchangers and the splitting of 2 streams. This network is shown below in Figure 34.

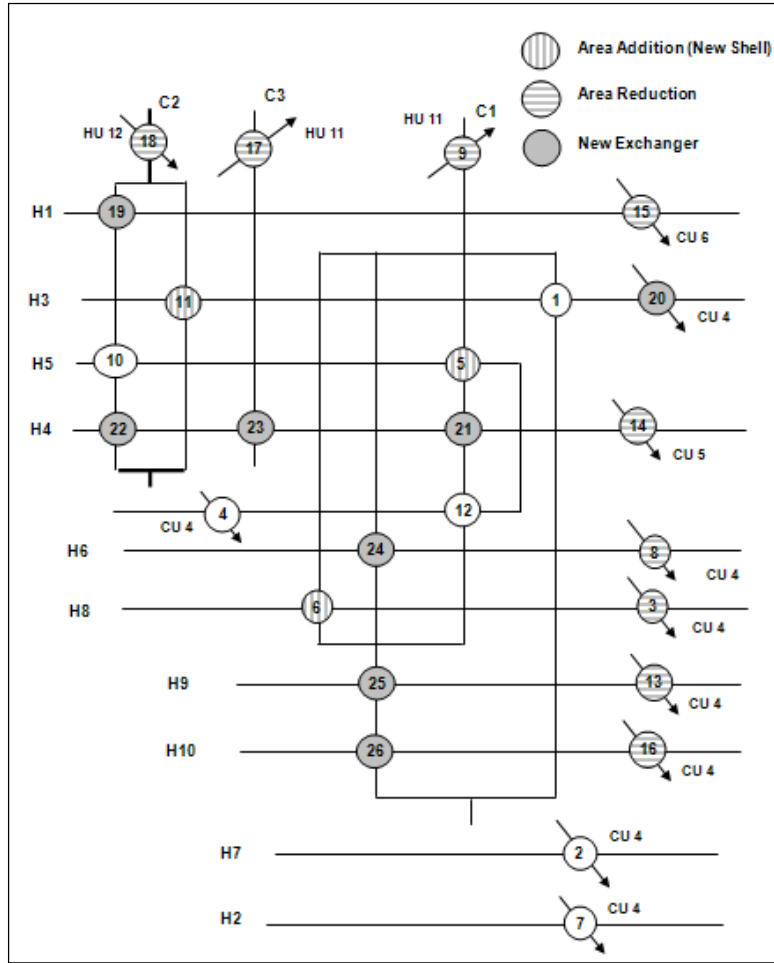


Figure 34. Retrofitted HEN for the MILP for Example 2, disallowing relocation

### 4.3.2 Process Pinch Results

The process pinch methodology proved to be very tedious and time consuming for Example 2. The high number of streams associated with Example 2 required extensive analysis and a large amount of manual computations in order to satisfy the heat balances and generate stream matches. The results for the process pinch methodology are shown below in Figure 35. The retrofitted HEN for the process pinch methodology required the addition of 9 new exchangers.

