CHAPTER II

THEORETICAL BACKGROUND AND LITERATURE REVIEW

2.1 Mathematical Methods

Mathematical methods are very useful for the synthesis of HEN since they automatically search among many designs, using optimization methodology as well as economic trade-offs between capital and utilities costs. Mathematical methods can provide good solution and also simultaneously optimize process flowsheet with heat integration; however, the non-convexities and size of problems cause difficulty in solving.

Most of mathematical optimization models for HEN synthesis rely on the assumptions of: (1) Constant heat capacity flowrates; (2) Fixed inlet and outlet temperatures; (3) Constant heat transfer coefficients; (4) Single-pass countercurrent heat exchangers; (5) Layout and pressure drop costs are neglected; (6) Operating cost in terms of the heat duties of utilities and (7) Investment cost in terms of the areas of the exchangers, and the following basic equations;

a) Splitter-mass balance $F_{In} = F_{out,1} + F_{out,2}$ (2.1)

b) Non-isothermal mixing heat balance $F \times T = F_1 \times T_1 + F_2 \times T_2$ (2.2)

c) Heat exchanger-heat balance $Q = UA(LMTD)$ (2.3)

And the cost functions include

Capital cost: $Fixed\ cost + Area\ cost$ (2.4)

Utilities cost: $C_{HU}Q_{HU} + C_{CU}Q_{CU}$ (2.5)

Note that equation (2.1) and (2.5) are linear, whereas, equation (2.2), (2.3) and (2.4) are nonlinear.

Furthermore, the systematic representation and discrete selection of stream matches and their corresponding exchangers defining the network configuration are not mentioned.

Hwa (1965) used superstructure representation combining several alternative network structure and defined objective function and constraints by a nonlinear model.

However, his approach would be usually trapped into local solution and undergone the question of the superstructure construction which guarantee the optimum design.

Kesler and Parker (1969) formulated a linear programming (LP) model for synthesis problem and used the heat content diagram F_{Cp} and T representation in which the utilities consumption is fixed and then divided heat content of each stream into small heat chunks in order to match the streams. As a result, this model generated many heat exchangers in their complex network configuration because of none of adjacent heat chunks assignment for the same match.

To handle discrete decisions, Lee, Masso and Rudd (1970) applied the tree search method (branch and bound methods) which generate network alternatives by sequential of stream matches until satisfying inlet and outlet conditions of streams. After that, Rathore and Powers (1975) and Grossmann and Sargent (1977) subsequently extended this technique. However, these techniques encountered the difficulties that the quantity of heat exchanger in each match was determined by the sequential assignment of match decisions and they did not meet the target for minimum utilities requirement to specify minimum temperature approach.

2.2 Heat Exchanger Network Synthesis

The HEN synthesis is one of the HEN design problems. Generally, there are two main approaches, sequential and simultaneous ones. Although the methodologies and tools of process modeling and optimization are advancing, a major challenge for the HENS problem is to develop superior models and efficient algorithms that can optimally obtain optimal heat exchanger network (HEN) with lower TAC. (Grossmann and Carnegie Mellon University, 1992).

2.2.1 Sequential Synthesis

2.2.1.1 Sequential Design with Physical Insight Based Method

Sequential methods can be achieved by insight-based techniques or with extensive use of optimization. The insight-based techniques are not effective to use for large-scale problems; however, it provides a clarification of optimization models (Sieniutycz and Jeżowski 2009).

To achieve feasible and reliable target for minimum utility consumption (for fixed heat recovery approach temperature; HRAT), Linnhoff and flower (1978) defined “pinch technology” which is physical insight based method to target minimum utility consumption, minimum number of units, as well as minimum total area (Grossmann and Carnegie Mellon University, 1992).

Due to is its simplicity and visualized solution algorithm, Pinch-technology-based approaches are widely used to give insight in design HEN in industry. However, it may not give and optimal solution or even a near-optimal solution.

For PT approaches, the evolution stage is needed to improve trade-off between number of matches and cost of utilities after the calculation of network structure and some basic parameters. The targeting stage provides the optimal ΔT^{min} value ($\Delta T^{min,opt}$), pinch temperature or the optimum HRAT. In case of multiple pinches, some subtasks are between-pinches problems and each of them is solved separately.

