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 Fin-tube, 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.

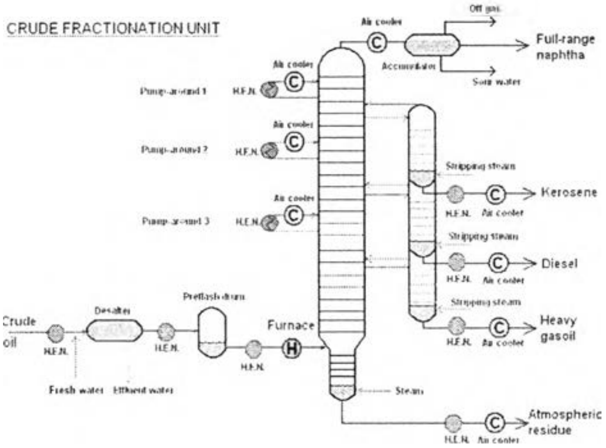

Figure 2.1 Crude fractionation unit.

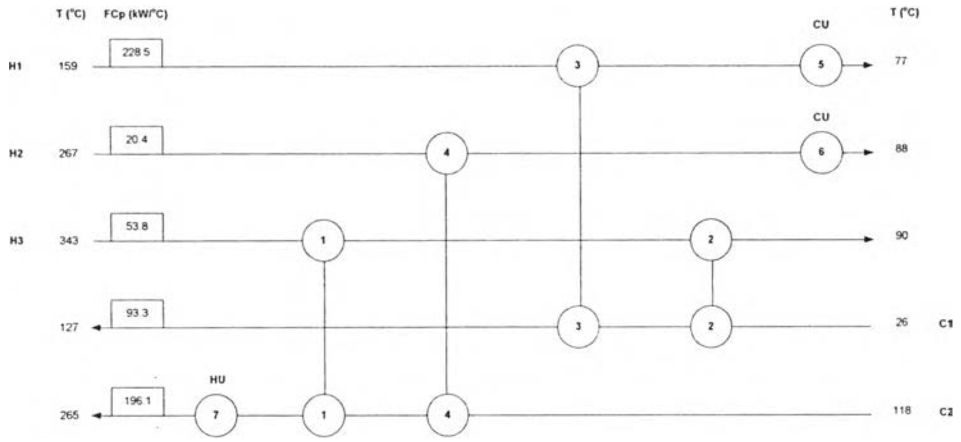

Figure 2.2 An example of grid diagram.

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 Coposite 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.

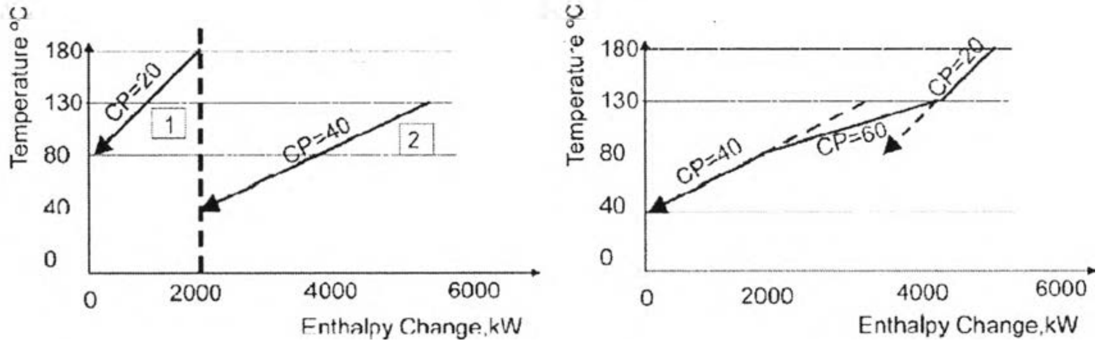

Figure 2.3 Construction of Composite Curves (Texas A&M University. "Network Pinch Analysis." 22.).

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.