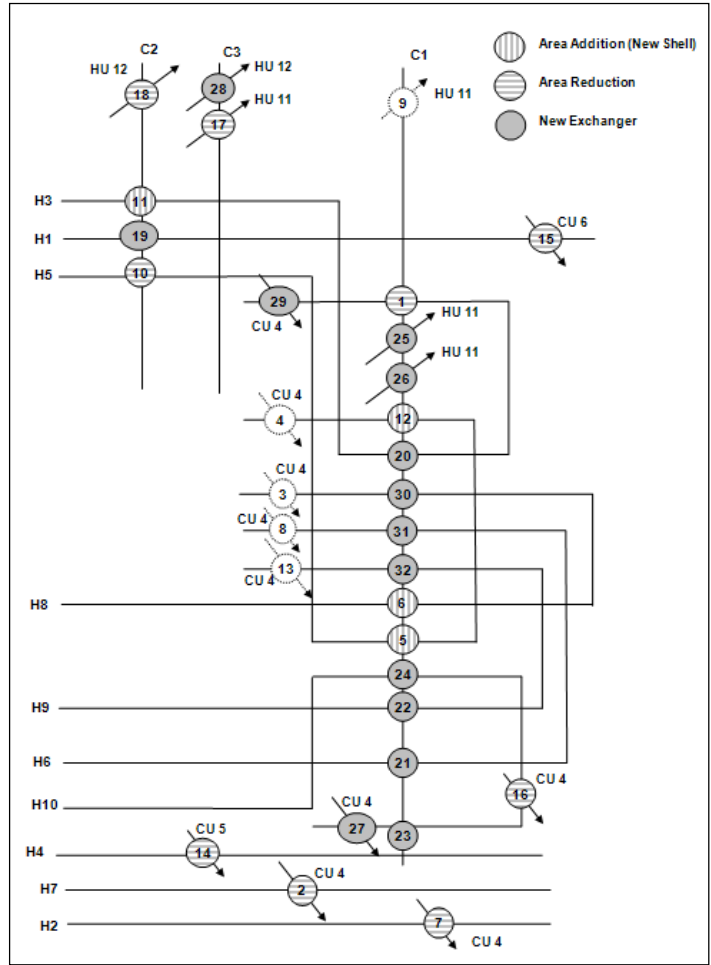


Figure 35. Retrofitted HEN for the process pinch methodology for Example 2, disallowing relocation

### 4.3.3 Pro-II Results

As with Example 1, the locations of the heat exchangers for the retrofitted network as defined by the process pinch result were simulated in Pro-II to further optimize the network. The results of this methodology are shown below in Figure 36.

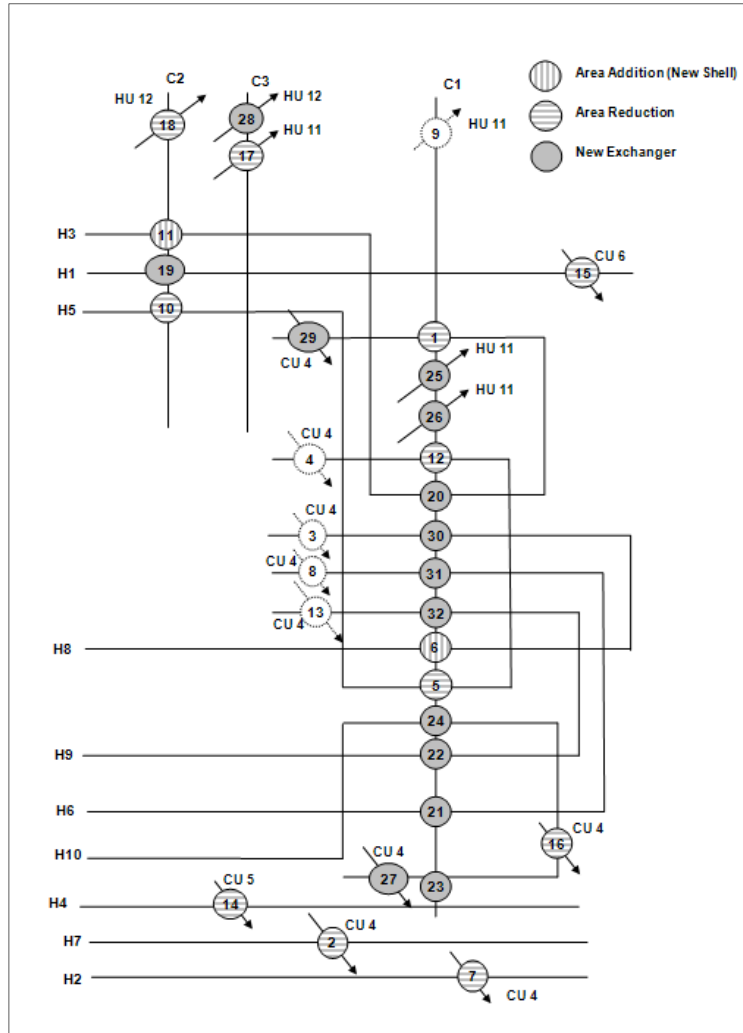


Figure 36. Retrofitted HEN for the Pro-II simulation for Example 2, disallowing relocation

#### 4.3.4 Cost Comparison

The final network areas and  $\Delta T_{\min}$  values for the MILP and process pinch methods are displayed in Table 21.

Table 21. Final network areas and  $\Delta T_{\min}$  values for Example 2 disallowing relocation.