Most of total annual cost is comes from number of matches in the HEN. Therefore, minimizing number of matches by eliminating loop, called “loop breaking”, is the main technique to decrease total annual cost. If HRAT is fixed, loop breaking will increase the utility usage. This increase of utility usage is called “energy penalty”. To minimize the energy penalty, the relaxation of outlet temperature is introduced.

To formulate the loop-breaking model, HEN is needed to model with given structure. However, the loop-breaking method changes mixed-integer linear programming (MILP) optimization model in case of fixed structure to either nonlinear programming (NLP) or MINLP optimization model. Generally, in case of MILP optimization models multiple global optima exist. Adding integer cuts can prevent redundant computation of the solutions; hence, all optimal solutions are generated. Finally, the best solution is chosen corresponding to the optimal total annual cost.

2.2.1.2 Sequential Design with Optimization Approaches

To synthesize systematically HEN, a superstructure concept is often applied even the case of known heat load distribution. In the sequential HEN synthesis, utility loads are fixed and the number of units is also given. It does not require discrete variable because only continuous variables are sufficient to eliminate the splitter, mixer and associated branches form the superstructure. That is easy to say, if the flow rate is defined at zero value, its stream is removed (Sieniutycz and Jeżowski, 2009).

The mathematical method developed firstly by Cerda and Westerberg (1983) and Cerda *et al.* (1983) was LP transportation allowed multiple utilities and constrained matches where pinch technology could not handle.

Papoulias and Grossmann (1983) developed an alternative model corresponding to the LP transshipment model which is based on heat cascade diagram. The advantage of LP transshipment model compared to transportation model is the smaller size of the problem.

Floudas *et al.* (1986) developed mathematical method for automated three major steps synthesis ability to HEN synthesis to guarantee the minimum utility target and handle the stream splitting. They are as follows:

Step 1: Predict the minimum utility cost by using LP transshipment model.

Step 2: Predict the minimum number of units and matches by using MILP transshipment model depending on the heat recovery predicted in step 1.

Step 3: Automatically derive the HEN structure by using NLP model with heat recovery and matches predicted in steps 1 and 2.

In third step, they generated a superstructure embedded all possible configurations for each involved stream in matches predicted in step 2.The network structures with minimum utility and number of units with or without stream splitting were generated by this approach.

In contrast, it had some limitations due to the sequential decomposition approach to the problem. The MILP in second step provides multiple solutions with different matches and heat load distributions for the same minimum number of units. The NLP in third step is non-convex problem and this may obtain local optima. The NLP does allow stream splitting. Furthermore, it required suboptimal networks because the value of HRAT must be specified before design step.

Many researchers tried to develop automated sequential synthesis for decade; however, they still encountered the limitations in their approaches.

2.2.2 Simultaneous Synthesis

In contrast to sequential approach, the simultaneous approach is more attractive since it is not based on the pinch and also heuristic concept. It uses a single-step mathematical programming formulation to trade-offs factors affecting the total annualized cost (TAC). It provides superior solutions through it results in complex numerical mathematic models.

There are at least two ways to cope with the difficulties of large-scale problems or even smaller ones: (a) development of robust efficient optimization techniques that can guarantee global minimum (though usually uncertain conditions), (b) application of the other stochastic mete-heuristic strategies, problem decomposition and problem linearization.

Dolan *et al.* (1989) used simulated annealing to optimize heat recovery level, the selection of matches and area with no fixed value of the temperature approaches. However, this was not a clear systematic method and took high computational time.

Floudas and Ciric (1989) extended the superstructure by Floudas *et al.* (1986) providing the possible selection of all matches and they used MINLP model to determine the existence of units. To reduce the number of iterations and infeasible configurations, the Generalized Benders decomposition method and incorporated the MILP transshipment model are applied in its master problem. This approach did not simultaneously optimize energy cost with the area and number of units.

