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(Energy Conservation for Petrochemical Industries by Pinch Technology and Mathematical Programming)

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บทคัดย่อ

ในอุตสาหกรรมปิโตรเลียมและปิโตรเคมี การบริหารจัดการการใช้พลังงานเป็นสิ่งจำเป็นในการควบคุมค่าใช้จ่ายของโรงงาน ในช่วง 10 ปีที่ผ่านมาโรงงานอุตสาหกรรมส่วนใหญ่มุ่งเน้นการปรับปรุงเครือข่ายแลกเปลี่ยนความร้อนเพื่อลดการใช้พลังงานของโรงงาน งานวิจัยนี้มุ่งเน้นการออกแบบเครือข่ายแลกเปลี่ยนความร้อนด้วยวิธีการพินช์โดยใช้โปรแกรมทางคณิตศาสตร์แบบ stage model ซึ่งเขียนด้วยโปรแกรมคอมพิวเตอร์ GAMS (General Algebraic Modeling System) เนื่องจากปริมาณพลังงานที่ใช้ และ พื้นที่แลกเปลี่ยนความร้อนของอุปกรณ์แลกเปลี่ยนความร้อนเปลี่ยนแปลงขึ้นกับอุณหภูมิที่จุดพินช์ หรือ ค่าความแตกต่างที่น้อยที่สุดระหว่างอุณหภูมืของสายร้อนและเย็น (ΔT_{min}) งานวิจัยนี้พัฒนาโปรแกรม VBA (Visual Basic for Applications) ร่วมกับการวิเคราะห์แบบพินช์ เพือคำนวณหาอุณหภูมิที่จุดพินช์ของเครือข่ายแลกเปลี่ยนความร้อนที่ให้ผลกำไรของโรงงานที่มากที่สุด ต่อจากนั้นโปรแกรม stage model จะคำนวณและออกแบบเครือข่ายแลกเปลี่ยนความร้อนที่เหมาะสมกับโรงงาน

Abstract

For petroleum and petrochemical industries, energy management is an important element to controlling total operating costs. Over the past decades, there appears to be an urgent need to retrofit the existing heat exchanger networks (HENs) of the plant to reduce the current utility consumption.A simple pinch design approach is proposed here to accomplish above-and-below pinch HEN design by stage-model mathematical programming using commercial software; GAMS.The energy and capital costs of a heat exchanger network are both dependent on the pinch temperature or minimum temperature approach (ΔT_{min}) which is set as a target design parameter prior to designing HEN. In this work, a retrofit potential program is developed using VBA (Visual Basic for Applications) to find the optimum ΔT_{min} at the targeting step.

Moreover, the program can automatically generate composite curves and grand composite curve of the process. Finally, the stage-model mathematical programming helps design the improved HEN with optimal profit or net present value (NPV).

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CHAPTER I
INTRODUCTION

Energy conservation and environmental care has become more important for the petroleum and petrochemical industry during the energy crisis of the early 1970’s. Now, due to the current situation, innovative and efficient ways are needed to improve energy efficiency and reduce emission. Crude distillation unit is an energy-intensive process and has received significant attention for better energy integration in petroleum industry.

In conventional oil refining, crude distillation unit (CDU) is the first step of process separating the crude oil into different fractions depending on the different boiling temperatures as shown in Figure 1.1. The products of the crude oil distillation unit can be either final products or feedstock to other plants for further processing. In the middle decades of 20th century, when some of oil refineries operating today were designed, each refinery was considered to process a certain type of crude. In the last two decades, the raw material fed to the refinery changes frequently the characteristics. This modification is explained by the availability of uncertain crude oil quality on the market and the change in quality of crude from traditional sources. This situation is one of the reasons to revamp CDU, to increase CDU flexibility. Conversely, separation costs should be rapidly reduced, to face the market concern. In crude distillation unit, the crude oil is preheated in two stages before entering the distillation column. The first stage is a heat exchanger network (HEN), where the oil is heated to an intermediate temperature by cooling distillation process streams and recovering the heat from condensers. Afterward, the crude oil enters a furnace to reach the required processing temperature. The more fuel consumed in the furnace, the larger the operating cost (Smith *et al.*, 2003). The primary objective of conventional energy analysis of a CDU is to maximize the yield of heat recovery in HEN. Normally the HEN of crude distillation unit, one of the most complex in oil refinery, need retrofit.

Heat exchanger networks (HENs) have been widely applied in industrial projects over the past decades because they provide significant energy and economic savings. Applications of HEN integration can be divided into two categories are grassroots and retrofit design. In oil refining, retrofit design are far more common than grassroots applications. Frequently, proper redesign of an existing network can reduce significantly the operating costs in a process. The major objectives of retrofit problems are the reduction of the utility consumption, the full utilization of the existing exchangers and identification of the required structural modifications.

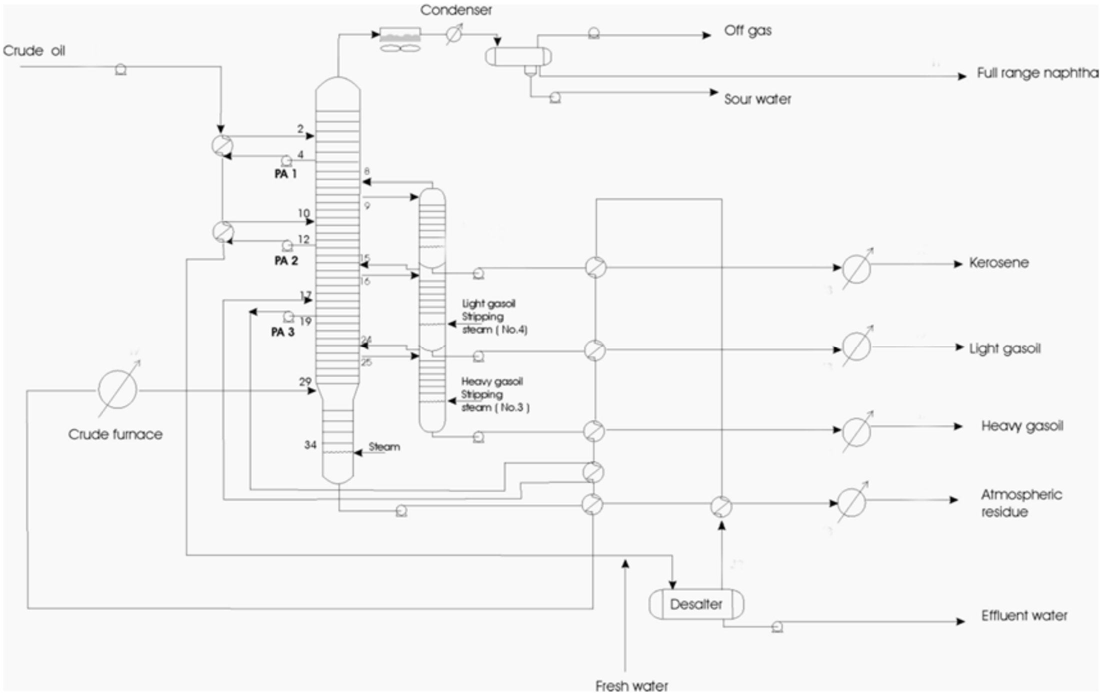

Condenser
Off gas
Crude oil
Full range naphtha
Sour water
2
4
PA 1
8
9
10
12
PA 2
15
16
17
19
PA 3
Light gasoil
Stripping
steam (No.4)
24
25
29
Heavy gasoil
Stripping
steam (No.3)
34
Steam
Crude furnace
Kerosene
Light gasoil
Heavy gasoil
Atmospheric
residue
Desalter
Effluent water
Fresh water

Figure 1.1 Crude distillation Unit (CDU)

CHAPTER II
LITERATURE REVIEW

Heat exchanger network (HEN) design is a key aspect of chemical process design. Previous research works (Linnhoff and Hinmarsh, 1983; Floudas et al., 1986; Yee and Grossmann, 1990) have mainly been directed to develop methods for the grassroots design of HEN's. However, during the past two decades, the retrofit of existing HEN has become more important than grassroots design. Because it gives a higher practical designed HEN in order to reduce significantly the operating costs.

Retrofit methods can be grouped into three broad categories which are thermodynamic based approaches including pinch analysis, mathematical programming methods and approaches combining both (Rezaei and Shafiei, 2009). The major objectives of retrofit problems are the reduction of the utility consumption, the full utilization of the existing exchangers and identification of the required structural modifications.

Retrofit mechanisms:

- Addition of one or more new heat exchangers (in series or parallel)
- Relocation of existing exchangers
- Area addition to existing heat exchangers
    - Adding a shell
    - Exchanging the bank of tubes by one more efficient (Brown Fintube, Houston, TX)
- Area reduction to existing heat exchangers
- Modify piping on one or both sides of the heat exchangers

2.1 Pinch Analysis Methods

Tjoe and Linnhoff (1986, 1987) proposed the first Pinch retrofit method by calculation procedure to determine the appropriate minimum temperature approach (ΔT_{min}) after retrofit by considering the energy savings, investment cost, and payback period. 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 (Texas A&M University, 2005). 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. The methodology is discussed next.

2.1.1 Stream Data

Often the original process will be illustrated in a process flow-sheet such as in Figure 2.1. 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 (Shenoy and Uday, 1995). The streams are arranged into this type of diagram because it will be useful later in the methodology. An example of grid diagram is illustrated in Figure 2.2.

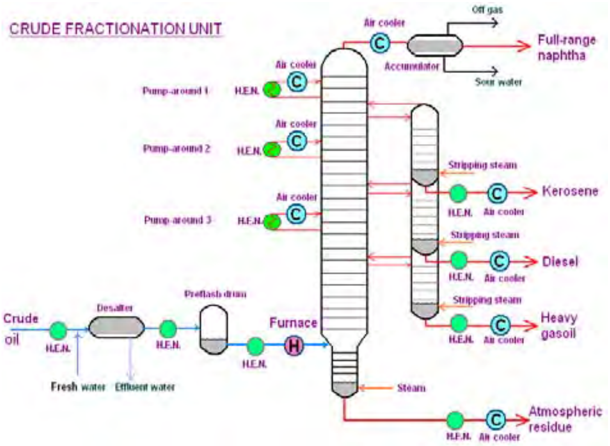

CRUDE FRACTIONATION UNIT
Off gas
Air cooler
C
Full-range naphtha
Accumulator
Sour water
Air cooler
C
Pump-around 1
H.E.N.
Air cooler
C
Pump-around 2
H.E.N.
Stripping steam
Kerosene
H.E.N.
Air cooler
Air cooler
C
Pump-around 3
H.E.N.
Stripping steam
Diesel
H.E.N.
Air cooler
Preflash drum
Stripping steam
Desalter
Furnace
Heavy gasoil
Crude oil
H.E.N.
H.E.N.
H
H.E.N.
H.E.N.
Air cooler
Fresh water
Effluent water
Steam
Atmospheric residue
H.E.N.
Air cooler

Figure 2.1 Crude fractionation unit.

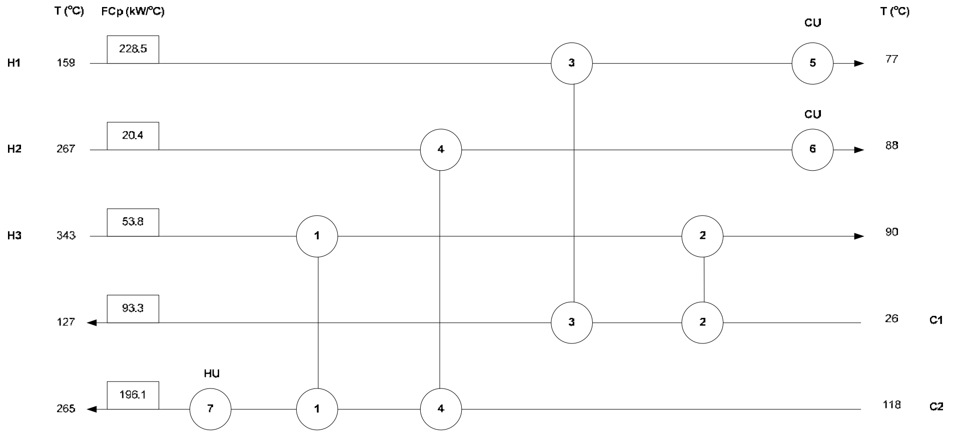


Figure 2.2 An example of grid diagram.

Specific thermodynamic data is required from the streams to perform the pinch methodology. These include the supply temperature of each stream (T_{in}) °C, the target temperature of each stream (T_{out}) °C, the mass flow rate (F) in kg/s, and the specific heat (Cp) in kJ/kg-°C. The heat capacity flow rate (FCp) in kW/°C can then be calculated by Equation 1.

$$FCp = F \times Cp \tag{1}$$

The second property that needs to be calculated is the enthalpy change of each stream given by Equation 2.

$$\Delta H = FCp \times \Delta T \tag{2}$$

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 which represent the temperature intervals for the hot and cold streams (Shenoy and Uday, 1995). Hot streams will then be combined to create one curve called the hot composite curve, while the cold streams are combined to create the cold composite curve. Figure 2.3 demonstrates how a hot composite curve (right) is developed from the straight line segments of each hot stream (left) in a network.

2.1.2 Composite Curves and ΔT_{min}

The hot and cold composite curves provide the minimum energy targets for a process (Linnhoff, 1998). 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 FCp values in each interval accordingly. The enthalpy requirement for each interval is calculated by Equation 2 using the temperatures for the appropriate interval. Plotting the cumulative enthalpy for each interval versus the temperature intervals shows the hot composite curve. 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 (Texas A&M University. "Network Pinch Analysis." 22.). 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. An example of a hot and cold composite curve is displayed in Figure 2.4.

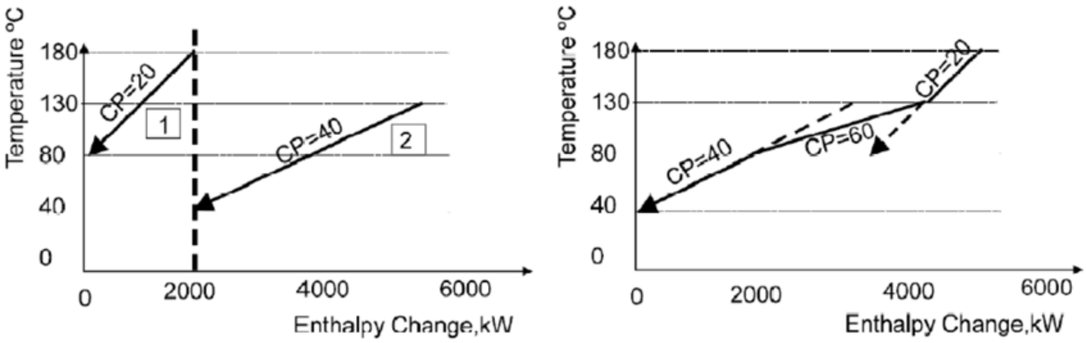


Figure 2.3 Construction of Composite Curves (Texas A&M University. "Network Pinch Analysis." 22.).

The point between the hot and cold composite curves that has the shortest vertical distance is the minimum temperature difference, ΔT_{min}, and is called the pinch point. The significance of the pinch is that different ΔT_{min} values correspond to different process-to-process heat transfer amounts in the system; at a certain ΔT_{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 (Texas A&M University. "Network Pinch Analysis." 23.). 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 2.5. These sections must be analyzed separately in the pinch methodology.

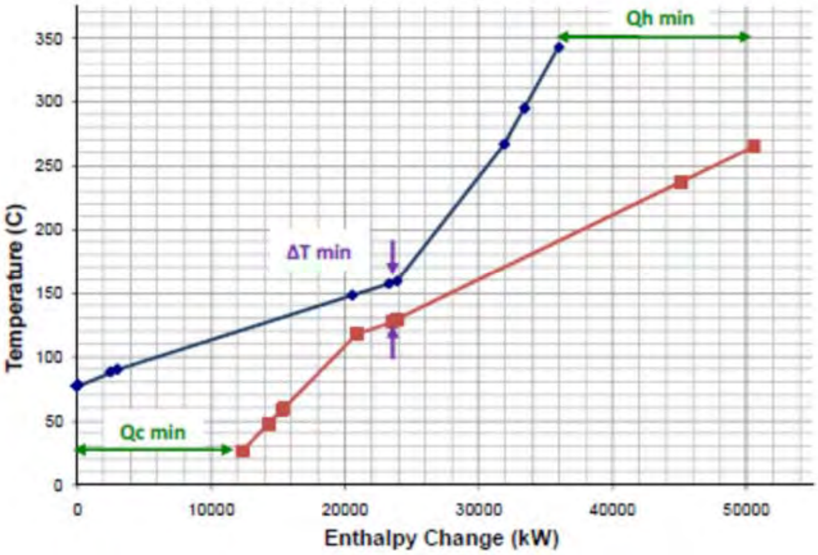


Figure 2.4 An example of a hot and cold composite curve.

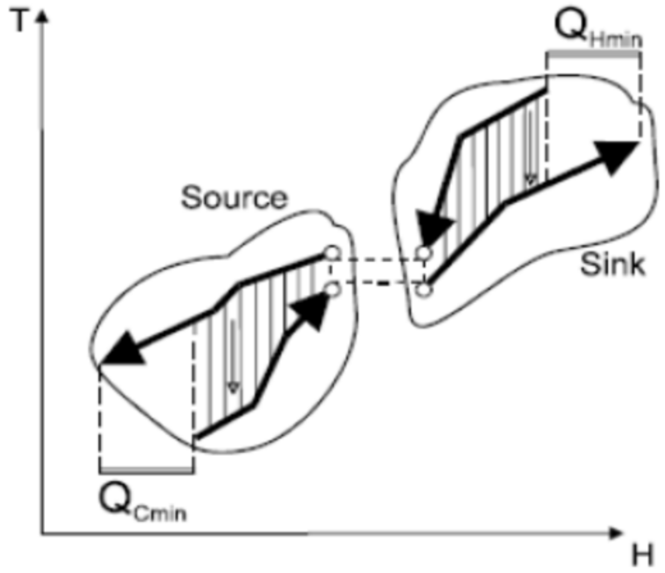


Figure 2.5 Sink and Source Separated at Pinch.

If α amount of heat is transferred from above the pinch to below the pinch, thus increasing the heat in the source α units, then the sink above the pinch must add α units of heat to restore balance in the system. This situation is illustrated in Figure 8. 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 a greater amount of energy than the process target. In a retrofit situation, obeying these rules corrects any exchangers that currently undergo cross-pinch heat transfer (Linnhoff, 1998). Analyzing the section above and below the pinch separately eliminates cross-pinch heat transfer. The pinch separates the process into a heat sink (above the pinch) and a heat source (below the pinch). Figure 2.5 and 2.6 show the source/sink and cross pinch heat transfer (Linnhoff, 1998).

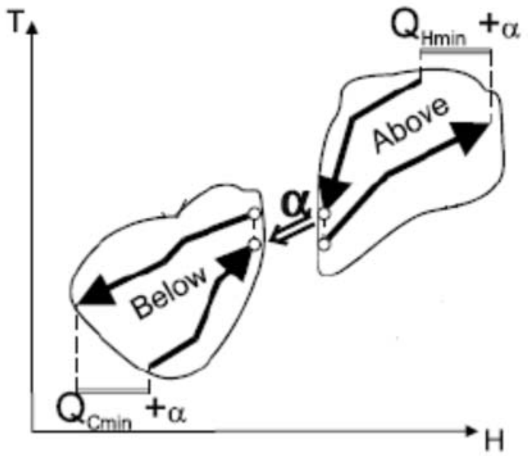


Figure 2.6 Cross pinch heat transfer.

To locate the pinch temperature, the ΔT_{min} is added to every cold stream temperature, shifting the cold composite curve up to touch the hot composite curve. An energy balance (Equation 3) is then done over each shifted temperature interval.

$$\Delta H_i = \left\{ \sum_{ColdStreams} FCp_C - \sum_{HotStreams} FCp_H \right\} \times \Delta T_i \tag{3}$$

The surplus heat is then cascaded down the intervals in order for heat recovery to take place between intervals. The minimum amount of heat required from the hot utility is added to the first interval and cascaded down. The pinch is located at the temperature where the heat flow is zero (Smith, 2005).

From the hot and cold composite curves, a grand composite curve 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 (Shenoy and Uday, 1995). It is created by shifting the cold composite curve towards the hot composite curve by an increment equal to the ΔT_{min} and then plotting the difference between the heat flows of both curves versus temperature. Figure 2.7 is an example of grand composite curve and illustrates the minimum hot and cold utilities, the pinch temperature, and the process-to-process heat exchange locations.

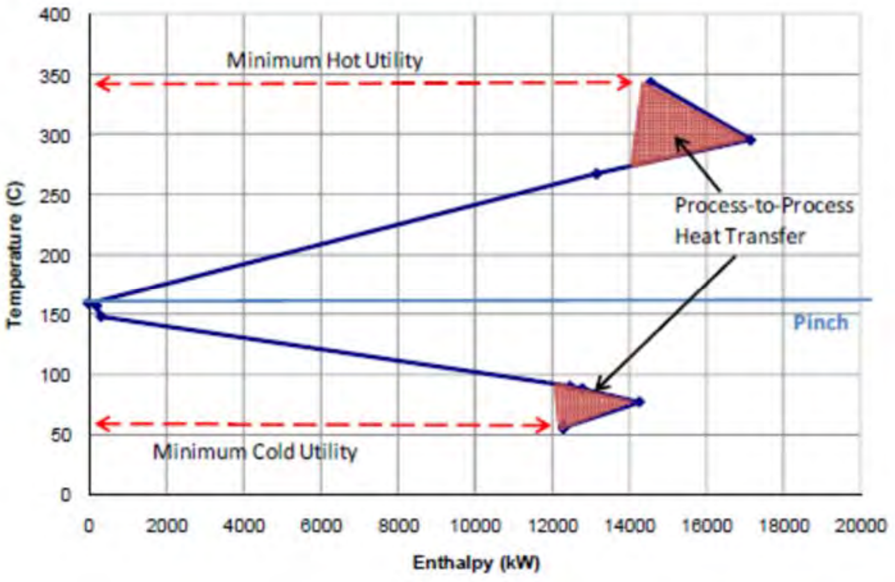


Figure 2.7 Grand Composite Curve.

2.1.3 Supertargeting

The next step in the retrofit process after the composite curves have been created is to calculate the optimum ΔT_{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 ΔT_{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.

2.1.3.1 Area Targeting

In order to determine the total network retrofit area for various ΔT_{min} values, it is necessary to understand the theory behind how pinch technology calculates the area. Figure 2.8 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.

For a grassroots design 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 (Texas A&M University. "Network Pinch Analysis." 122). The goal of the retrofit process is to increase energy savings and decrease total cost by moving X towards the target curve. As the ΔT_{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 ideally improve 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.

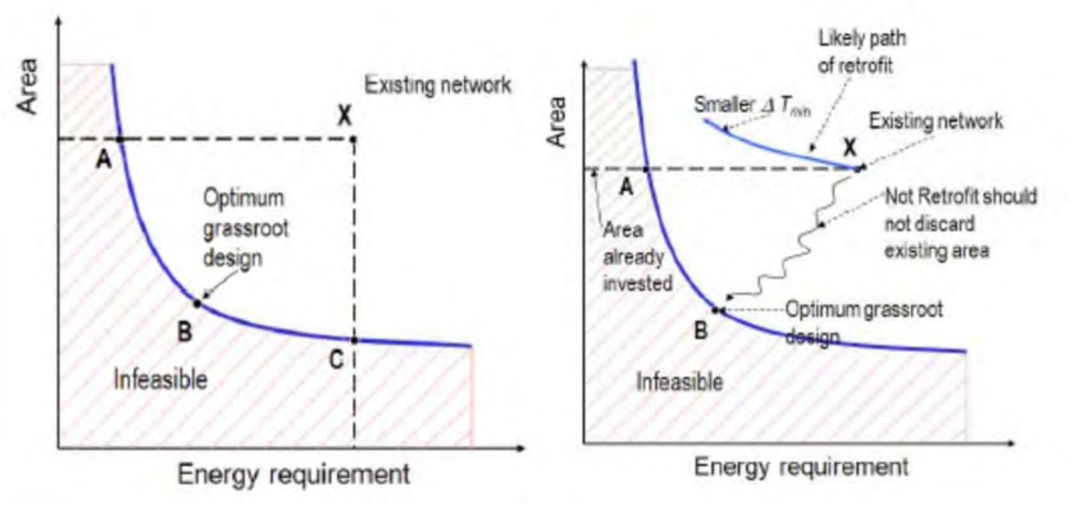

Area
Existing network
X
A
Optimum grassroot design
B
C
Infeasible
Energy requirement
Likely path of retrofit
Smaller ΔT_{min}
Existing network
X
Area
A
Not Retrofit should not discard existing area
Area already invested
Optimum grassroot design
B
Infeasible
Energy requirement

Figure 2.8 Area vs. Energy requirement diagram for typical network (Texas A&M University. "Network Pinch Analysis." 123.).

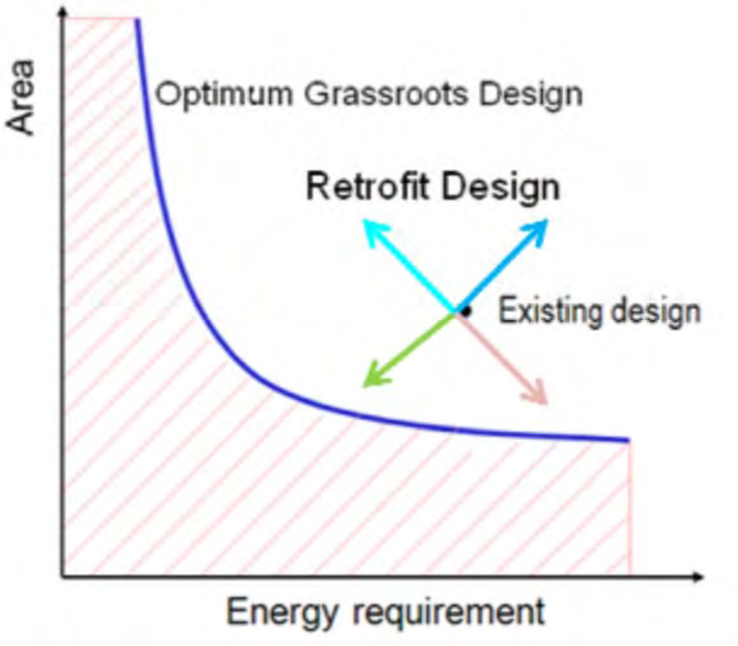


Figure 2.9 Four possible option of doing retrofit (Texas A&M University. "Network Pinch Analysis." 123.).

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 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.

2.1.3.2 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, vertical heat transfer is used. Essentially, for each ΔT_{min} value that we choose to analyze for our current process, we will have an ideal minimum hot and cold utility requirement. The hot and cold composite curves including the utility streams can be divided into enthalpy intervals as in Figure 2.10.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 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 Aideal by calculating the area required for each separate enthalpy region and summing them with Equation 4.

$$A_{ideal} = \sum_{k}^{\text{int}\,ervals-k} \frac{1}{\Delta T_{LMk}} \left[\sum_{i}^{HotStreamsI} \frac{q_{i,k}}{h_i} + \sum_{j}^{ColdStreamsJ} \frac{q_{j,k}}{h_j} \right] \qquad (4)$$

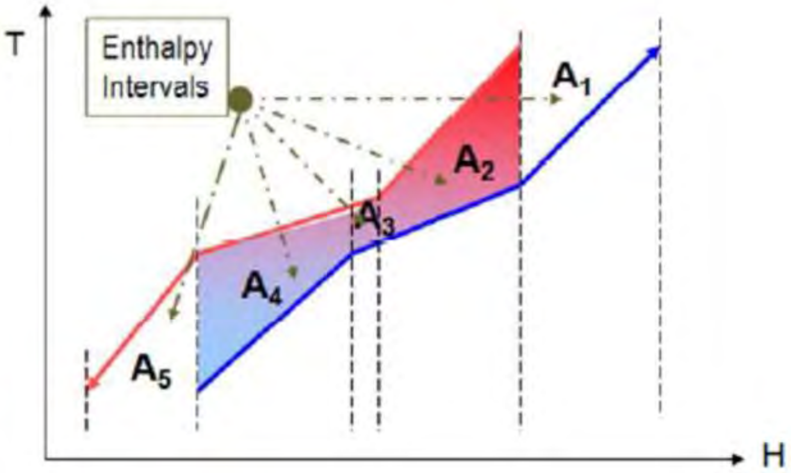


Figure 2.10 Vertical heat transfer area intervals (Texas A&M University. "Network Pinch Analysis." 123.).

Where $q_{i,k}$ is the stream duty on hot stream i in enthalpy interval k, $q_{j,k}$ is the stream duty on cold stream j in enthalpy interval k, h_i and h_j are the film transfer coefficients for hot stream i and cold stream j, and ΔT_{LMk} is the log mean temperature difference for interval k. To calculate the log mean temperature difference, Equation 5 is used.

$$\Delta T_{LM} = \frac{\Delta T_H - \Delta T_C}{\ln\left(\frac{\Delta T_H}{\Delta T_C}\right)} \tag{5}$$

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 the specifics of the retrofitted design are not yet known, it is assumed that each exchanger in the network will have an equal area. This will allow the optimum ΔT_{min} to be determined by estimating the total cost, the return on investment (ROI), the net present value (NPV) and payback period.

2.1.3.3 Area Efficiency

Now that we have developed the grassroots design curve by calculating the ideal area for various ΔT_{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 2.11 To determine our retrofit curve, "area efficiency" will be used. Area efficiency, α, is a factor used to quantify how close an existing network is to the predicted targets of the grassroots design. The closer α 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.

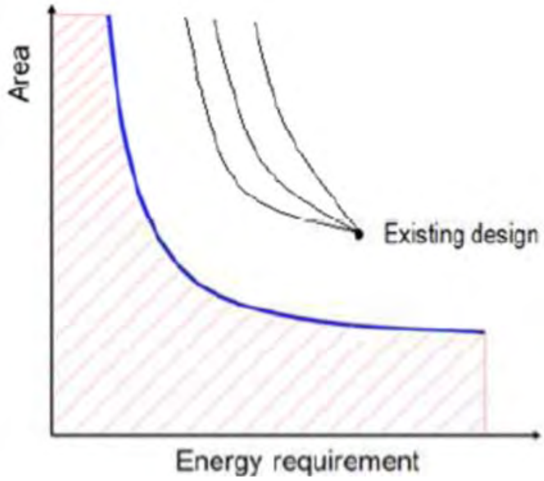


Figure 2.11 Area vs. Energy Requirement with Several Design Curve Options (Texas A&M University. "Network Pinch Analysis." 123.).

Area efficiency is defined in Equation 6.

$$\alpha = \frac{A_{ideal}}{A_{existing}} \tag{6}$$

Using Figure 2.12, 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 the current process would have if the network were designed from scratch with its current utility usage and current ΔT_{min} value. A_{ideal} is the grassroots area for the current process after we have altered the ΔT_{min} value and correspondingly determined the new utility requirements. $A_{existing}$ is the original network area and $A_{retrofit}$ is the new retrofit area.

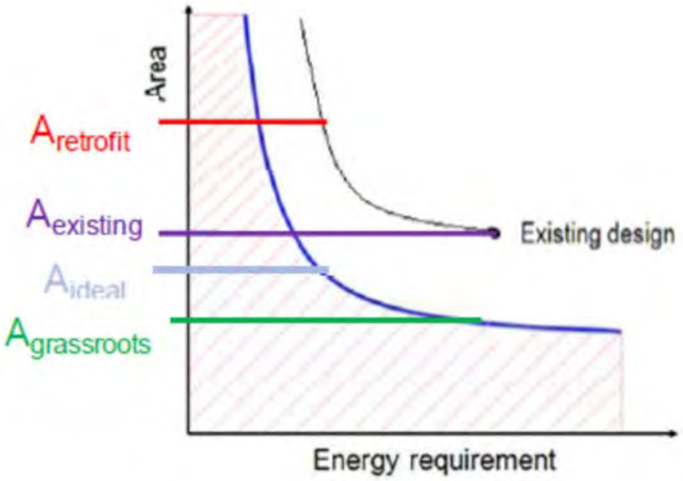


Figure 2.12 Area vs. Energy Requirement - Area Locations.

Because it is desired to improve the use of area, the area efficiency α should be greater than or equal to $\alpha_{current}$. As α increase, the retrofit area will decrease assuming that the utility consumption stays constant. This means that a higher α value corresponds to a lower total area and thus lower area costs. Because the goal is to increase energy savings and decrease total costs, α must be as high as possible. As can be seen by Figure 2.13 there are an infinite number of α values that can be chosen for the retrofit design even we look only between an α of unity and our current α value.

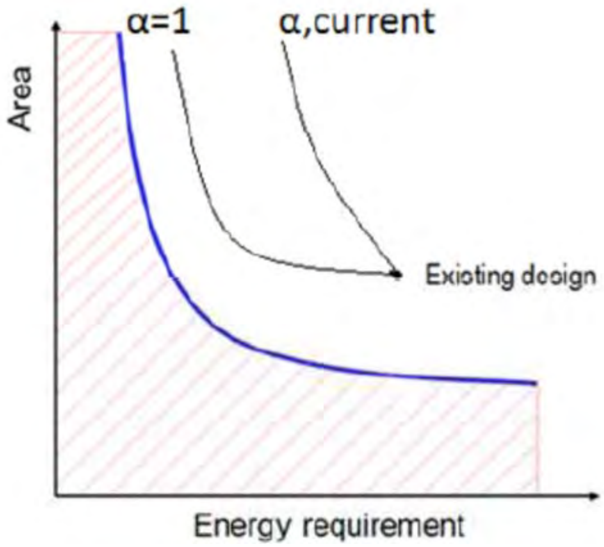


Figure 2.13 Impact of Alpha Value.

$A_{retrofit}$ can be calculated by Equation 7;

$$A_{retrofit} = \frac{A_{ideal} - A_{ideal1}}{\Delta\alpha} + A_{existing} \text{ ,} \tag{7}$$

Where A_{ideal1} is the value of A_{ideal} calculated in Equation 4 with the maximum ΔT value tested, and $\Delta\alpha=1$ for $\alpha < 0.9$ and $\Delta\alpha= \alpha_{current}$ for $\alpha \geq 0.9$ (Linnhoff, 1998).

Finally, a retrofit curve can be developed. By changing the ΔT_{min} value of the process, we obtained a unique composite curve. From this composite curve, the utility requirement of the process was calculated using the same procedure as before. With the utility requirements, vertical heat transfer was used within enthalpy intervals to calculate the ideal area had the network been a grassroots design. 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 ΔT_{min} value, we calculated the area efficiency according to Equation 6. Then by assuming a constant value of α we generated a retrofit curve to calculate the retrofit area for various ΔT_{min} values.

2.1.3.4 Opitmum ΔT_{min} Value

The optimum value ΔT_{min} must be determined before designing the network. The optimal ΔT_{min} is different for the grassroots and retrofit cases. For the grassroots case, being the original design it is sufficient to analyze the Total Annualized Cost. The Total Annualized Cost (TAC) vs. ΔT_{min} diagram for a constant α value of 1 is used. Figure 2.14 illustrates a typical TAC vs. ΔT_{min} diagram.

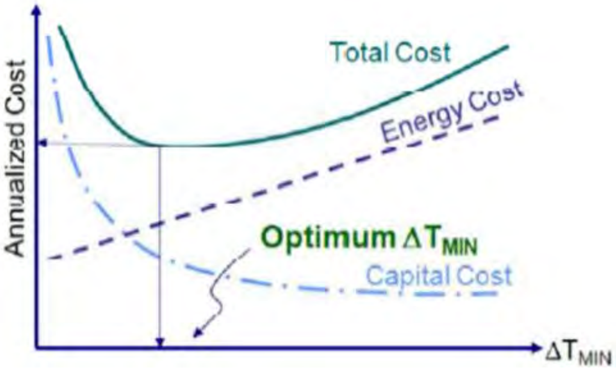


Figure 2.14 Typical TAC vs. ΔT_{min} Diagram.