	Original HEN	Retrofitted HEN (No Relocation)		
		MILP	Process Pinch	Pro-II
$\Delta T_{\min}$	126.7	10.0	39.0	35.0
Network Area	8,332	11,572	9,358	8,868

\* T in °C, A in m<sup>2</sup>

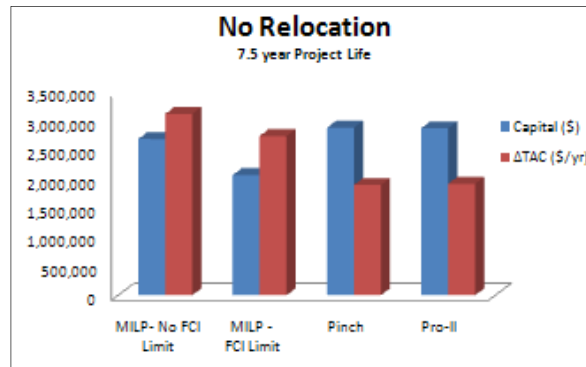
The cost comparison for Example 2 differs slightly from Example 1. The MILP is analyzed for one objective function: maximizing savings ( $\Delta TAC$ ). The objective function is solved with and without a limit on the fixed capital investment. From these results the return on investment is calculated. The results

for the cost comparisons are shown below for project lives of 7.5 and 15 years.

**7.5 year project life (No Relocation):**

**Table 22. Fixed capital investment results and cost analysis for Example 2**

7.5 years	MILP		Pinch	Pro-II
	No FCI Limit	FCI Limit		
Capital (\$)	2,688,788	2,067,098	2,882,604	2,873,990
ΔTAC (\$/yr)	3,121,267	2,740,233	1,896,811	1,917,004
ROI	131.0%	146.0%	79.1%	80.0%

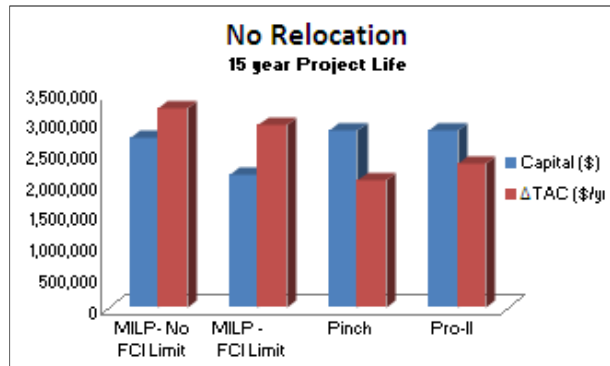


**Figure 37. Cost and profit analysis for Example 2 for a project life of 7.5 years**

**15 year project life (No Relocation):**

**Table 23. Fixed capital investment results and cost analysis for Example 2**

15 years	MILP		Pinch	Pro-II
	No FCI Limit	FCI Limit		
Capital (\$)	2,765,715	2,178,645	2,882,604	2,873,990
ΔTAC (\$/yr)	3,255,391	2,981,823	2,088,984	2,338,623
ROI	124.0%	144.0%	79.1%	80.0%



**Figure 37. Cost and profit analysis for Example 2**



From these results it can be seen that the MILP is the most beneficial choice in each aspect of the cost analysis as well as the profit criteria.

#### 4.4 Allow Relocation (Example 2)

This analysis of Example 2 allows the relocation of existing heat exchangers. This approach is designed to generate solutions that may be better than those found by disallowing exchanger relocation.

##### 4.4.1 MILP Results

The MILP produced a retrofitted heat exchanger network which required the addition of only 5 new exchangers and relocated 5 existing exchangers. This network is shown below in Figure 38.