Yee and Grossmann (1990) proposed MINLP model based on the superstructure representation. Even though the superstructure representation was not embed all possible matches in structure, it easily enforced 0-1 binary variables in constraint on stream splitting and was easily solved with commercial solvers for isothermal mixing assumption. Also, simultaneous synthesis method without fixing HRAT and minimum temperature approaches of exchangers (EMAT) could specify inlet and outlet temperatures as inequalities. In comparison with other methods, it did not guarantee the optimal solution. (Grossmann and Carnegie Mellon University, 1992)

The series paper of simultaneous optimization models for heat integration by Yee and Grossmann, (1990) is divided into three parts.

In the first part of Yee *et al.* (1990), the simultaneous optimization, where each of subsequent steps in procedure does not depend on its previous steps, is introduced for area and energy targeting. Due to the simplicity, a stage-wise superstructure is first presented and developed properly for various heat integration problems. In contrast to spaghetti designs, the proposed superstructure treats temperatures in each stage as variables being optimized; therefore, the number of stages is unequal to the number of energy interval and there is no need to fix HRAT or EMAT. The objective function for simultaneous optimization of energy and area targets involves both utilities and area-cost terms. When the utility requirement for network is fixed, the simultaneous model modified to only minimize total area requirement is called area-targeting model. In the examples, they demonstrated that the simultaneous model can trade-offs between utilities and area cost. As shown in the examples, the obtained solutions are quite efficient; however, these models may provide multiple local solutions. In the last section, the proposed model for area targeting is applied for the design of multi-stream heat exchangers. Unlike the previous area targeting model, the fixed flows need to be considered as variables.

In the second part of Yee and Grossmann, (1990), the superstructure representation proposed in part I is applied to a MINLP model which trade-offs simultaneously between utility cost, fixed charge for the number of units, and heat transfer area cost for the network. Due to the assumption of isothermal mixing, the constraints of MINLP model, optimizing simultaneously for the HRAT, EMAT, number of units, number of splits and heat transfer area, are linear. In the case of stream split, a suboptimization is used to find out from the optimal split ratio. The MINLP can be solved easily on the network design. Furthermore, the model is possible to match hot-to-hot or cold-to-cold streams and consider inlet and outlet temperatures as variables. Examples show that some heuristic rules do not achieve optimization simultaneously.

In the third part of Yee *et al.* (1990), to simultaneously optimize or synthesize of the HEN and process, the stage-wise representation in part I is embedded into the given process flowsheet or superstructure and, then, optimize the combined model which treats flow and temperature of potential hot and cold streams as variables and no need to specify the HRAT and EMAT. To design the model, either NLP or MINLP is used. The computational time of NLP formulation is required less than that of MINLP. Since it cannot treat fixed cost charges and does not use binary variables so it tends to obtain only an approximation solution of the network structure and not impose constraints on the network structure.

Of the easy way to overcome the drawbacks of the synthesis approaches is by combining the approaches. Hostrup *et al.*, (2001) combined two different approaches, thermodynamic insight and structural optimization, to help each other in the synthesis and design process. Thermodynamic insight based approach firstly generate non-optimal flowsheet which is the good initial-estimated flowsheet for optimization approach. The later one uses the MINLP model to find the optimal solution. Lastly, the optimal solution is screened to improve the robustness and efficiency by the analysis step.

The Synheat model by Yee and Grossmann (1990) only comprises of non-linear expressions that consist of linear terms and non-convex terms describing the area costs. To date, HEN synthesis problems have not been solved to reach global optimality and have not obtained even feasible solution in some cases. In the work of Björk and Westerlund (2002), the modified global optimization strategy which allows stream splits and contract algorithm is applied to ensure global convergence on Synheat model. The new global optimization strategy based on the convexification of non-convex terms is used to ensure global convergence for non-convex model. The model will be convex if a piece-wise linear function can approximate the non-convex terms where their solution will be underestimated solutions compared to the solution of the original problems. The global optimal solution of this global optimization technique can be found with standard MINLP solvers. Due to avoiding non-convex constraints the isothermal mixing is assumed. However, extending the Synheat model with some continuous variables and linear and non-convex constraints is applied to synthesis model without isothermal mixing assumption. This extended Synheat model also applies global optimization strategy. However, the computational time to find the global optimum for a model without isothermal assumption is higher than a model with isothermal assumption. From the examples, the solutions obtained from one of these non-convex models close to the global optimal solutions.