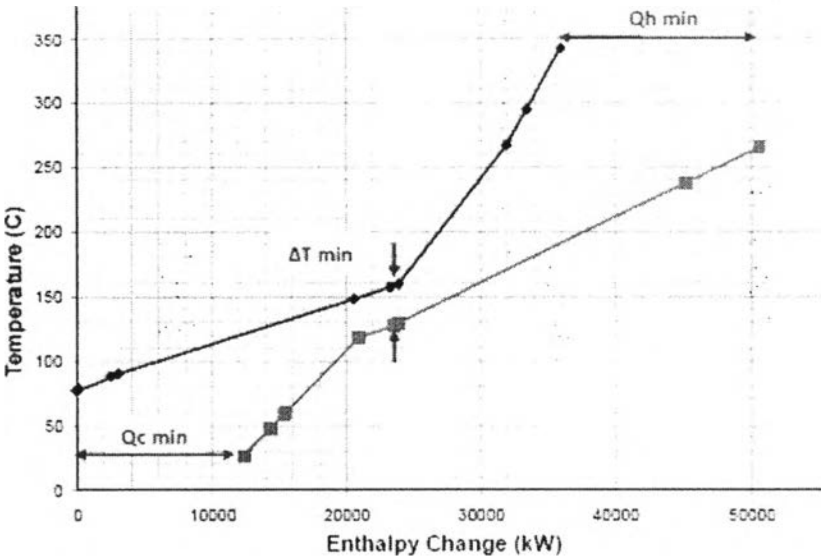

Figure 2.4 An example of a hot and cold composite curve.

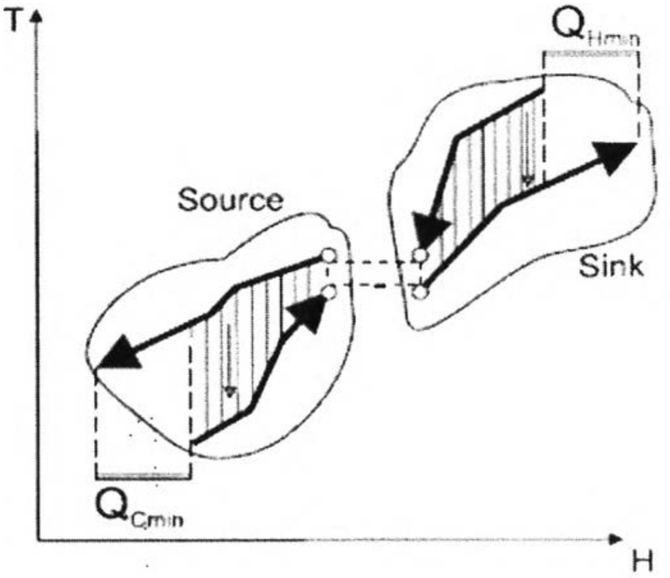

Figure 2.5 Sink and Source Separated at Pinch.

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).

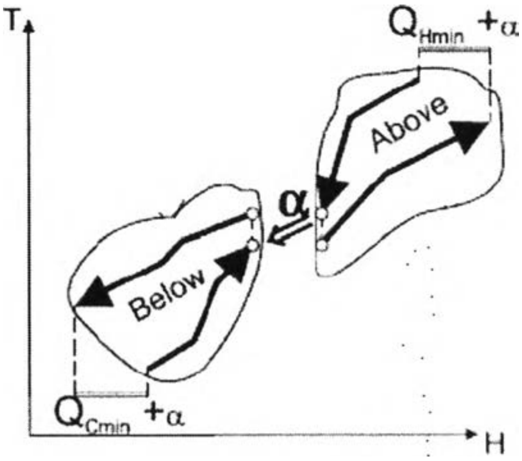

Figure 2.6 Cross pinch heat transfer.

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.

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

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.