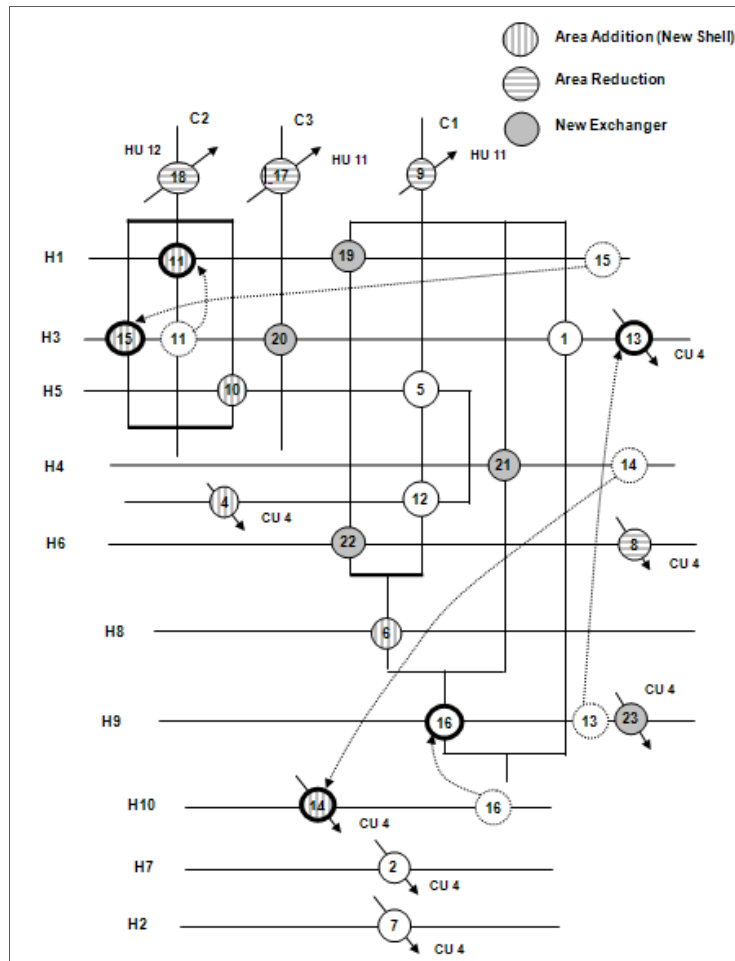


Figure 38. Retrofitted HEN for MILP, allowing exchanger relocation

### 4.4.2 Process Pinch Results

The process pinch methodology was especially time consuming for this scenario. By allowing the relocation of existing heat exchangers, the user is required to analyze numerous scenarios and account for the subsequent looping that is associated with changes in the heat exchanger network. The optimal solution that was found for the process pinch methodology required the addition of 9 new exchangers and the relocation of 7 existing exchangers. The retrofitted network is shown below in Figure 39.

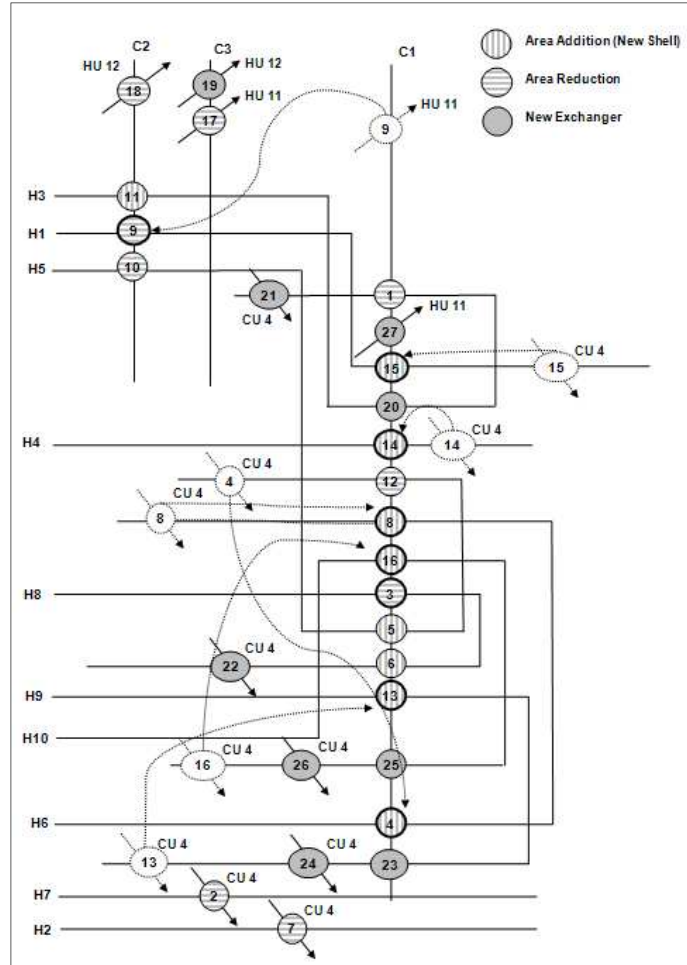


Figure 39. Retrofitted HEN for process pinch methodology, allowing exchanger relocation

### 4.4.3 Pro-II Results

The process pinch network was simulated in Pro-II to further optimize the area distributions. The results for the Pro-II retrofitted network are shown below in Figure 40.