•There are various methodologies to grass-root design HEN even in sequential or one-step approaches. However, those results may not be optimal. Finding optimization solutions, Barbaro and Bagajewicz (2005) proposed a new one-step MILP based on the transportation-transshipment model to obtain better computational time, cost-optimal networks and also cost-effective solution. Furthermore, they have the assumption of non-isothermal mixing, stream splitting and bypass, multiple matches between two streams and able to counting units or even number of shells. The streams splitting and units counting are handled by the flow rate consistency and especial constraints, respectively. In addition, some changes during the design stage are allowed by using binary variables. However, this model requires streams to be divided into intervals and thus the solution may slightly change with the different number of intervals.

Like the stage-wise superstructure, the new method which uses an interval-based mixed integer nonlinear program superstructure (IBMS) model is generated for HEN synthesis. In contrast to stage-wise superstructure, each interval temperature of IBMS model is defined by either the supply or target temperatures of involved streams and there is no need initialization steps to provide global solution for large-scale HEN problems. The IBMS model allows for crisscross heat exchanger to handle streams with different heat transfer coefficients and constrained matches and avoids nonlinear mixing equation in the model by mixing streams at equal temperatures. Furthermore, the IBMS model can handle multiple utilities selection because of setting heat capacity flow rates of streams as variables. However, there are some defects demonstrated in the examples involving split streams (Isafiade and Fraser, 2008).

Bogataj and Bagajewicz (2008) studied the influence of heat integration on the solution of water allocation planning (WAP) and proposed a new approach for simultaneous synthesis to solve the energy efficient water allocation problems in case of multi-contaminant in water. The NLP model is used to formulate water network

(WN) superstructure, whereas, the MINLP model is used for modified HEN synthesis. The modified HEN allows non-isothermal mixing of direct and indirect heat exchange in exchangers. To obtain global or at least good local solutions, WN and modified HEN superstructure are integrated. Due to the non-linear and non-convex terms in combined model, the continuous values obtained from WN solution are used as the initial value for inlet condition of HEN synthesis.

Due to the assumption of isothermal mixing, the area cost will be overestimated. Huang *et al.* (2012) have modified stagewise superstructure of Hasan et al. (2009). They allowed streams to fully bypass a stage and allow either first or end stage to have no heat exchanger. Furthermore, they added two more stages at the stage 0 and stage K+1 (K=maximum number from either hot process streams or cold process streams) to adjust the final temperature of hot and cold process streams by cold and hot utilities, respectively. In contrast to isothermal mixing assumption, the outlet temperature from one substream heat exchanger can be varied. Thus, we need additional flow and temperature changes variables in the substream at each exchanger. Also, they proposed new bounds for temperature changes and logical constraints to achieve the better HEN solutions. In addition, they proposed two new ways to handle the numerical difficulties in computation of LMTD that result from constant approach temperatures. However, the previous LMTD approximations are more effectively than their approaches. In the last part of their work, they demonstrated that stage bypass variables and constraints enhance solution quality and efficiency even in the very large and practical problems.

Since the stagewise-superstructure HEN model done by Yee and Grossmann (1990), does not allow non-isothermal mixing and cross flow compared to a hyperstructure model which allows cyclic matching whenever hot and cold process streams are divided into two substreams at pinch temperature. In addition, hyperstructure-based approach applying pinch-based transshipment model requires partition temperature interval which may lead to suboptimal network. Huang and Karimi (2012) proposed a simultaneous model based formulation on hyperstructure of multistage stream superstructures. It allows possible cyclic matches between hot and cold process streams which may reduce required heat exchanger area and result in superior HEN synthesis with lower TACs. They also featured their model by a cross flow which exclude from the existing formulations based on stagewise superstructure and gains better solutions than any other.