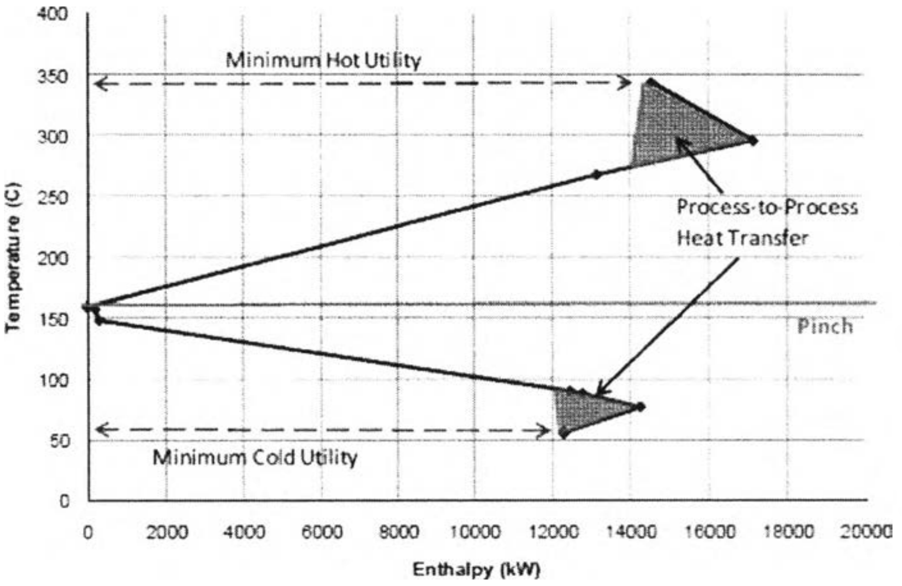

Figure 2.7 Grand Composite Curve.

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.

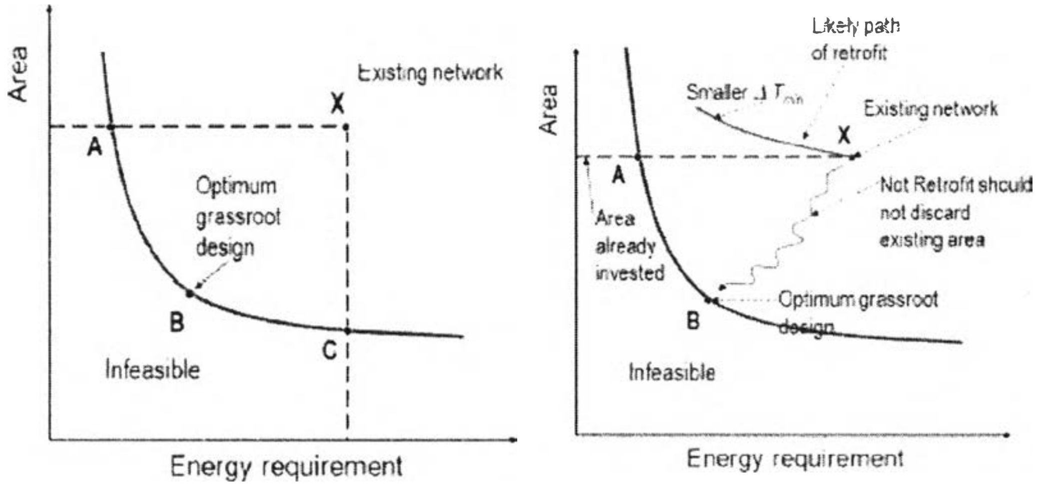

Figure 2.8 Area vs. Energy requirement diagram for typical network (Texas A&M University. "Network Pinch Analysis." 123.).