The minimum on the total cost curve corresponds to the optimum ΔT_{min} value. Total annualized cost (TAC) is a function of the annualized operating cost (OC_A) and the annualized capital cost (CC_A) according to Equation 8.

$$TAC = OC_A - CC_A \tag{8}$$

The annualized operating cost and capital cost are calculated by Equations 8, and 9 respectively.

$$OC_A = C_{HU} \times C_{CU} \tag{9}$$

$$CC_A = CC \times \frac{i \times (1+i)^n}{(1+i)^n - 1} \tag{10}$$

$$CC = N_{Min} \left[a + b \left(\frac{A_{retrofit}}{N_{Min}} \right)^c \right] \tag{11}$$

Where C_{HU} is the cost of the hot utility and C_{CU} is the cost of the cold utility. CC is the capital cost, *i* is the interest rate, n is the number of years, N_{min} is the minimum number of exchangers in the network, $A_{retrofit}$ is the retrofitted area for the new network and a, b, and c are cost law constants that vary according to materials of construction, pressure rating and type of exchanger. The minimum number of heat exchangers, N_{min}, is calculated by Equation 12;

$$N_{\min} = \lfloor S_{ap} - 1 \rfloor + \lfloor S_{bp} - 1 \rfloor, \tag{12}$$

where S_{ap} is the number of streams above the pinch and S_{bp} is the number of streams below the pinch.

Because the operating costs and the capital costs are both a function of ΔT_{min}, a compromise must be made when a network design is to be retrofitted. As ΔT_{min} increases, the energy requirements will increase while the area requirements will decrease. Thus, the operating costs will increase. However, as ΔTmin 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 ΔT_{min}, it is expected that the TAC curve when plotted with ΔT_{min} will have a minimum value. This value correlates to the optimum ΔT_{min} (Shenoy and Uday, 1995). For the retrofit case, the optimum ΔT_{min} value is determined by evaluating the return on investment (ROI), the net present value (NPV), and payback period (PBP). These three methods are used to measure the profitability and each of them will evaluate the options for ΔT_{min} and determine an optimum value. Choosing between these ΔT_{min} values is case specific and is for the user to determine. ROI is the ratio of profit to investment. In the retrofit case, profit is due to savings from decreased utility consumption and the investment is the cost of added area (Equations 13 and 14). ROI is calculated by Equation 15.

$$Savings = U_{saving}\left(P_{HU} + P_{CU}\right) \tag{13}$$

Where U_{saving} is the utility difference between the original network and the retrofit network, and P_{HU}, P_{CU} are the price of the hot and cold utilities.

$$Investment = aN_{add} + bN_{add}\left(\frac{A_{add}}{N_{add}}\right)^{c} \tag{14}$$

Where a,b, and c are the same cost law coefficients, N_{add} is the additional heat exchangers for the retrofit, and A_{add} is the additional area for the retrofit.

$$ROI = \frac{Savings}{Investment} \tag{15}$$

The NPV is based on future cash flows for a certain number of years, n, and a specific interest rate. The goal is find the ΔT_{min} value that will maximize the NPV.

Again, the cash flow for retrofit is the found by the savings from the decreased utilities calculated in Equation 14. The NPV is calculated by Equation 16.

$$NPV = \sum_{i=1}^{n} \frac{savings_i}{(1+rate)_i} - Investment \qquad (16)$$

The PBP will determine the length of time necessary for the savings to pay for the investment. Therefore, it is ideal to have a small value for the PBP. The PBP is calculated by Equation 17

.

$$PBP = \frac{Investment}{Savings} \qquad (17)$$

By plotting the ROI, NPV, and PBP verses the change in energy for a variety of ΔT_{min} values allows the maximums and minimums to be easily analyzed. The ROI will always tend toward a high ΔT_{min} value because of the balance between the savings from utility and the investment from the amount of added area. A large ΔT_{min} causes the added area and thus the investment to be very low compared to the savings and thus increases the ROI. Obviously the PBP will change significantly depending on the maximum number of years set. A longer limit will provide a smaller ΔT_{min} because the time to break even has been increased and therefore the amount of area addition, the main cost, is increased.

2.1.4 Heat Exchanger Matches

Now that the retrofit area has been calculated for each ΔT_{min} and the optimum ΔT_{min} value has been determined, the next step is to generate the stream matches for heat exchange in the new network. The first step to designing the new

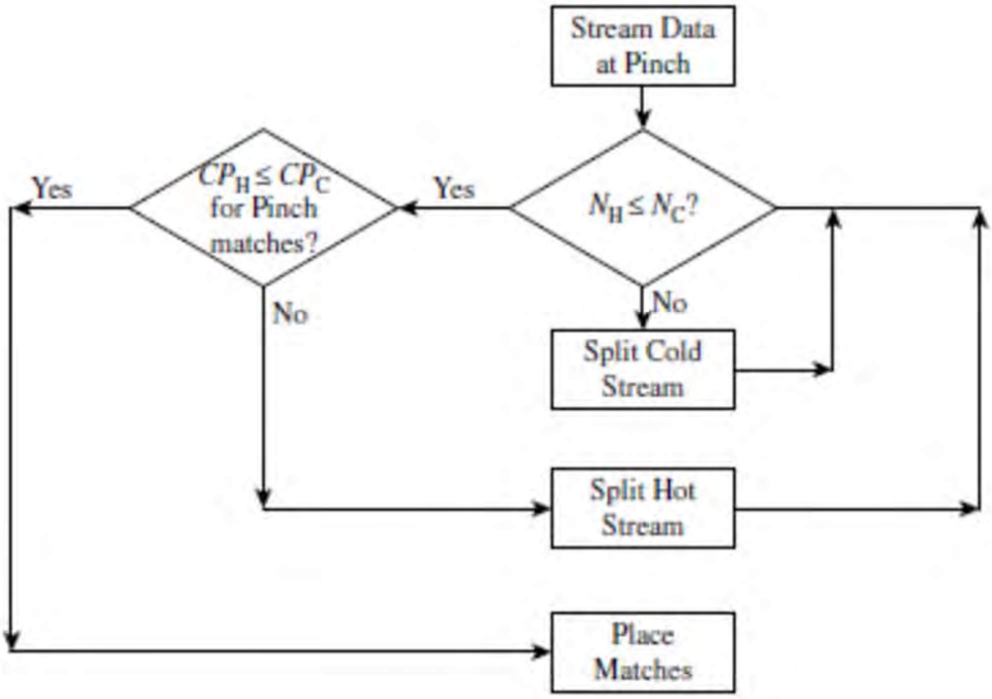

Stream Data at Pinch
$N_H \leq N_C$?
Yes
No
$CP_H \leq CP_C$ for Pinch matches?
Yes
No
Split Cold Stream
Split Hot Stream
Place Matches

Figure 2.15 Above pinch design.

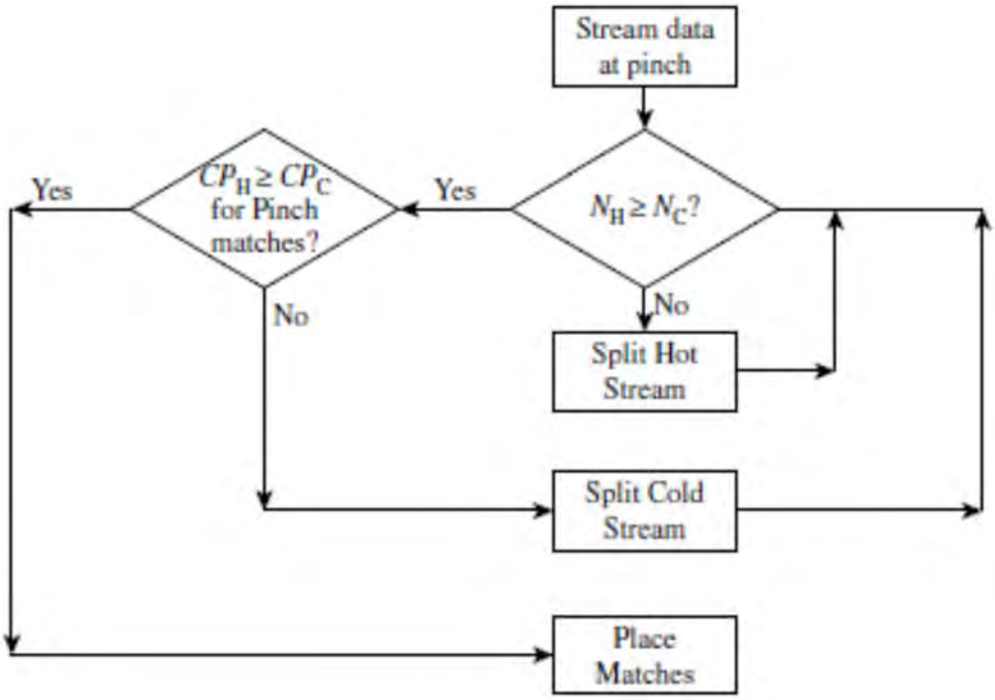

Stream data at pinch
$N_H \geq N_C$?
Yes
No
$CP_H \geq CP_C$ for Pinch matches?
Yes
No
Split Hot Stream
Split Cold Stream
Place Matches

Figure 2.16 Below pinch design.

network is to locate the existing exchangers that 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 (FCp) values. For streams above the pinch (to the left of the dashed line in the grid diagram), $FCp_{HOT} \leq FCp_{COLD}$.

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 (Texas A&M University. "Network Pinch Analysis." 49). The heat requirements for each stream are calculated according to Equation 18. 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.

$$Q = FCp\left(T_{in} - T_{target}\right) \qquad (18)$$

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 (Texas A&M University. "Network Pinch Analysis." 138.).

2.1.5 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 matchwise area distribution. The matchwise area distribution determines the area for each heat exchanger based on the streamwise area distribution. Matchwise area is calculated according to Equation 20.

$$A = \frac{A}{U \times T_{LM}} \tag{20}$$

$$U = \frac{1}{\frac{1}{h_{ih}} + \frac{1}{h_{jc}}} \tag{21}$$

Despite the fact that satisfactory results were reported, there is still a lack of systematic and specific procedure to produce the modified HEN designs. Kotjabasakis and Linnhoff (1988) presented an industrial retrofit case using the sensitivity tables to demonstrate situations of debottlenecking, fouling, and other issue. Fraser and Gillespie (1989) purposed the pinch design tools in an example grassroots design and then applied to the retrofit case study. Fraser and Gillespie (1992) also presented the use of pinch technology to analyze the possibilities for saving for the retrofit of an oil refinery. Ahmed and Polley (1990) and Polley et al. (1990) presented some enhancements to the existing retrofit targeting procedure of Tjoe and Linnhoff (1986,1987) by introducing a relationship between pressure drop and heat transfer coefficient to enable the area targets generated to reflect pressure drop limitations in the process. Farhanieh and Sunden (1990) analyzed an existing refinery HEN using both grassroots via pinch design method and retrofit design methods in the case study. The integration of heat pumps into the HEN is also investigated. Nilsson and Sunden (1994) proposed the two analysis methods in combination, pinch technology and MIND method. A multi-period cost optimization of the operating strategy is performed using the MIND method. The results from the Pinch analysis are then input to the MIND optimization. The system cost of the total energy system of the refinery is optimized with regard to flexibility in the process system as well as changes of energy costs and the operating conditions of the cogeneration unit. The combination of methods shows that significant capital savings can be achieved when the energy saving potential of the process system is integrated in the overall operating strategy of the energy system. It is, in this case, possible to compare investments in energy saving measures to investments in increased steam production capacity. From the above listed, the goal of pinch analysis is to maximize the process-to-process heat recovery and minimize the utility consumption of the system. The disadvantage of this method is that there is no general rule for area distribution within a network in the design step. Therefore application of pinch approaches depends on the designer experience and become difficult to apply to large scale problems. Lakshmanan and Ban˜ ares-Alca´ntara (1996, 1998) introduced the retrofit thermodynamic diagram as a visualization tool for developing retrofit solution by inspection for case studies. Li and Yao (1998) studied the use of pinch based methods for retrofitting largescale processes. van Reisen et *al*. (1995) presented a prescreening and decomposition method to analyze heat exchanger networks for retrofitting. It evaluates the economic potential of sub-networks and uses existing retrofit analysis procedures. van Reisen et *al*. (1998) developed an extension of path analysis (van Reisen et *al*. (1995)) for the HENs retrofit problem leading to retrofit by structural targeting. Varbanov and Klemes (2000) developed a heuristic topology modification procedure to complement the network pinch methodology (Tojoe and Linnhoff (1986) and extended by Asante and Zhu (1996, 1997)) for heat exchanger network retrofit. It considers, under the Network Pinch framework, two important cases, the retrofit initialization and topology modification, when the direct application of the classic network pinch concept and rules is not possible. With the help of a system of simple heuristics, these limitations are overcome which extends the application range of the network pinch framework. Markowski (2000) presented the retrofit of heat exchanger network using a pinch based approach which makes it possible to consider the thermal resistance of fouling deposits forming on heat transfer surfaces. In this approach, the criterion of minimum sensitivity of heat exchanger to fouling effects is accounted. Polley and Amidpour (2000) examined the problems with existing retrofit analysis approaches and proposed a structural targeting procedure which involves decomposing the problem and analyzing separate components individually. Li and Chang (2010) developed the pinch retrofit method by adding a systematic procedure derived from simple pinch analysis after the step of cross-pinch match is removed.

2.2 Mathematical Programming Methods

Over last decade there have been considerable advances in mathematical programming techniques for the HEN retrofit problem. Yee and Grossmann (1987) proposed an MILP assignment transshipment formulation for retrofit HENs. It is an extension of the MILP transshipment model (Papoulias and Grossmann (1983)). Zhelev et *al*. (1987) developed an algorithm for retrofit HENs which a network is retrofitted through comparison of grassroots network design for the problem. Ciric and Floudus (1989) proposed a two-stage approach consisting of a match selection stage, and optimization stage. Central to this strategy is mathematical model for retrofit at level of matches. The match selections stage used a mixed integer linear programming (MILP) formulation that incorporates explicitly the cost associated with each potential match of streams and involves all possible options for modifications. The solution of this formulation provides information on which exchangers should be reassigned or newly installed, and whether there is a need to increase or decrease the area of the existing exchangers. The optimization stage takes advantage of this information, and a superstructure is postulated and formulated as a nonlinear programming (NLP) problem. The solution of the NLP provides the actual retrofitted network from optimizing the matching order and flow configuration.

Unfortunately, the MILP model dose not account for areas quite reliably and involes a large number of integer variables that make its application to industrial size problem difficult (Briones and Kokossis, 1999). These two-stage approach were later combined into a single stage by Ciric and Floudas (1990), using a mixed integer nonlinear (MINLP) formulation to incorporate all possible stream matches, network configuration and existing exchanger reassignment in single mathematical formulation. Predetermination of the utility consumption causes failure in area-utility trade off and solution may be trapped at local optima (Rezaei and Shafiei, 2009). Yee and Grossmann (1991) provided a systematic procedure which also had two-stage, in this procedure however a targeting or pre-screening stage and an optimization stage were used. In the pre-screening stage, the economic feasibility of the project is analyzed with lower bounds on cost for utility, additional area, and structural modifications. The bounds are used to construct a prescreening cost plot to estimate the maximum savings that can be achieved. However only the number of new units required to achieve the optimization investment determined was carried forward to the optimization stage. During the optimization stage, the heat recovery level was allowed to vary an MINLP formulation was used to simultaneously optimize the capital-energy trade off and all the network parameters. Because the MINLP model is very detailed, different types of binary variables are needed in their formulation. This issue may restrict the application of the model to small scale problems.

2.2.1 MINLP Model for Grassroots Design

The MILP model is based on the stage-wise superstructure representation proposed by Yee and Grossmann (1990). The superstructure for the problem is show in Figure 2.15. Within each stage of the superstructure, potential exchangers between any pair of hot and cold streams can occur.

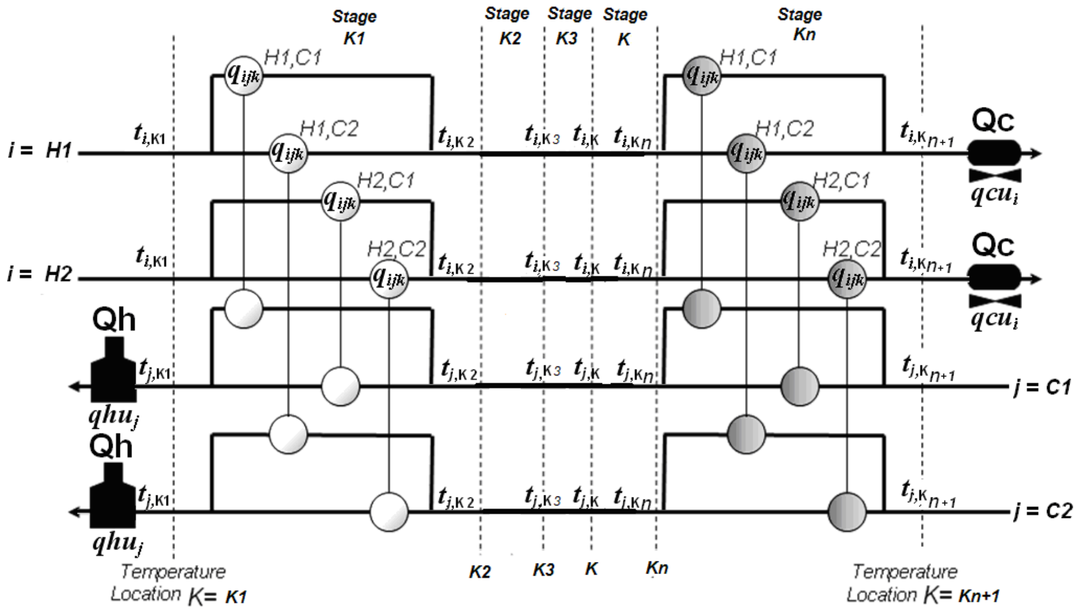

Stage K1
Stage K2
Stage K3
Stage K
Stage Kn
H1,C1
H1,C2
H2,C1
H2,C2
q ijk
i = H1
i = H2
t i,K1
t i,K2
t i,K3
t i,K
t i,Kn
t i,Kn+1
Qc
qcu i
Qh
qhu j
t j,K1
t j,K2
t j,K3
t j,K
t j,Kn
t j,Kn+1
j = C1
j = C2
K2
K3
K
Kn
Temperature Location K= K1
Temperature Location K= Kn+1

Figure 2.17 N-stage superstructure.

In each stage, the corresponding process stream is split and directed to an exchanger for a potential match between each hot stream and each cold steam. It is assumed that the outlets of the exchangers are isothermally mixed, which simplifies the calculation of the stream temperature for the next stage, since no information of flows is needed in the model. The outlet temperatures of each stage are treated as variables in the optimization. The number of stages should in general coincide with the number of temperature intervals to ensure maximum energy recovery. However, in most cases selecting the number of stages as the maximum of hot and cold streams suffices. A heater or cooler is placed at the outlet of the superstructure for each process stream. Optimization of the MINLP model identifies the least cost network embedded within the superstructure by identifying which exchangers are needed and the flow configuration of the streams. A major advantage of this model is its capability of easily handling constraints for forbidding stream splits. Process streams are divided into two sets, set HP for hot streams, represented by index i, and set CP for cold streams, represented by index j. Index k is used to denote the superstructure stage given by the sets ST. Indices HU and CU correspond to the heating and cooling utilities respectively. Also, the following parameters and variables are used in the formulation:

Parameters

TIN = inlet temperature of stream

TOUT = outlet temperature of stream

F = heat capacity flow rate

U = overall heat transfer coefficient

CCU = unit cost for cold utility

CHU = unit cost of hot utility

CF = fixed charge for exchangers

C = area cost coefficient

β = exponent for area cost

NOK = total number of stages

Ω = upper bound for heat exchanger

Γ = upper bound for temperature difference

Variables

dt_{ijk} = temperature approach for match (i,j) at temperature location k

$dtcu_i$ = temperature approach for match of hot stream i and cold utility

$dthu_j$ = temperature approach for match of cold stream j and hot utility

q_{ijk} = heat exchanged between hot process stream i and cold process stream j in stage k

qcu_i = heat exchanged between hot stream i and cold utility

qhu_j = heat exchanged between hot stream and cold stream j

$t_{i,k}$ = temperature of hot stream i at hot end of stage k

$t_{j,k}$ = temperature of cold stream j at hot end of stage k

z_{ijk} = binary variable to denote existence of match (i,j) in stage k

zcu_i = binary variable to denote that cold utility exchanges heat with stream i

zhu_j = binary variable to denote that hot utility exchanges heat with stream j

With above definitions, the formulation can now be presented.

2.2.1.1 Overall Heat Balance for each Stream

$$(TOUT_j - TIN_j)F_j = \sum_{k \in ST} \sum_{i \in HP} q_{ijk} + qhu_j \qquad \mathrm{j \in CP}$$

$$(TIN_i - TOUT_i)F_i = \sum_{k \in ST} \sum_{j \in CP} q_{ijk} + qcu_i \qquad \mathrm{i \in HP} \tag{22}$$

2.2.1.2 Heat Balance of each Stream at each Stage

$$(t_{j,k} - t_{j,k+1})F_j = \sum_{i \in HP} q_{ijk} \qquad \mathrm{j \in CP,\ k \in ST}$$

$$(t_{i,k} - t_{i,k+1})F_i = \sum_{j \in CP} q_{ijk} \qquad \mathrm{i \in HP,\ k \in ST} \tag{23}$$

2.2.1.3 Assignment of Superstructure Inlet Temperature

$$TIN_j = t_{j,N+1} \qquad \mathrm{j \in CP}$$

$$TIN_i = t_{i,1} \qquad \mathrm{i \in HP} \tag{24}$$

2.2.1.4 Feasibility of Temperature

$$t_{j,k} \geq t_{j,k+1} \qquad \mathrm{j \in CP,\ k \in ST}$$

$$TOUT_j \geq t_{j,1} \qquad \mathrm{j \in CP}$$

$$t_{i,k} \geq t_{i,k+1} \qquad \mathrm{i \in HP,\ k \in ST}$$

$$TOUT_i \leq t_{i,N+1} \qquad \mathrm{i \in HP} \tag{25}$$

2.2.1.5 Hot and Cold Utility Load

$$(TOUT_j - t_{j,1})F_j = qhu_j \qquad \mathrm{j \in CP}$$

$$(t_{i,N} - TOUT)F_i = qcu_i \qquad \mathrm{i \in HP} \tag{26}$$

2.2.1.6 Logical Constraints

$$q_{ijk} - \Omega z_{ijk} \leq 0 \qquad \mathrm{i \in HP, j \in CP, k \in ST}$$

$$qhu_j - \Omega zhu_j \leq 0 \qquad \mathrm{j \in CP}$$

$$qcu_i - \Omega zcu_i \leq 0 \qquad \mathrm{i \in HP} \qquad (27)$$

z_{ijk}, zcu_i, $zhu_{j = 0,1}$

2.2.1.7 Calculation of Approach Temperatures

$$dt_{ijk} \leq t_{i,k} - t_{j,k} + \Gamma(1 - z_{ijk}) \qquad \mathrm{i \in HP, j \in CP, k \in ST}$$

$$dt_{ijk} \leq t_{i,k+1} - t_{j,k+1} + \Gamma(1 - z_{ijk}) \qquad \mathrm{i \in HP, j \in CP, k \in ST}$$

$$dthu_j \leq TOUT_{HU} - t_{j,1} + \Gamma(1 - zhu_j) \qquad \mathrm{j \in CP}$$

$$dtcu_i \leq t_{i,NOK+1} - TOUT_{CU} + \Gamma(1 - zcu_i) \quad \mathrm{i \in HP} \qquad (28)$$

2.2.1.8 Objective Function

$$LMTD \approx \left[(dt1 \times dt2) \times (dt1 + dt2)/2 \right]^{1/3} \qquad (29)$$

min

$$\sum_{i \in HP} CCUqcu_i + \sum_{j \in CP} CHUqhu_j + \sum_{i \in HP} \sum_{j \in CP} \sum_{k \in ST} CF_{ij} z_{ijk} + \sum_{i \in HP} CF_{i,CU} zcu_i + \sum_{j \in CP} CF_{j,HU} zhu_j$$

$$+ \sum_{ii \in HP} \sum_{j \in CP} \sum_{k \in ST} C_{ij} \left[\frac{q_{ijk}}{U_{ij} \left[(dt_{ijk} dt_{ijk+1})(dt_{ijk} + dt_{ijk+1}) \right]^{1/3}} \right]^{\beta_{ij}}$$

$$+ \sum_{i \in HP} C_{i,CU} \left[\frac{qcu_i}{\left(U_{i,CU} \left[(dtcu_i)(TOUT_i - TIN_{CU}) \{ dtcu_i + (TOUT_i - TIN_{CU}) \} / 2 \right]^{1/3} \right)} \right]^{\beta_{i,CU}}$$

$$+ \sum_{j \in CP} C_{HU,j} \left[\frac{qhu_j}{\left(U_{HU,j} \left[(dthu_j)(TIN_{HU} - TOUT_j) \{ dthu_j + (TIN_{HU} - TOUT_j) \} / 2 \right]^{1/3} \right)} \right]^{\beta_{j,HU}}$$

(30)

where $\frac{1}{U_{ij}} = \frac{1}{h_i} + \frac{1}{h_j}; \frac{1}{U_{i,CU}} = \frac{1}{h_i} + \frac{1}{h_{CU}}; \frac{1}{U_{HU,j}} = \frac{1}{h_j} + \frac{1}{h_{HU}}$

The continuous variables (t, q, qhu, qcu, dt, dtcu, dthu) are non-negative and the discrete variables z, zcu, zhu are 0-1. The nonlinearities in the objective function Equation 9 may lead to more than one local optimal solution due to their nonconvex nature.

Papalexandri and Pisikopoulos (1993) addressed the problem of redesigning a HEN in order to improve its flexibility. The multiperiod MINLP approach of Floudas and Grossmann (1987) is utilized in the generation of a multiperiod hyperstructure network representation used in the simultaneous optimization of the operation costs and retrofit investment costs of the retrofit HENS problem. The desired flexibility target is achieved through an iterative procedure between the flexibility analysis and the MINLP retrofit HENS problem. Papalexandri and Pisikopoulos (1993) presented the retrofit of HEN with variable operating conditions. With the assumption of no dual streams, a multiperiod network representation is used in an MINLP formulation of the retrofit HENS problem. The MINLP model couples synthesis techniques for HEN multiperiod operation and retrofit strategies. An iterative scheme may be used to integrate this problem with flexibility analysis. Jezˇowski (1994) proposed the mathematical methods for retrofit design which topics covered are sequential synthesis, global or simultaneous synthesis, knowledge-based systems, and mathematical methods for retrofit network design. Konukman et *al.* (1995) presented a controllable design of heat exchanger networks as constrained nonlinear optimization problem. The objective of this method is to find the individual exchanger areas and bypass fractions which minimize the total annualized cost (or the total area) of the given heat exchanger network structure and, at the same time, to satisfy all the target temperature constraints (hard or soft) for a set of disturbances predefined in all possible directions. This is achieved by solving only one constrained optimization problem which considers the exchanger model equations (heat transfer and mixing) and constraints (resiliency index, heat load and the minimum approach temperature) simultaneously for all possible predefined disturbance directions. Nielsen et *al.*

(1996) presented an object-oriented modeling which is used to create a HENs problem representation and simulated annealing to solve this problem in order to extend HENs to include concurrent exchangers as well as heat capacity flow rates that are not constant. The computer software HEN Explorer is developed in this approach to HENs. Nielsen et *al*. (1997) used an industrial retrofit HENs problem as an example for presenting a realistic HENs problem. Zhelev et *al*. (1998) developed an operability analysis approach for existing HENs in which networks working in conditions of process stream parameter variation. Athier et *al*. (1998) proposed a two-level strategy for retrofit design. A simulated annealing algorithm is used to solve the master problem of generating and iteratively modifying a HEN topology. The slave problem involves NLP optimization of the operating parameters of the network. Zamora and Grossmann (1998) proposed a global optimization algorithm to rigorously optimize the Synheat model under the simplifying assumptions of linear area cost functions and no stream splitting. The approach relies on the use of convex underestimators for the heat transfer area. Later, the approach was extended to account for the nonlinear area cost functions. Abbas et *al*. (1999) proposed a novel approach to the retrofit problem using constraint logic programming (CLP). It employs a set of heuristics derived from an interactive retrofit method published earlier (Lakshmanan and Bañares-Alcántara, 1996), and used CLP to efficiently prune out unattractive solutions. Nie and Zhu (1999) developed a two-step model for HENs retrofit. At the first stage, the unit-based model is used to indicate which units require additional area. In the second stage, special attention is paid to these units, where area distribution, shell arrangements, the use of heat-transfer enhancement, and other options are optimized for these units. At the same time, the units without additional area requirement are modeled using simple models. Thus units with and without additional area requirements are treated differently during optimization. By doing this, the pressure drop can be calculated accurately while the overall model remains simple and easy to solve. Ma, Hui, and Yee (2000) proposed an MILP model for HEN retrofit. A two-step solution procedure is proposed to overcome the problems associated with the nonconvexities of the MINLP model. First the constant approach temperature MILP model is solved to determine the fixed network structure, and then the MINLP model is solved for determining match reassignments.

Silva and Zemp (2000) presented a new approach considering the distribution of heat transfer area and pressure drop in retrofit. The problem is described as a non-linear model, and the additional area required for the new network condition and available pressure drop are estimated based on economical optimisation (or process requirements). Zhang and Zhu (2000) proposed a systematic method for HEN retrofit which modification to the network topology is considered simultaneously with changes to the process parameters such as stream flow rates and temperatures.

2.2.2 MILP Retrofit Design Model (Barbaro et *al.*)

The retrofit model is developed from the grass-root model, that is, the basic structure of the grass-root model is conserved and additional sets of constraints are included to consider the network modifications. The model relies on a transshipment concept, more specifically, the temperature span of each stream in the problem is divided into several smaller temperature intervals and then each temperature interval of a hot stream is considered to exchange heat with temperature intervals of cold streams observing the rules of heat balance and heat exchange feasibility, etc. Binary variables are used to indicate the existence of heat exchanger between a hot stream "*i*" and a cold stream "*j*" in an interval "*m*" as illustrated in Figure 2.16. The model employs a one-step strategy to simultaneously optimize both the network structure and the heat exchanger areas. The objective is to minimize the total cost, which includes the utilities cost (i.e. operating cost) and the investment cost of the heat exchanger network.

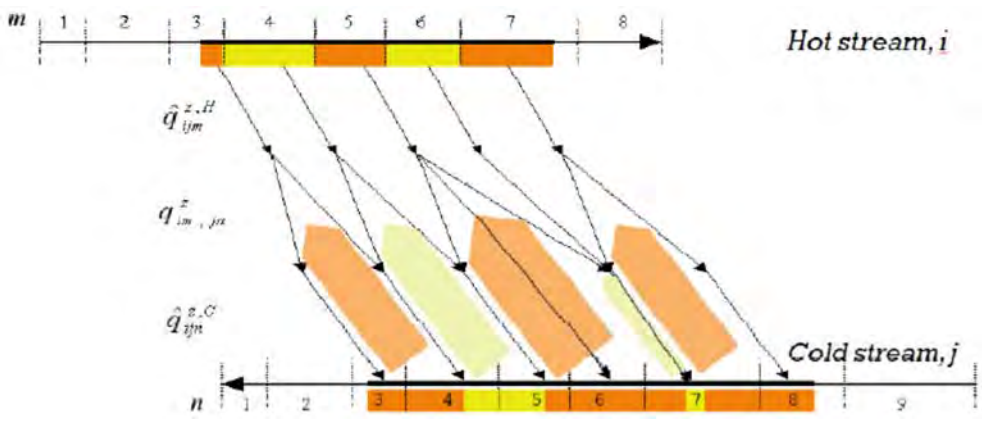


Figure 2.18 Transportation and Transshipment Model.

In retrofit cases there are several exchangers that already present in the network and one wants to determine changes to this network that will allow a net reduction in the total annual cost. To achieve this objective, there are several options, namely:

- addition of new heat exchangers units
- area expansion/reduction of existing exchangers
- relocation of existing units.

These options are aimed at enhancing the heat integration among process streams and reducing the use of utilities and therefore the operation cost. In essence, the retrofit problem is to optimally add new exchangers, add area to existing exchangers and/or relocate them (if necessary) such that a certain economic objective is met. Among others,one can

i) Maximize the cost saving on utilities minus the annualized capital cost.
ii) Maximize the net present value of the retrofit.
iii)Maximize the return of the investment.
iv) Maximize the utility cost savings subject to a certain capital investment limit.

Indeed, the MILP is more practical optimizing scenarios, such as non-isothermal mixing, exchanger relocation, repiping costs, and incorporating various costs for exchanger area manipulation. The MILP also maintains the complex of the retrofit problem by not making any of the simplifying assumptions. Moreover the ability of the MILP is to easily change 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. An in depth presentation of the MILP procedure and its associated equations is presented in the paper by Nguye et *al*., titled “All-At-Once and Step-Wise Detailed Retrofit of Heat Exchanger Networks Using an MILP Model".

2.3 Combining Pinch and Mathematical Programming Methods

Asante and Zhu (1996, 1997, 1999) combined mathematical optimization techniques with a better understanding of the retrofit problem, based on thermodynamic analysis and practical engineering, to produce a systematic procedure capable of efficiently solving industrial-size retrofit problems. The network pinch concept provides new insight to the HEN retrofit problem and plays an important role in selecting promising modifications, forming the foundation of the new method. This concept, when applied to mathematical formulation, significantly simplified the mathematical models while maintaining good quality of solutions. This approach allows the design tasks to be automated with user interactions. In addition, this procedure also employs a two-stage approach for retrofit HEN design. The first stage is the diagnosis stage which is made up two steps. In the first step the HEN bottleneck is identified and in the second step a mixed integer linear programming (MILP) formulation is used to select a single modification which will best overcome the identified bottleneck. These two steps are repeated in a loop to yield the required set of promising topology modification. In the second stage, the optimization stage, the HEN obtained after implementation of the modifications is optimized using non-linear optimization techniques to minimize the cost of additional surface area employed. However, the success of this approach is sensible to the order of MILPs and suboptimal networks may be obtained by different users for the same problem. Kovabvc and Glavibvc (1995) proposed the combined thermodynamic and computational methods for retrofit HENs. The grand composite and extended grand composite curves are used to eliminate unattractive structures. MINLP is used for optimizing the network using a superstructure. Briones and Kokossis (1996) presented a rigorous and systematic optimisation method for the retrofit design of heat exchanger networks. The approach addresses the problem as a multi-task effort and applies a decomposition scheme which makes use of both mathematical programming and pinch analysis methods. The different tasks include targets for structural modifications and heat transfer area changes, the development and optimisation of the retrofitted network and the analysis of its complexity against economic penalties and trade-offs. The decomposition stages embed targeting information which supports screening and facilitates an effective optimisation search. As such, the decomposition not only bypasses the limitations of past decomposition techniques but exploits its features toward the development of an interactive design tool. Marechal and Kvalitventzeff (1996) combined pinch analysis and mathematical techniques. The analyze step uses the pinch method to propose a set of utilities that may satisfy the minimum energy requirement. The generate step uses a mixed integer linear programming (MILP) optimization to select the utilities to be used and calculates their optimal flow rates. Kovac-Kralj and Glavic (1997) presented the sequential structural and parameter optimization of retrofitted complex and energy intensive continuous processes. A method for sequential optimization of retrofits, combined sequential approach has been developed using pinch analysis, an improved optimization procedure and mixed integer nonlinear programming (MINLP) or nonlinear programming (NLP) algorithms. Pinch analysis gives many alternative retrofit designs for postulating a superstructure. The superstructure, material and energy flow rates have been optimized sequentially by a direct search method using ASPEN PLUS simulator with energy and material bounds. The heat exchanger network of the superstructure obtained, flashes and compressor were optimized simultaneously with the MINLP or NLP algorithms. Bruno, Fernandez, Castells and Grossmann (1998) presented an MINLP model for performing structural and parameter optimization of utility plants. The combined methods combine advantages of the thermodynamic, heuristic and mathematical methods by using many boundaries. Briones and Kokossis (1999) also combined the use of thermodynamics and mathematical programming techniques, two-step methodology similar to the grassroots designs, the methodology includes a targeting and an optimization stage. In the first step, two MILP models (HEAT and TAME model) are solved for auditing of existing network and screening of the most promising modifications. These MILPs are employed by targeting procedure and determine the trade off among energy, number of units, structural modification and heat transfer area. A superstructure is constructed at the optimization step to account for all possible configurations within a network. This methodology reports improvement up to 40% against the established techniques. Varbanov and Klemes (2000) developed the HEN retrofit techniques which is proposed by Tjoe and Linnhoff and extended by Asante and Zhu. It considers two important cases in which the classic network pinch methodology is not directly applicable. The first is the case of retrofit initiation when a network pinch cannot be identified. The application of this new approach provides the opportunity to exploit the power of the network pinch concept and framework for a more broad range of HENs. The second case is the enhancement of topology modifications selection in which heat cannot be transferred from below to above the network pinch. This presented systematic approach, built on a system of simple heuristic rules, obtains an ordered set of topology alteration alternatives, and in some cases identifies a topology modifications sequence in one step, which may substantially simplify and speed up the modification procedure. Varbanov et al. (2000) proposed two-stage procedure for a correct solution of the optimization problem. Using pinch analysis techniques, the suggested methodology combines the heuristic and mathematical programming approaches in their best aspects. The first stage, an appropriate HEN retrofit superstructure is to be built by using pinch analysis and heuristic path construction, while at the second one the optimal set of retrofit modifications is obtained using mathematical programming. These two integrated components result in simple and efficient retrofit procedure. Kovac-Kralj et *al*. (2000) presented the using rigorous models for simultaneous parameter and structural optimization of an existing complex and energy intensive continuous. The method that was recently developed to sequentially optimize retrofits has been extended to a stepwise simultaneous superstructural approach, using available process simulators and optimization software capabilities. An extended procedure has been employed for retrofits using a three-step approach: (i) generation of a process superstructure by pinch analysis; (ii) formulation of a mixed integer nonlinear programming (MINLP) model and its simplification into a relaxed nonlinear programming (NLP) model; (iii) simultaneous optimization, first by a process simulator and than by the NLP algorithm. Zhu et *al*. (2000) developed a targeting strategy for allowing heat transfer enhancement to be an option for HEN retrofit.