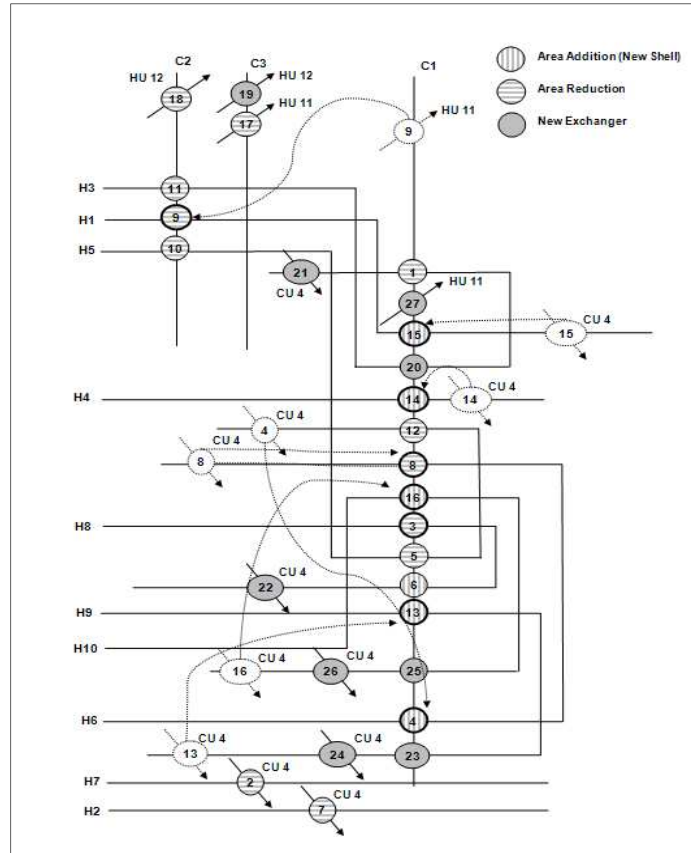


Figure 40. Retrofitted HEN for the Pro-II simulation, allowing exchanger relocation

#### 4.4.4 Cost Analysis

The final network areas and  $\Delta T_{\min}$  values for the MILP and process pinch methods are displayed in Table 24.

Table 24. Final network areas and  $\Delta T_{\min}$  values for Example 2 allowing relocation.

	Original HEN	Retrofitted HEN (Relocation Allowed)		
		MILP	Process Pinch	Pro-II
$\Delta T_{\min}$	126.7	10.0	39.0	35.0
Network Area	8,332	11,049	10,328	7,695

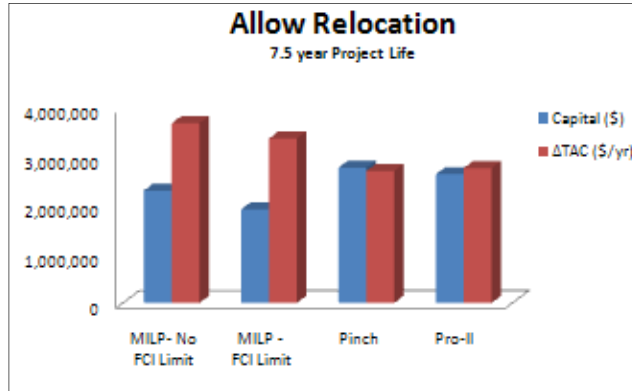
\* T in °C, A in m<sup>2</sup>

The cost analysis for the scenarios allowing relocation is performed identically to those scenarios which disallow relocation. The MILP was run by maximizing the savings ( $\Delta TAC$ ) and by limiting and not-limiting the fixed capital investments. The results for project lives of 7.5 and 15 years are shown below.