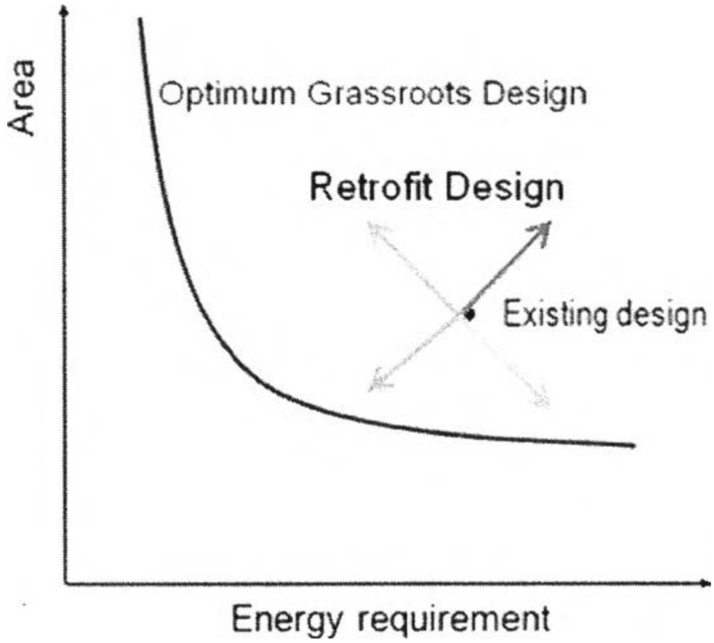

Figure 2.9 Four possible option of doing retrofit (Texas A&M University. "Network Pinch Analysis." 123.).

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.

$$A_{ideal} = \sum_{k}^{intervals-k} \frac{1}{\Delta T_{LMk}} \left[\sum_{i}^{HotStreamsI} \frac{q_{i,k}}{h_i} + \sum_{j}^{ColdStreamsJ} \frac{q_{j,k}}{h_j} \right] \tag{4}$$

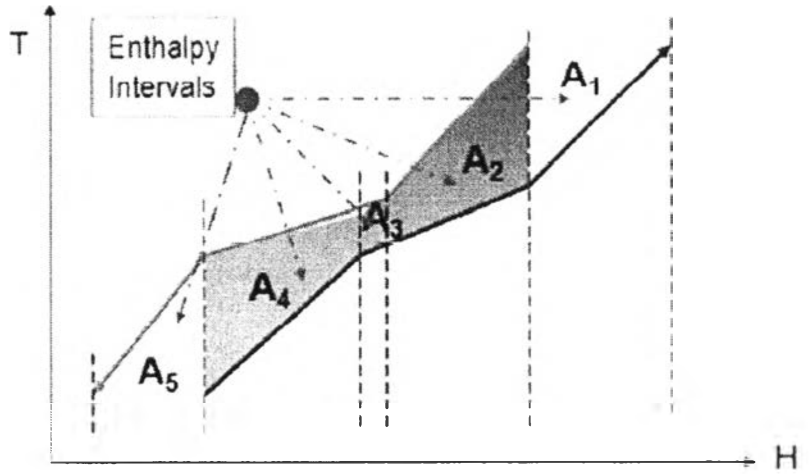

Figure 2.10 Vertical heat transfer area intervals (Texas A&M University. "Network Pinch Analysis." 123.).

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.

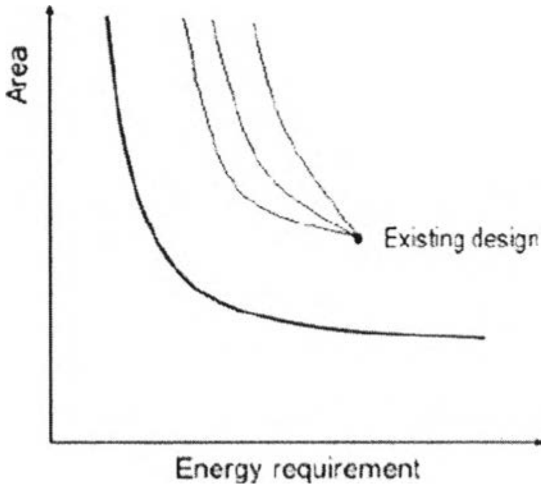

Figure 2.11 Area vs. Energy Requirement with Several Design Curve Options (Texas A&M University. "Network Pinch Analysis." 123.).

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.