From the above listed technologies, it is necessary for a design method to allow for both automated and interactive generation of retrofit design. The automation of a design process can save time significantly, while interaction allows users to assess modifications on a much wider basis including qualitative aspects.

CHAPTER III

EXPERIMENTAL

3.1 Software

3.1.1 Microsoft Excel Spreadsheet

3.1.2 Mathematical Programming Software (GAMS)

3.1.3 Visual Basic for Application (VBA)

3.2 Experimental Procedures

3.2.1 Doing Data Extraction from the Case Study

The first step is to prepare the data for doing retrofit of heat exchanger network (HEN) in crude distillation unit. The data compose of stream properties and thermal condition of each stream such as supply temperature, target temperature, heat capacity, and enthalpy change.

3.2.2 Develop Grassroots and Retrofit Potential Program

In this work, a grassroots and a retrofit potential program was developed using visual basic for application (VBA) of pinch technology which is automatically find the optimum point in targeting step. Moreover, the program can automatically generate problem table, composite curves, grand composite curve, streams diagram, area calculation region, return on investment, net present value, capital energy trade-off, and payback curve. The grassroots and retrofit potential program allows user to easily change the objective function which consent to optimize a variety of cost function. Moreover, these programs allow the user to quickly and easily change parameters that would allow the evaluation of a numerous scenarios.

3.2.3 Applied the Retrofit Potential Program to the Real Refinery Plant or Case Study

A retrofit potential program will be applied to two specific retrofit situations. The first is a problem adapted from Ciric and Floudas (1989) and will be named Example 1. The second problem is adapted from Barbaro et. al (2005) and will be named Example 2. The results for Example 1 and Example 2 presented in the Discussion section.

3.2.4 Studying the Retrofit of CDU Using MILP Procedure

The forth step is to study the retrofit design for HEN of crude distillation unit by using the MILP model developed by Barbaro et *al*. (2005) Indeed, this model is developed from the grassroots model that is the basic structure of the grassroots model is conserved and additional sets of constraints are included to consider the network modifications.

3.2.5 Compare the Ability of the Retrofit Model of HENs and Evaluate the Most Effective and Useful Methodology for CDU

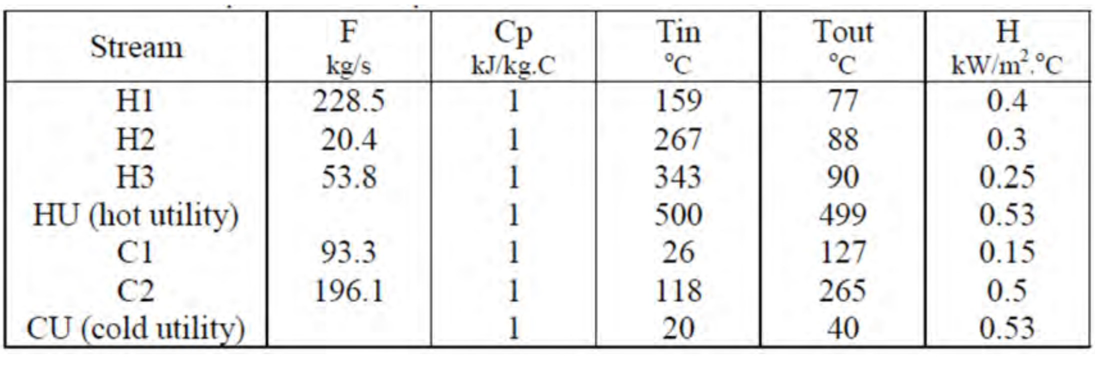
The fifth step is to evaluate the most effective and useful methodology for crude distillation unit.

CHAPTER IV
RESULTS AND DISCUSSION

4.1 Example 1

This problem is adapted from Ciric and Floudas (1989). It consists of three hot and two cold process streams and one hot and one cold utility stream. The current design has two coolers and one heater in the process. The stream data is shown in Table 4.1. The existing exchanger network configuration is shown in Figure 4.1. The existing network does not have splitting. This case disallows heat exchanger relocation, but alterations in the HEN may only include new exchanger and area addition or reduction to existing exchangers, as well as the introduction of stream splitting. 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. The life time used for annualized costs and net present value calculations is 5 years, the interest rate is 10%.The allowed amount of area addition are 20% of the corresponding existing area; the allowed amount of area reduction is 50% of the existing area; the maximum area per shell is 5,000 (m^2); the maximum number of shells per exchanger is 4. The minimum allowable EMAT is 10°C. Finally, assuming 350 working days in a year, the annualized cost (\$/year) per 1 MJ/hr utility consumed is 26.4 for hot utility and 5.55 for cold utility. Table 4.2 identifies the existing heat exchangers' original areas, which were calculated using the log mean temperature difference.

Table 4.1 Stream properties for Example 1 (Ciric and Floudas, 1989)



Stream	F kg/s	Cp kJ/kg.C	Tin °C	Tout °C	H kW/m^2.°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

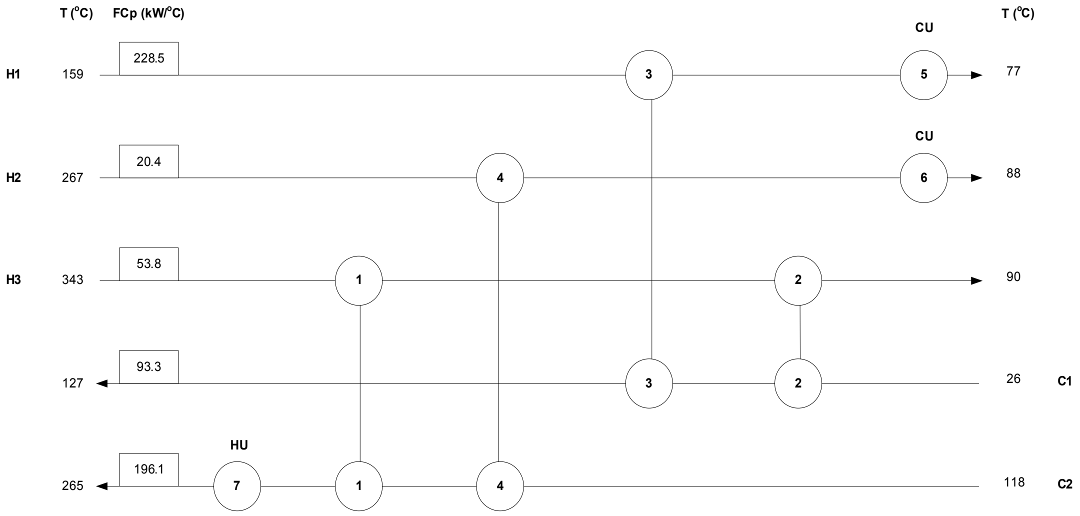
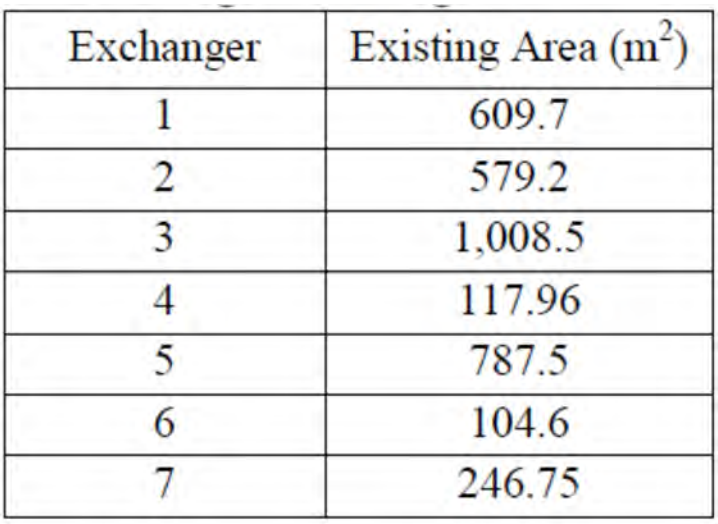

T (°C)
FCp (kW/°C)
T (°C)
CU
H1
159
228.5
3
5
77
CU
H2
267
20.4
4
6
88
H3
343
53.8
1
2
90
127
93.3
3
2
26
C1
HU
265
196.1
7
1
4
118
C2

Figure 4.1 Original heat exchanger network for Example 1.

Table 4.2 Existing heat exchanger areas for Example 1



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

The cost relations for area adjustment for Example 1 are taken from the paper by Barbaro etal.(2005)and are shown Equation 4.1, 4.2, 4.3 and 4.4. A cost is assigned to splitting of $10,000.

Heat exchanger cost (\$) = 17,300 + [857×Area (m^2)] (4.1)

Area addition cost (\$) = 8,650 + [857×$\text{Area}_{\text{added}}$($m^2$)] (4.2)

Area reduction cost (\$) = 8,650 + [5×$\text{Area}_{\text{reduced}}$ (m^2)] (4.3)

New shell = 17,300 + [857×$\text{Area}_{\text{shell}}$ (m^2)] (4.4)

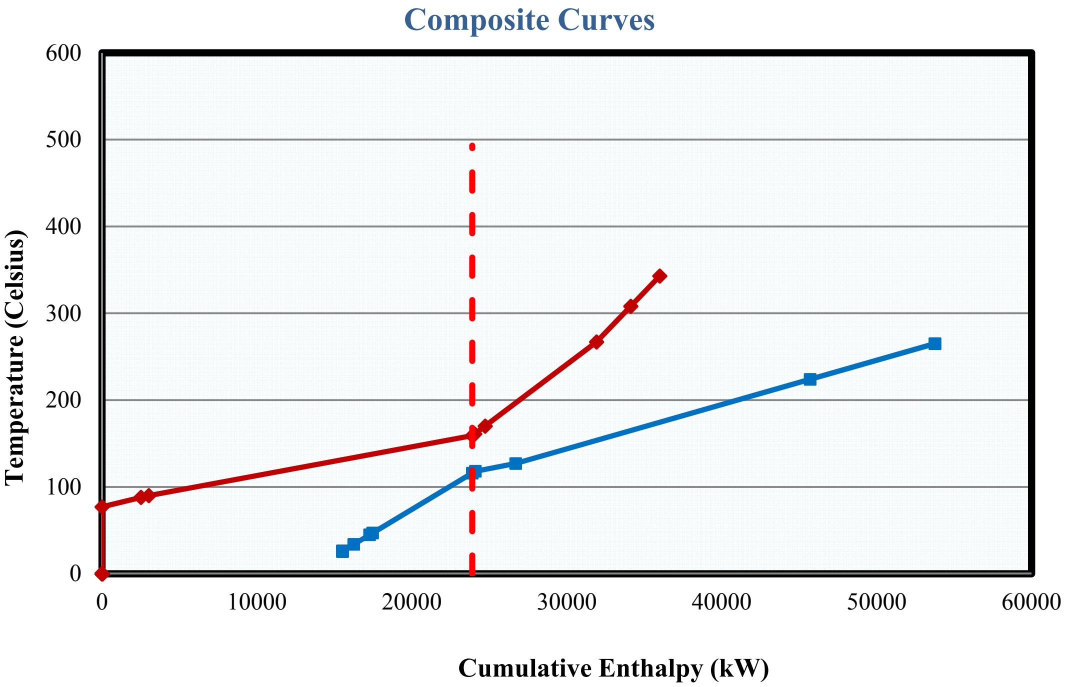


Figure 4.2 Composite curves of the existing network.

4.1.1 Discussion

In this section, the results for the retrofitted design of the process pinchand the MILPare compared.Each method was applied to the same HEN retrofit problem using the sameconstraints and cost functions.Furthermore, we will only discuss the results of disallowing the relocation of existing heat exchangers.This scenario allows manipulating the area of existing exchangers as well asadding new exchangers and introducing streamsplitting.

4.1.1.1 ProcessPinch Results

The ΔT_{min} maximizing the ideal NPV was determined from the graph below. It shows the maximum NPV of $584,748.3 occurs at a ΔT_{min} of 25.2 °C with hot and cold utility savings of 4,133 kW.

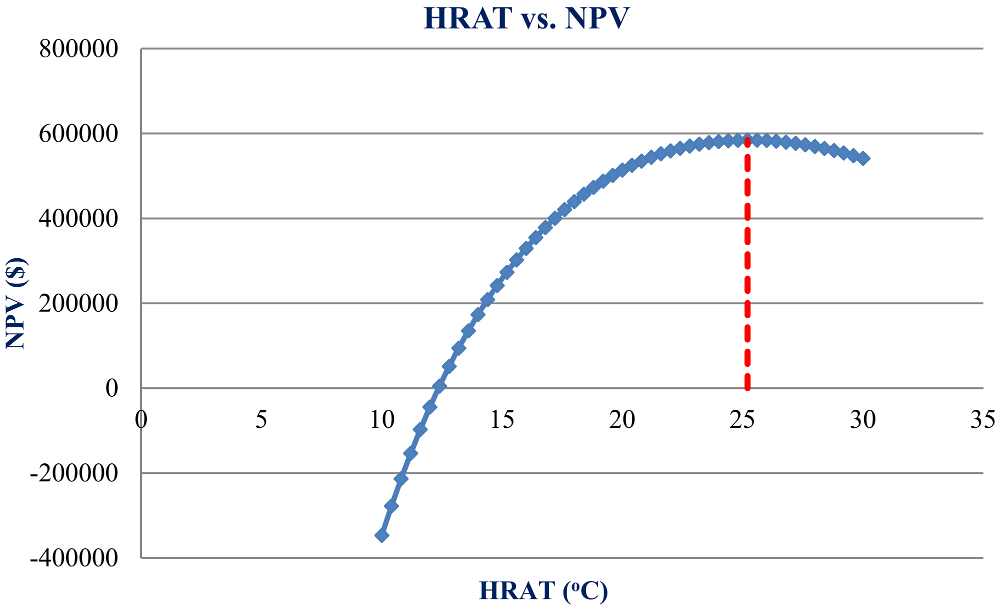


Figure 4.3HRAT versus NPV.

Now that the optimum ΔT_{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 at 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 4.5.

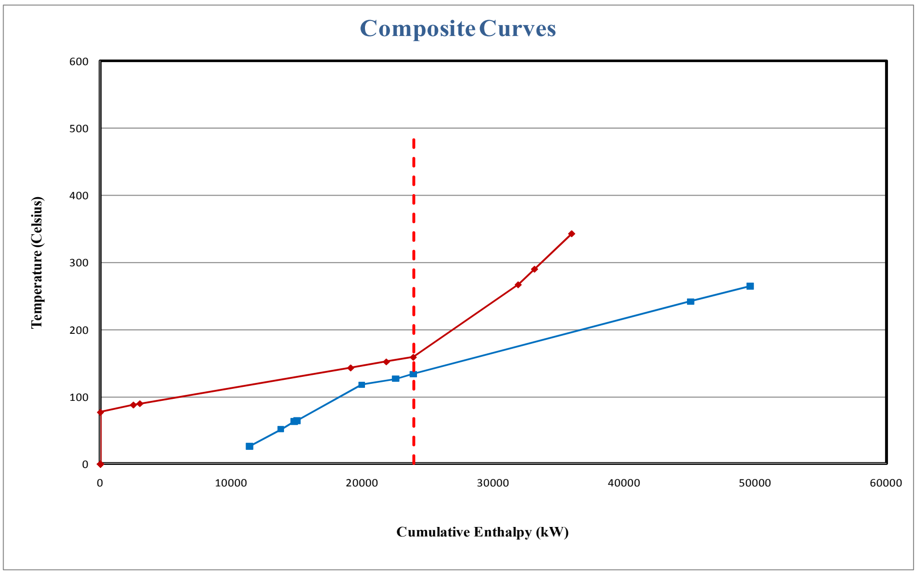


Figure 4.4 Composite curves of HEN retrofit at ΔT_{min}=25.2°C.

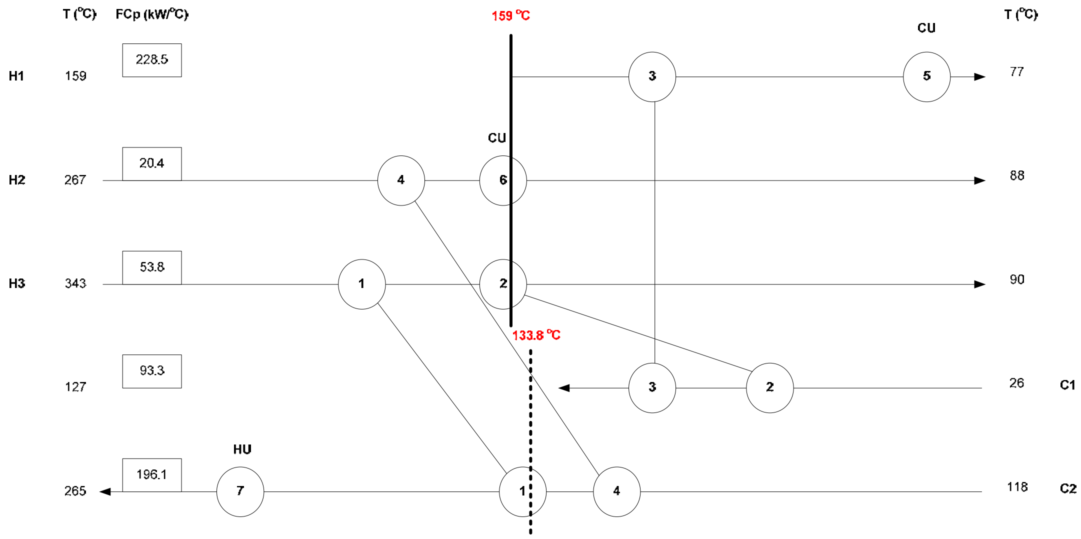


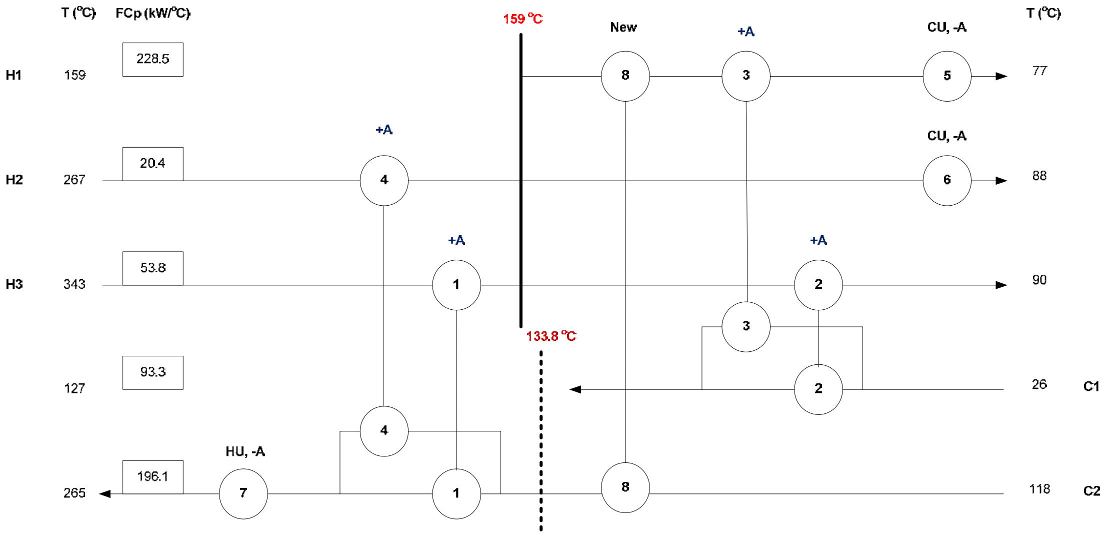
Figure 4.5 Grid diagram for the original heat exchanger network for Example 1.

The first step to design the new network is to locate the existing exchangers that transferheat across the pinch. For Example 1, exchangers 1, 2, 4 and 6 transfer heat across the pinch. Because pinchtechnology does not allow cross-pinch heat transfer, we must eliminate these exchangers andessentially reuse them. We do this by moving each exchanger to one side of the pinch and then alteringthe 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 beginmatching 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 ourretrofitted network has the minimum number of heat exchangers possible, we want to maximize theheat 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 (FCp)values. For streams above the pinch (to the left of the dashed line in the grid diagram), $FCp_{HOT} \leq FCp_{COLD}$.Matches below the pinch are made in a similar fashion except $FCp_{COLD} \leq FCp_{HOT}$. These two matching rulesensure 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 thepinch. 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 usesomething called the “Tick-Off” rule which states that we want to satisfy the heat requirements of atleast one of the streams connected by each exchanger. This will ensure the minimum number of heatexchangers for the network.

As above procedure we can find one alternative design for above the pinch and three alternative designs for below the pinch which also can be formed as three heat exchanger network as shown below.

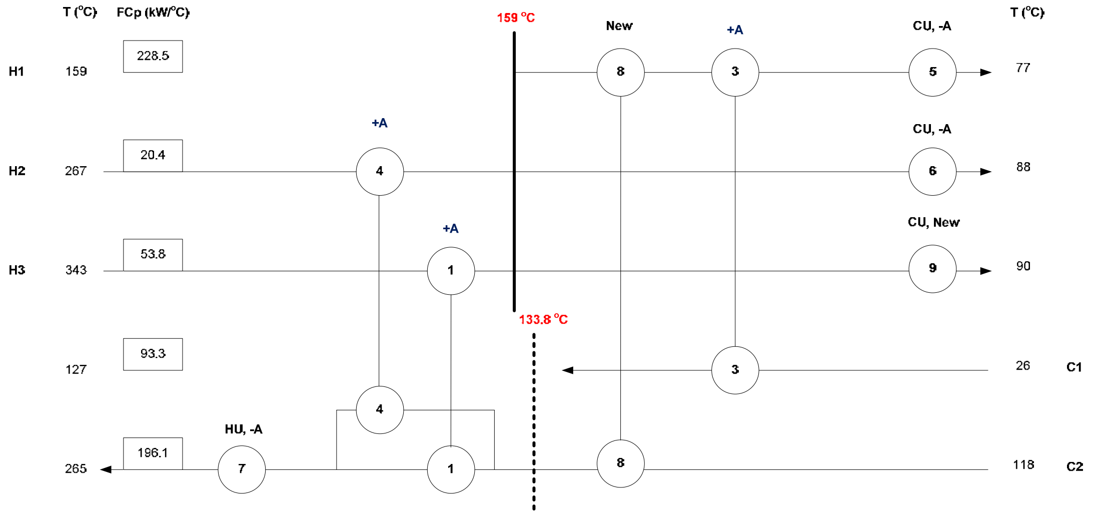

T (°C)
FCp (kW/°C)
159 °C
New
+A
CU, -A
T (°C)
H1
159
228.5
8
3
5
77
+A
CU, -A
H2
267
20.4
4
6
88
+A
+A
H3
343
53.8
1
2
90
3
133.8 °C
127
93.3
2
26
C1
4
HU, -A
265
196.1
7
1
8
118
C2

Notation: New exchanger (New), Area addition (+A); New shell (NS), Area reduction (-A)

Figure 4.6 Retrofitted heat exchanger results (1st alternative design at ΔT_{min}=25.2°C).

Table 4.3 Retrofitted heat exchanger results (1^{st}alternative design at ΔT_{min}= 25.2°C)

Heat Exchanger	Original area (m^2)	Load after retrofit (kW)	Retrofit area (m^2)	Area change (m^2)	Remarks
1	609.70	9899.20	858.19	248.49	Area addition (new shell)
2	579.20	3712.20	857.70	278.50	Area addition (new shell)
3	1008.50	5711.10	1125.13	116.63	Area addition
4	117.96	2203.20	264.70	146.74	Area addition (new shell)
5	787.50	9927.52	639.96	-147.54	Area reduction
6	104.60	1448.4	82.96	-21.64	Area reduction
7	246.75	13625.92	197.78	-48.97	Area reduction
8	-	3098.38	530.06	530.06	New exchanger

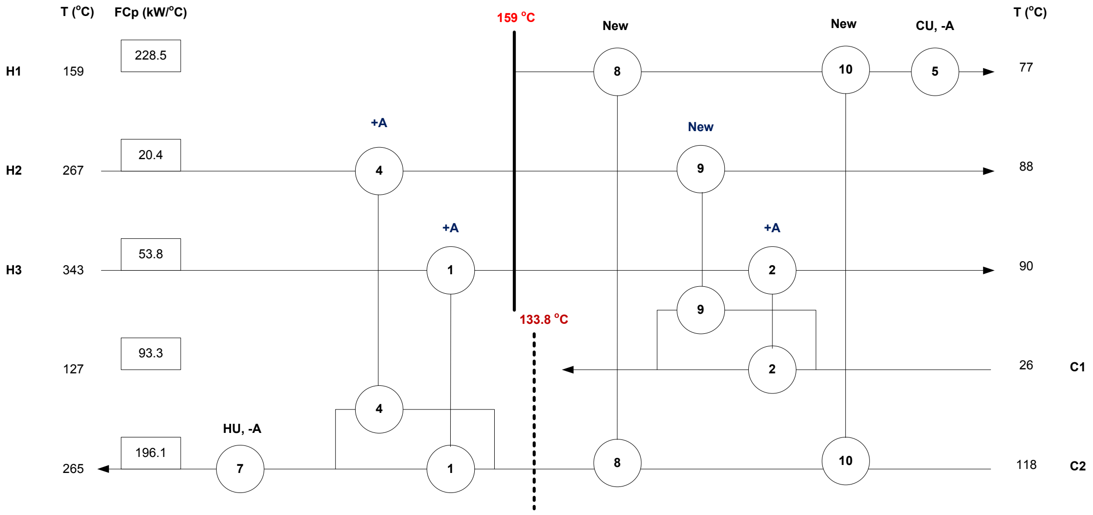

T (°C)
FCp (kW/°C)
159 °C
New
+A
CU, -A
T (°C)
H1
159
228.5
8
3
5
77
+A
CU, -A
H2
267
20.4
4
6
88
+A
CU, New
H3
343
53.8
1
9
90
133.8 °C
127
93.3
3
26
C1
4
HU, -A
265
196.1
7
1
8
118
C2

Notation: New exchanger (New), Area addition (+A); New shell (NS), Area reduction (-A)

Figure 4.7 Retrofitted heat exchanger results (2^{nd} alternative design at ΔT_{min}= 25.2°C).

Table 4.4 Retrofitted heat exchanger results (2^{nd} alternative design at ΔT_{min}=25.2°C)

Heat Exchanger	Original area (m^2)	Load after retrofit (kW)	Retrofit area (m^2)	Area change (m^2)	Remarks
1	609.70	9899.20	858.19	248.49	Area addition (new shell)
2	579.20	-	-	-	Non-operation
3	1008.50	9423.30	2088.30	1079.80	Area addition (new shell)
4	117.96	2203.20	264.70	146.74	Area addition (new shell)
5	787.50	6215.32	450.45	-337.05	Area reduction
6	104.60	1448.4	82.96	-21.64	Area reduction
7	246.75	13625.92	197.78	-48.97	Area reduction
8	-	3098.38	530.06	530.06	New exchanger
9	-	3712.2	236.65	236.65	New exchanger


T (°C)
FCp (kW/°C)
159 °C
New
New
CU, -A
T (°C)
H1
159
228.5
8
10
5
77
+A
New
H2
267
20.4
4
9
88
+A
+A
H3
343
53.8
1
2
90
133.8 °C
9
127
93.3
2
26
C1
4
HU, -A
265
196.1
7
1
8
10
118
C2

Notation: New exchanger (New), Area addition (+A); New shell (NS), Area reduction (-A)

Figure 4.8 Retrofitted heat exchanger results (3^{rd} alternative design at ΔT_{min}= 25.2°C).

Table 4.5 Retrofitted heat exchanger results (3^{rd} alternative design at ΔT_{min}= 25.2°C)

Heat Exchanger	Original area	Load after retrofit	Retrofit area	Area change	Remarks

	(m^2)	(kW)	(m^2)	(m^2)	
1	609.70	9899.20	858.19	248.49	Area addition (new shell)
2	579.20	3712.20	857.70	278.50	Area addition (new shell)
3	1008.50	-	-	-	Non-operation
4	117.96	2203.20	264.70	146.74	Area addition (new shell)
5	787.50	11375.92	704.34	-83.16	Area reduction
6	104.60	-	-	-	Non-operation
7	246.75	13625.92	197.78	-48.97	Area reduction
8	-	3098.38	530.06	530.06	New exchanger
9	-	1448.4	622.12	622.12	New exchanger
10	-	4262.70	451.39	451.39	New exchanger

To make the comparison even more fair, retrofitted heat exchanger using pinch technology is compared by considering the economic data presented below.

Table 4.6 Physical properties of HEN for original HEN and Process pinch

		Retrofitted HEN using process pinch		
	Original HEN	1stalternative design	2ndalternative design	3rdalternative design
ΔT_{min}(°C)	43.1	25.2	25.2	25.2
Network area (m^2)	3,454.21	4,556.48	4,709.08	4,486.27
No. of Exchangers	7	8	8	8
Hot Utilities (kW)	17,759	13,625.92	13,625.92	13,625.92
Cold Utilities (kW)	15,510	11,375.92	11,375.92	11,375.92

Table 4.7 Cost summary for Example 1 for original HEN and Process pinch

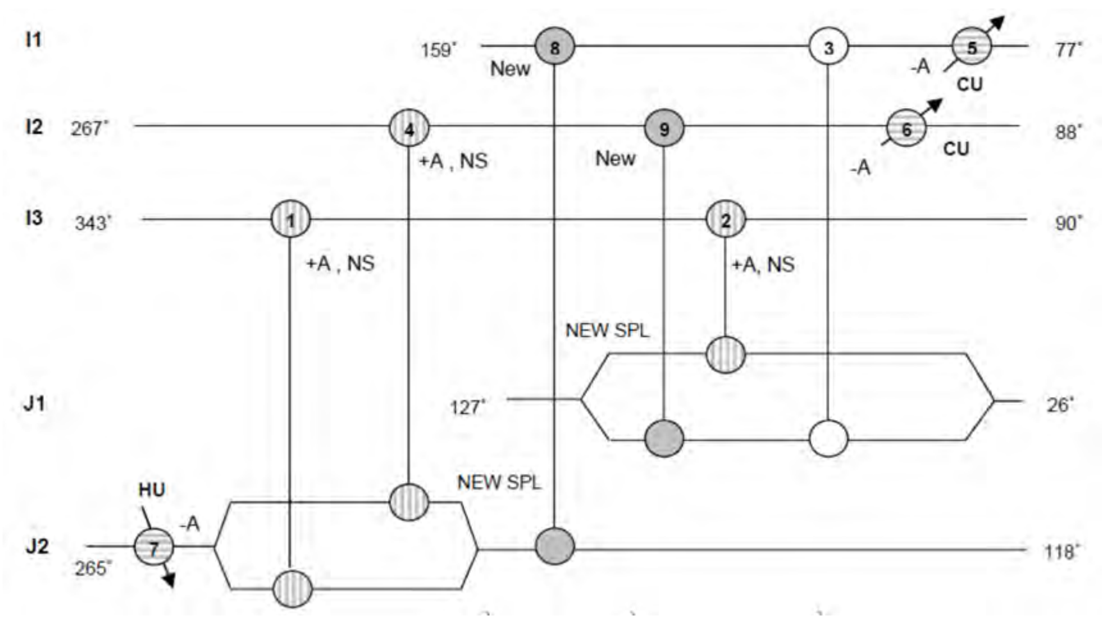
	Retrofitted HEN using process pinch		
Original HEN	1stalternative design	2ndalternative design	3rdalternative design

Hot Utility Cost ($/yr)	1,687,815.36	1,295,007.4	1,295,007.4	1,295,007.4
Cold Utility Cost ($/yr)	309,889.80	227,290.9	227,290.9	227,290.9
Total capital investment ($)		1,256,493.6	2,045,655.9	1,700,701.3
Energy saving ($/yr)		475,406.8	475,406.8	475,406.8
Total annualized cost ($/yr)		1,853,758.2	2,061,937.2	1,970,939.0
Net present value (over 5 yrs)		545,672.4	-243,489.9	101,464.7
Return on investment (ROI)		37.84%	23.24%	27.95%

The following tables represent the cost comparison among three alternative designs at ΔT_{min}= 25.2°C. It is also clear that the 1st alternative design has the highest net present value and return on investment as well as the lowest total annualized cost with no suitable loop and path for area/heat duty distribution.Due to the fact that the economic data of the 1st alternative design, the result is high enough without considering the loops and paths adjustment of 2nd and 3rd alternative designs. In addition, loops and paths adjustment can be used to adjust the heat duty and/or area on the exchangers within the loop by shifting the heat around the exchangers. While, the inlet and outlet temperatures remain the same for the adjusted network.

4.1.1.2 MILPResults

The retrofitted design for the MILP which was stated by Nguyen et al. (2010) is shown below in Figure 4.9. The network includes two newexchangers (E8 and E9), an increase in existing exchanger area (E1, E2, and E4), and a reduction inexisting exchanger area (E5, E6, and E7). Of the seven existing exchangers only one exchanger remainedunchanged (E3). The increase in area to exchangers E8 and E9 was in the form of adding new shells. It isinteresting 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 betweenprocess 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 utilitiesrequired by the system.


I1
I2
I3
J1
J2
159°
267°
343°
127°
265°
77°
88°
90°
26°
118°
1
2
3
4
5
6
7
8
9
New
New
+A , NS
+A , NS
+A, NS
-A
-A
-A
CU
CU
HU
NEW SPL
NEW SPL

Notation: New exchanger (New), Area addition (+A); New shell (NS), Area reduction (-A), New split (NEW SPL)

Figure 4.9 Retrofitted heat exchanger network for Example 1 (Nguyen et al., 2010).

Table 4.8 Retrofitted heat exchanger results for Example 1 (Nguyen et al., 2010)

Heat exchanger	Original area (m^2)	Load after retrofit (MJ/hr)	Retrofit area (m^2)	Area change (m^2)	
1	610.10	9868.27	966.08	355.97	Area Addition (New Shell)
2	584.15	3743.14	864.59	280.44	
3	1009.87	5222.57	1009.87	0	
4	121.53	2098.53	261.93	140.4	Area Addition (New Shell)
5	852.4	9262.54	644.41	-208.01	Area Reduction
6	95.06	1095.48	70.02	-25.04	
7	246.81	12608.02	184.65	-62.16	
8	0	4251.89	937.84		New Exchangers
9	0	457.59	148.85		

4.1.1.3*CostComparison*

Since Example 1 represents a relatively smaller project, it was decided to show the data for a project life of 5 years. Each method was applied to the same HEN retrofit problem using the same constraints and cost functions to determine the optimal solution.

Table 4.9 Physical properties of HEN for original HEN, process pinch and MILP

		Retrofitted HEN	
	Original HEN	Process pinch	MILP
ΔT_{min} (^oC)	43.1	25.2	20.01
Network area (m^2)	3,454.21	4,556.48	5,088.24
No. of Exchangers	7	8	9
Hot Utilities (kW)	17,759	13,625.92	12,608
Cold Utilities (kW)	15,510	11,376	10,358

Table 4.10 Cost summary for Example 1

		Retrofitted HEN	
	Original HEN	Process pinch	MILP
Hot Utility Cost ($/yr)	1,687,815.36	1,295,007.40	1,198,264
Cold Utility Cost ($/yr)	309,889.80	227,290.90	206,953
Total capital investment ($)		1,256,493.60	1,730,945
Energy saving ($/yr)		475,406.80	577,192
Total annualized cost ($/yr)		1,853,758.20	1,861,835.93
Net present value (over 5 yrs)		545,672.40	457,066.92
Return on investment (ROI)		37.84%	33.35%

The following tables represent the cost comparison between the two methodologies. It is clear that the process pinch has the highest net present value and the return on investment as well as the lowest total annualized cost.