Huang and Karimi (2013) used mathematical programming to obtain more cost-guided approach of simultaneous synthesis. They propose a superstructure that combines the best features of a single-stage superstructure by Floudas et al. 1986 and Floudas and Ciric (1989) and a multistage superstructure by Yee and Grossmann (1990). The single-stage superstructure forbids repeated matching of a pair of process streams (called cyclic matching) which may help decrease TAC in some cases as shown by Kemp (2007). Due to the isothermal mixing assumption, the multistage superstructure is restricted. Their posed superstructure allows series of matches on a process substream, cross flows, cyclic matching and the use of multiple utilities at any stages providing superior solutions (lower TACs). However, its solution speed is not improved.

In 2014, Jongsuwat *et al.* extended the stage-wise superstructure approach that was proposed by Yee et al. (1990). The extended model allows non-isothermal mixing and multiple matches per branch stage and stream splitting. To obtain good initial values for the MINLP, they also proposed a strategy by using a heuristic initialization strategy. The results after solving each step are used as the initial values of the next step.

The main approaches of HEN synthesis are sequential and simultaneous techniques. The simultaneous methods tend to obtain better solutions than sequential methods because they trade-off between operating costs and capital costs. In this work, Liang *et al.* (2013) focused on the simultaneous approaches with the MINLP formulations. The model is based on a stage-wise superstructure representation by Yee and Grossmann (1990).Due to the isothermal mixing assumption, the area cost may overestimates. Therefore, they also focus on the HEN with non-isothermal mixing. The non-isothermal mixing assumption introduces non-linear terms, heat balances for each heat exchanger and heat mixing equations; consequently, the initialization steps and a new two-level algorithm are developed to obtain the feasible starting point for optimization problems and then achieve optimal solution.

To solve the large HEN synthesis problems, the recently published work mostly used efficient optimization algorithms. Instances for some of optimization algorithms are: Genetic algorithm (GA), Simulated Annealing techniques (SA), etc. Genetic algorithm belongs to a new generation type of methods called Evolution Algorithms (EA) and the method which also belongs to evolution algorithm is called differential evolution (DE). The computational time of differential evolution is less than genetic algorithm and evolution algorithm which accurately solve problems which are difficult to solve or are difficult to formulate mathematically. The sake of Yerramsetty and Murty (2008)'s work is to formulate a differential evolution based model (DEM) for solving the HEN synthesis problem and then comparing is performance with other methods. In general, differential evolution based model decomposes the problem into subproblems. However, differential evolution in this work is modified to simultaneously optimize the HEN. Since minimum approach temperature (MAT) is the significant parameter affecting the cost of HEN. In this work, HEN with very low or very high minimum temperature approach is eliminated automatically and then optimized accurately in the solution process. They demonstrated that the proposed HEN synthesis model without assumption of isothermal mixing considering stream splitting is robust and also accurate in evaluating the global cost of network. Notwithstanding, this cost models do not deliberate the costs associated with the stream splitting.

The easy way to deal with phase changes is done by assuming isothermal conditions; however, it may give inferior or unacceptable networks, especially in the case of multicomponent phase changes. To ameliorate the networks, Hasan *et al.* (2010) modified stagewise superstructure by Yee and Grossmann (1990). In addition, they proposed the MINLP formulation to approximate non-isothermal T-H via empirical cubic correlations and a solution algorithm (iterative algorithm) to ensure minimum temperature approach at any points in heat exchangers. Not only does the model allow mixture condensation and evaporation but it also allows multiple utilities, bypass any stages completely.

With the reason of high computational time, especially for large-scale HEN synthesis, specially -tailored genetic algorithm based on a hybrid genetic algorithm can overcome this difficulty and also increase the quality of the solution.

This method combines genetic algorithm and the idea of subnets which each subnet considered and treated as a single subproblem. Therefore, each of subproblems can be solved easily by genetic algorithm and then the combined single subnets are solved again by the same algorithm. The method by Brandt *et al.* (2012) provided a HEN with higher amount of subnetworks which seems to have the presence of fewer heat exchangers. Furthermore, they demonstrate the application of their method through a very large scale problem which finally obtains better results and computational effectiveness compared to the application of genetic algorithm.