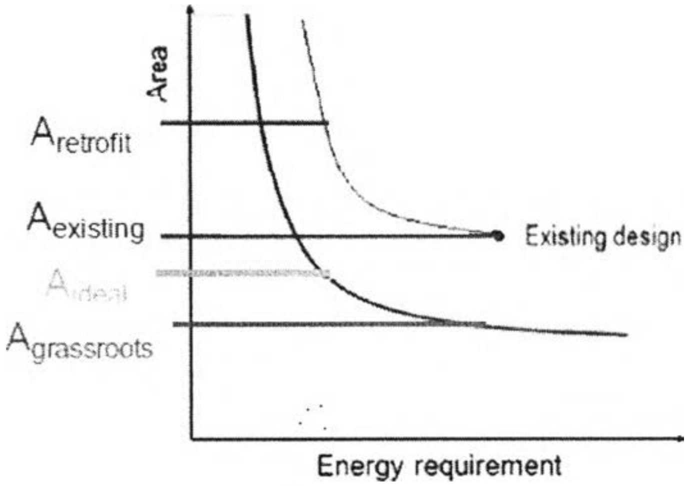

Figure 2.12 Area vs. Energy Requirement - Area Locations.

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.

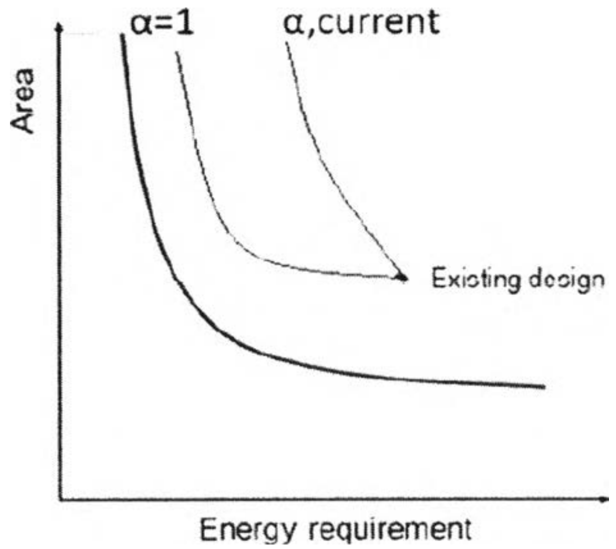

Figure 2.13 Impact of Alpha Value.

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

$$A_{retrofit} = \frac{A_{ideal} - A_{ideal1}}{\Delta\alpha} + A_{existing} , \quad (7)$$

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.

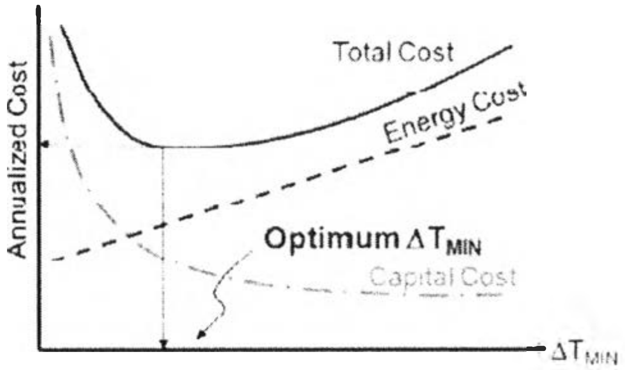

Figure 2.14 Typical TAC vs. ΔT_{min} Diagram.

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.