As above result, it is apparent that process pinch design is still a powerful procedure to do HEN retrofit which extremely depends on the selection of the best network from all possibilities. However, the MILP allows the user to quickly and easily change parameters that would allow the evaluation of a numerous scenarios.

4.2Example 2

The second problem is adapted from Barbaroet. al (2005).This problem is the retrofitting of a crude distillation unit. The network consists of 18 streamsand 18 exchangers. The current design uses two hot utilities and three cold utilities. The stream data is shown in Table 4.11. The existing exchanger network configuration is shown in Figure 4.10. The existingnetwork does not have splitters. For this example we will compare the results of 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 toexisting exchangers. The original HEN consumes 67,988.25 kW of hot utility and 75,076.08 kW of cold utility. Table 4.12 identifies the existing exchangers' original areas, which were calculated using the log meantemperature difference. The amount and costs of each utility used is shown in Table 4.13. The results willbe compared for a project life of 5 years and presented in the discussion section. 350 workingdays per year is assumed.

The maximum values of area addition and reduction thatcan be made to existing shells are 10% and 40% of the corresponding existing area;respectively (except for the two exchangers E5 & E12 serving the match I5.J1 where thecorresponding percentages are 20% and 30%). The maximum area per shell is 5,000 (m^2); the maximum number of shells per exchanger is4. This problem is also disallowed all hot streams and C3 cold stream splitting. The model was run maximizing the net present value. The pair of exchangers (E10, E11) and thethree exchangers (E12, E1, and E5) are not allowed to change their relative order (althoughE12 and E5 are allowed to switch position. The cost relations for area adjustment for Example 2 are shown Equation 4.5, 4.6, 4.7 and 4.8. A cost is assigned to splitting of \$20,000.

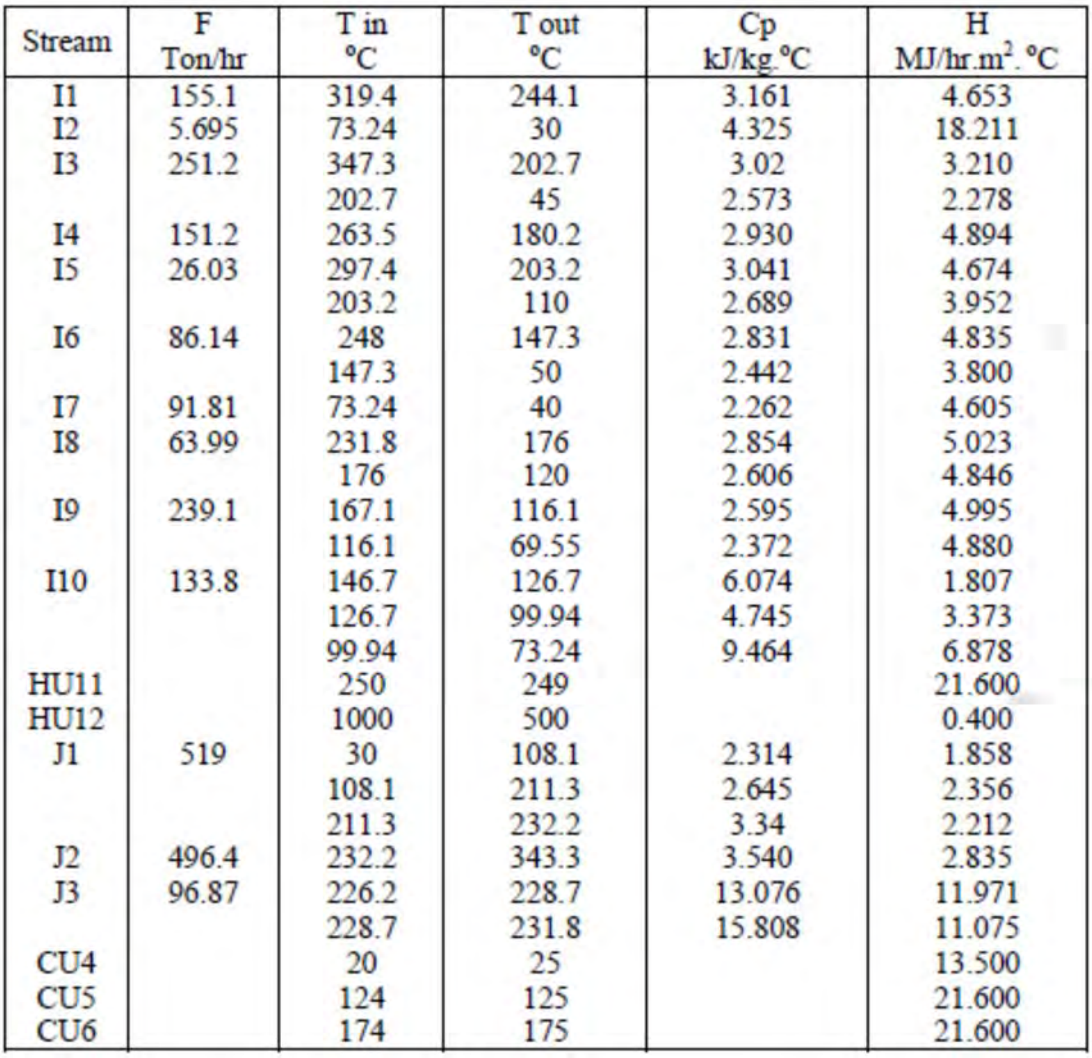
$$\text{Heat exchanger cost (\$)} = 26{,}460 + [389 \times \text{Area (m}^2)] \tag{4.5}$$

$$\text{Area addition cost (\$)} = 13{,}230 + [857 \times \text{Area}_{\text{added}} (\text{m}^2)] \tag{4.6}$$

$$\text{Area reduction cost (\$)} = 13{,}230 + [5 \times \text{Area}_{\text{reduced}} (\text{m}^2)] \tag{4.7}$$

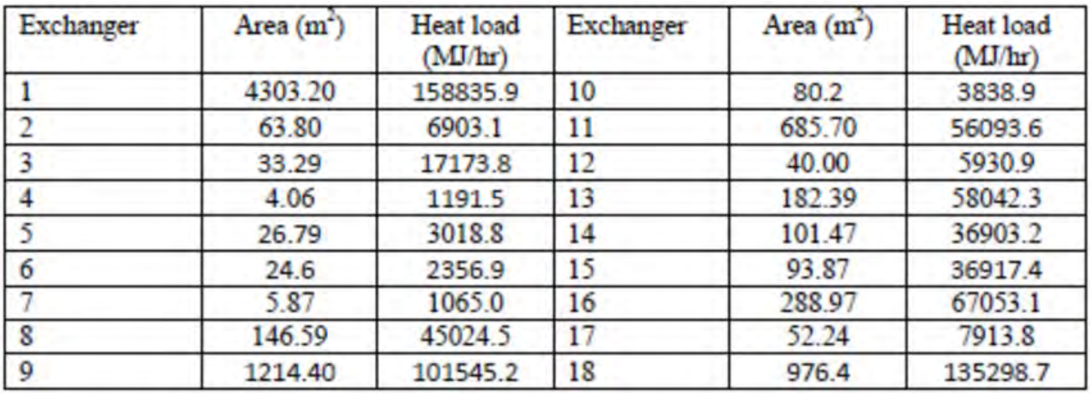
$$\text{New shell} = 26{,}460 + [857 \times \text{Area}_{\text{shell}} (\text{m}^2)] \tag{4.8}$$

Table 4.11 Stream properties for Example 2 (Nguyen et al., 2010)



Stream	F Ton/hr	T in °C	T out °C	Cp kJ/kg.°C	H MJ/hr.m^2. °C
I1	155.1	319.4	244.1	3.161	4.653
I2	5.695	73.24	30	4.325	18.211
I3	251.2	347.3	202.7	3.02	3.210
		202.7	45	2.573	2.278
I4	151.2	263.5	180.2	2.930	4.894
I5	26.03	297.4	203.2	3.041	4.674
		203.2	110	2.689	3.952
I6	86.14	248	147.3	2.831	4.835
		147.3	50	2.442	3.800
I7	91.81	73.24	40	2.262	4.605
I8	63.99	231.8	176	2.854	5.023
		176	120	2.606	4.846
I9	239.1	167.1	116.1	2.595	4.995
		116.1	69.55	2.372	4.880
I10	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
HU11		250	249		21.600
HU12		1000	500		0.400
J1	519	30	108.1	2.314	1.858
		108.1	211.3	2.645	2.356
		211.3	232.2	3.34	2.212
J2	496.4	232.2	343.3	3.540	2.835
J3	96.87	226.2	228.7	13.076	11.971
		228.7	231.8	15.808	11.075
CU4		20	25		13.500
CU5		124	125		21.600
CU6		174	175		21.600

Table 4.12 Existing exchangers in the network, Example 2 (Nguyen et al., 2010)



Exchanger	Area (m^2)	Heat load (MJ/hr)	Exchanger	Area (m^2)	Heat load (MJ/hr)
1	4303.20	158835.9	10	80.2	3838.9
2	63.80	6903.1	11	685.70	56093.6
3	33.29	17173.8	12	40.00	5930.9
4	4.06	1191.5	13	182.39	58042.3
5	26.79	3018.8	14	101.47	36903.2
6	24.6	2356.9	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	1214.40	101545.2	18	976.4	135298.7

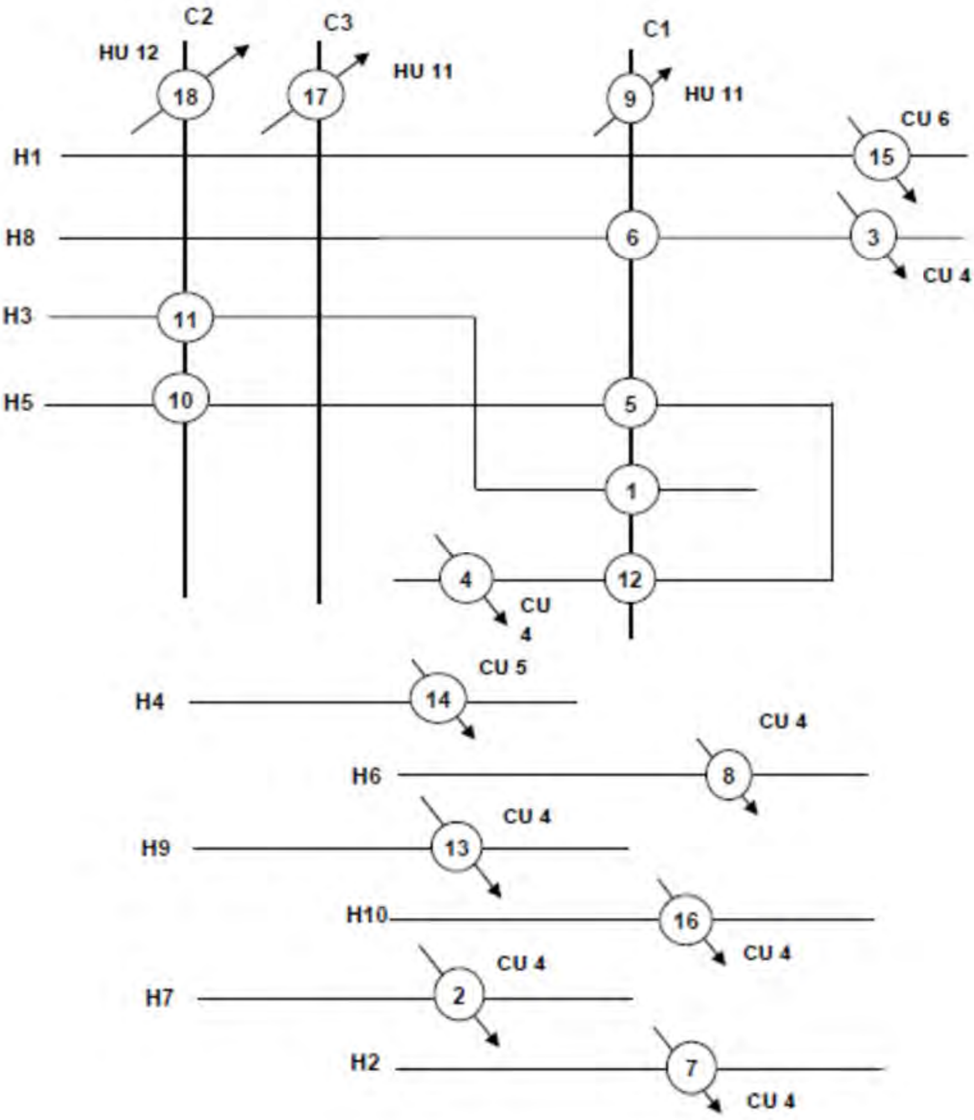

C2
C3
C1
HU 12
HU 11
HU 11
18
17
9
CU 6
H1
15
H8
6
3
CU 4
H3
11
H5
10
5
1
4
12
CU
4
CU 5
H4
14
CU 4
H6
8
CU 4
H9
13
H10
16
CU 4
CU 4
H7
2
H2
7
CU 4

Figure 4.10 Original heat exchanger network for Example 2(Nguyen et al., 2010).

Table 4.13 Utilities in the original network (Nguyen et al., 2010)

Hot utility	Cost (cent/MJ)	Amount (MJ/hr)	Cold utility	Cost (cent/MJ)	Amount (MJ/hr)
HU11	0.2351	109459	CU4	0.0222	196453.3
HU12	0.4431	135298.7	CU5	0.0773	36903.2
			CU6	0.1518	36917.4
Total hot utilities (MJ/hr)		244757.7	Total cold utilities (MJ/hr)		270273.9

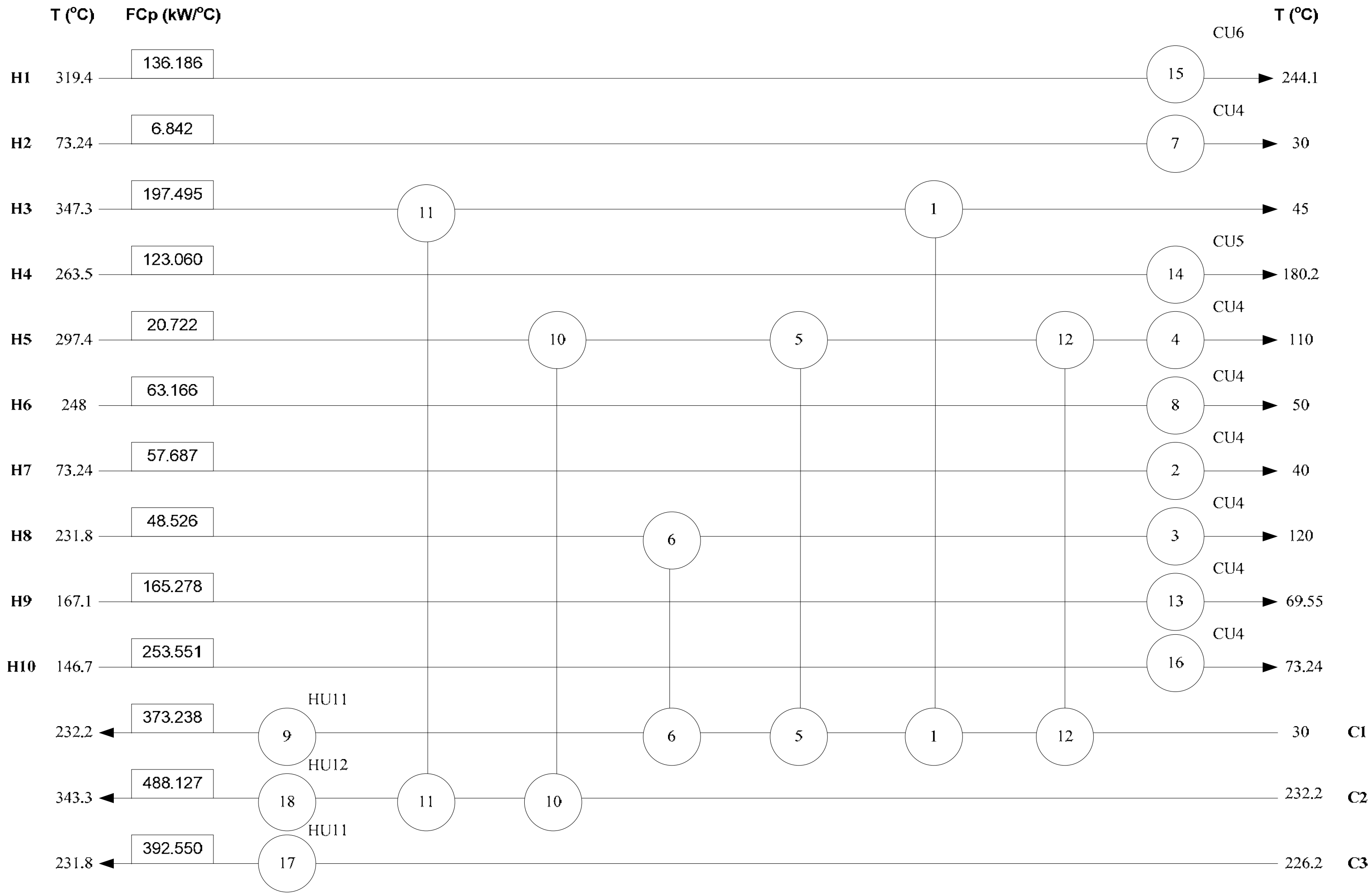

T (°C)
FCp (kW/°C)
T (°C)
H1
319.4
136.186
15
CU6
244.1
H2
73.24
6.842
7
CU4
30
H3
347.3
197.495
11
1
45
H4
263.5
123.060
14
CU5
180.2
H5
297.4
20.722
10
5
12
4
CU4
110
H6
248
63.166
8
CU4
50
H7
73.24
57.687
2
CU4
40
H8
231.8
48.526
6
3
CU4
120
H9
167.1
165.278
13
CU4
69.55
H10
146.7
253.551
16
CU4
73.24
232.2
373.238
9
HU11
6
5
1
12
30
C1
343.3
488.127
18
HU12
11
10
232.2
C2
231.8
392.550
17
HU11
226.2
C3

Figure 4.11 Grid diagram of Example 2.

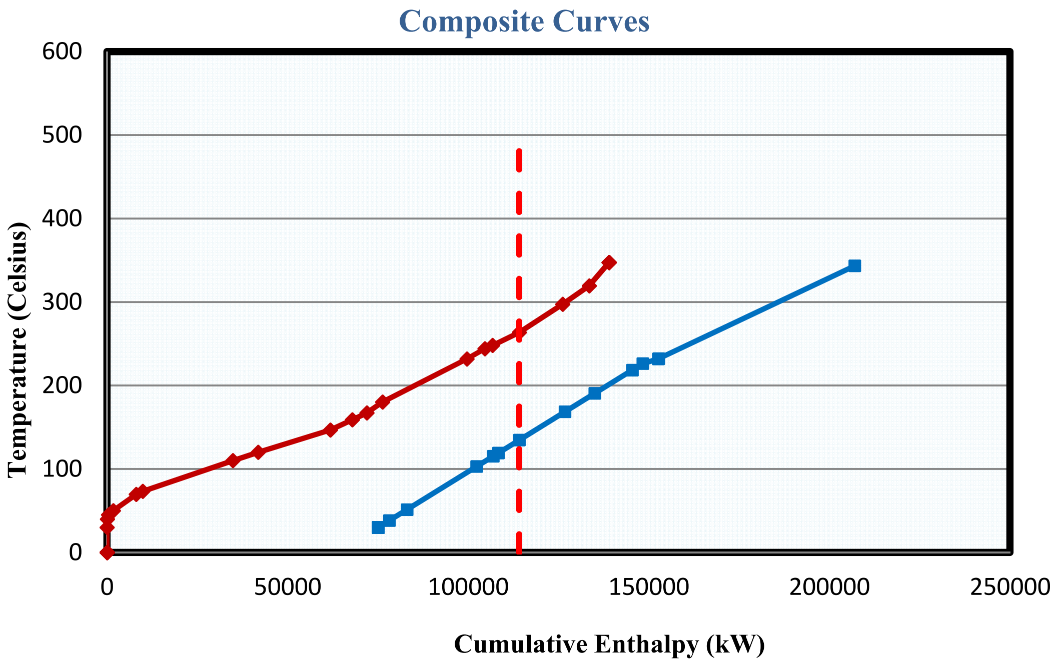


Figure 4.12 Composite curves of the existing HEN.

4.2.1 Discussion

In this section the results for the retrofitted design of the MILP and process pinch are compared. Each method was applied to the same HEN retrofit problem using the sameconstraints and cost functions.This scenario allows each methodology to manipulate the area of existing exchangers as well asadding new exchangers and introducing split streams.

4.2.1.1 ProcessPinch Results

The ΔT_{min} maximizing the ideal NPV was determined from the graph below. It shows the maximum NPV of $18,300,099.7 occurs at a ΔT_{min} of 13 °C with hot and cold utility savings of 45,675.91 kW.

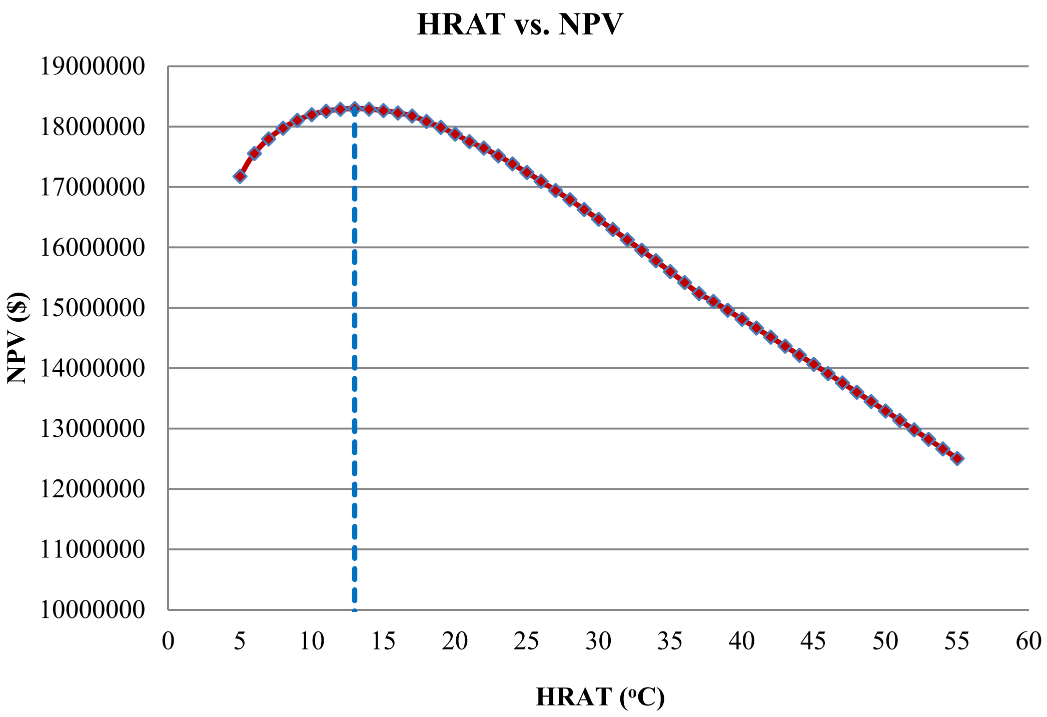


Figure 4.13HRAT versus NPV.

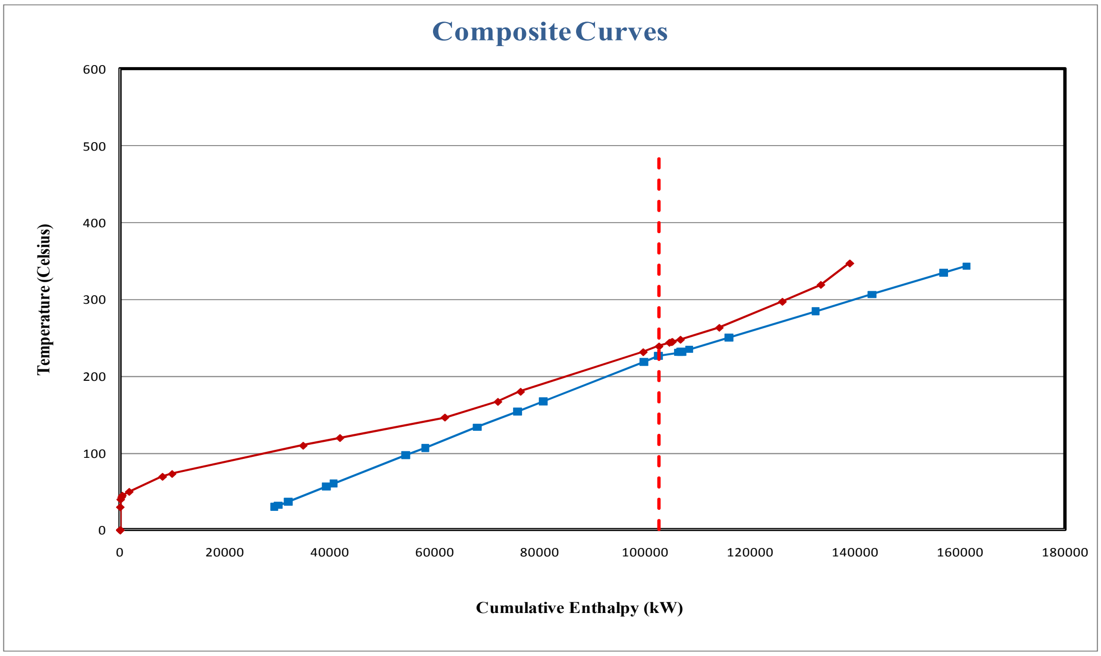


Figure 4.14 Composite curves of HEN retrofit which maximize NPV at a ΔT_{min} of 13°C.

Now that the optimum ΔT_{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 at the middle of the grid. For this section, Example 2 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 4.15.

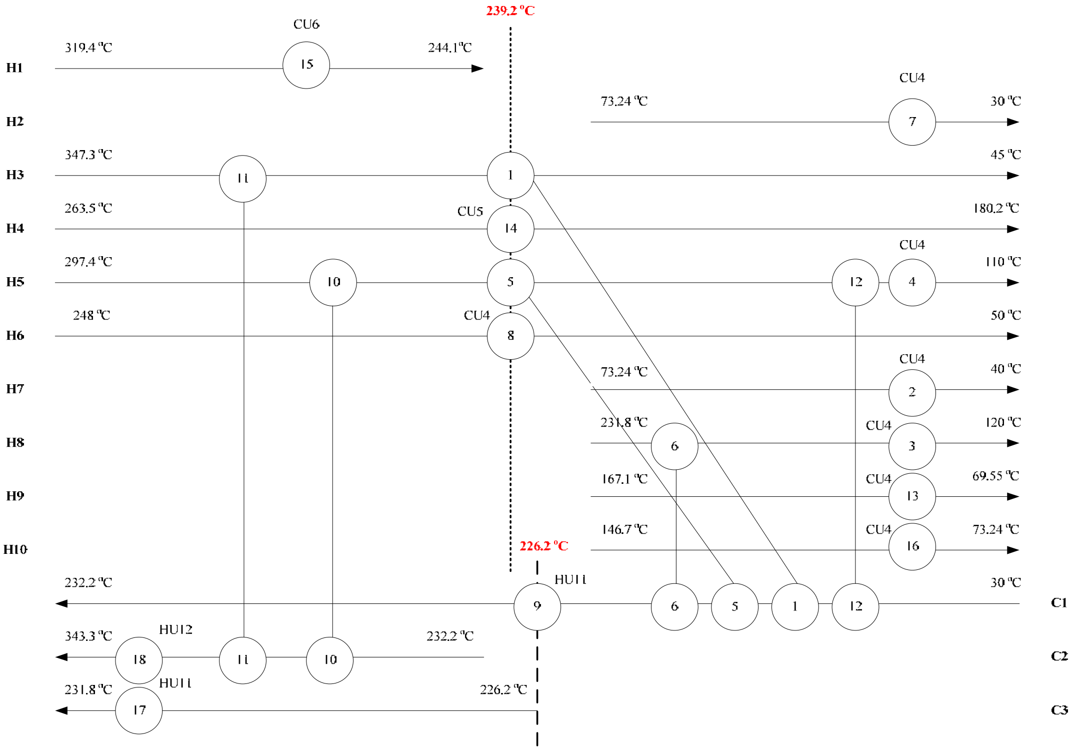

239.2 °C
CU6
319.4 °C
15
244.1°C
H1
CU4
73.24 °C
30 °C
7
H2
347.3 °C
11
1
45 °C
H3
263.5 °C
CU5
14
180.2 °C
H4
CU4
297.4 °C
10
5
12
4
110 °C
H5
248 °C
CU4
8
50 °C
H6
CU4
73.24 °C
40 °C
2
H7
231.8 °C
6
CU4
3
120 °C
H8
167.1 °C
CU4
13
69.55 °C
H9
146.7 °C
CU4
16
73.24 °C
H10
226.2 °C
232.2 °C
HU11
9
6
5
1
12
30 °C
C1
343.3 °C
HU12
18
11
10
232.2 °C
C2
231.8 °C
HU11
17
226.2 °C
C3

Figure 4.15 Cross pinch grid diagram for Example 2.

The first step to design the new network is to locate the existing exchangers that transfer heat across the pinch. For Example 2, exchangers 1, 5, 8, 9, 14 and 15 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 (FCp) values. Form streams above the pinch (to the left of the dashed line in the grid diagram), $FCp_{HOT} \leq FCp_{COLD}$. Matches below the pinch are made in a similar fashion except $FCp_{COLD} \leq FCp_{HOT}$. 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.

As above procedure we can find 3 alternative designs for above the pinch and 3 alternative designs for below the pinch as shown below which also can be formed as 9 heat exchanger network.

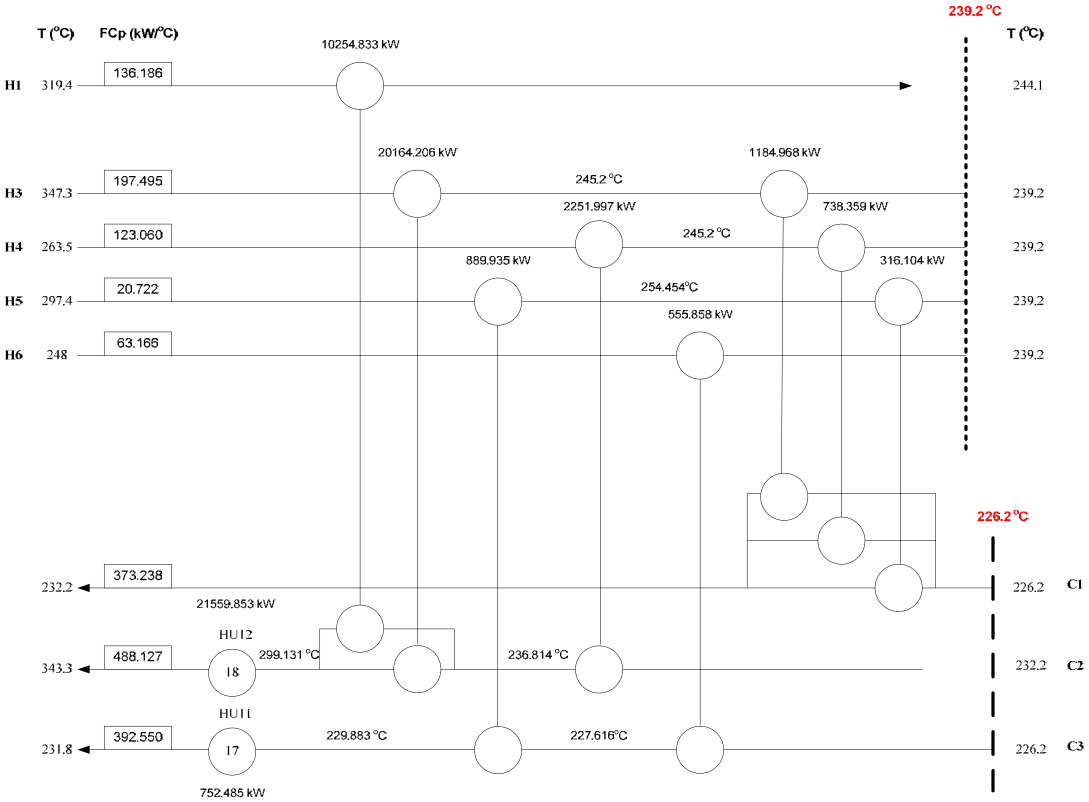

239.2 °C
T (°C)
FCp (kW/°C)
T (°C)
10254.833 kW
H1
319.4
136.186
244.1
20164.206 kW
1184.968 kW
H3
347.3
197.495
245.2 °C
2251.997 kW
738.359 kW
239.2
H4
263.5
123.060
245.2 °C
239.2
889.935 kW
316.104 kW
H5
297.4
20.722
254.454°C
239.2
555.858 kW
H6
248
63.166
239.2
226.2 °C
232.2
373.238
226.2
C1
21559.853 kW
HU12
343.3
488.127
18
299.131 °C
236.814 °C
232.2
C2
HU11
231.8
392.550
17
229.883 °C
227.616°C
226.2
C3
752.485 kW

Figure 4.16 Above pinch retrofitted results (1^{st} alternative design at ΔT_{min}= 13 °C).

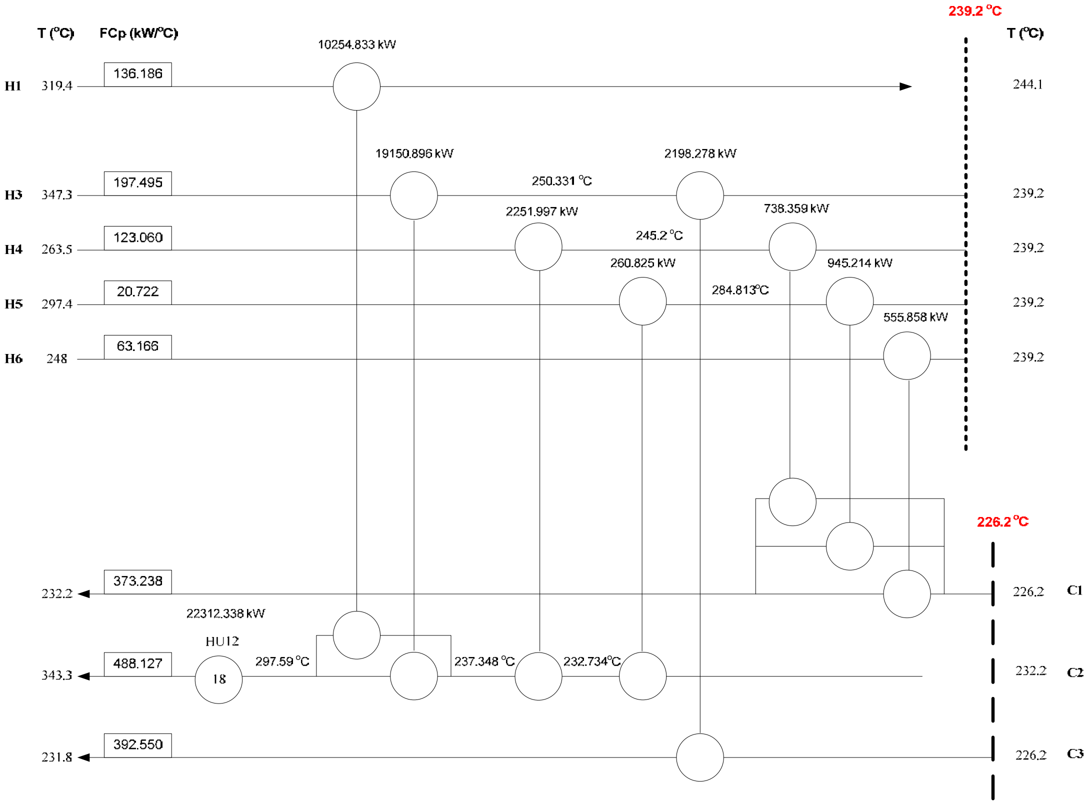

239.2 °C
T (°C)
FCp (kW/°C)
T (°C)
10254.833 kW
H1
319.4
136.186
244.1
19150.896 kW
2198.278 kW
H3
347.3
197.495
250.331 °C
239.2
2251.997 kW
738.359 kW
H4
263.5
123.060
245.2 °C
239.2
260.825 kW
945.214 kW
H5
297.4
20.722
284.813°C
239.2
555.858 kW
H6
248
63.166
239.2
226.2 °C
232.2
373.238
226.2
C1
22312.338 kW
HU12
343.3
488.127
18
297.59 °C
237.348 °C
232.734°C
232.2
C2
231.8
392.550
226.2
C3

Figure 4.17 Above pinch retrofitted results (2^{nd} alternative design at ΔT_{min}= 13 °C).