To develop more efficient and superior algorithm for synthesizing large HENs and to solve a complex non-convex MINLP models, Huang and Karimi (2014) improvised a tailor-made heuristic search strategy to modify the outer approximation with equality relaxation and augmented penalty (OA/ER/AP) algorithm which does not need a feasible initial point as original approach by Viswanathan and Grossman (1990). Their tailor-made search strategy propose three smaller and simpler modifications of MILP master problem (MP) that prioritize, limit, fix or eliminate some heat exchanger in different ways. The better HEN without premature termination is provided. They clarified the computational effectiveness and efficiency by giving seven examples from literatures about of the application of their strategy to two recent HENS of Huang et al. (2012) based on modified stagewise superstructure and Huang and Karimi (2013) presents a new multistage superstructure. Their algorithm demonstrates more computation effectiveness than the commercial MINLP solvers and also provides, even in large problem with 39 process streams, good or better solution compared to solutions reported in the literature.

2.3 HEN Retrofit

In contrast to HEN synthesis, the retrofit design has no standard formulation to deal with the fixed cost of structural changes. Systematic identification of optimal retrofit designs is considerably more difficult than for grassroots networks since they are case-dependent (Sieniutycz and Jeżowski, 2009). In recent years, the redesign of an existing network can often reduce the operating costs in a process. In addition, a network may require redesign when process modifications in the plant alter the conditions of the process streams (Yee, Grossmann and Carnegie Mellon University. Engineering Design Research Center, 1988). The major objectives of retrofit design are the reduction of utility use in the existing network, the full utilization of the existing heat exchangers, and the identification of the required structural modifications (Ciric and Floudas, 1990). The improved heat recovery for the HENs can be achieved through various retrofit techniques, including implementing intensified heat transfer techniques, adding additional heat transfer area, installing new exchangers, and reconfiguring heat recovery structure (e.g. repiping) (Bulatov *et al.*, 2013). Physical heat exchanger retrofit is achieved by either structural or parameter changes. In general, structural modifications can be grouped into four broad categories. New exchangers can be purchased, the area of existing exchangers can be increased or decreased, streams can be repiped, and existing exchangers can be reassigned from one match to another. When formulating and solving HEN retrofit optimization, logical conditions and binaries are required causing the difficulties on structural changes. The later ones mean the increase or decrease of surface area and also the addition of new splitters, mixers and heat exchangers. However, most of retrofit designs focus mainly on the changes of heat exchangers.

In common with HEN synthesis, there are two main classes in retrofit design: insight-based and optimization-based. In case of insight-based methods, they are based on the pinch concept. The first effort is addressed in Tjoe and Linhoff (1996). The firstly determine level of energy recovery by targeting step and then evolve by using heat loops and paths to a retrofit network. Although they achieve some targets, they do not account an investment cost. The method of Yee and Grossmann is presented in the series of works (Yee and Grossmann, 1987, 1988, 1991). In 1987, they first develop the MILP assignment-transshipment model to predict the structural changes to obtain a certain level of energy recovery (HRAT). The objectives are to maximize the use of the existing exchangers, minimize addition of new units and then minimize the reassignment of existing units to different streams. However, for the retrofit case, since capital cost causes mainly from revamping on the network, those cannot account for the trade-offs between energy and capital costs existing network. Thus, it is necessary to simultaneously consider both energy and modification costs. After that, Yee and Grossmann propose two sequential stages of prescreening and optimization.

The prescreening stage evaluate economic retrofit feasibility of existing HEN by calculating the lower bounds of utility cost, additional area and structural modifications relative to various heat recovery approach temperature. Then, the best saving cost is chosen. In the next stage, the novel superstructure with fixed number of units is constructed. The objective of optimization stage is to determine a retrofit network with least total annual cost. In order to properly tradeoffs between capital and energy cost, energy recovery, heat loads, EMAT, and stream matches are need to be optimized. Finally in 1991, they developed a one-stage approach (simultaneous approach) to address structural changes cost and additional area cost by applying a complex but general superstructure specific for HEN retrofit (Yee and Grossmann, 1998).