**7.5 year project life (Allow Relocation):**

**Table 25. Fixed capital investment results and cost analysis for Example 2**

7.5 years	MILP		Pinch	Pro-II
	No FCI Limit	FCI Limit		
Capital (\$)	2,312,497	1,927,230	2,783,876	2,649,655
$\Delta$ TAC (\$/yr)	3,696,437	3,383,736	2,714,661	2,774,196
ROI	143.0%	156.0%	110.8%	118.0%

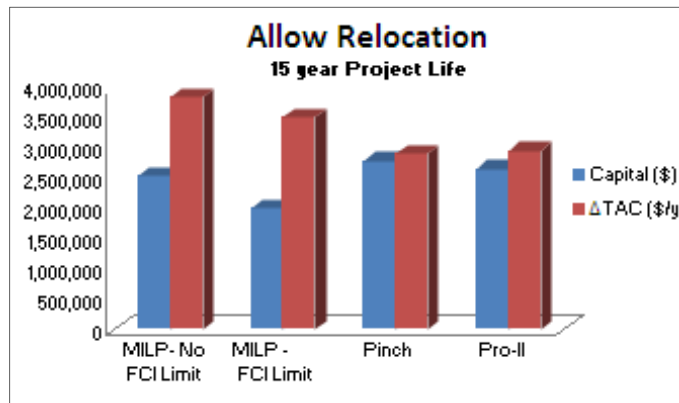


**Figure 41. Cost and profit analysis for Example 2**

**15 year project life (Allow Relocation):**

**Table 26. Fixed capital investment results and cost analysis for Example 2**

15 years	MILP		Pinch	Pro-II
	No FCI Limit	FCI Limit		
Capital (\$)	2,540,805	1,985,910	2,783,876	2,649,655
$\Delta$ TAC (\$/yr)	3,835,383	3,508,306	2,900,252	2,950,839
ROI	130.0%	152.0%	110.8%	118.0%



**Figure 41. Cost and profit analysis for Example 2**

## 5. Recommendations

From the results presented in the Discussion section, it is clear that the MILP had the optimum HEN retrofit design. The MILP allows the user to quickly and easily change parameters that would allow the evaluation of a numerous scenarios. This methodology can be tailored to enforce penalties for situations that the user wishes to avoid. In the instance of disallowing exchanger relocation, the relocation of existing exchangers was highly penalized, and therefore not considered. A separate application of this program may wish to penalize the addition of new exchangers or possibly stream splitting. The MILP allows changes to be made to the program and their impact on the optimal solution evaluated with minimal requirements of time and effort.

The process pinch design method was the second best methodology to use for the retrofiting. It had several disadvantages compared to the MILP. First, it is a very time-consuming process. Unless a software program is available that offers an easy way to change all of the parameters that the MILP can, then the methodology is not user-friendly. All calculations must be performed by the user. Secondly, relying on user computation instead of a computer risks increased error in the results. Thirdly, the pinch methodology does not have a way to deal with the various scenarios that the MILP can account for. For example, relocation is a limitation of pinch technology. We addressed this issue by extending pinch technology to include the relocation of existing exchangers. Also, as an additional improvement we incorporated the advanced software optimization capabilities of Pro-II. Even with both of these improvements on pinch technology, the MILP still generated better results in a shorter time frame. Fourth, the process pinch requires a background in the methodology before it can be performed. With the MILP, a user could input the parameters relevant to a specific network and let the program do the rest. However, with pinch technology, the user would need to understand the basic concepts and then understand how to apply the concepts to a specific example. Lastly, the pinch design method cannot merely add penalties to results that are not desired; the methodology does not allow for penalties to be incorporated.

Table 26 summarizes the computational time requirements as well as the amount of user involvement that is required for each of the retrofit methodologies. Since time for project completion plays a large role in the selection process for projects, it is important to note that the MILP requires the least computational time as well as the lowest level of user involvement.

**Table 26. Computation time and user-involvement comparison between retrofit methodologies**

	Example 1					
	No Relocation			Relocation Allowed		
Computation time (hr)	MILP 0.1	Process Pinch 5	Pro-II 3	MILP 2	Process Pinch 5	Pro-II 3
	Example 2					
	No Relocation			Relocation Allowed		
Computation time (hr)	MILP 5	Process Pinch 9	Pro-II 7	MILP 5	Process Pinch 10	Pro-II 8
Computer Simulation						
Manual/Computer						
Manual						

The reasons stated above clearly identify why the MILP is the methodology to use in industry. However, besides being more user friendly and time-efficient, we have not discussed why pinch technology fails to produce the optimum solutions that MILP does. We believe that the source of the failing of the process pinch as a competitor in the retrofit process lies with the determination of the optimum  $\Delta T_{\min}$  value. Because this value is determined prior to the design of the retrofit process, the entire subsequent methodology relies on the accuracy of the assumption that the optimum value was legitimate enough to produce the most economical solution. If a different  $\Delta T_{\min}$  value is chosen as the optimum value, it may have a significant effect on the design of the network. The exchanger matches above and below the pinch are directly affected by the location of the pinch. Furthermore, the likelihood that the global optimum  $\Delta T_{\min}$  value is the same for the final retrofit design and for the design where equal exchanger area is assumed is low.