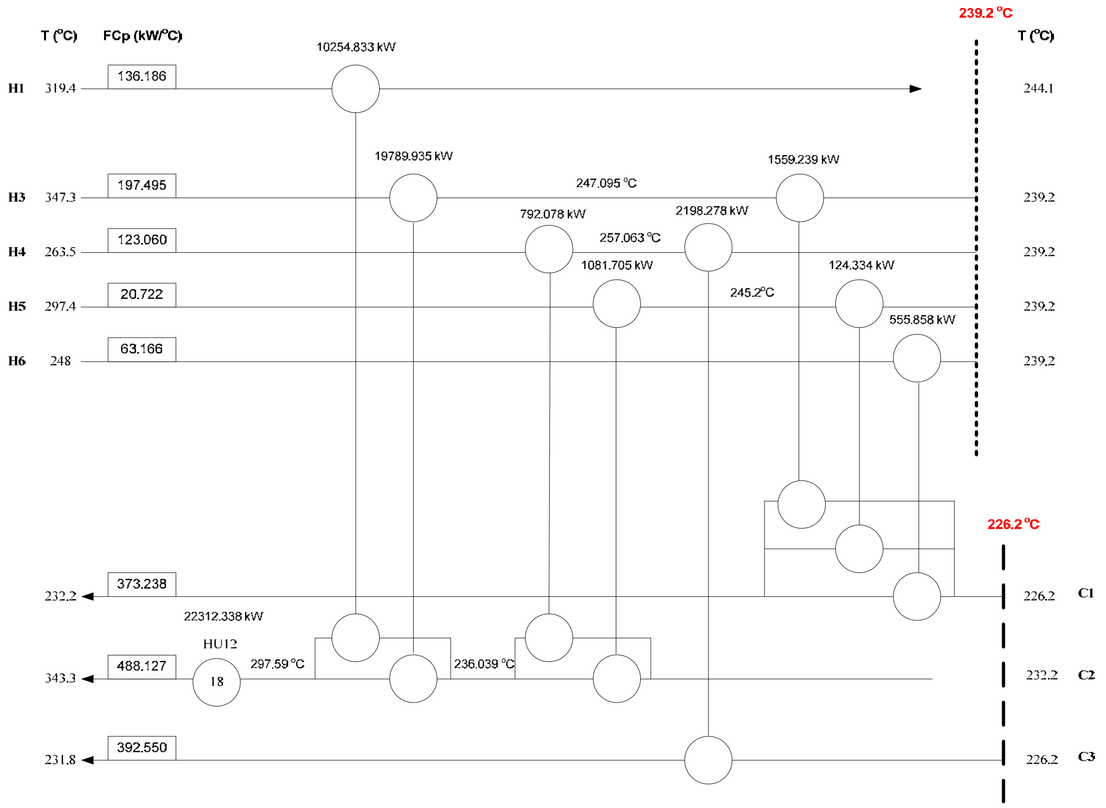

239.2 °C
T (°C)
FCp (kW/°C)
T (°C)
10254.833 kW
H1
319.4
136.186
244.1
19789.935 kW
1559.239 kW
247.095 °C
H3
347.3
197.495
239.2
792.078 kW
2198.278 kW
257.063 °C
H4
263.5
123.060
239.2
1081.705 kW
124.334 kW
245.2°C
H5
297.4
20.722
239.2
555.858 kW
H6
248
63.166
239.2
226.2 °C
232.2
373.238
226.2
C1
22312.338 kW
HU12
18
297.59 °C
236.039 °C
343.3
488.127
232.2
C2
231.8
392.550
226.2
C3

Figure 4.18 Above pinch retrofitted results (3rd alternative design at ΔTmin= 13 °C).

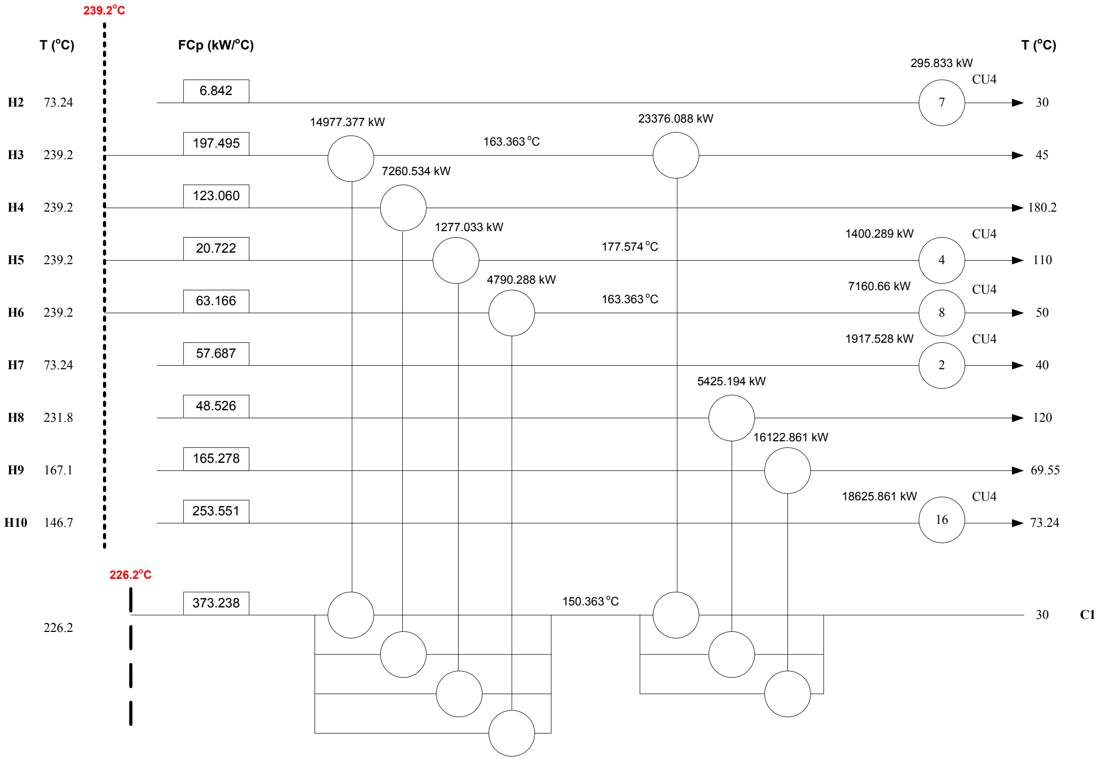

239.2°C
T (°C)
FCp (kW/°C)
T (°C)
295.833 kW
CU4
H2
73.24
6.842
7
30
14977.377 kW
23376.088 kW
163.363 °C
H3
239.2
197.495
45
7260.534 kW
H4
239.2
123.060
180.2
1277.033 kW
1400.289 kW
CU4
177.574 °C
H5
239.2
20.722
4
110
4790.288 kW
7160.66 kW
CU4
163.363 °C
H6
239.2
63.166
8
50
1917.528 kW
CU4
H7
73.24
57.687
2
40
5425.194 kW
H8
231.8
48.526
120
16122.861 kW
H9
167.1
165.278
69.55
18625.861 kW
CU4
H10
146.7
253.551
16
73.24
226.2°C
150.363 °C
226.2
373.238
30
C1

Figure 4.19 Below pinch retrofitted results (1st alternative design at ΔTmin= 13 °C).

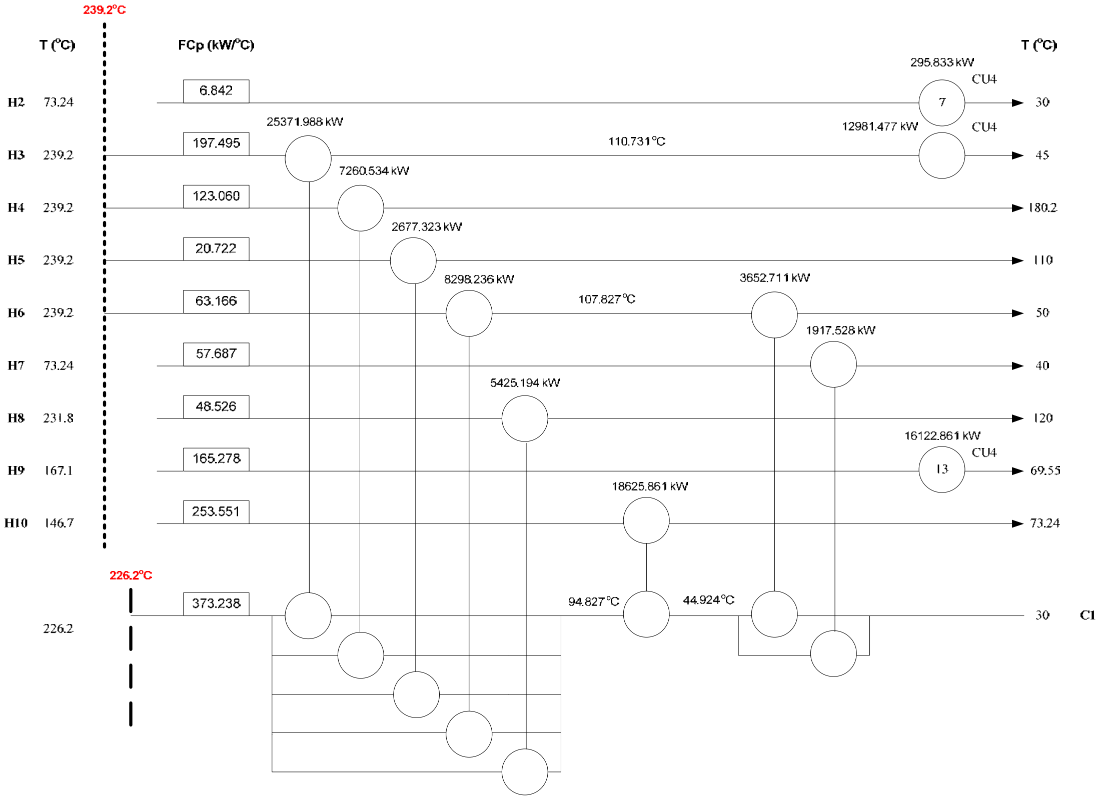

239.2°C
T (°C)
FCp (kW/°C)
T (°C)
H2
73.24
6.842
295.833 kW
CU4
7
30
H3
239.2
197.495
25371.988 kW
110.731°C
12981.477 kW
CU4
45
7260.534 kW
H4
239.2
123.060
180.2
2677.323 kW
H5
239.2
20.722
110
8298.236 kW
3652.711 kW
H6
239.2
63.166
107.827°C
50
1917.528 kW
H7
73.24
57.687
40
5425.194 kW
H8
231.8
48.526
120
16122.861 kW
CU4
H9
167.1
165.278
13
69.55
18625.861 kW
H10
146.7
253.551
73.24
226.2°C
373.238
226.2
94.827°C
44.924°C
30
C1

Figure 4.20 Below pinch retrofitted results (2nd alternative design at ΔT$_{min}$= 13 °C).

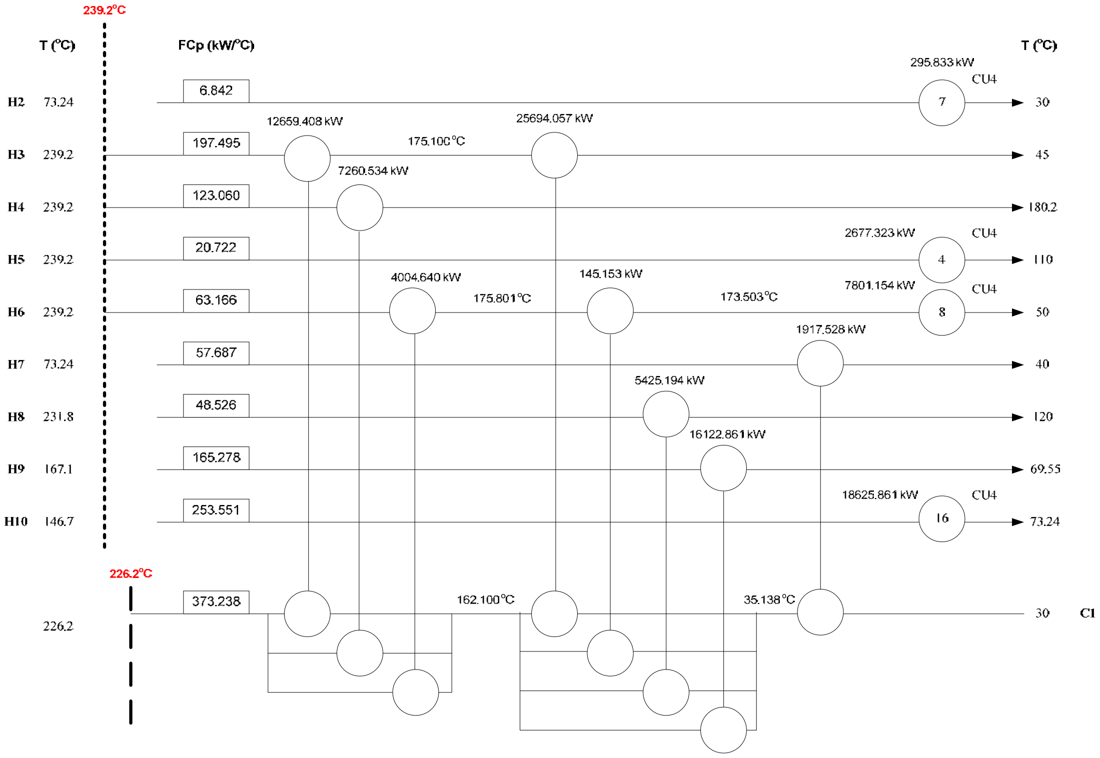

239.2°C
T (°C)
FCp (kW/°C)
T (°C)
H2
73.24
6.842
295.833 kW
CU4
7
30
H3
239.2
197.495
12659.408 kW
175.100°C
25694.057 kW
45
7260.534 kW
H4
239.2
123.060
180.2
2677.323 kW
CU4
H5
239.2
20.722
4
110
4004.640 kW
145.153 kW
7801.154 kW
CU4
H6
239.2
63.166
175.801°C
173.503°C
8
50
1917.528 kW
H7
73.24
57.687
40
5425.194 kW
H8
231.8
48.526
120
16122.861 kW
H9
167.1
165.278
69.55
18625.861 kW
CU4
H10
146.7
253.551
16
73.24
226.2°C
373.238
226.2
162.100°C
35.138°C
30
C1

Figure 4.21 Below pinch retrofitted results (3rd alternative design at ΔT$_{min}$= 13 °C).

All above and below pinch designs can be formed as 9 heat exchanger networks. By doing this, we begin with the 1st network which combines the 1st above and the 1st below pinch design. Then, the 2nd network is the combination of the 2nd above and the 1st below pinch design. After that, the 3rd above and the 1st below pinch design are combined to be the 3rd network. So, we do the same procedure until we got 9 retrofitted heat exchanger networks.

As done in Example one, this problem is also compared by considering the economic data presented below.

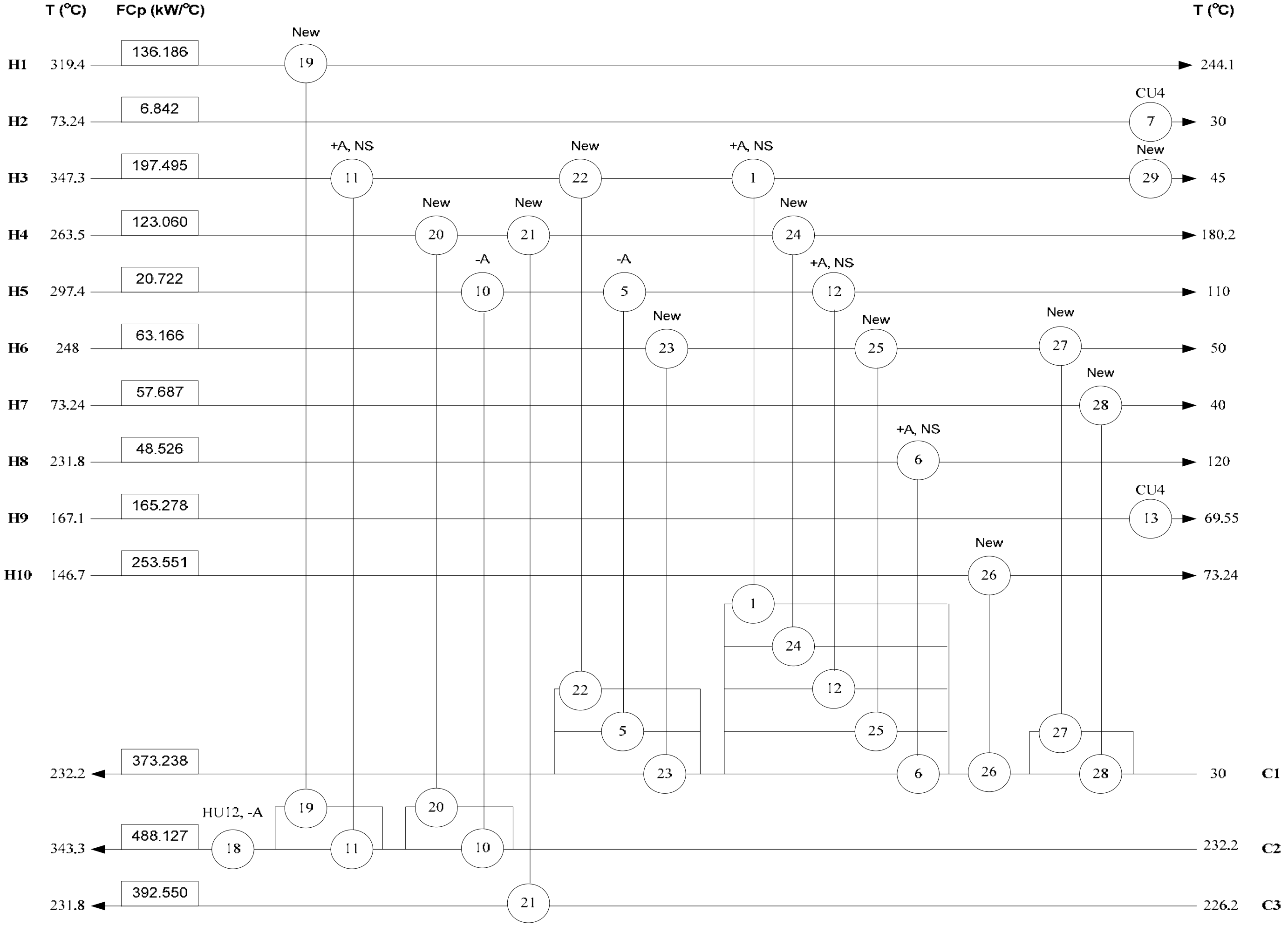
Table 4.14 Physical properties of HEN for original HEN and Process pinch retrofit

	ΔT_{min} (°C)	Network area (m^2)	No. of Exchangers	Hot Utilities (kW)	Cold Utilities (kW)
Original HEN	128.89	8,323.82	18	67,988.25	75,076.08
1st alternative design	13	16,862.44	22	22,312.34	29,400.17
2nd alternative design	13	16,405.63	21	22,312.34	29,400.17
3rd alternative design	13	16,386.54	21	22,312.34	29,400.17
4th alternative design	13	16,708.70	21	22,312.34	29,400.17
5th alternative design	13	15,935.10	20	22,312.34	29,400.17
6th alternative design	13	15,971.78	20	22,312.34	29,400.17
7th alternative design	13	20,195.55	22	22,312.34	29,400.17
8th alternative design	13	19,783.81	21	22,312.34	29,400.17
9th alternative design	13	19,761.73	21	22,312.34	29,400.17

Table 4.15 Cost summary for Example 2 for original HEN and Process pinch retrofit

	Hot Utility Cost ($/yr)	Cold Utility Cost ($/yr)	Total capital investment ($)	Energy saving ($/yr)	Total annualized cost ($/yr)	Net present value (over 5 yrs)	Return on investment (ROI)
Original HEN	1,687,815.36	309,889.80					
1st alternative design	2,942,376.22	197,371.58	5,379,312.39	5,134,471.17	4,558,796.85	14,084,374.09	95.45%
2nd alternative design	2,989,706.92	197,371.58	4,930,728.84	5,087,140.47	4,487,792.35	14,353,537.01	103.17%
3rd alternative design	2,989,706.92	197,371.58	4,890,794.37	5,087,140.47	4,477,257.74	14,393,471.48	104.01%
4th alternative design	2,942,376.22	197,371.58	5,123,316.75	5,134,471.17	4,491,265.85	14,340,369.73	100.22%
5th alternative design	2,989,706.92	197,371.58	4,552,083.36	5,087,140.47	4,387,906.63	14,732,182.50	111.75%
6th alternative design	2,989,706.92	197,371.58	4,533,270.35	5,087,140.47	4,382,943.80	14,750,995.50	112.22%
7th alternative design	2,942,376.22	197,371.58	6,958,725.88	5,134,471.17	4,975,442.15	12,504,960.60	73.79%
8th alternative design	2,989,706.92	197,371.58	6,544,148.49	5,087,140.47	4,913,408.39	12,740,117.36	77.74%
9th alternative design	2,989,706.92	197,371.58	6,502,622.05	5,087,140.47	4,902,453.82	12,781,643.80	78.23%

The following tables represent the cost comparison among 9 alternative designs at ΔT_{min}= 13°C. It is also clear that the 6th alternative design has the highest net present value and return on investment as well as the lowest total annualized. The heat exchanger network retrofit result is illustrated below.


T (°C)
FCp (kW/°C)
T (°C)
H1 319.4 136.186 → 244.1
H2 73.24 6.842 → 30
H3 347.3 197.495 → 45
H4 263.5 123.060 → 180.2
H5 297.4 20.722 → 110
H6 248 63.166 → 50
H7 73.24 57.687 → 40
H8 231.8 48.526 → 120
H9 167.1 165.278 → 69.55
H10 146.7 253.551 → 73.24
C1 232.2 ← 373.238 30
C2 343.3 ← 488.127 232.2
C3 231.8 ← 392.550 226.2
New 19
CU4 7
+A, NS 11
New 22
+A, NS 1
New 29
New 20
New 21
New 24
-A 10
-A 5
+A, NS 12
New 23
New 25
New 27
New 28
+A, NS 6
CU4 13
New 26
1
24
12
22
5
25
27
23
6
26
28
HU12, -A 18
19
11
20
10
21

Notation: New exchanger (New), Area addition (+A); New shell (NS), Area reduction (-A)

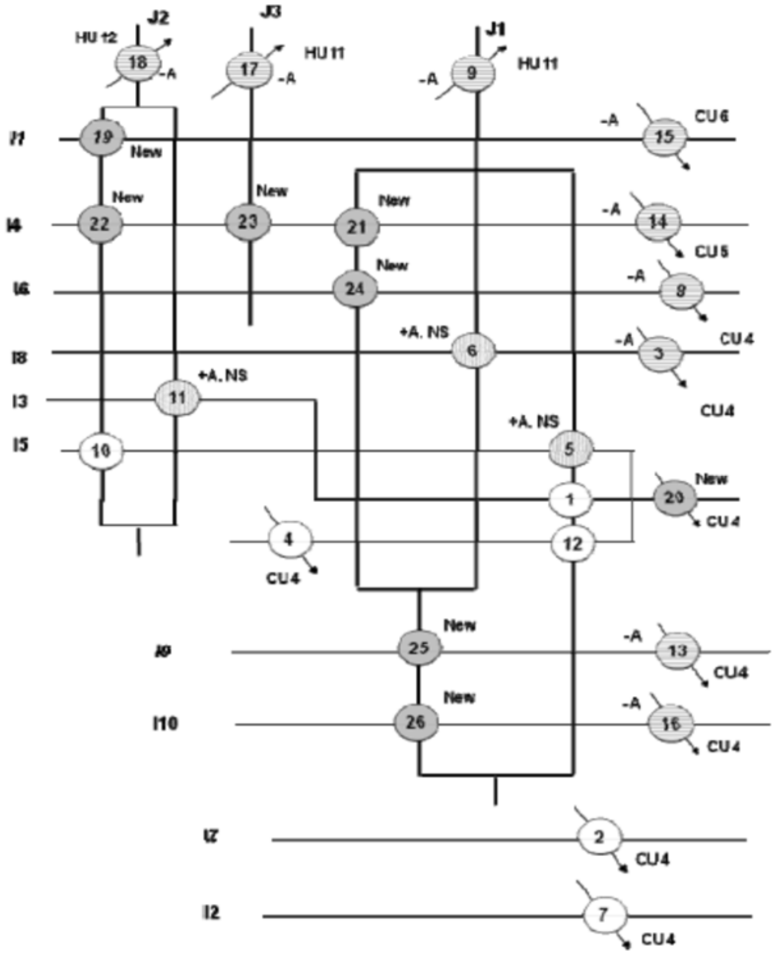
Figure 4.22 Retrofitted heat exchanger results (6th alternative design at ΔT_{min}= 13°C).

Table 4.16 Retrofitted heat exchanger results (6th alternative design at ΔT_{min}= 13°C.)

Heat Exchanger	Original area (m^2)	Load after retrofit (kW)	Retrofit area (m^2)	Area change (m^2)	Remarks
1	4303.20	25371.99	5271.72	968.52	Area addition (new shell)
2	63.80	-	-	-	-
3	33.29	-	-	-	-
4	4.06	-	-	-	-
5	26.79	124.33	24.06	-2.73	Area reduction
6	24.60	5425.19	1004.10	979.50	Area addition (new shell)
7	5.87	295.83	5.87	0.00	-
8	146.59	-	-	-	-
9	1214.40	-	-	-	-
10	80.20	1081.71	70.81	-9.39	Area reduction
11	658.70	19789.94	1987.03	1328.33	Area addition (new shell)
12	40.00	2677.32	479.03	439.03	Area addition (new shell)
13	182.39	16122.86	182.39	0.00	-
14	101.47	-	-	-	-
15	93.87	-	-	-	-
16	288.97	-	-	-	-
17	52.24	-	-	-	-
18	976.40	22312.34	593.70	-382.70	Area reduction
19	-	10254.83	1517.08	-	New exchanger
20	-	792.08	60.77	-	New exchanger
21	-	2198.28	118.48	-	New exchanger
22	-	1559.24	335.08	-	New exchanger
23	-	555.86	97.37	-	New exchanger
24	-	7260.53	456.23	-	New exchanger
25	-	8298.24	1605.07	-	New exchanger
26	-	18625.86	1233.17	-	New exchanger
27	-	3652.71	245.31	-	New exchanger
28	-	1917.53	268.32	-	New exchanger
29	-	12981.48	415.85	-	New exchanger

4.2.1.2 MILP Results

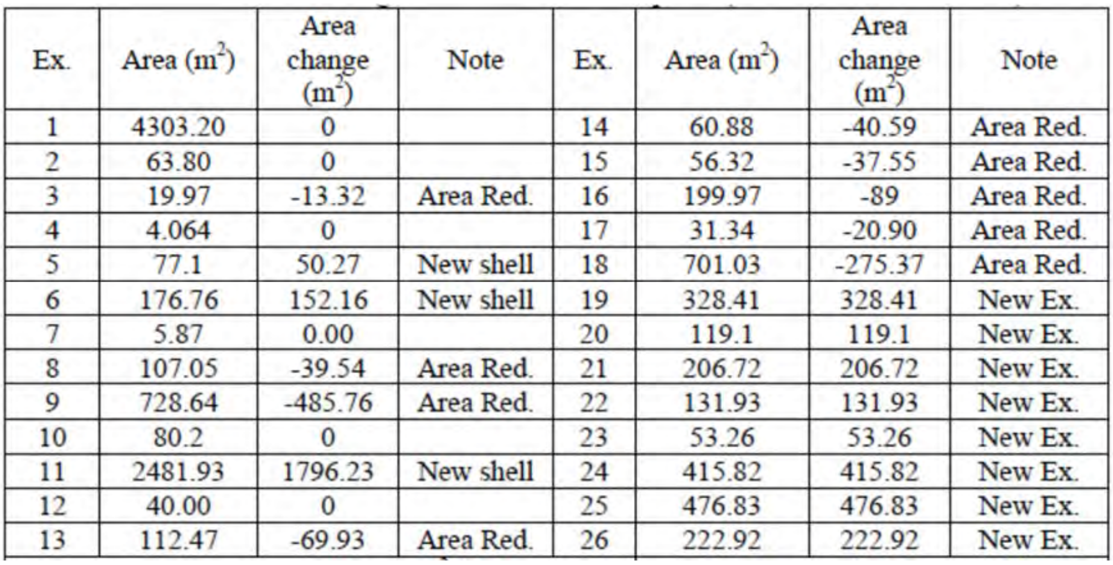
As can be seen in Figure 11 which was stated by Nguyen et al. (2010), splitting is introduced to the two streams J1, J2 and there are eight new exchangers added to the network (exchangers 19 to 26, highlighted by using gray background). Exchangers in the retrofitted network are summarized in Table 7. In addition to eight brand new exchangers, three exchangers are expanded by means of adding new shell: exchangers 5, 6 and 11; the total added area is 3953.65 (m^2). As the result of increased heat recovery; the use of utilities is decreased and all the exchangers involving utilities in the retrofitted network (except exchanger 4) is reduced in area (9 exchangers 3, 8, 9, 13, 14, 15, 16, 17, 18).


J2
J3
J1
HU 12
18
-A
17
-A
HU 11
-A
9
HU 11
I1
19
New
-A
15
CU6
I4
New
22
New
23
21
New
-A
14
CU5
I6
24
New
-A
8
I8
+A. NS
6
-A
3
CU4
I3
11
+A. NS
CU4
I5
10
+A. NS
5
1
20
New
CU4
4
CU4
12
I9
25
New
-A
13
CU4
I10
26
New
-A
16
CU4
I7
2
CU4
I2
7
CU4

Notation: New exchanger (New), Area addition (+A); New shell (NS), Area reduction (-A), New split (NEW SPL)

Figure 4.23 Retrofitted heat exchanger network for Example 2 (Nguyen et al., 2010).

Table 4.17 Retrofitted heat exchanger results for Example 2 (Nguyen et al., 2010)



Ex.	Area (m^2)	Area change (m^2)	Note	Ex.	Area (m^2)	Area change (m^2)	Note
1	4303.20	0		14	60.88	-40.59	Area Red.
2	63.80	0		15	56.32	-37.55	Area Red.
3	19.97	-13.32	Area Red.	16	199.97	-89	Area Red.
4	4.064	0		17	31.34	-20.90	Area Red.
5	77.1	50.27	New shell	18	701.03	-275.37	Area Red.
6	176.76	152.16	New shell	19	328.41	328.41	New Ex.
7	5.87	0.00		20	119.1	119.1	New Ex.
8	107.05	-39.54	Area Red.	21	206.72	206.72	New Ex.
9	728.64	-485.76	Area Red.	22	131.93	131.93	New Ex.
10	80.2	0		23	53.26	53.26	New Ex.
11	2481.93	1796.23	New shell	24	415.82	415.82	New Ex.
12	40.00	0		25	476.83	476.83	New Ex.
13	112.47	-69.93	Area Red.	26	222.92	222.92	New Ex.

4.2.1.3 Cost Comparison

Example 2 represents a relatively larger project; it was also decided to show the data for a project life of 5 years. Each method was applied to the same HEN retrofit problem using the same constraints and cost functions to determine the optimal solution.

Table 4.18 Physical properties of HEN for original HEN, process pinch and MILP

		Retrofitted HEN	
	Original HEN	Process pinch	MILP
ΔT_{min} (°C)	128.89	13	50.09
Network area (m^2)	8,323.82	15,971.78	11,205.53
No. of Exchangers	18	20	26
Hot Utilities (kW)	67,988.25	22,312.34	38,577.14
Cold Utilities (kW)	75,076.08	29,400.17	45,664.97

Table 4.19 Cost summary for Example 2

		Retrofitted HEN	
	Original HEN	Process pinch	MILP
Hot Utility Cost ($/yr)	7,197,511.85	2,989,706.92	4,386,378.00
Cold Utility Cost ($/yr)	1,076,707.12	197,371.58	600,779.40
Total capital investment ($)		4,533,270.35	2,021,622.00
Energy saving ($/yr)		5,087,140.47	3,286,573.00
Total annualized cost ($/yr)		4,382,943.80	5,391,482.00
Net present value (over 5 yrs)		14,750,995.50	10,437,076.14
Return on investment (ROI)		112.22%	162.57%

The following tables represent the cost comparison between the process pinch and the MILP. It is clear that the process pinch method has the highest net present value and lowest total annualized cost. However a small investment of the MILP model gives the highest ROI.

As above result, it is apparent that process pinch design is still a powerful procedure to do HEN retrofit which extremely depends on the selection of the best network from all possibilities. However, the MILP allows the user to quickly and easily change parameters that would allow the evaluation of a numerous scenarios.

CHAPTER V
CONCLUSIONS AND RECOMMENDATIONS

As the results presented for example 1 and 2, it is apparent that HEN retrofit design by pinch is still a powerful procedure to do HEN retrofit based on ease and economic of use, as well as the ability to tailor the program to solve a wide range of retrofit problems which extremely depends on the selection of the best network from all possibilities. Moreover, process pinch incorporated the advanced software optimization capabilities of visual basic for application (VBA)program is available that offers an easy way to change all of the parameters that the MILP can, then the methodology is more user-friendly than before.

Despite the fact that the process pinch design method achieved better results, it also hadseveral drawbacks in the determination of the optimum ΔT_{min} (HRAT) step. Because this value is determined prior to the design of the retrofit process, theentire subsequent methodology relies on the accuracy of the assumption that the optimum value waslegitimate enough to produce the most economical solution. In addition, process pinchdo not explicitly account for the cost of structural changes-implemented in the determination of the optimum ΔT_{min} (HRAT) step. If a different ΔT_{min} value is chosen as theoptimum value, it may have a significant effect on the design of the network. The exchanger matchesabove and below the pinch are directly affected by the location of the pinch. Furthermore, thelikelihood that the global optimum ΔT_{min} value is the same for the final retrofit design and for the designwhere equal exchanger area is assumed is low.Moreover, the likelihood is also low that the global optimum design will have the ΔT_{min} value that pinch technology determines based on equal exchanger areas. The optimization of the retrofittednetwork for pinch technology begins after the “optimum” ΔT_{min} value has already determined. As aresult, the ΔT_{min} is not a part of the optimization process. This is a problem because both exchangerarea and exchanger duty, the two aspects of a heat exchanger network that are important toretrofitting, are directly affected by the ΔT_{min} values.

However, the MILP allows the user to quickly and easily change parameters that would allow the evaluation of a numerous scenarios.In additionthe MILP hadseveral disadvantages compared to the pinch design. First, the MILP requires a background in the basic concepts of mathematical model and then the user need to understand how to apply the concepts to a specific example. Second, the user should understand how to interpret the result from the program which is a complicated process, MILP is not user-friendly.

To conclude, pinch technology no doubt was a pivotal point in heat integration technology andprovided 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.

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Appendix B Manual for grassroots and retrofit potential programs

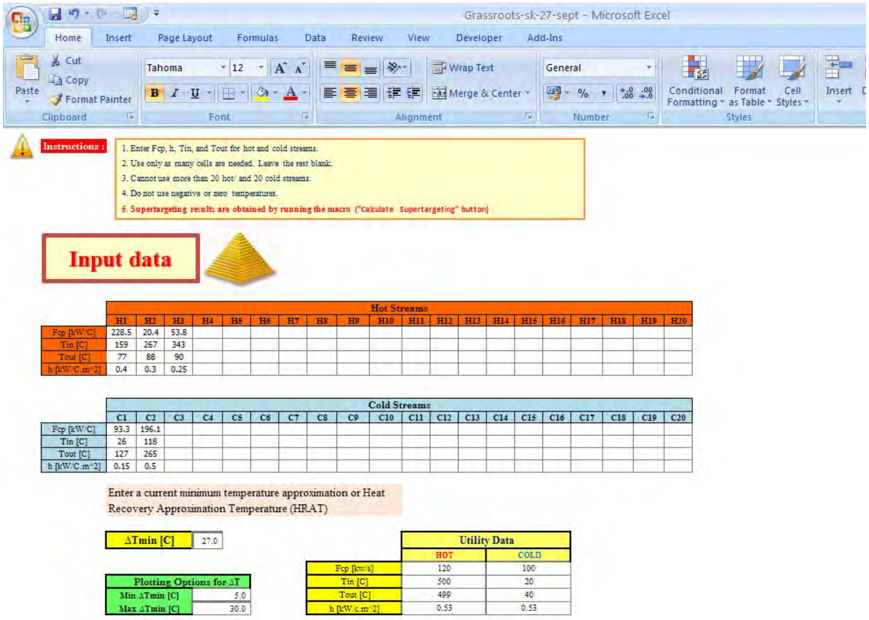
B1 Potential Grassroots Program

B1.1 Background

So far the use of Pinch Analysis has been considered for setting the energy targets for a process. These targets are dependent on the choice of the DT_{min} for the process. Lowering the value of DT_{min} lowers the target for minimum energy consumption for the process.