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

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

$$PBP = \frac{Investment}{Savings} \tag{17}$$

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

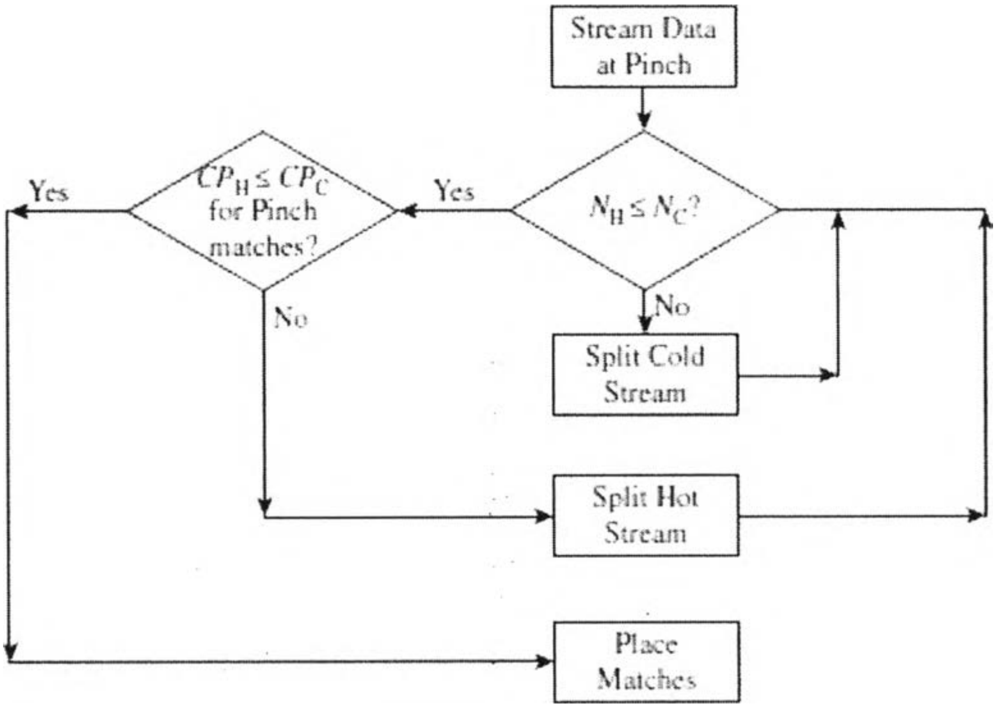

Figure 2.15 Above pinch design.

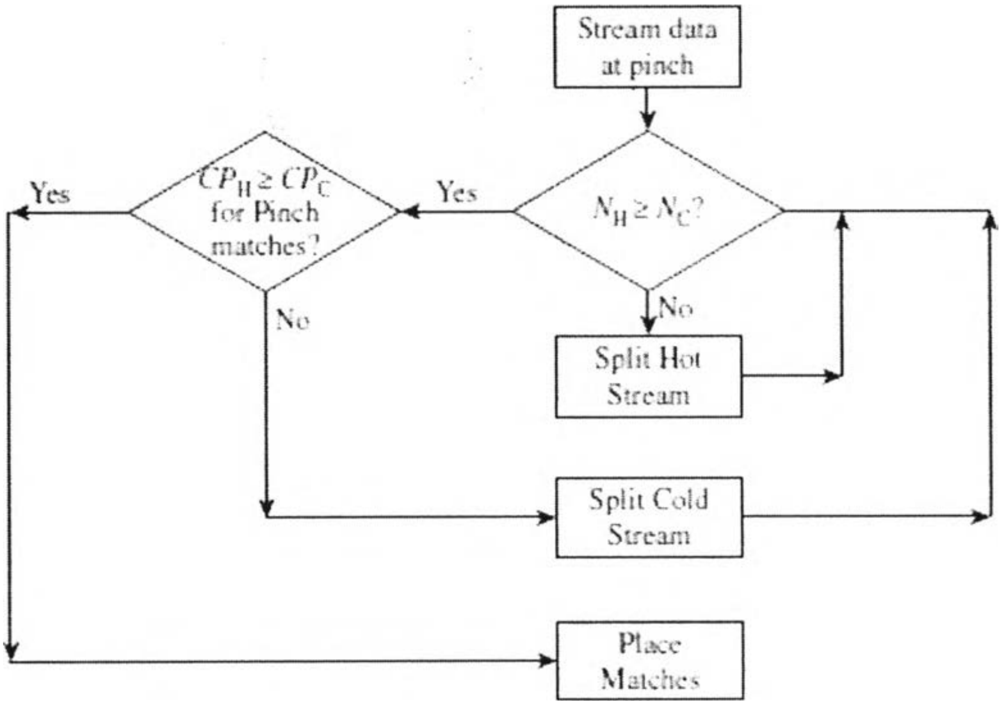

Figure 2.16 Below pinch design.

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.

$$Q = FCp(T_{in} - T_{target}) \tag{18}$$

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.