In 1989, the primary work of Ciric and Floudas presented a two-stage approach of the stages of MILP and NLP to the retrofit problem. The former stage selects process stream matches and match-exchanger assignment to minimize investment cost based on the estimates of required heat-transfer area. The aim of the later one is to minimize the total modification cost and provide the actual retrofit network formulated based on a postulated network superstructure.

In this contemporary work, Ciric and Floudas (1990) presented one-stage approach of a MINLP to simultaneous selects process stream matches, match-heat exchanger assignments and optimize network structure. Furthermore, their formulation considers the piping costs from the actual network configuration, heat-transfer rating, different types of exchangers, heat-transfer coefficients as well as pressure drop for existing heat exchangers. To solve the MINLP, the Generalized Benders Decomposition technique that the first subproblem (master subproblem) selected the process stream matches and heat loads and the second substream (primal substream) determined the optimal network configuration and match-exchanger assignments is introduced.

Asante and Zhu (1996) proposed the new two-stage retrofit procedure, a diagnosis stage and an optimization stage. The diagnosis stage is introduced to identify and select promising topology modifications to be made to the initial HEN. The optimization stage, then, produces the final retrofit design by optimizing the heat exchanger area, configuration and branch flowrates of any stream splits. The advantages of automated approach are that the procedure is automated, users are able to interact over the design process and combine the features of pinch and mathematical programming techniques. This method cannot guarantee the solution with the minimum cost retrofit designs; however, this ensures not only the simple and practical configurations but also the retrofit cost close to the minimum.

Athier et al. (1998) developed a new two-level procedure derived from their proposed grassroots model for retrofitting HEN considering the placement/assignment of existing and new exchangers, additional area requirement and the cost of repiping. The upper level using a simulated annealing algorithm to propose the configurations of network where provided topology will be used in a lower level of NLP to determine the optimal area of new and existing exchangers.

Due to the problems of pinch technique that not involving the implementation cost and providing many modifications, Zhu and Asante (1999) proposed a new modeling approach for HEN retrofit design to estimate modification cost for all potential options prior to design, allow for both automated and interactive generation of retrofit design and solve the large industrial problems. The design procedure, not requiring a predefined heat recovery as an initial for design process, consists of diagnosis stage, an evaluation stage and a cost optimization stage. The first stage is introduced to search for topology changes with the objective function of maximization of heat recovery potential. To obtain the promising options by screening out the impractical options from the first stage, the evaluation stage is used to estimate the cost for topology changes and also consider the safety and operability issues. In the final stage of optimization, the selected options are optimized by simultaneously trading off between the capital investment cost and energy recovery. In this stage, none of the exchangers in network is relocated except the exchangers involving in stream split configurations.

To reduce solution time and generate good solution, two-step approach of screening and optimization is required. Ma (2000) used the Constant Approach Temperature (CAT) model to find the possible network structure in the first step where the area calculations are liberalized and the model could be solved as a MILP problem. To finalize the HEN, an MINLP model is then used in the second step where the actual approach temperature is considered.

Besides pinch analysis, the mathematical programming methods is used to find the cost optimal network structures among the various structures because a rigorous optimization of the structure, sizes of heat exchangers and utility usage can be achieved. Björk and Nordman (2005) modified the Synheat model using superstructure. It limits the feasible region more than the original Synheat model did where the constraints in modified model are used to ensure that existing heat exchanger is used at once. To describe whether an existing area is high enough or additional area is needed; some extra binary variables are required. Even though the extra constraints will fasten the solution time, they will decrease the quality of the solutions but not in very essential manner. Duo to a non-convex MINLP model, the authors relied on a hybrid solution strategy which is not sensitive to the large-scale problems. It composes of a genetic algorithm decomposing the large problem into several subproblems and performing the assignment of streams into subproblems and a deterministic optimization method optimizing the design and operational conditions within each subproblem.