For certain types of applications such as refinery crude preheat trains, where there are few matching constraints between hot and cold streams; it is possible to set capital cost targets in addition to the energy targets. This allows the consideration of the trade-offs between capital and energy in order to obtain an optimum value of DT_{min} ahead of network design.

B1.2 MS office incorporated with Visual Basic for Application (VBA) Program


Grassroots-sk-27-sept - Microsoft Excel
Home
Insert
Page Layout
Formulas
Data
Review
View
Developer
Add-Ins
Cut
Copy
Paste
Format Painter
Clipboard
Tahoma
12
Font
Wrap Text
Merge & Center
Alignment
General
Number
Conditional Formatting
Format as Table
Cell Styles
Styles
Insert
Input data

Instructions :

1. Enter Fcp, h, Tin, and Tout for hot and cold streams.
2. Use only as many cells are needed. Leave the rest blank.
3. Cannot use more than 20 hot/ and 20 cold streams.
4. Do not use negative or zero temperatures.
5. Supertargeting results are obtained by running the macro ("Calculate Supertargeting" button)

	Hot Streams																			
	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10	H11	H12	H13	H14	H15	H16	H17	H18	H19	H20
Fcp [kW/C]	228.5	20.4	53.8																	
Tin [C]	159	267	343																	
Tout [C]	77	88	90																	
h [kW/C.m^2]	0.4	0.3	0.25																	

	Cold Streams																			
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20
Fcp [kW/C]	93.3	196.1																		
Tin [C]	26	118																		
Tout [C]	127	265																		
h [kW/C.m^2]	0.15	0.5																		

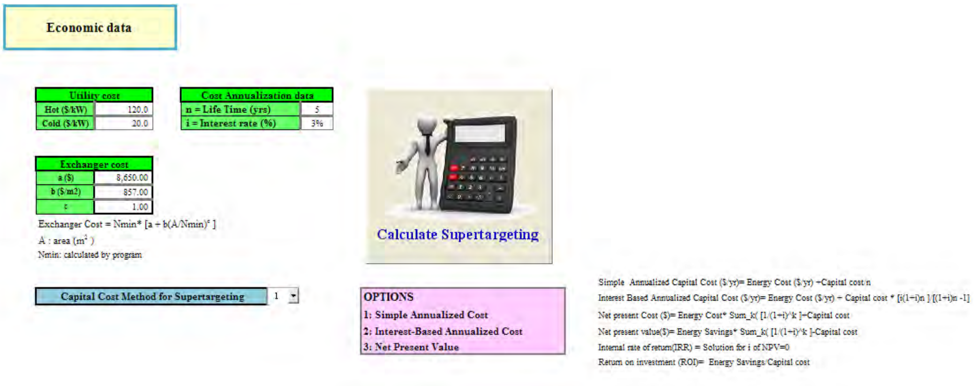
Enter a current minimum temperature approximation or Heat Recovery Approximation Temperature (HRAT)

ΔTmin [C]	27.0

Plotting Options for ΔT	
Min ΔTmin [C]	5.0
Max ΔTmin [C]	30.0

	Utility Data	
	HOT	COLD
Fcp [kw/s]	120	100
Tin [C]	500	20
Tout [C]	499	40
h [kW/c.m^2]	0.53	0.53

Figure B1 MS office Program Feature.



Economic data

Utility cost	
Hot ($/kW)	120.0
Cold ($/kW)	20.0

Cost Annualization data	
n = Life Time (yrs)	5
i = Interest rate (%)	3%

Exchanger cost	
a ($)	8,650.00
b ($/m2)	857.00
c	1.00

Exchanger Cost = Nmin* [a + b(A/Nmin)^c]

A : area (m^2)

Nmin: calculated by program

Capital Cost Method for Supertargeting: 1

OPTIONS
1: Simple Annualized Cost
2: Interest-Based Annualized Cost
3: Net Present Value

Simple Annualized Capital Cost ($/yr)= Energy Cost ($/yr) +Capital cost/n

Interest Based Annualized Capital Cost ($/yr)= Energy Cost ($/yr) + Capital cost * [i(1+i)n]/[(1+i)n -1]

Net present Cost ($)= Energy Cost* Sum_k([1/(1+i)^k]+Capital cost

Net present value($)= Energy Savings* Sum_k([1/(1+i)^k]-Capital cost

Internal rate of return(IRR) = Solution for i of NPV=0

Return on investment (ROI)= Energy Savings/Capital cost

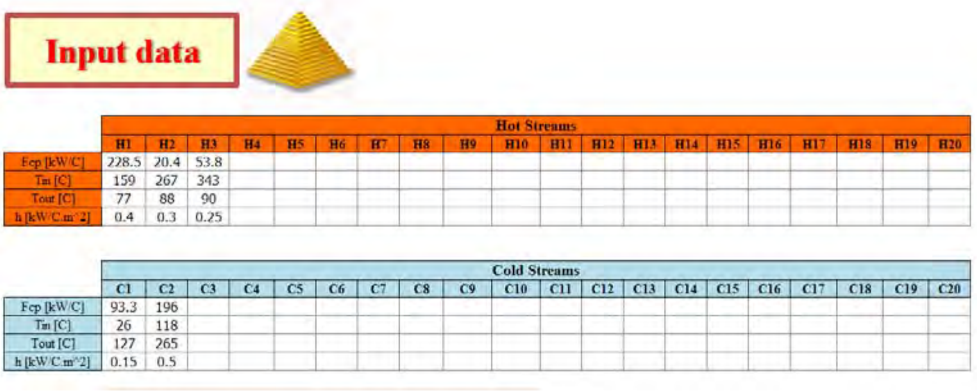
Figure B1 (Cont.) MS office Program Feature.

Warning:

- Enter Fcp, h, Tin, and Tout for hot and cold streams.
- Use only as many cells are needed. Leave the rest blank.
- Cannot use more than 20 hot and 20 cold streams.
- Do not use negative or zero temperatures.
- Supertargeting results are obtained by running the macro ("Calculate Supertargeting" button)

B1.3 Instructions

B1.3.1 Enter Fcp (kW/^{o}C), h (kW/^{o}C.m^2), Tin (^{o}C), and Tout (^{o}C) for hot and cold streams as shown in Figure 2B.



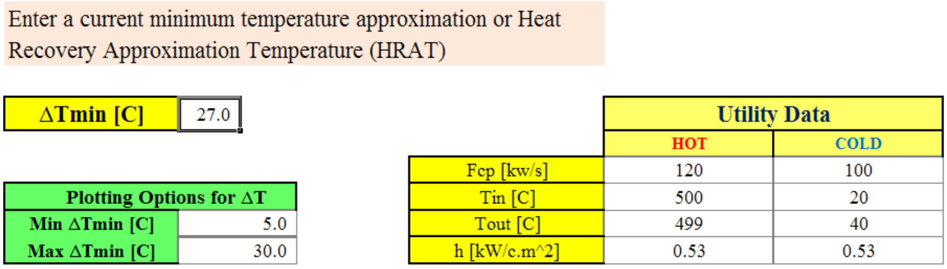
Input data

	Hot Streams																			
	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10	H11	H12	H13	H14	H15	H16	H17	H18	H19	H20
Fcp [kW/C]	228.5	20.4	53.8																	
Tin [C]	159	267	343																	
Tout [C]	77	88	90																	
h [kW/C.m^2]	0.4	0.3	0.25																	

	Cold Streams																			
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20
Fcp [kW/C]	93.3	196																		
Tin [C]	26	118																		
Tout [C]	127	265																		
h [kW/C.m^2]	0.15	0.5																		

Figure B2 Input Fcp, h, Tin, and Tout.

B1.3.2 Enter a current minimum temperature approximation or Heat Recovery Approximation Temperature (HRAT), HRAT region for calculation, and Utility Data as illustrated in Figure 3B.



Enter a current minimum temperature approximation or Heat Recovery Approximation Temperature (HRAT)

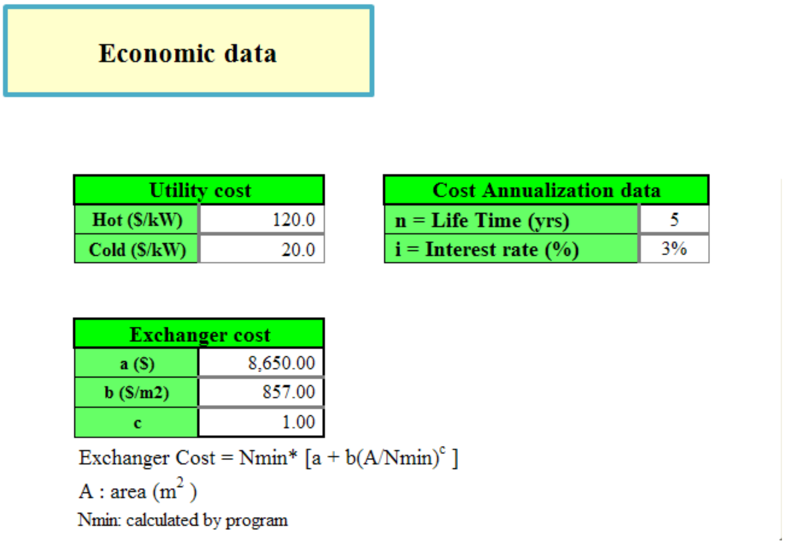
ΔTmin [C]	27.0

Plotting Options for ΔT	
Min ΔTmin [C]	5.0
Max ΔTmin [C]	30.0

	Utility Data	
	HOT	COLD
Fcp [kw/s]	120	100
Tin [C]	500	20
Tout [C]	499	40
h [kW/c.m^2]	0.53	0.53

Figure B3 HRAT, HRAT region for calculation, and Utility Data.

B1.3.3 Enter an Economic Data which consisted of Utility cost, Cost annualized data, and Exchanger cost (Cost law coefficient). As illustrated in Figure 4B.



Economic data

Utility cost	
Hot (\$/kW)	120.0
Cold (\$/kW)	20.0

Cost Annualization data	
n = Life Time (yrs)	5
i = Interest rate (%)	3%

Exchanger cost	
a (\$)	8,650.00
b (\$/m2)	857.00
c	1.00

Exchanger Cost = Nmin* [a + b(A/Nmin)^c]

A : area (m^2)

Nmin: calculated by program

Figure B4 Economic Data.

B1.3.4 Select an option for Capital Cost Method for Supertargeting which are

- Simple Annualized Cost

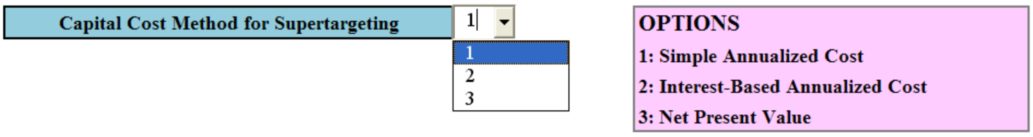
$$SimpleAnnualizedCost = EnergyCost + \frac{CapitalCost}{n}$$

- Interest Base Annualized Cost

$$InterestBaseAnnualizedCost = EnergyCost + CapitalCost \times \frac{i \times (i+i)^n}{(i+1)^n - 1}$$

- Net Present Value

$$NPV = EnergySaving \times \sum_{k=1}^{n} \frac{1}{(1+i)^k} - CapitalCost\ .$$



Capital Cost Method for Supertargeting 1

1
2
3

OPTIONS
1: Simple Annualized Cost
2: Interest-Based Annualized Cost
3: Net Present Value

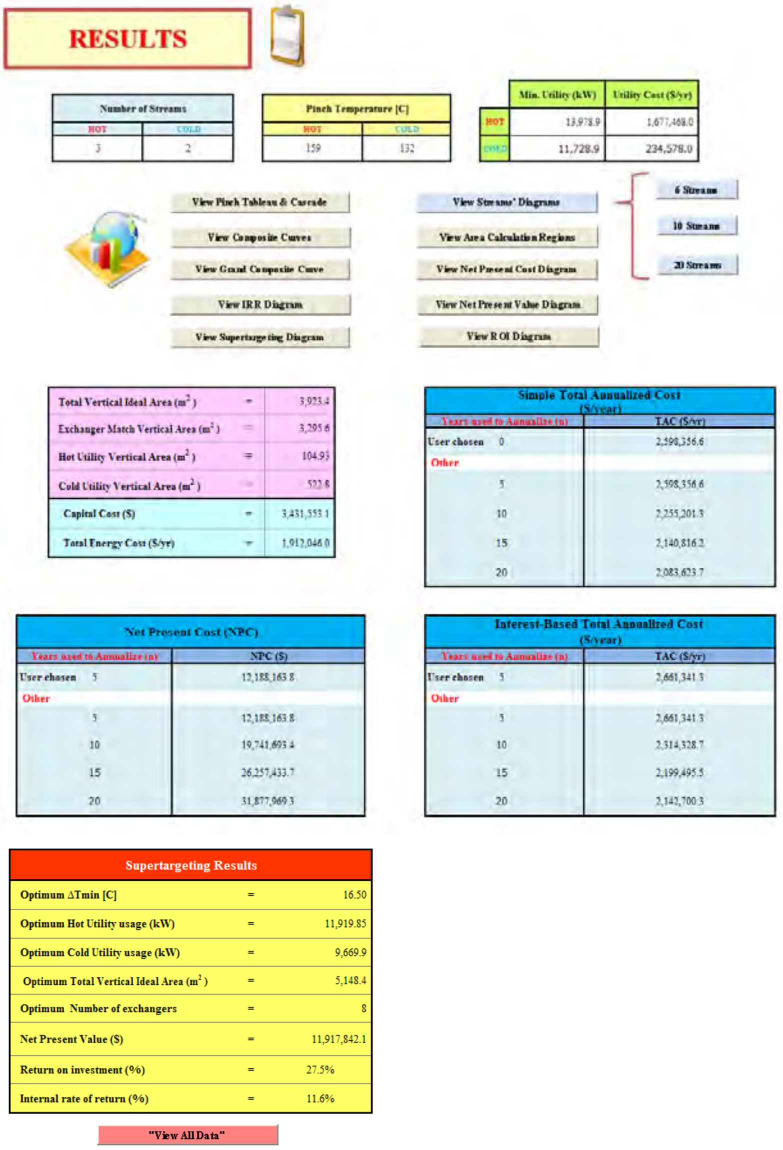
Figure B5 Capital Cost Method for Supertargeting.

B1.3.5 Supertargeting results are obtained by running the macro ("Calculate Supertargeting" button)

Calculate Supertargeting

Figure B6 Calculate Supertargeting Button.

B1.4 Main results: The Program can automatically generate results as shown in Figure 7B.


RESULTS
View Pinch Tableau & Cascade
View Composite Curves
View Grand Composite Curve
View IRR Diagram
View Supertargeting Diagram
View Streams' Diagrams
View Area Calculation Regions
View Net Present Cost Diagram
View Net Present Value Diagram
View R OI Diagram
6 Streams
10 Streams
20 Streams
"View All Data"

Number of Streams	
HOT	COLD
3	2

Pinch Temperature [C]	
HOT	COLD
159	132

	Min. Utility (kW)	Utility Cost ($/yr)
HOT	13,978.9	1,677,468.0
COLD	11,728.9	234,578.0

Total Vertical Ideal Area (m^2)	=	3,923.4
Exchanger Match Vertical Area (m^2)	=	3,295.6
Hot Utility Vertical Area (m^2)	=	104.93
Cold Utility Vertical Area (m^2)	=	522.8
Capital Cost ($)	=	3,431,553.1
Total Energy Cost ($/yr)	=	1,912,046.0

Simple Total Annualized Cost ($/year)		
Years used to Annualize (n)		TAC ($/yr)
User chosen	0	2,598,356.6
Other		
	5	2,598,356.6
	10	2,255,201.3
	15	2,140,816.2
	20	2,083,623.7

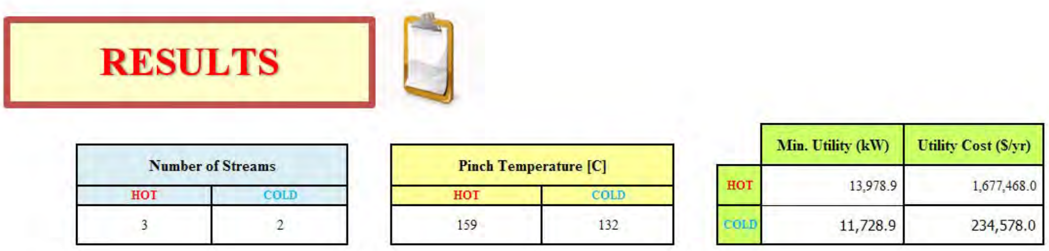
Net Present Cost (NPC)		
Years used to Annualize (n)		NPC ($)
User chosen	5	12,188,163.8
Other		
	5	12,188,163.8
	10	19,741,693.4
	15	26,257,433.7
	20	31,877,969.3

Interest-Based Total Annualized Cost ($/year)		
Years used to Annualize (n)		TAC ($/yr)
User chosen	5	2,661,341.3
Other		
	5	2,661,341.3
	10	2,314,328.7
	15	2,199,495.5
	20	2,142,700.3

Supertargeting Results		
Optimum ΔTmin [C]	=	16.50
Optimum Hot Utility usage (kW)	=	11,919.85
Optimum Cold Utility usage (kW)	=	9,669.9
Optimum Total Vertical Ideal Area (m^2)	=	5,148.4
Optimum Number of exchangers	=	8
Net Present Value ($)	=	11,917,842.1
Return on investment (%)	=	27.5%
Internal rate of return (%)	=	11.6%

Figure B7 Main Results Feature.

B1.5 Number of streams, Pinch temperature, Minimum utility, and Utility cost are shown at the top of result as illustrated in Figure 8B.



Number of Streams	
HOT	COLD
3	2

Pinch Temperature [C]	
HOT	COLD
159	132

	Min. Utility (kW)	Utility Cost ($/yr)
HOT	13,978.9	1,677,468.0
COLD	11,728.9	234,578.0

Figure B8 Number of streams, Pinch temperature, Minimum utility, and Utility cost.

B1.6 There are 13 command buttons; "View Pinch Tableau & Cascade", "View Composite Curves", "View Grand Composite Curve", "Streams' Diagrams", "6 Streams", "10 Streams", "20 Streams", "Area Calculation Regions", "Net Present Cost", "Net Present Value", "Internal rate of return", "Return on investment", and "Supertargeting diagram" which can automatically show those results

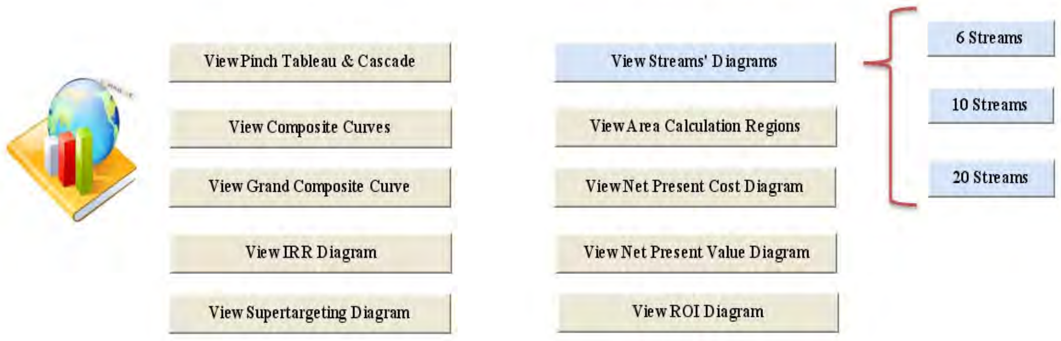
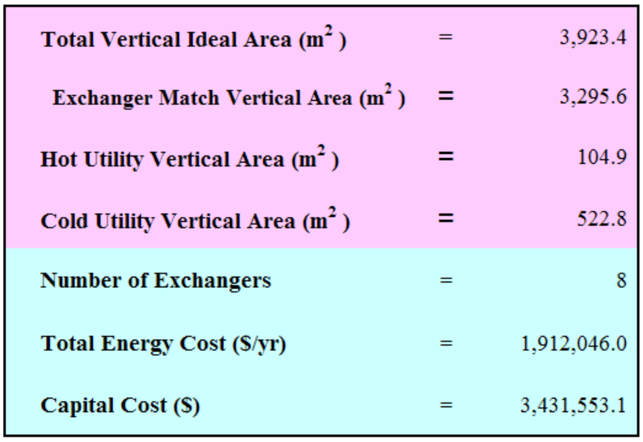

View Pinch Tableau & Cascade
View Composite Curves
View Grand Composite Curve
View IRR Diagram
View Supertargeting Diagram
View Streams' Diagrams
View Area Calculation Regions
View Net Present Cost Diagram
View Net Present Value Diagram
View ROI Diagram
6 Streams
10 Streams
20 Streams

Figure B9 All 13 command buttons.

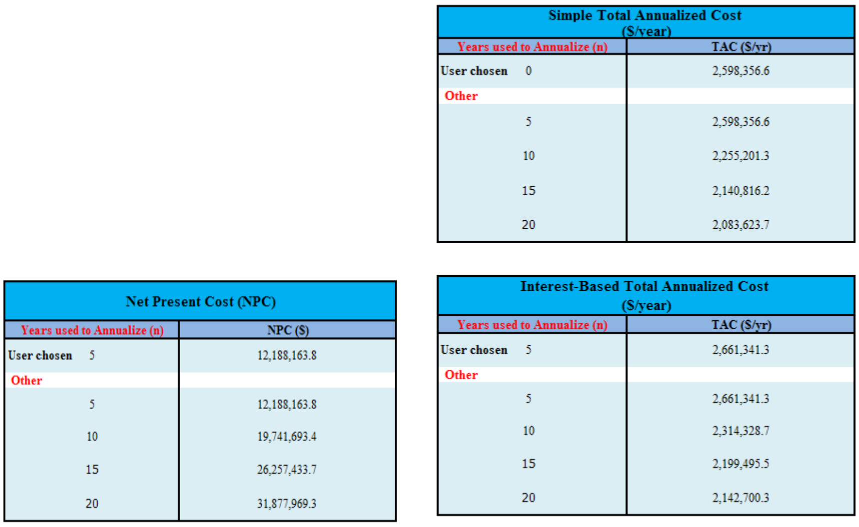
B1.7 Total vertical ideal area, Exchanger match vertical ideal area, Hot utility vertical ideal area, Cold utility vertical ideal area, Number of exchangers, Capital cost, and Energy cost are shown in the table as illustrated in Figure 10B.



Total Vertical Ideal Area (m^2)	=	3,923.4
Exchanger Match Vertical Area (m^2)	=	3,295.6
Hot Utility Vertical Area (m^2)	=	104.9
Cold Utility Vertical Area (m^2)	=	522.8
Number of Exchangers	=	8
Total Energy Cost ($/yr)	=	1,912,046.0
Capital Cost ($)	=	3,431,553.1

Figure B10 Ideal area, Number of exchangers, Energy cost, and Capital cost table.

B1.8 Simple total annualized cost, Interest-based total annualized cost, and Net present cost are shown in the table as shown in Figure 11B.



Simple Total Annualized Cost ($/year)

Years used to Annualize (n)	TAC ($/yr)
User chosen 0	2,598,356.6
Other	
5	2,598,356.6
10	2,255,201.3
15	2,140,816.2
20	2,083,623.7

Net Present Cost (NPC)

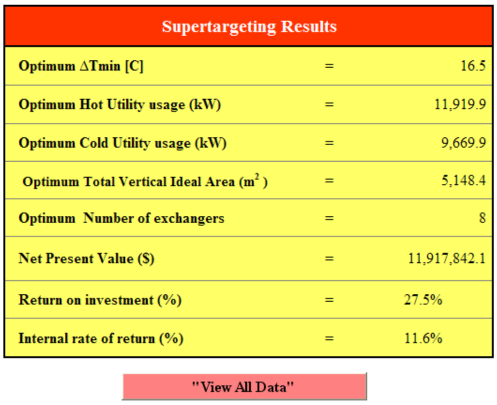
Years used to Annualize (n)	NPC ($)
User chosen 5	12,188,163.8
Other	
5	12,188,163.8
10	19,741,693.4
15	26,257,433.7
20	31,877,969.3

Interest-Based Total Annualized Cost ($/year)

Years used to Annualize (n)	TAC ($/yr)
User chosen 5	2,661,341.3
Other	
5	2,661,341.3
10	2,314,328.7
15	2,199,495.5
20	2,142,700.3

Figure B11 Simple total annualized cost, Interest-based total annualized cost, and Net present cost.

B1.9 Supertargeting results are shown in Figure 12B. View all data command button can automatically show all data in detail.

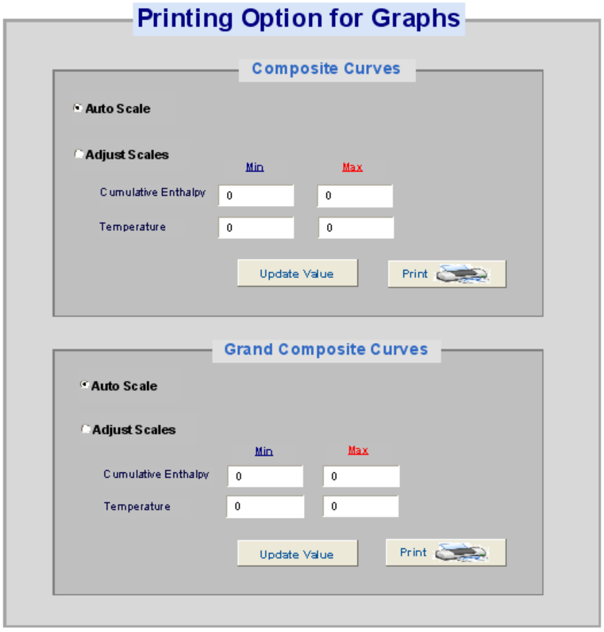


Supertargeting Results		
Optimum ΔTmin [C]	=	16.5
Optimum Hot Utility usage (kW)	=	11,919.9
Optimum Cold Utility usage (kW)	=	9,669.9
Optimum Total Vertical Ideal Area (m^2)	=	5,148.4
Optimum Number of exchangers	=	8
Net Present Value ($)	=	11,917,842.1
Return on investment (%)	=	27.5%
Internal rate of return (%)	=	11.6%

"View All Data"

Figure B12 Supertargeting results and View all data command button.

B1.10 Printing option for Composite curves and Grand composite curve which is used for adjusting an axis scale as illustrated in Figure 13B. There are 2 options auto scale and adjust scale. Push update value button every time after selecting an option and input scale value.



Printing Option for Graphs

Composite Curves

● Auto Scale

○ Adjust Scales

	Min	Max
Cumulative Enthalpy	0	0
Temperature	0	0

Grand Composite Curves

● Auto Scale

○ Adjust Scales

	Min	Max
Cumulative Enthalpy	0	0
Temperature	0	0

Figure B13 Printing option for Composite Curves and Grand Composite Curve.

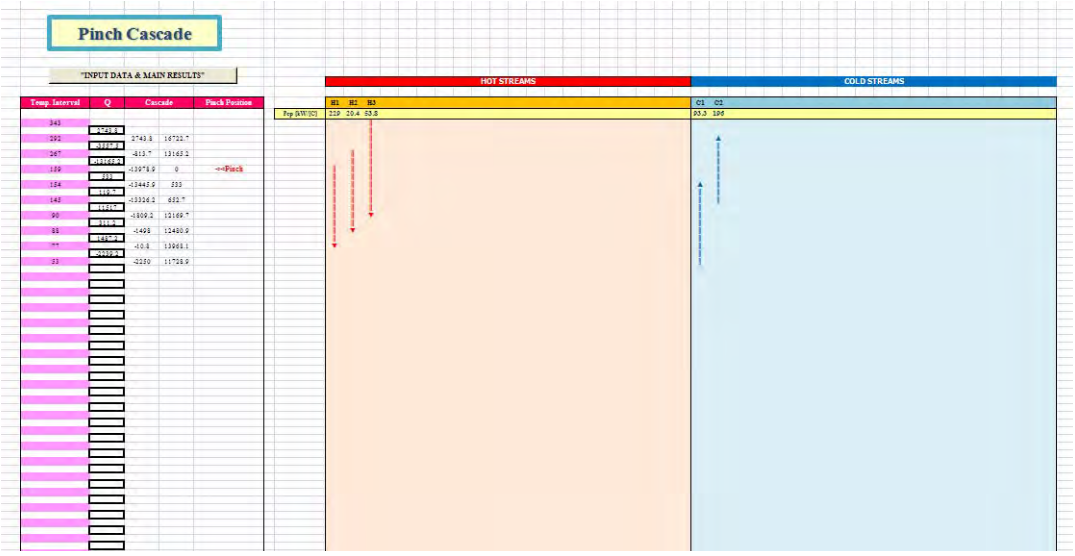
B1.11 Worksheets

B1.11.1 "INPUT DATA & MAIN RESULTS"

Sheet "INPUT DATA & MAIN RESULTS" is consist of 2 parts Input data and results as illustrated in Figure 1B, 7B.

B1.11.2 Tableau & Stream Cascade

Sheet "Tableau & Stream Cascade" shows problem table or pinch cascade and stream plot as shown in Figure 39. Automatically show when push "View Pinch Tableau & Stream Cascade" button in sheet "INPUT DATA & MAIN RESULTS".



Pinch Cascade

"INPUT DATA & MAIN RESULTS"

Temp. Interval	Q	Cascade		Pinch Position
343				
	2743.8			
292		2743.8	16722.7	
	-3557.5			
267		-813.7	13165.2	
	-13165.2			
159		-13978.9	0	<-<Pinch
	533			
154		-13445.9	533	
	119.7			
143		-13326.2	652.7	
	11517			
90		-1809.2	12169.7	
	311.2			
88		-1498	12480.9	
	1487.2			
77		-10.8	13968.1	
	-2239.2			
53		-2250	11728.9	

	HOT STREAMS			COLD STREAMS	
	H1	H2	H3	C1	C2
Fcp (kW/(C)	229	20.4	53.8	93.3	196

Figure B14 Sheet "Tableau & Stream Cascade".

B1.11.3 Composite curves

Sheet "Composite curves" shows composite curves of input stream data which automatically show when push "View Composite Curves" button in sheet "INPUT DATA & MAIN RESULTS".

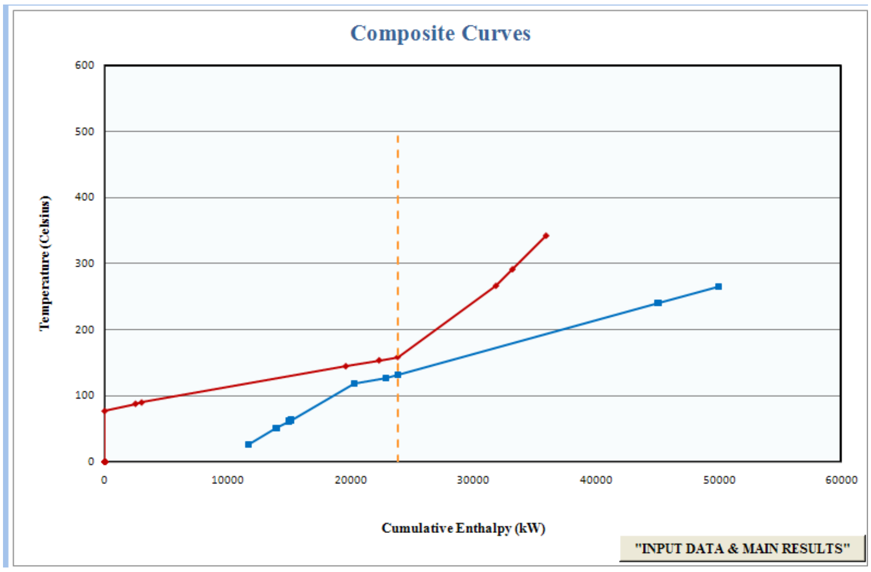


Figure B15 Sheet “Composite Curves”.

B1.11.4 Grand Composite

Sheet “Grand composite” show Grand composite curve of input stream data which automatically show when push “View Grand Composite Curve” button in sheet “INPUT DATA & MAIN RESULTS”.

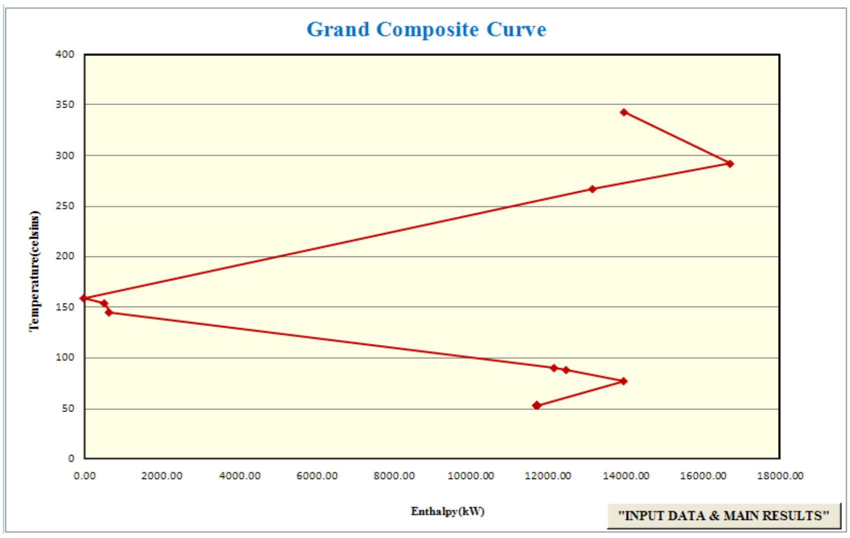


Figure B16 Sheet “Grand Composite”.

B1.11.5 Stream Diagram, 20 Streams, 10 Streams, and 6 Streams

Sheet "Stream Diagram", "20 Streams", "10 Stream", and "6 Steams" show 40 streams' diagram, 20 streams' diagram, 10 streams' diagram, and 6 streams' diagram, respectively of input stream data which automatically show when push "View Streams' Diagram", "20 streams' diagram", "10 streams' diagram", and "6 streams' diagram" button, respectively in sheet "INPUT DATA & MAIN RESULTS".

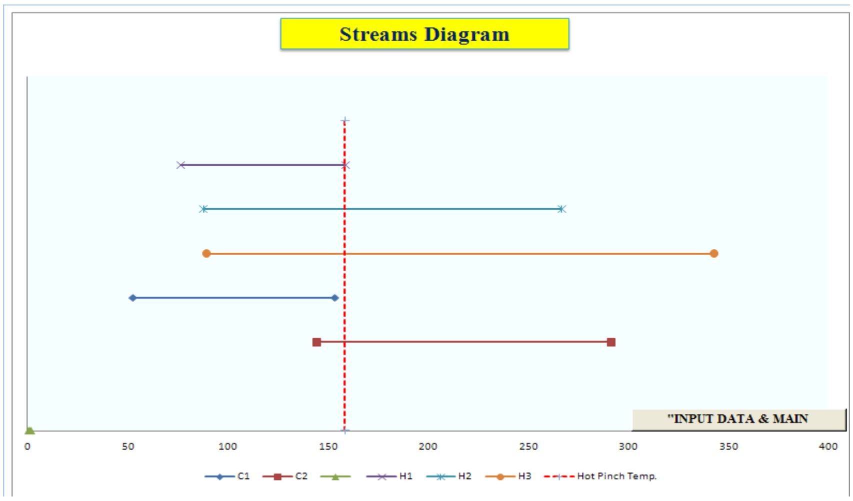

Streams Diagram
"INPUT DATA & MAIN
0
50
100
150
200
250
300
350
400
C1
C2
H1
H2
H3
Hot Pinch Temp.

Figure B17 Sheet "6 Streams".

B1.11.6 Area Calculation Region

Sheet "Area Calculation Region" shows Vertical heat transfer area calculation region of input stream data and utility data which automatically show when push "View Area Calculation Region" button in sheet "INPUT DATA & MAIN RESULTS".