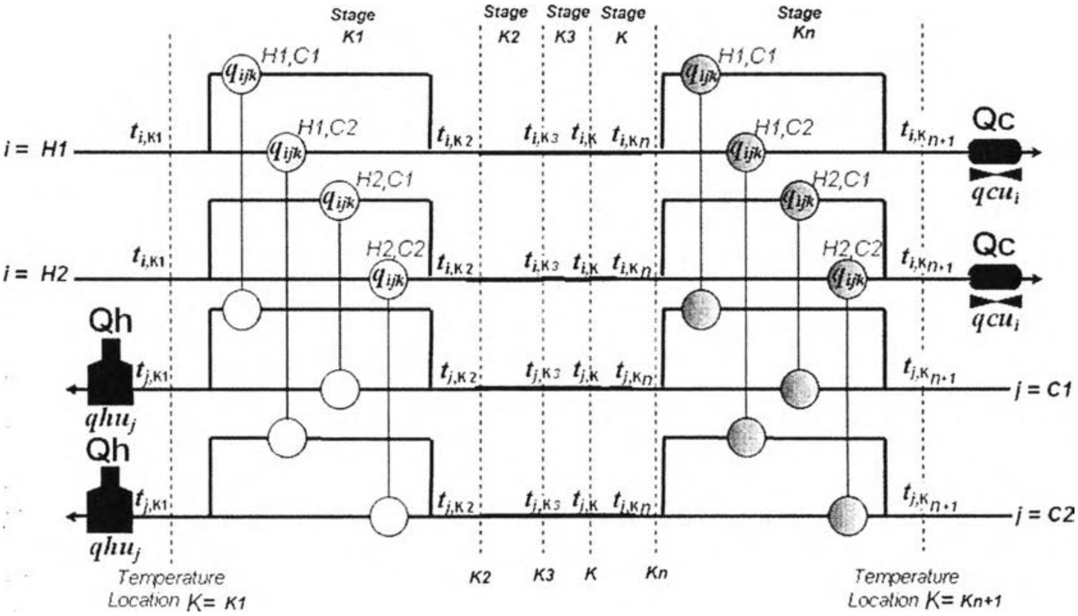

Figure 2.17 Two-stage superstructure.

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*

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

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

2.2.1.2 *Heat Balance of each Stream at each Stage*

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

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

2.2.1.3 *Assignment of Superstructure Inlet Temperature*

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

$$TIN_i = t_{i,1} \qquad i\in HP \qquad (24)$$

2.2.1.4 *Feasibility of Temperature*

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

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

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

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

2.2.1.5 *Hot and Cold Utility Load*

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

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

2.2.1.6 Logical Constraints

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

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

$$qcu_i - \Omega zcu_i \leq 0 \qquad i \in HP \tag{27}$$

z_{ijk}, zcu_i, $zhu_j = 0,1$

2.2.1.7 Calculation of Approach Temperatures

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

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

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

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

2.2.1.8 Objective Function

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

min

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

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

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

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

(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.

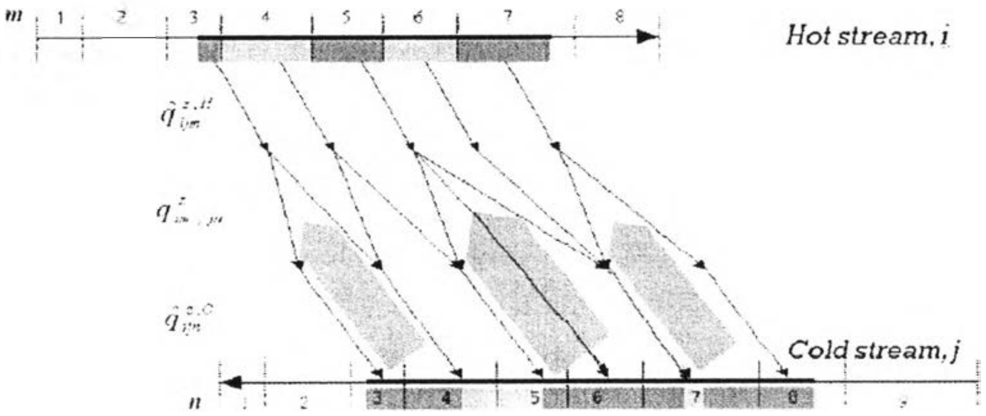

Figure 2.18 Transportation and Transshipment Model.

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.