Moreover, the likelihood is also low that the global optimum design will have the  $\Delta T_{\min}$  value that pinch technology determines based on equal exchanger areas. The optimization of the retrofitted network for pinch technology begins after the "optimum"  $\Delta T_{\min}$  value has already determined. As a result, the  $\Delta T_{\min}$  is not a part of the optimization process. This is a problem because both exchanger area and exchanger duty, the two aspects of a heat exchanger network that are important to retrofitting, are directly affected by the  $\Delta T_{\min}$  values.

To conclude, pinch technology no doubt was a pivotal point in heat integration technology and provided a very systematic method to retrofit an existing network. However, as engineering has progressed and emphasis has been placed on improving heat integration technology, pinch technology finds itself not being able to compete with the new technologies created.

## Appendix

The following graphs illustrate the comparisons between the methodologies of MILP, Process Pinch, and Pro-II. The objective function for the MILP was manipulated to maximize  $\Delta TAC$  separately from NPV and ROI. The different objective functions are shown below.

$$\Delta TAC = \text{Annual Savings} - \text{Annualized Fixed Capital Investment.}$$

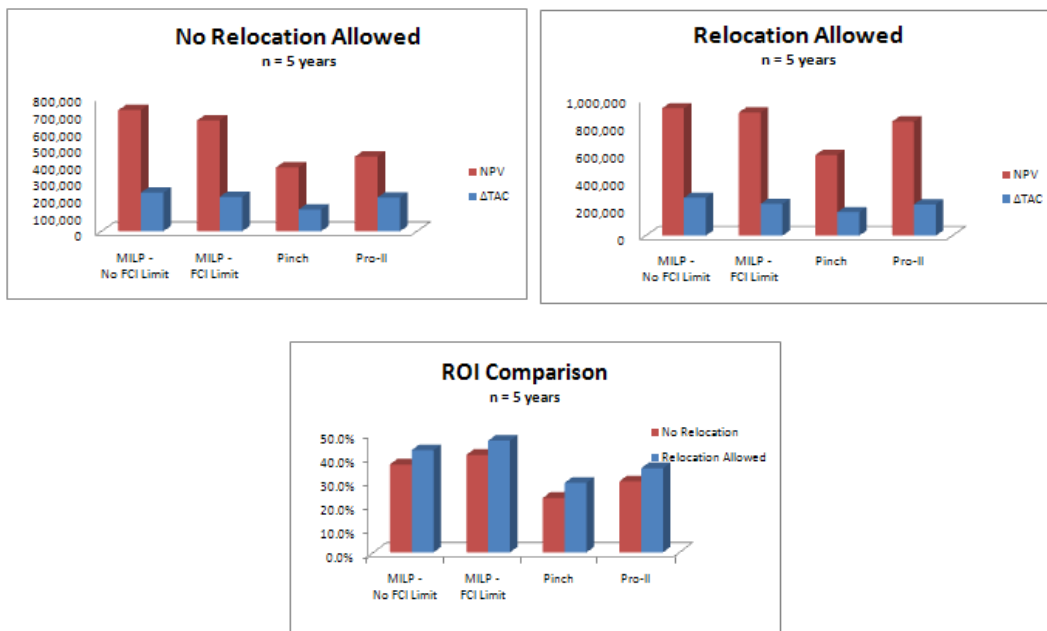
$$\text{Net Present Value} = \sum(\text{Discount Factor}_i * \text{Utility Cost Savings}_i) - \text{Total Capital Cost}$$

The analysis of Return on Investment was calculated from the results of maximizing the Net Present Value objective function. The equation for calculating Return on Investment is shown below.

$$\text{Return on Investment} = \text{Utility Cost Annual Savings} / \text{Total Capital Cost}$$

Another analysis for the MILP includes enforcing a limit on the fixed capital investment versus allowing the model to determine the optimal fixed capital investment.

These comparisons are shown for project life spans of 5, 10, and 15 years.



**Figure A1. Result Comparisons for a project life of 5 years.**



Figure A2. Result Comparisons for a project life of 10 years.



Figure A3. Result Comparisons for a project life of 15 years.



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