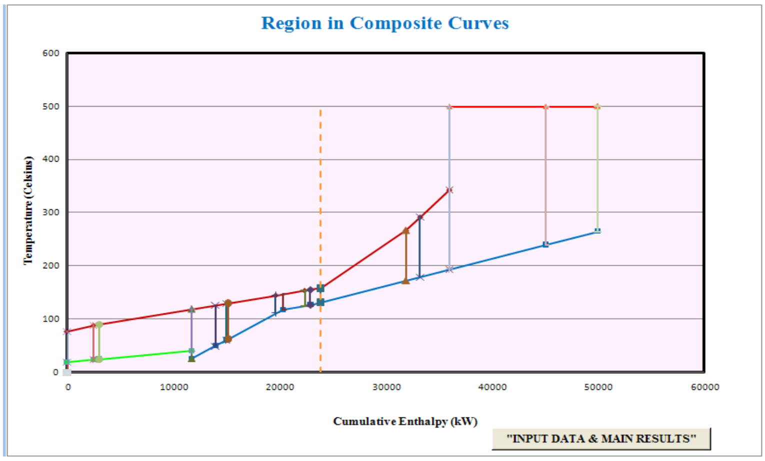


Figure B18 Sheet “Area Calculation Region”.

B1.11.7 Supertargeting

Sheet “Supertargeting” shows Economic Trade-off of selecting option and input stream data which automatically show when push “View Supertargeting Diagram” button in sheet “INPUT DATA & MAIN RESULTS”.

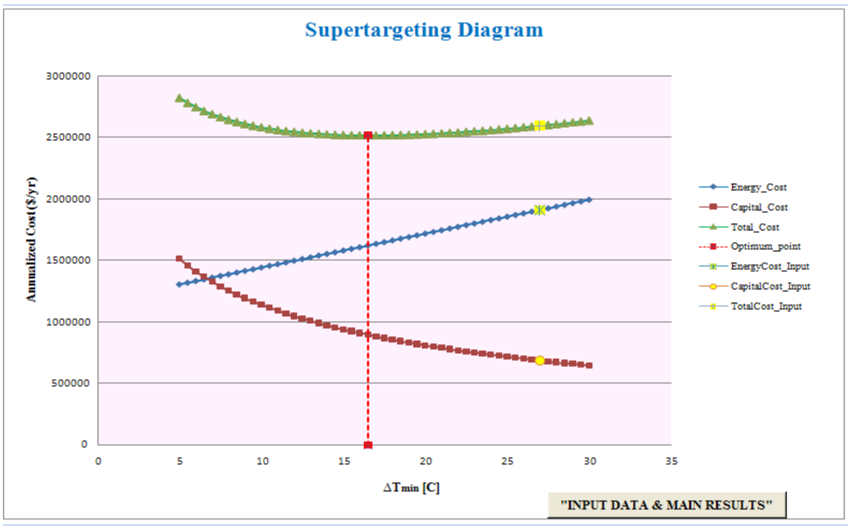


Figure B19 Sheet “Supertargeting”.

B1.11.8 IRR, NPC, NPV, ROI

Sheet “IRR”, “NPC”, “NPV”, and “ROI” show Rate of Return, Net Present Cost, Net Present Value, and Return on investment, respectively which automatically show when push “View IRR Diagram”, “View Net Present Cost”, “View Net Present Value”, and “View ROI Diagram” button, respectively in sheet “INPUT DATA & MAIN RESULTS”.

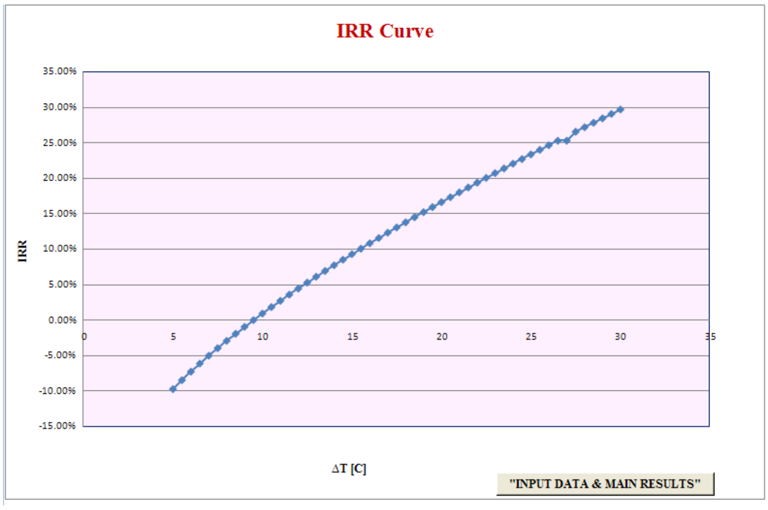


Figure B20 Sheet “IRR”.

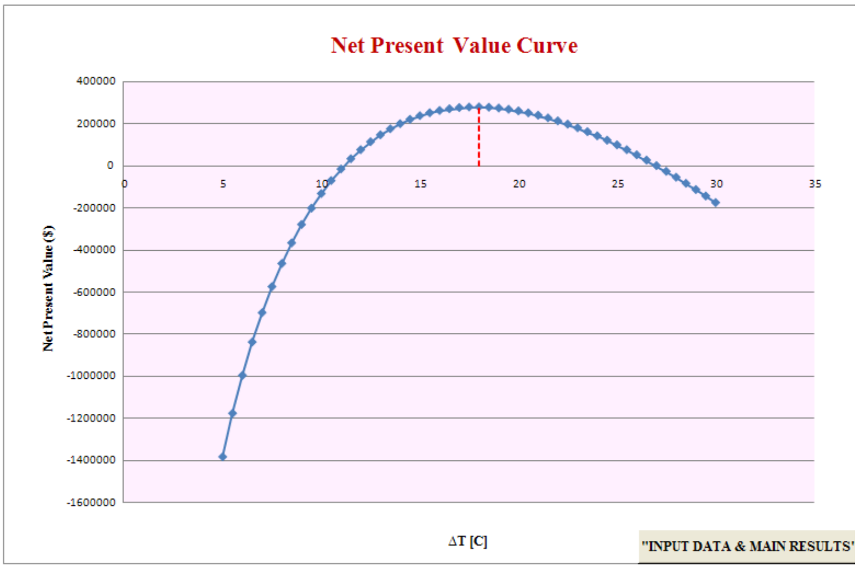


Figure B21 Sheet “NPV”.

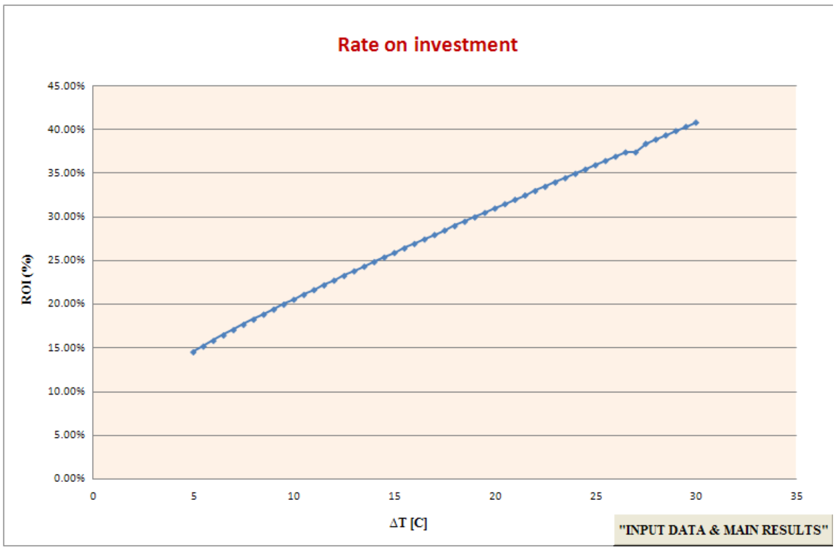


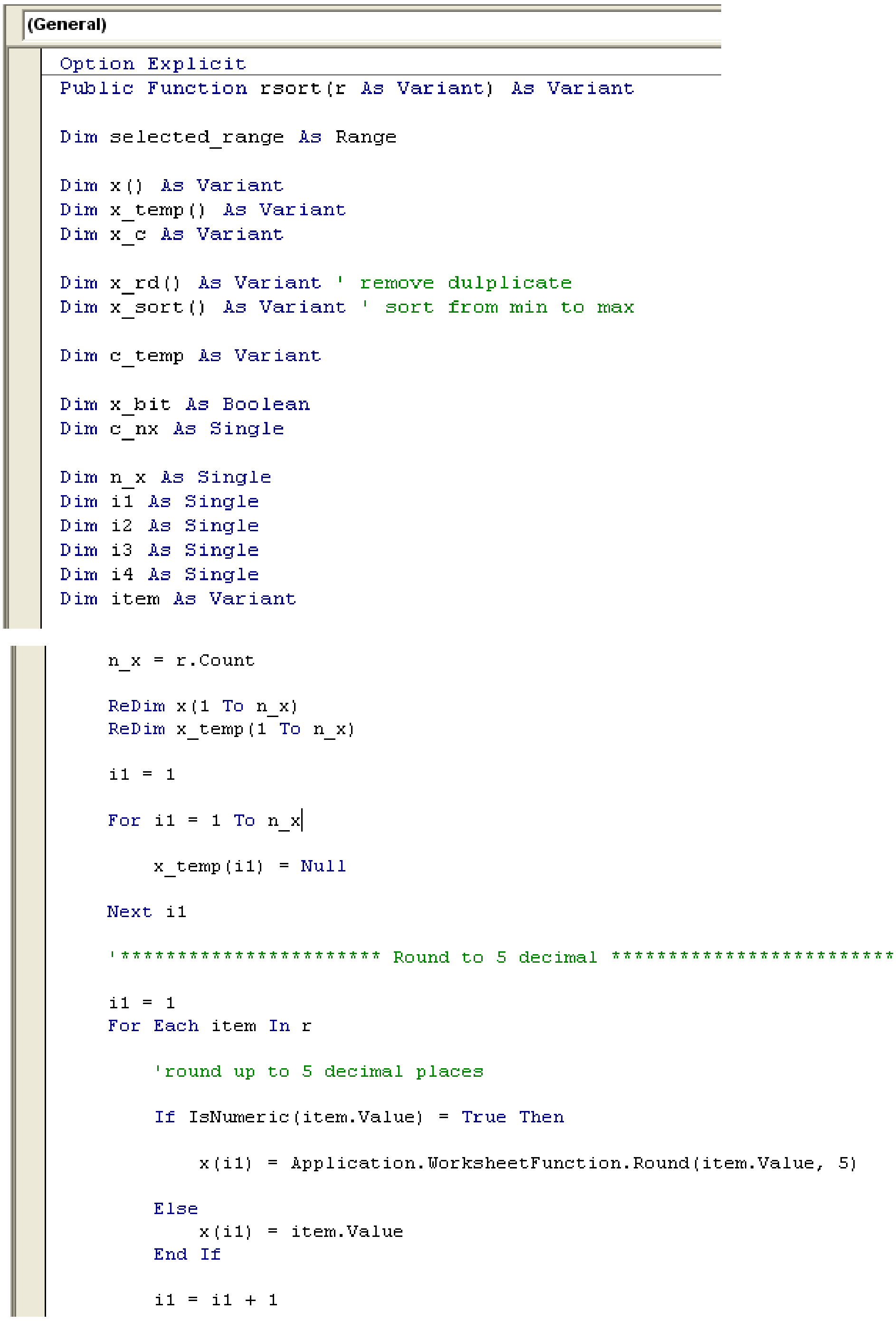
Figure B22 Sheet "ROI".

B1.11.9 Aux-arrange temp, Aux-Cascade, Aux-Graphs, Aux-Aideal, and Supertargeting Calculation

Sheet "Aux-arrange temp", "Aux-Cascade", "Aux-Graphs", "Aux-Aideal", and "Supertargeting Calculation" is an auxiliary sheet which contain formula and functions for evaluation the results.

B1.12 Visual Basic for Application (Source code)

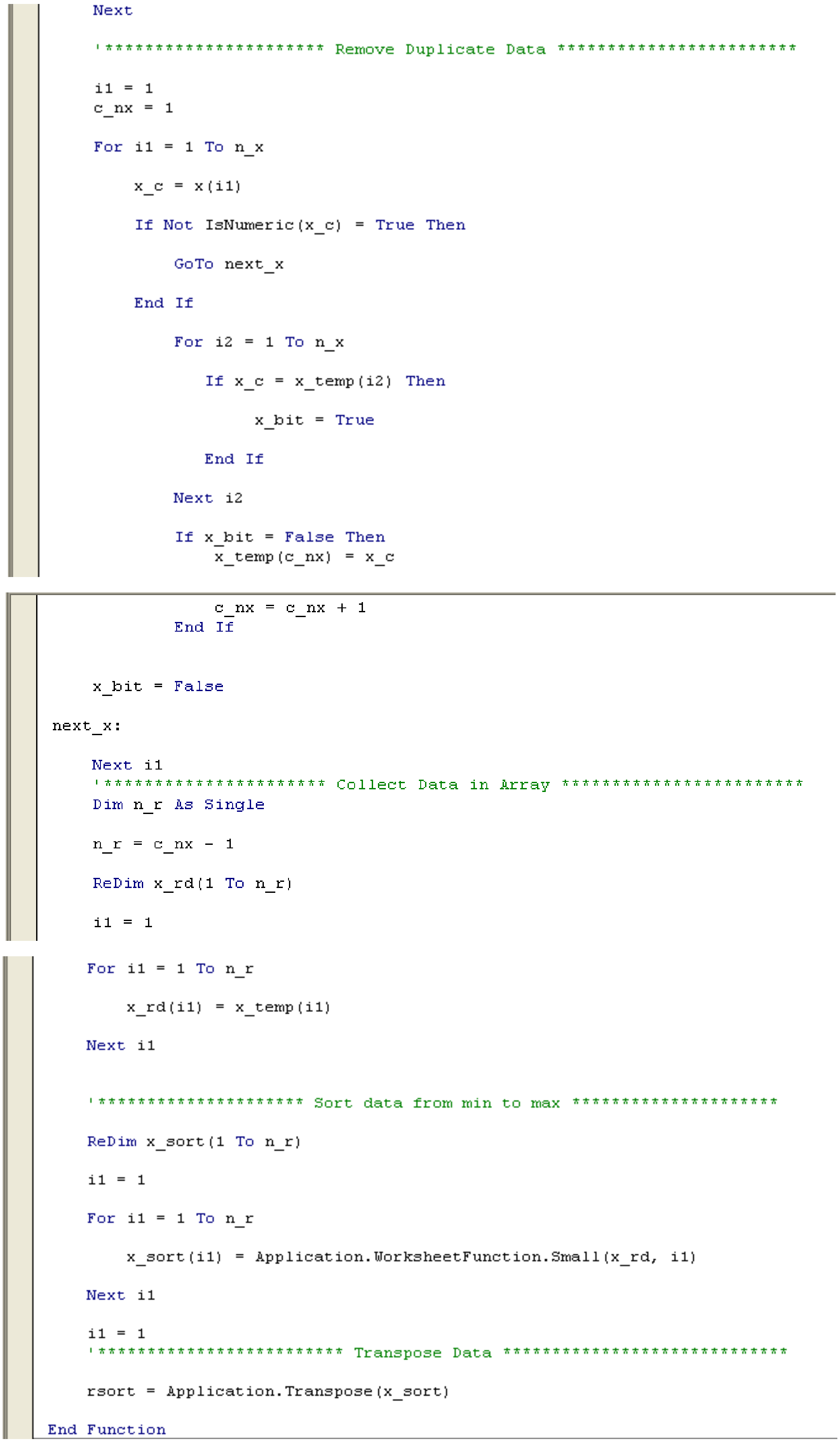
B1.12.1 Sort Data Function (in Module 4)



```
Option Explicit
Public Function rsort(r As Variant) As Variant

Dim selected_range As Range

Dim x() As Variant
Dim x_temp() As Variant
Dim x_c As Variant

Dim x_rd() As Variant ' remove dulplicate
Dim x_sort() As Variant ' sort from min to max

Dim c_temp As Variant

Dim x_bit As Boolean
Dim c_nx As Single

Dim n_x As Single
Dim i1 As Single
Dim i2 As Single
Dim i3 As Single
Dim i4 As Single
Dim item As Variant
```

```
    n_x = r.Count

    ReDim x(1 To n_x)
    ReDim x_temp(1 To n_x)

    i1 = 1

    For i1 = 1 To n_x

        x_temp(i1) = Null

    Next i1

    '*********************** Round to 5 decimal *************************

    i1 = 1
    For Each item In r

        'round up to 5 decimal places

        If IsNumeric(item.Value) = True Then

            x(i1) = Application.WorksheetFunction.Round(item.Value, 5)

        Else
            x(i1) = item.Value
        End If

        i1 = i1 + 1
```

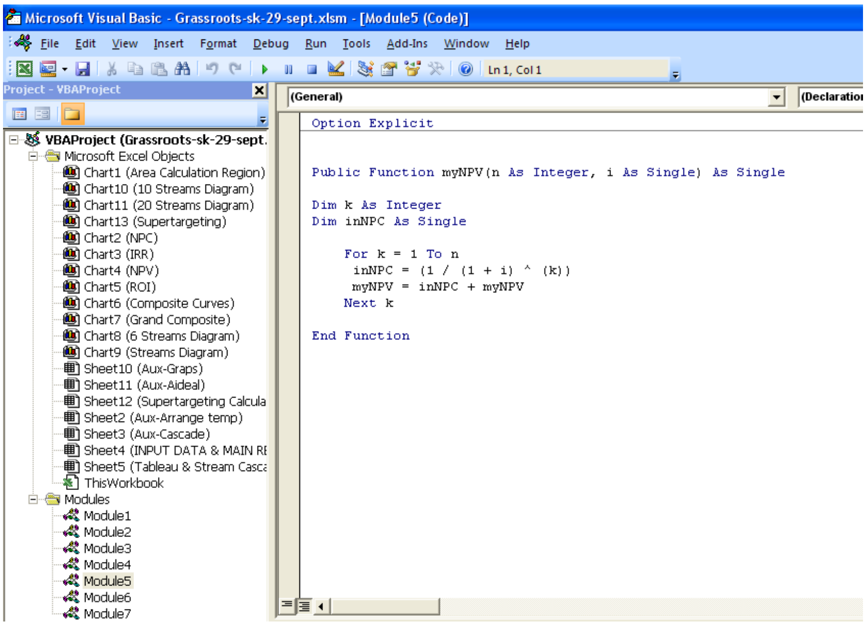
Figure B23 Sort Data Function (in Module 4).



```
    Next

    '********************** Remove Duplicate Data ************************

    i1 = 1
    c_nx = 1

    For i1 = 1 To n_x

        x_c = x(i1)

        If Not IsNumeric(x_c) = True Then

            GoTo next_x

        End If

            For i2 = 1 To n_x

               If x_c = x_temp(i2) Then

                    x_bit = True

               End If

            Next i2

            If x_bit = False Then
                x_temp(c_nx) = x_c
                c_nx = c_nx + 1
            End If


    x_bit = False

next_x:

    Next i1
    '*********************** Collect Data in Array ************************
    Dim n_r As Single

    n_r = c_nx - 1

    ReDim x_rd(1 To n_r)

    i1 = 1

    For i1 = 1 To n_r

        x_rd(i1) = x_temp(i1)

    Next i1


    '********************* Sort data from min to max *********************

    ReDim x_sort(1 To n_r)

    i1 = 1

    For i1 = 1 To n_r

        x_sort(i1) = Application.WorksheetFunction.Small(x_rd, i1)

    Next i1

    i1 = 1
    '************************ Transpose Data ***************************

    rsort = Application.Transpose(x_sort)

End Function
```

Figure B23 (Cont.) Sort Data Function (in Module 4).

B1.12.2 Discount Factor Function (in Module 5)


Microsoft Visual Basic - Grassroots-sk-29-sept.xlsm - [Module5 (Code)]
File Edit View Insert Format Debug Run Tools Add-Ins Window Help
Ln 1, Col 1
Project - VBAProject
(General)
(Declaratio
VBAProject (Grassroots-sk-29-sept.
Microsoft Excel Objects
Chart1 (Area Calculation Region)
Chart10 (10 Streams Diagram)
Chart11 (20 Streams Diagram)
Chart13 (Supertargeting)
Chart2 (NPC)
Chart3 (IRR)
Chart4 (NPV)
Chart5 (ROI)
Chart6 (Composite Curves)
Chart7 (Grand Composite)
Chart8 (6 Streams Diagram)
Chart9 (Streams Diagram)
Sheet10 (Aux-Graps)
Sheet11 (Aux-Aideal)
Sheet12 (Supertargeting Calcula
Sheet2 (Aux-Arrange temp)
Sheet3 (Aux-Cascade)
Sheet4 (INPUT DATA & MAIN RE
Sheet5 (Tableau & Stream Casc
ThisWorkbook
Modules
Module1
Module2
Module3
Module4
Module5
Module6
Module7

```
Option Explicit


Public Function myNPV(n As Integer, i As Single) As Single

Dim k As Integer
Dim inNPC As Single

    For k = 1 To n
     inNPC = (1 / (1 + i) ^ (k))
     myNPV = inNPC + myNPV
    Next k

End Function
```

Figure B24 Discount factor function (in Module 5).

1.12.3B Vary DTmin procedure (in Module 7)

```
Option Explicit
Sub Supertargeting()


'---------- To collect Hot & Cold Utility of base case ----------


    Sheets("Aux-Cascade").Select
    Range("C18").Select
    Selection.Copy


    Sheets("Aux-Aideal").Select
    Range("BR19").Select
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False


    Sheets("Aux-Cascade").Select
    Range("C20").Select
    Application.CutCopyMode = False

    Selection.Copy
    Sheets("Aux-Aideal").Select
    Range("BR20").Select
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False

    Sheets("Aux-Cascade").Select
    Application.CutCopyMode = False

'------------ To collect capitalcost of base case -------------

    Sheets("Aux-Aideal").Select
    Range("BS14").Select
    Selection.Copy
    Range("BS13").Select
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
    Application.CutCopyMode = False



'----------------- To vary delta T 50 times -----------------


'**************************************************************1

    Sheets("INPUT DATA & MAIN RESULTS").Select
    Range("F34").Select
    Selection.Copy

    Range("AH53").Select
    ActiveSheet.Paste
    Application.CutCopyMode = False

    Range("F34").Select
```

```
  ActiveCell.FormulaR1C1 = "=R[-32]C[28]"


  Sheets("Aux-Aideal").Select
  Range("ca15:ct15").Select
  Selection.Copy
  Sheets("Supertargeting Calculations").Select
  Range("C11").Select
  Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False

'************************************************************2

  Sheets("INPUT DATA & MAIN RESULTS").Select
  Range("F34").Select

  ActiveCell.FormulaR1C1 = "=R[-31]C[28]"


  Sheets("Aux-Aideal").Select
  Range("ca15:ct15").Select
  Selection.Copy
  Sheets("Supertargeting Calculations").Select
  Range("C12").Select
  Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False

'************************************************************3

  Sheets("INPUT DATA & MAIN RESULTS").Select
  Range("F34").Select

  ActiveCell.FormulaR1C1 = "=R[-30]C[28]"


  Sheets("Aux-Aideal").Select
  Range("ca15:ct15").Select
  Selection.Copy
```

```
Sheets("Supertargeting Calculations").Select
Range("C13").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False

'************************************************************4

Sheets("INPUT DATA & MAIN RESULTS").Select
Range("F34").Select

ActiveCell.FormulaR1C1 = "=R[-29]C[28]"



Sheets("Aux-Aideal").Select
Range("ca15:ct15").Select
Selection.Copy
Sheets("Supertargeting Calculations").Select
Range("C14").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False

'************************************************************5

Sheets("INPUT DATA & MAIN RESULTS").Select
Range("F34").Select

ActiveCell.FormulaR1C1 = "=R[-28]C[28]"



Sheets("Aux-Aideal").Select
Range("ca15:ct15").Select
Selection.Copy
Sheets("Supertargeting Calculations").Select
Range("C15").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False

'************************************************************6
```

```
Sheets("INPUT DATA & MAIN RESULTS").Select
Range("F34").Select

ActiveCell.FormulaR1C1 = "=R[-27]C[28]"



Sheets("Aux-Aideal").Select
Range("ca15:ct15").Select
Selection.Copy
Sheets("Supertargeting Calculations").Select
Range("C16").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False

'**************************************************************************7

Sheets("INPUT DATA & MAIN RESULTS").Select
Range("F34").Select

ActiveCell.FormulaR1C1 = "=R[-26]C[28]"



Sheets("Aux-Aideal").Select
Range("ca15:ct15").Select
Selection.Copy
Sheets("Supertargeting Calculations").Select
Range("C17").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False

'**************************************************************************8

Sheets("INPUT DATA & MAIN RESULTS").Select
Range("F34").Select

ActiveCell.FormulaR1C1 = "=R[-25]C[28]"
```

```
Sheets("Aux-Aideal").Select
Range("ca15:ct15").Select
Selection.Copy
Sheets("Supertargeting Calculations").Select
Range("C18").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False

'************************************************************9

Sheets("INPUT DATA & MAIN RESULTS").Select
Range("F34").Select

ActiveCell.FormulaR1C1 = "=R[-24]C[28]"


Sheets("Aux-Aideal").Select
Range("ca15:ct15").Select
Selection.Copy
Sheets("Supertargeting Calculations").Select
Range("C19").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False

'***********************************************************10

Sheets("INPUT DATA & MAIN RESULTS").Select
Range("F34").Select

ActiveCell.FormulaR1C1 = "=R[-23]C[28]"


Sheets("Aux-Aideal").Select
Range("ca15:ct15").Select
Selection.Copy
Sheets("Supertargeting Calculations").Select
Range("C20").Select
```

```
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False

'************************************************************11

Sheets("INPUT DATA & MAIN RESULTS").Select
Range("F34").Select

ActiveCell.FormulaR1C1 = "=R[-22]C[28]"


Sheets("Aux-Aideal").Select
Range("ca15:ct15").Select
Selection.Copy
Sheets("Supertargeting Calculations").Select
Range("C21").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False

'************************************************************12

Sheets("INPUT DATA & MAIN RESULTS").Select
Range("F34").Select

ActiveCell.FormulaR1C1 = "=R[-21]C[28]"


Sheets("Aux-Aideal").Select
Range("ca15:ct15").Select
Selection.Copy
Sheets("Supertargeting Calculations").Select
Range("C22").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False
```

```
'***********************************************************13

  Sheets("INPUT DATA & MAIN RESULTS").Select
  Range("F34").Select

  ActiveCell.FormulaR1C1 = "=R[-20]C[28]"



  Sheets("Aux-Aideal").Select
  Range("ca15:ct15").Select
  Selection.Copy
  Sheets("Supertargeting Calculations").Select
  Range("C23").Select
  Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
     :=False, Transpose:=False


  '***********************************************************14

  Sheets("INPUT DATA & MAIN RESULTS").Select
  Range("F34").Select

  ActiveCell.FormulaR1C1 = "=R[-19]C[28]"



  Sheets("Aux-Aideal").Select
  Range("ca15:ct15").Select
  Selection.Copy
  Sheets("Supertargeting Calculations").Select
  Range("C24").Select
  Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
     :=False, Transpose:=False


  '***********************************************************15

  Sheets("INPUT DATA & MAIN RESULTS").Select
```

```
Range("F34").Select

ActiveCell.FormulaR1C1 = "=R[-18]C[28]"


Sheets("Aux-Aideal").Select
Range("ca15:ct15").Select
Selection.Copy
Sheets("Supertargeting Calculations").Select
Range("C25").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False


'***********************************************************16

Sheets("INPUT DATA & MAIN RESULTS").Select
Range("F34").Select

ActiveCell.FormulaR1C1 = "=R[-17]C[28]"


Sheets("Aux-Aideal").Select
Range("ca15:ct15").Select
Selection.Copy
Sheets("Supertargeting Calculations").Select
Range("C26").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False


'***********************************************************17

Sheets("INPUT DATA & MAIN RESULTS").Select
Range("F34").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[28]"
```

```
Sheets("Aux-Aideal").Select
Range("ca15:ct15").Select
Selection.Copy
Sheets("Supertargeting Calculations").Select
Range("C27").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False


'************************************************************18

Sheets("INPUT DATA & MAIN RESULTS").Select
Range("F34").Select

ActiveCell.FormulaR1C1 = "=R[-15]C[28]"


Sheets("Aux-Aideal").Select
Range("ca15:ct15").Select
Selection.Copy
Sheets("Supertargeting Calculations").Select
Range("C28").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False


'************************************************************19

Sheets("INPUT DATA & MAIN RESULTS").Select
Range("F34").Select

ActiveCell.FormulaR1C1 = "=R[-14]C[28]"


Sheets("Aux-Aideal").Select
Range("ca15:ct15").Select
Selection.Copy
```

```
Sheets("Supertargeting Calculations").Select
Range("C29").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False





'******************************************************************20

Sheets("INPUT DATA & MAIN RESULTS").Select
Range("F34").Select

ActiveCell.FormulaR1C1 = "=R[-13]C[28]"



Sheets("Aux-Aideal").Select
Range("ca15:ct15").Select
Selection.Copy
Sheets("Supertargeting Calculations").Select
Range("C30").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False


'******************************************************************21

Sheets("INPUT DATA & MAIN RESULTS").Select
Range("F34").Select

ActiveCell.FormulaR1C1 = "=R[-12]C[28]"



Sheets("Aux-Aideal").Select
Range("ca15:ct15").Select
Selection.Copy
Sheets("Supertargeting Calculations").Select
```

```
Range("C31").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False


'**************************************************************22

Sheets("INPUT DATA & MAIN RESULTS").Select
Range("F34").Select

ActiveCell.FormulaR1C1 = "=R[-11]C[28]"



Sheets("Aux-Aideal").Select
Range("ca15:ct15").Select
Selection.Copy
Sheets("Supertargeting Calculations").Select
Range("C32").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False



'**************************************************************23

Sheets("INPUT DATA & MAIN RESULTS").Select
Range("F34").Select

ActiveCell.FormulaR1C1 = "=R[-10]C[28]"



Sheets("Aux-Aideal").Select
Range("ca15:ct15").Select
Selection.Copy
Sheets("Supertargeting Calculations").Select
Range("C33").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False
```

```
'************************************************************24

Sheets("INPUT DATA & MAIN RESULTS").Select
Range("F34").Select

ActiveCell.FormulaR1C1 = "=R[-9]C[28]"


Sheets("Aux-Aideal").Select
Range("ca15:ct15").Select
Selection.Copy
Sheets("Supertargeting Calculations").Select
Range("C34").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
   :=False, Transpose:=False


'************************************************************25

Sheets("INPUT DATA & MAIN RESULTS").Select
Range("F34").Select

ActiveCell.FormulaR1C1 = "=R[-8]C[28]"


Sheets("Aux-Aideal").Select
Range("ca15:ct15").Select
Selection.Copy
Sheets("Supertargeting Calculations").Select
Range("C35").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
   :=False, Transpose:=False


'************************************************************26

Sheets("INPUT DATA & MAIN RESULTS").Select
```

```
  Range("F34").Select

  ActiveCell.FormulaR1C1 = "=R[-7]C[28]"


  Sheets("Aux-Aideal").Select
  Range("ca15:ct15").Select
  Selection.Copy
  Sheets("Supertargeting Calculations").Select
  Range("C36").Select
  Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False




'**********************************************************27

  Sheets("INPUT DATA & MAIN RESULTS").Select
  Range("F34").Select

  ActiveCell.FormulaR1C1 = "=R[-6]C[28]"


  Sheets("Aux-Aideal").Select
  Range("ca15:ct15").Select
  Selection.Copy
  Sheets("Supertargeting Calculations").Select
  Range("C37").Select
  Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False


  '**********************************************************28

  Sheets("INPUT DATA & MAIN RESULTS").Select
  Range("F34").Select
```

```
ActiveCell.FormulaR1C1 = "=R[-5]C[28]"


Sheets("Aux-Aideal").Select
Range("ca15:ct15").Select
Selection.Copy
Sheets("Supertargeting Calculations").Select
Range("C38").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False


'******************************************************************29

Sheets("INPUT DATA & MAIN RESULTS").Select
Range("F34").Select

ActiveCell.FormulaR1C1 = "=R[-4]C[28]"


Sheets("Aux-Aideal").Select
Range("ca15:ct15").Select
Selection.Copy
Sheets("Supertargeting Calculations").Select
Range("C39").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False


'******************************************************************30

Sheets("INPUT DATA & MAIN RESULTS").Select
Range("F34").Select

ActiveCell.FormulaR1C1 = "=R[-3]C[28]"


Sheets("Aux-Aideal").Select
```

```
Range("ca15:ct15").Select
Selection.Copy
Sheets("Supertargeting Calculations").Select
Range("C40").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False


'************************************************************31

Sheets("INPUT DATA & MAIN RESULTS").Select
Range("F34").Select

ActiveCell.FormulaR1C1 = "=R[-2]C[28]"


Sheets("Aux-Aideal").Select
Range("ca15:ct15").Select
Selection.Copy
Sheets("Supertargeting Calculations").Select
Range("C41").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False


'************************************************************32

Sheets("INPUT DATA & MAIN RESULTS").Select
Range("F34").Select

ActiveCell.FormulaR1C1 = "=R[-1]C[28]"


Sheets("Aux-Aideal").Select
Range("ca15:ct15").Select
Selection.Copy
Sheets("Supertargeting Calculations").Select
Range("C42").Select
```

```
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False


'***********************************************************33

Sheets("INPUT DATA & MAIN RESULTS").Select
Range("F34").Select

ActiveCell.FormulaR1C1 = "=R[0]C[28]"



Sheets("Aux-Aideal").Select
Range("ca15:ct15").Select
Selection.Copy
Sheets("Supertargeting Calculations").Select
Range("C43").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False


'***********************************************************34

Sheets("INPUT DATA & MAIN RESULTS").Select
Range("F34").Select

ActiveCell.FormulaR1C1 = "=R[1]C[28]"



Sheets("Aux-Aideal").Select
Range("ca15:ct15").Select
Selection.Copy
Sheets("Supertargeting Calculations").Select
Range("C44").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False
```

```
'****************************************************************35

Sheets("INPUT DATA & MAIN RESULTS").Select
Range("F34").Select

ActiveCell.FormulaR1C1 = "=R[2]C[28]"



Sheets("Aux-Aideal").Select
Range("ca15:ct15").Select
Selection.Copy
Sheets("Supertargeting Calculations").Select
Range("C45").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False


'****************************************************************36

Sheets("INPUT DATA & MAIN RESULTS").Select
Range("F34").Select

ActiveCell.FormulaR1C1 = "=R[3]C[28]"



Sheets("Aux-Aideal").Select
Range("ca15:ct15").Select
Selection.Copy
Sheets("Supertargeting Calculations").Select
Range("C46").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False


'****************************************************************37

Sheets("INPUT DATA & MAIN RESULTS").Select
Range("F34").Select
```

```
ActiveCell.FormulaR1C1 = "=R[4]C[28]"


Sheets("Aux-Aideal").Select
Range("ca15:ct15").Select
Selection.Copy
Sheets("Supertargeting Calculations").Select
Range("C47").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False


'*************************************************************38

Sheets("INPUT DATA & MAIN RESULTS").Select
Range("F34").Select

ActiveCell.FormulaR1C1 = "=R[5]C[28]"


Sheets("Aux-Aideal").Select
Range("ca15:ct15").Select
Selection.Copy
Sheets("Supertargeting Calculations").Select
Range("C48").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False


'*************************************************************39

Sheets("INPUT DATA & MAIN RESULTS").Select
Range("F34").Select

ActiveCell.FormulaR1C1 = "=R[6]C[28]"
```

```
Sheets("Aux-Aideal").Select
Range("ca15:ct15").Select
Selection.Copy
Sheets("Supertargeting Calculations").Select
Range("C49").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False


'**************************************************************40

Sheets("INPUT DATA & MAIN RESULTS").Select
Range("F34").Select

ActiveCell.FormulaR1C1 = "=R[7]C[28]"


Sheets("Aux-Aideal").Select
Range("ca15:ct15").Select
Selection.Copy
Sheets("Supertargeting Calculations").Select
Range("C50").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False


'**************************************************************41

Sheets("INPUT DATA & MAIN RESULTS").Select
Range("F34").Select

ActiveCell.FormulaR1C1 = "=R[8]C[28]"


Sheets("Aux-Aideal").Select
Range("ca15:ct15").Select
Selection.Copy
Sheets("Supertargeting Calculations").Select
```

```
    Range("C51").Select
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False


    '***************************************************42

    Sheets("INPUT DATA & MAIN RESULTS").Select
    Range("F34").Select

    ActiveCell.FormulaR1C1 = "=R[9]C[28]"


    Sheets("Aux-Aideal").Select
    Range("ca15:ct15").Select
    Selection.Copy
    Sheets("Supertargeting Calculations").Select
    Range("C52").Select
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False



'***************************************************43

    Sheets("INPUT DATA & MAIN RESULTS").Select
    Range("F34").Select

    ActiveCell.FormulaR1C1 = "=R[10]C[28]"


    Sheets("Aux-Aideal").Select
    Range("ca15:ct15").Select
    Selection.Copy
    Sheets("Supertargeting Calculations").Select
    Range("C53").Select
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False


'************************************************************44

Sheets("INPUT DATA & MAIN RESULTS").Select
Range("F34").Select

ActiveCell.FormulaR1C1 = "=R[11]C[28]"



Sheets("Aux-Aideal").Select
Range("ca15:ct15").Select
Selection.Copy
Sheets("Supertargeting Calculations").Select
Range("C54").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False


'************************************************************45

Sheets("INPUT DATA & MAIN RESULTS").Select
Range("F34").Select

ActiveCell.FormulaR1C1 = "=R[12]C[28]"



Sheets("Aux-Aideal").Select
Range("ca15:ct15").Select
Selection.Copy
Sheets("Supertargeting Calculations").Select
Range("C55").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False


'************************************************************46
```

```
Sheets("INPUT DATA & MAIN RESULTS").Select
Range("F34").Select

ActiveCell.FormulaR1C1 = "=R[13]C[28]"


Sheets("Aux-Aideal").Select
Range("ca15:ct15").Select
Selection.Copy
Sheets("Supertargeting Calculations").Select
Range("C56").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False


'************************************************************47

Sheets("INPUT DATA & MAIN RESULTS").Select
Range("F34").Select

ActiveCell.FormulaR1C1 = "=R[14]C[28]"


Sheets("Aux-Aideal").Select
Range("ca15:ct15").Select
Selection.Copy
Sheets("Supertargeting Calculations").Select
Range("C57").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False


'************************************************************48

Sheets("INPUT DATA & MAIN RESULTS").Select
Range("F34").Select
```

```
  ActiveCell.FormulaR1C1 = "=R[15]C[28]"


  Sheets("Aux-Aideal").Select
  Range("ca15:ct15").Select
  Selection.Copy
  Sheets("Supertargeting Calculations").Select
  Range("C58").Select
  Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False


  '******************************************************49

  Sheets("INPUT DATA & MAIN RESULTS").Select
  Range("F34").Select

  ActiveCell.FormulaR1C1 = "=R[16]C[28]"


  Sheets("Aux-Aideal").Select
  Range("ca15:ct15").Select
  Selection.Copy
  Sheets("Supertargeting Calculations").Select
  Range("C59").Select
  Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False




'******************************************************50

  Sheets("INPUT DATA & MAIN RESULTS").Select
  Range("F34").Select
```

```
ActiveCell.FormulaR1C1 = "=R[17]C[28]"


Sheets("Aux-Aideal").Select
Range("ca15:ct15").Select
Selection.Copy
Sheets("Supertargeting Calculations").Select
Range("C60").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False


'*************************************************************51

Sheets("INPUT DATA & MAIN RESULTS").Select
Range("F34").Select

ActiveCell.FormulaR1C1 = "=R[18]C[28]"


Sheets("Aux-Aideal").Select
Range("ca15:ct15").Select
Selection.Copy
Sheets("Supertargeting Calculations").Select
Range("C61").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False


'******************** INPUT Delta T**********************

Sheets("INPUT DATA & MAIN RESULTS").Select

Range("AH53").Select
Selection.Copy
Range("F34").Select
ActiveSheet.Paste
Application.CutCopyMode = False
```

```
    Sheets("Aux-Aideal").Select
    Range("ca15:ct15").Select
    Selection.Copy
    Sheets("Supertargeting Calculations").Select
    Range("C66").Select
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False


    Sheets("Aux-Aideal").Select
    Application.CutCopyMode = False


    Sheets("INPUT DATA & MAIN RESULTS").Select
    ActiveWindow.ScrollWorkbookTabs Position:=xlFirst
End Sub
```

B2 Potential Retrofit Program

B2.1 Background

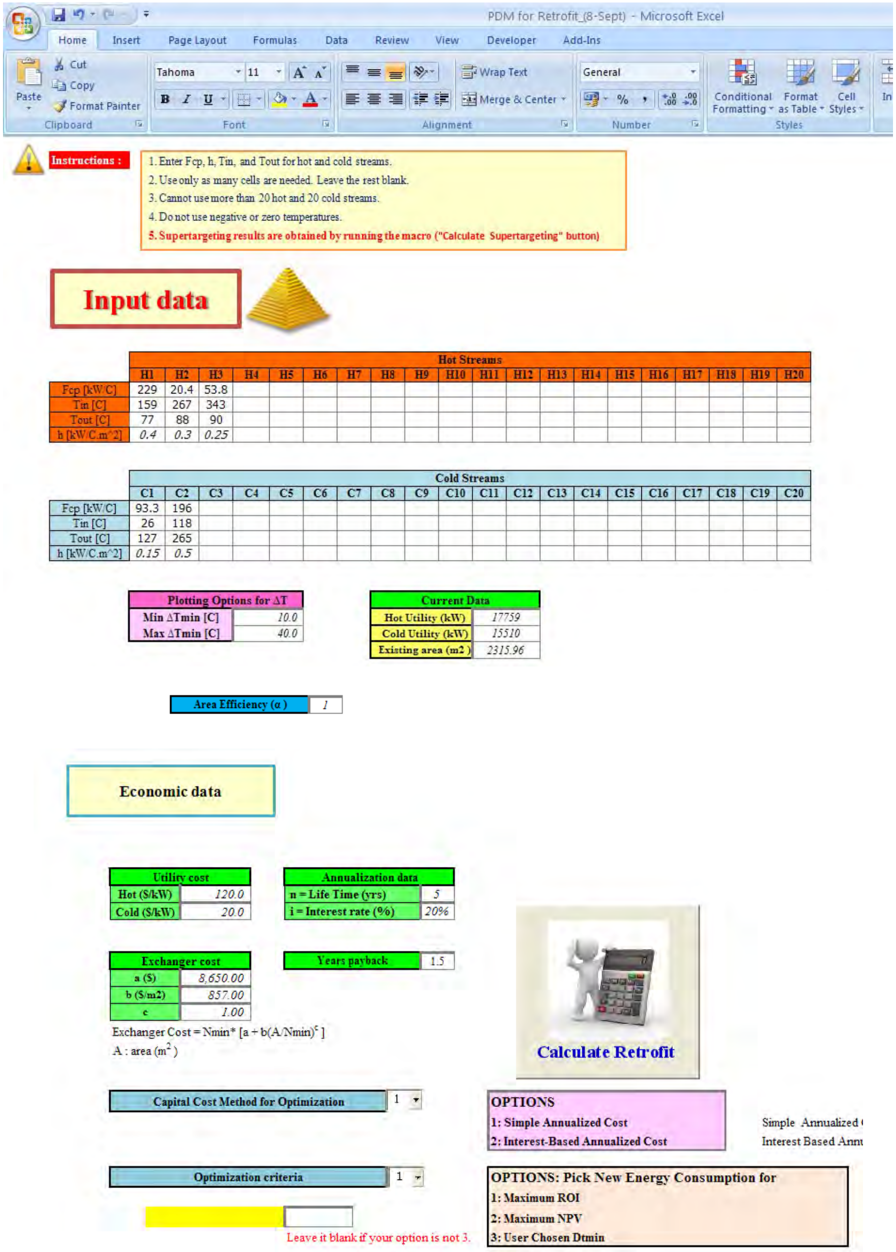
Heat exchanger network (HEN) design is a key aspect of chemical process design. Previous research work (Linnhoff and Hinmarsh, 1983; Floudas et al., 1986; Yee and Grossmann, 1990) has mainly been directed to develop methods for the grassroots design of HEN's. However, during the past two decades, the retrofit of existing HEN has become more important than grassroots design. Because it gives a higher practical designed HEN in order to reduce significantly the operating costs.

Retrofit methods can be grouped into three broad categories which are thermodynamic based approaches including pinch analysis, mathematical programming methods and approaches combining both (Rezaei and Shafiei, 2009). The major objectives of retrofit problems are the reduction of the utility consumption, the full utilization of the existing exchangers and identification of the required structural modifications.

Retrofit mechanisms:

- Addition of one or more new heat exchangers (in series or parallel)
- Relocation of existing exchangers
- Area addition to existing heat exchangers
    - Adding a shell
    - Exchanging the bank of tubes by one more efficient (Brown Fintube, Houston, TX)
- Area reduction to existing heat exchangers
- Modify piping on one or both sides of the heat exchangers

B2.2 MS office incorporated with Visual Basic for Application (VBA) Program


PDM for Retrofit_(8-Sept) - Microsoft Excel
Home
Insert
Page Layout
Formulas
Data
Review
View
Developer
Add-Ins
Paste
Cut
Copy
Format Painter
Clipboard
Tahoma
11
B
I
U
Font
Wrap Text
Merge & Center
Alignment
General
%
Number
Conditional Formatting
Format as Table
Cell Styles
Styles
In

Instructions :

1. Enter Fcp, h, Tin, and Tout for hot and cold streams.
2. Use only as many cells are needed. Leave the rest blank.
3. Cannot use more than 20 hot and 20 cold streams.
4. Do not use negative or zero temperatures.
5. **Supertargeting results are obtained by running the macro ("Calculate Supertargeting" button)**

Input data

	Hot Streams																			
	H1	**H2**	**H3**	**H4**	**H5**	**H6**	**H7**	**H8**	**H9**	**H10**	**H11**	**H12**	**H13**	**H14**	**H15**	**H16**	**H17**	**H18**	**H19**	**H20**
Fcp [kW/C]	229	20.4	53.8																	
Tin [C]	159	267	343																	
Tout [C]	77	88	90																	
h [kW/C.m^2]	*0.4*	*0.3*	*0.25*																	

	Cold Streams																			
	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**	**C13**	**C14**	**C15**	**C16**	**C17**	**C18**	**C19**	**C20**
Fcp [kW/C]	93.3	196																		
Tin [C]	26	118																		
Tout [C]	127	265																		
h [kW/C.m^2]	*0.15*	*0.5*																		

Plotting Options for ΔT	
Min ΔTmin [C]	*10.0*
Max ΔTmin [C]	*40.0*

Current Data	
Hot Utility (kW)	*17759*
Cold Utility (kW)	*15510*
Existing area (m2)	*2315.96*

Area Efficiency (α)	*1*

Economic data

Utility cost	
Hot ($/kW)	*120.0*
Cold ($/kW)	*20.0*

Annualization data	
n = Life Time (yrs)	*5*
i = Interest rate (%)	*20%*

Exchanger cost	
a ($)	*8,650.00*
b ($/m2)	*857.00*
c	*1.00*

Years payback	1.5

Exchanger Cost = Nmin* [a + b(A/Nmin)^c]
A : area (m^2)

Calculate Retrofit

Capital Cost Method for Optimization 1

OPTIONS
1: Simple Annualized Cost
2: Interest-Based Annualized Cost

Simple Annualized
Interest Based Annu

Optimization criteria 1

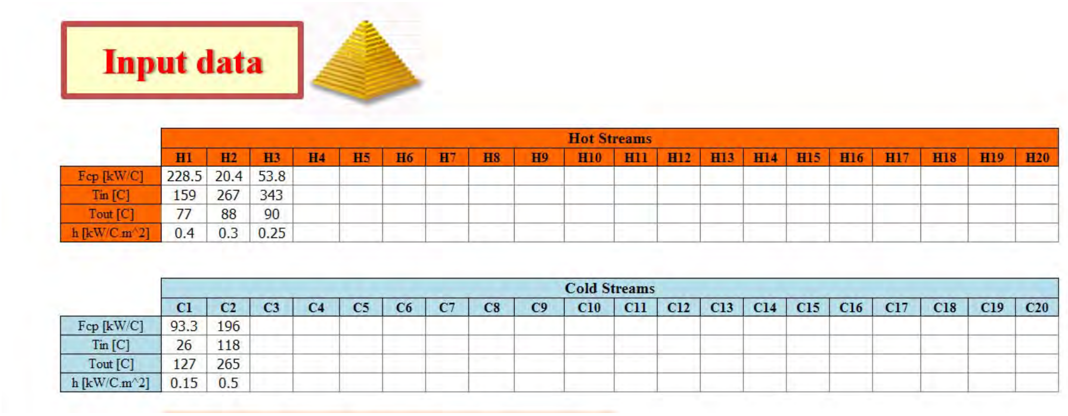
Leave it blank if your option is not 3.

OPTIONS: Pick New Energy Consumption for
1: Maximum ROI
2: Maximum NPV
3: User Chosen Dtmin

Figure B25 MS office Program Feature.

B2.3 Instructions

B2.3.1 Enter Fcp (kW/°C), h (kW/°C.m^2), Tin (°C), and Tout (°C) for hot and cold streams as shown in Figure 26B.



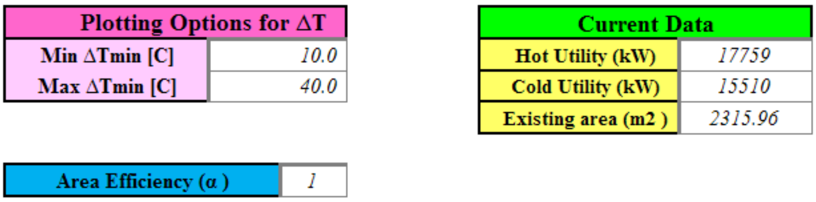
Input data

	Hot Streams																			
	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10	H11	H12	H13	H14	H15	H16	H17	H18	H19	H20
Fcp [kW/C]	228.5	20.4	53.8																	
Tin [C]	159	267	343																	
Tout [C]	77	88	90																	
h [kW/C.m^2]	0.4	0.3	0.25																	

	Cold Streams																			
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20
Fcp [kW/C]	93.3	196																		
Tin [C]	26	118																		
Tout [C]	127	265																		
h [kW/C.m^2]	0.15	0.5																		

Figure B26 Input Fcp, Tin, Tout, and h.

B2.3.2 Enter plotting options for ΔTmin, Current Data, and Area efficiency (α) as illustrated in Figure 53.



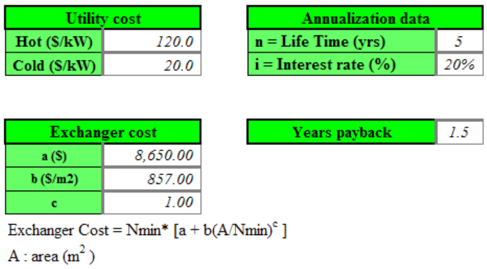
Plotting Options for ΔT	
Min ΔTmin [C]	10.0
Max ΔTmin [C]	40.0

Current Data	
Hot Utility (kW)	17759
Cold Utility (kW)	15510
Existing area (m2)	2315.96

Area Efficiency (α)	1

Figure B27 Plotting options for ΔTmin, Current data, and Area efficiency.

B2.3.3 Enter an Economic Data which consisted of Utility cost, Cost annualized data, Exchanger cost (cost law coefficient), and Years payback.



Utility cost	
Hot (\$/kW)	120.0
Cold (\$/kW)	20.0

Annualization data	
n = Life Time (yrs)	5
i = Interest rate (%)	20%

Exchanger cost	
a (\$)	8,650.00
b (\$/m2)	857.00
c	1.00

Years payback	1.5

Exchanger Cost = Nmin* [a + b(A/Nmin)^c]

A : area (m^2)

Figure B28 Economic data.

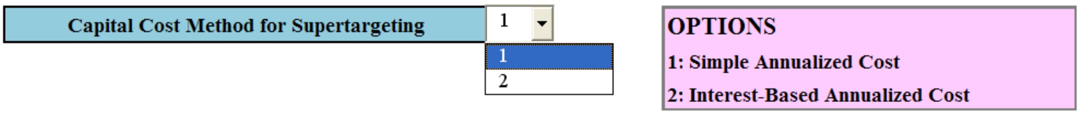
B2.3.4 Select an option for Capital Cost Method for Supertargeting which are

- Simple Annualized Cost

$$SimpleAnnualizedCost = EnergyCost + \frac{CapitalCost}{n}$$

- Interest Base Annualized Cost

$$InterestBaseAnnualizedCost = EnergyCost + CapitalCost \times \frac{i \times (i+i)^n}{(i+1)^n - 1}$$



Capital Cost Method for Supertargeting 1

1
2

OPTIONS
1: Simple Annualized Cost
2: Interest-Based Annualized Cost

Figure B29 Option for Capital cost method for supertargeting.

B2.3.5 Select an option for the optimum HEN

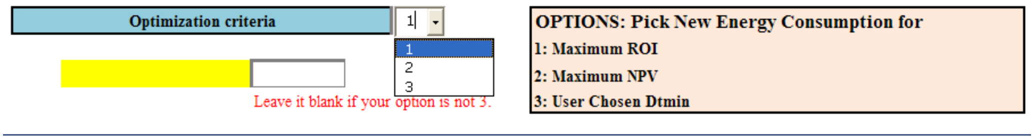
- Maximum ROI

ROI = Energy saving/Total investment

- Maximum NPV

$$NPV = [Energy\_saving \times \sum_{i=1}^{k} \frac{1}{(1+i)^k}] - Total\_investment$$

- User Chosen DT$_{min}$



Optimization criteria: 1

Leave it blank if your option is not 3.

OPTIONS: Pick New Energy Consumption for
1: Maximum ROI
2: Maximum NPV
3: User Chosen Dtmin

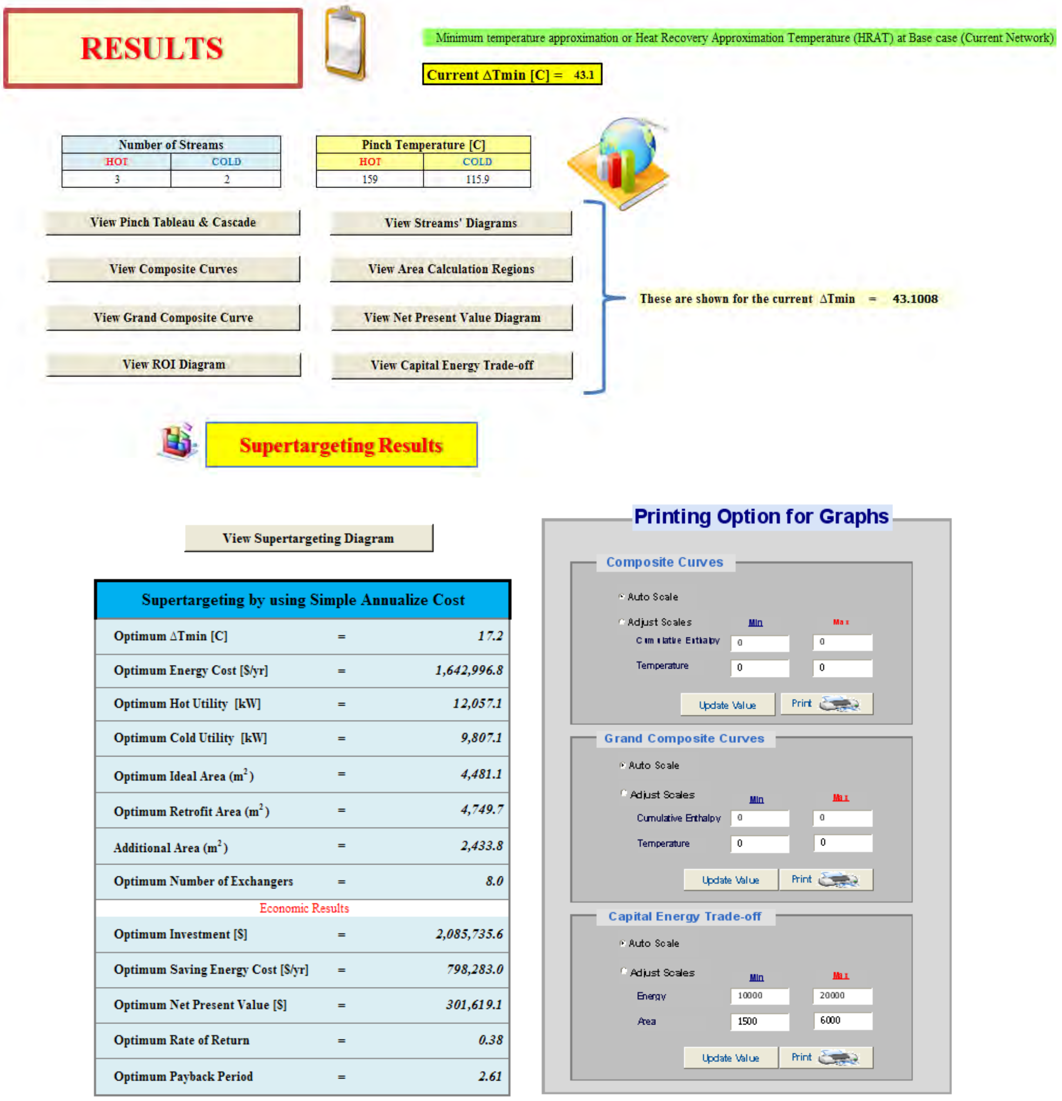
Figure B30 Options for the optimum HEN.

B2.3.6 Supertargeting results are obtained by running the macro ("Calculate Supertargeting" button)

Calculate Supertargeting

Figure B31 Calculate Supertargeting Button.

B2.4 Main results: The Program can automatically generate results as shown in Figure 32B.


RESULTS
View Pinch Tableau & Cascade
View Streams' Diagrams
View Composite Curves
View Area Calculation Regions
View Grand Composite Curve
View Net Present Value Diagram
View ROI Diagram
View Capital Energy Trade-off
Supertargeting Results
View Supertargeting Diagram
Printing Option for Graphs
Update Value
Print

Minimum temperature approximation or Heat Recovery Approximation Temperature (HRAT) at Base case (Current Network)

Current ΔTmin [C] = 43.1

Number of Streams	
HOT	COLD
3	2

Pinch Temperature [C]	
HOT	COLD
159	115.9

These are shown for the current ΔTmin = 43.1008

Supertargeting by using Simple Annualize Cost		
Optimum ΔTmin [C]	=	17.2
Optimum Energy Cost [$/yr]	=	1,642,996.8
Optimum Hot Utility [kW]	=	12,057.1
Optimum Cold Utility [kW]	=	9,807.1
Optimum Ideal Area (m^2)	=	4,481.1
Optimum Retrofit Area (m^2)	=	4,749.7
Additional Area (m^2)	=	2,433.8
Optimum Number of Exchangers	=	8.0
Economic Results		
Optimum Investment [$]	=	2,085,735.6
Optimum Saving Energy Cost [$/yr]	=	798,283.0
Optimum Net Present Value [$]	=	301,619.1
Optimum Rate of Return	=	0.38
Optimum Payback Period	=	2.61

Composite Curves

● Auto Scale

○ Adjust Scales

	Min	Max
Cumulative Enthalpy	0	0
Temperature	0	0

Grand Composite Curves

● Auto Scale

○ Adjust Scales

	Min	Max
Cumulative Enthalpy	0	0
Temperature	0	0

Capital Energy Trade-off

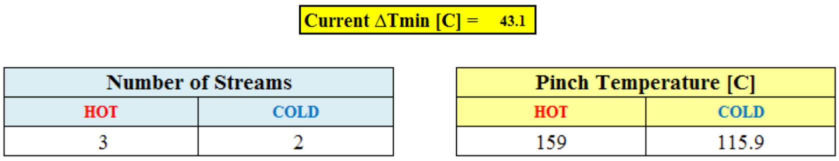
● Auto Scale

○ Adjust Scales

	Min	Max
Energy	10000	20000
Area	1500	6000

Figure B32 Main Results Feature.

B2.4.1 Number of streams, Pinch temperature, and Current ΔT_{min} are shown at the top of result as illustrated in Figure 33B.



Current ΔTmin [C] = 43.1

Number of Streams	
HOT	COLD
3	2

Pinch Temperature [C]	
HOT	COLD
159	115.9

Figure B33 Number of streams, Pinch temperature, and Current ΔT_{min}.

B2.4.2 There are 8 command buttons; "View Pinch Tableau & Cascade", "View Composite Curves", "View Grand Composite Curve", "View Streams' Diagrams", "View Area Calculation Regions", "View Net Present Value Diagram", "View Capital Energy Trade-off", "View Return on investment diagram" which can automatically show those results when clicked.

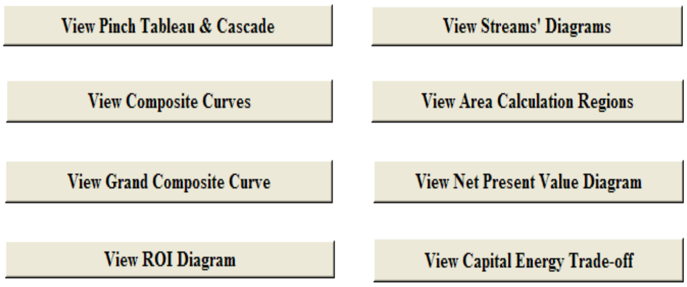
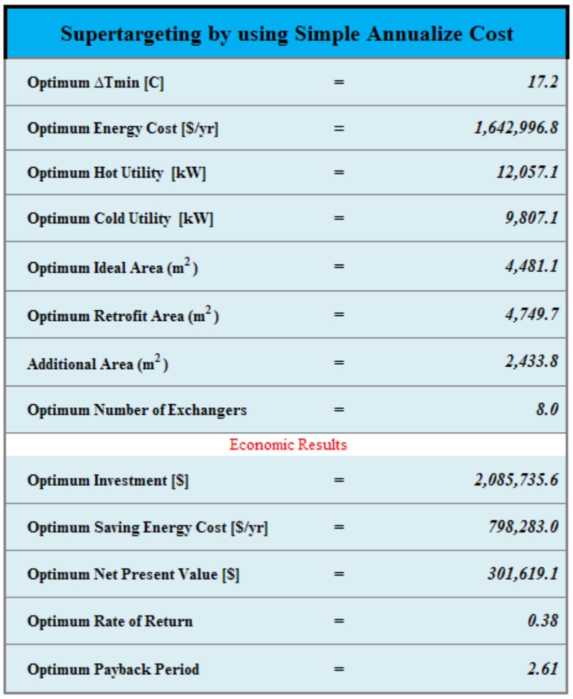

View Pinch Tableau & Cascade
View Streams' Diagrams
View Composite Curves
View Area Calculation Regions
View Grand Composite Curve
View Net Present Value Diagram
View ROI Diagram
View Capital Energy Trade-off

Figure B34 Command buttons.

B2.4.3 Retrofit results

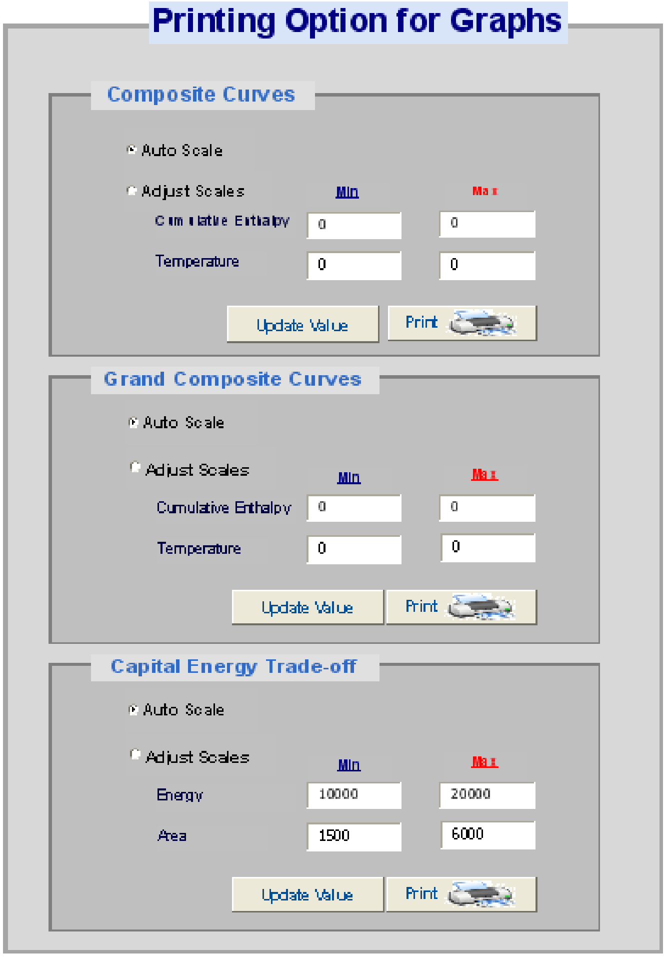
Supertargeting results with an option selected are shown in the table as illustrated in Figure 35B.



Supertargeting by using Simple Annualize Cost		
Optimum ΔTmin [C]	=	17.2
Optimum Energy Cost [\$/yr]	=	1,642,996.8
Optimum Hot Utility [kW]	=	12,057.1
Optimum Cold Utility [kW]	=	9,807.1
Optimum Ideal Area (m^2)	=	4,481.1
Optimum Retrofit Area (m^2)	=	4,749.7
Additional Area (m^2)	=	2,433.8
Optimum Number of Exchangers	=	8.0
Economic Results		
Optimum Investment [\$]	=	2,085,735.6
Optimum Saving Energy Cost [\$/yr]	=	798,283.0
Optimum Net Present Value [\$]	=	301,619.1
Optimum Rate of Return	=	0.38
Optimum Payback Period	=	2.61

Figure B35 Supertargeting Results by selected an option.

B2.4.4 Printing option for Composite curves, Grand composite curve and Capital-Energy Trade-off which is used for adjusting an axis scale as illustrated in Figure 36B. There are 2 options auto scale and adjust scale. Push update value button every time after selecting an option and input scale value.



Printing Option for Graphs

Composite Curves

● Auto Scale

○ Adjust Scales

	Min	Max
Cumulative Enthalpy	0	0
Temperature	0	0

Grand Composite Curves

● Auto Scale

○ Adjust Scales

	Min	Max
Cumulative Enthalpy	0	0
Temperature	0	0

Capital Energy Trade-off

● Auto Scale

○ Adjust Scales

	Min	Max
Energy	10000	20000
Area	1500	6000

Figure B36 Printing option for graphs.

B2.5 Worksheets

B2.5.1 “INPUT DATA & MAIN RESULTS”

Sheet “INPUT DATA & MAIN RESULTS” is consist of 2 parts Input data and results as illustrated in Figure 25B, 32B.

B2.5.2 Tableau & Stream Cascade

Sheet “Tableau & Stream Cascade” shows problem table or pinch cascade and stream plot as shown in Figure 14B. Automatically show when push “View Pinch Tableau & Stream Cascade” button in sheet “INPUT DATA & MAIN RESULTS”.

B2.5.3 Composite curves

Sheet “Composite curves” shows composite curves of input stream data which automatically show when push “View Composite Curves” button in sheet “INPUT DATA & MAIN RESULTS”. As illustrated in Figure 15B.

B2.5.4 Grand Composite

Sheet “Grand composite” show Grand composite curve of input stream data which automatically show when push “View Grand Composite Curve” button in sheet “INPUT DATA & MAIN RESULTS”. As shown in Figure 16B.

B2.5.5 Stream Diagram, 20 Streams, 10 Streams, and 6 Streams

Sheet “Stream Diagram”, show 40 streams’ diagram of input stream data which automatically show when push “View Streams Diagram” button, in sheet “INPUT DATA & MAIN RESULTS”. As illustrated in Figure 17B.

B2.5.6 Area Calculation Region

Sheet “Area Calculation Region” shows Vertical heat transfer area calculation region of input stream data which automatically show when push “View Area Calculation Region” button in sheet “INPUT DATA & MAIN RESULTS”. As shown in Figure 18B.

B2.5.7 Supertargeting

Sheet “Supertargeting” shows Economic Trade-off of selecting option and input stream data which automatically show when push “View Supertargeting Diagram” button in sheet “INPUT DATA & MAIN RESULTS”.

B2.5.8 NPV, ROI

Sheet “NPV” and “ROI” show Net Present Value and Return on investment, respectively which automatically show when push “View Net Present Value”, “View ROI Diagram” button, respectively in sheet “INPUT DATA & MAIN RESULTS”.

B2.5.9 Capital Energy Trade-off

Sheet “Capital Energy Trade-off” show the retrofit areas-energy curve from the selected area efficient (α) which automatically show when push “View Capital Energy Trade-off” button in sheet “INPUT DATA & MAIN RESULTS”.

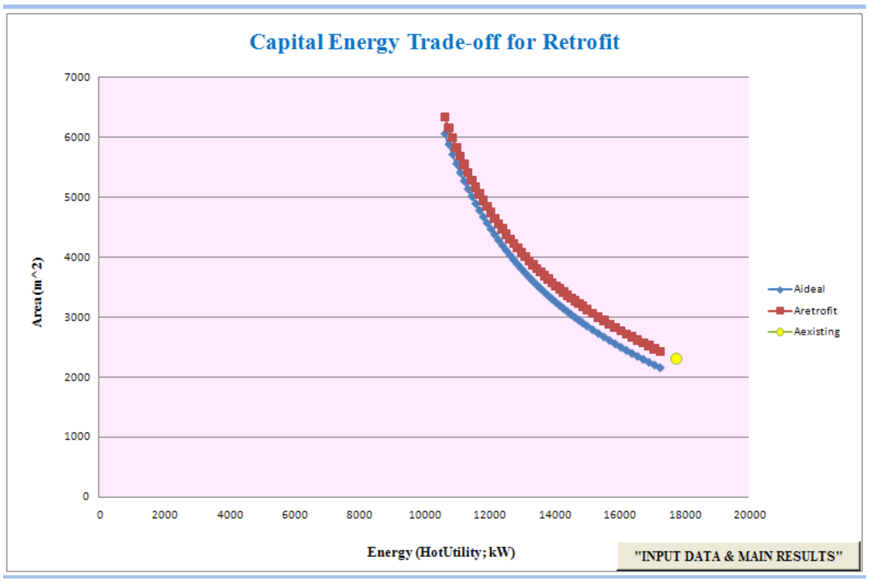


Figure B37 Capital Energy Trade-off Diagram.

B2.5.10 Payback curve

Sheet "Payback curve" shows payback diagram of input stream data at 1, 2, 3, and selected year payback which automatically show when push "View Payback Diagram" button in sheet "INPUT DATA & MAIN RESULTS"

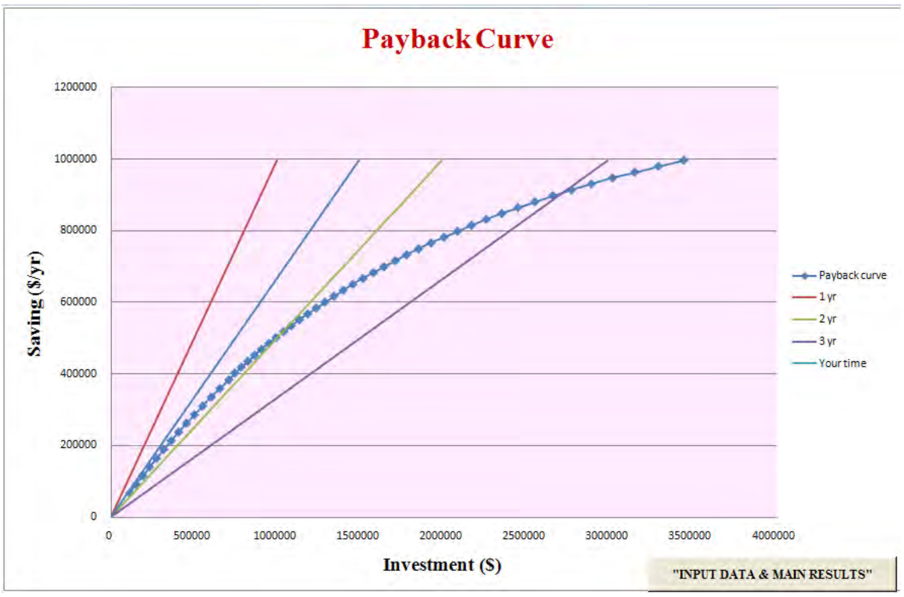


Figure B38 Payback Diagram.

B2.6 Visual Basic for Application (Source code)

B2.6.1 Sort Data Function (in Module 4)

As shown in Figure 24B

B2.6.2 Discount Factor Function (in Module 5)

As shown in Figure 25B

B2.6.3 Vary DTmin procedure (in Module 7)

Source code is covered in more detail in section

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1993	M.S.	Chemical Engineering	Texas A&M Kingsville University	USA
1997	D. Eng	Chemical Engineering	Lamar University	USA

Special skill/Research Interest :

- Applications of pinch technology for energy conservation
- Process simulation and control
- Heat exchanger networks and design
- Distillation column design

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2002 – 2005 (GPA: 3.94) Bodindecha (Sing Singhaseni) School,
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Extra-Curricular Activities:

2010 (April) Staff in “The 1st National Research Symposium on Petroleum, Petrochemicals, and Advanced Materials” and “The 16th PPC Symposium on Petroleum, Petrochemicals, and Polymers” April 22, 2010 at Montien Hotel, Bangkok

2009 – Present Student President of Petroleum technology, The Petroleum and Petrochemical College, Chulalongkorn University

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