In 2008, Ponce-Ortega *et al.* modeled a MINLP formulation to consider simultaneously HEN structures and operational and structural process modifications. It, also, considers the plant layout. As a consequence, it allows repiping the reassignment of existing exchangers to different streams in order to maximize the use of existing area and heat exchangers. For complex network configuration, the superstructure without the assumption of no bypass streams, no stream splitting as well as isothermal mixing. The model also considers the fixed and variable cost of piping depending on the distance and the flow rate and the relocation of a given heat exchanger. Furthermore, it considers explicitly the utility and capital cost of units and also isothermal process streams usually involving in chemical process. Since the MINLP is non-convex, the optimal solution can only be guaranteed with the optimization methods. Otherwise, the near optimal solutions are obtained by the local methods.

Since the existing network pinch approach assumed constant thermal properties of streams, not considered stream split fraction and achieved cost optimization after the diagnosis stage, the design cannot guarantee the cost of selected potential modifications. Smith *et al.* (2010) modified and extended the network pinch approach by Asante and Zhu (1996) to eliminate these restrictions. To handle with the streams where thermal properties are highly dependent on temperature, the multi-segment formulations are employed. The entire rage of temperature is decomposed into several intervals of constant thermal properties. In their work, the node-based representation is employed where each node is related to its temperature that means a new node is defined only if the temperature varies. Since the multi-segmented stream data are employed, the equations are nonlinear with the respect to temperature. Therefore, the node temperatures are calculated sequentially. After that, the area for each exchanger is calculated and then compare to the existing one of each exchanger. In the new network pinch approach, the structure search in diagnosis stage and the cost optimization is combined into one-stage approach to avoid missing potentially cost effective designs in diagnosis stage by ranking the cost of the alternative designs. To solve with this nonlinear problem, the SA algorithm is applied because it provides good quality solutions and can handle many constraints in formulation with a small number of simplifications to the HEN models to ensure solving convergence. However, it requires high computational time. In order to in improve computational time, the SA algorithm is modified to run model one time in searching one type of structural modification even though its solution is slightly worse than those obtained from running model hundred times.

In 2010, Kovac retrofitted heating of natural gas in the methanol process by adding additional equations and constraints to MINLP stage-wise model by Yee and Grossmann. The proposed model takes an account for use of existing and new exchanger area but not considers the displacement of existing exchangers.

Apart from new rigorous one-step MILP formulation for HEN synthesis, Nguyen *et al.* (2010) also proposed a model for retrofit design considering the addition and relocation of heat exchangers allowing control of repiping costs as well as splitting. The model employs a one-step strategy to not only simultaneously optimize both the network structure and the heat exchanger areas but also consider all the costs associated with new shells, area addition to existing shells, relocation, and piping changes from which the network topology changes. In contrast to one step design, they considered step-wise changes that provide an optimal solution (or at least near optimal solution) within an acceptable time by running model with the limitation on the number of new units and the number of relocation. If doing that, a range of solutions, not just one, are obtained and then chosen the best one by the user decision.

In contrast to other previous works that are nonlinear and hard-to-solve-globally, the linear programming model is used to optimize a network by proper selection of heat transferred between hot and cold intervals and provide a globally optimal solution. In the case of retrofit design, the pinch technology is much more heuristic procedure that requires experience in trial and error than systematical algorithm and it may obtains non-optimal solutions because the capital cost could be miscalculated in targeting step but calculated only in design step. Besides, some problems are arise in the case of crude units such as having only one cold stream versus many hot streams at the pinch causing unrealistic designs, having second pinch, exhibiting of extended pinch or continuous pinch, obtaining the excessive number of units due to the tick-off rule and having many various options to explore by hand. Thus, Bagajewicz *et al.* (2013) proposed Heat Integration Transportation (HIT) model which is mathematical programming-based MILP model. Unlike pinch technology, Heat Integration Transportation (HIT) model does not rely on a sequence of targeting followed by design step. It simultaneously takes into account the trade-offs between energy saving and capital costs. Since the model is linear, the linear solver can be applied. They, also, demonstrated that the pinch technique is excessive and unrealistic in terms of the number of splits and it less saving and more complex than HIT model. Since the retrofit design based on pinch technique consists of two main stages, (i) retrofit targeting and (ii) retrofit design. The main objectives of the first task are saving more energy and capital investment cost.

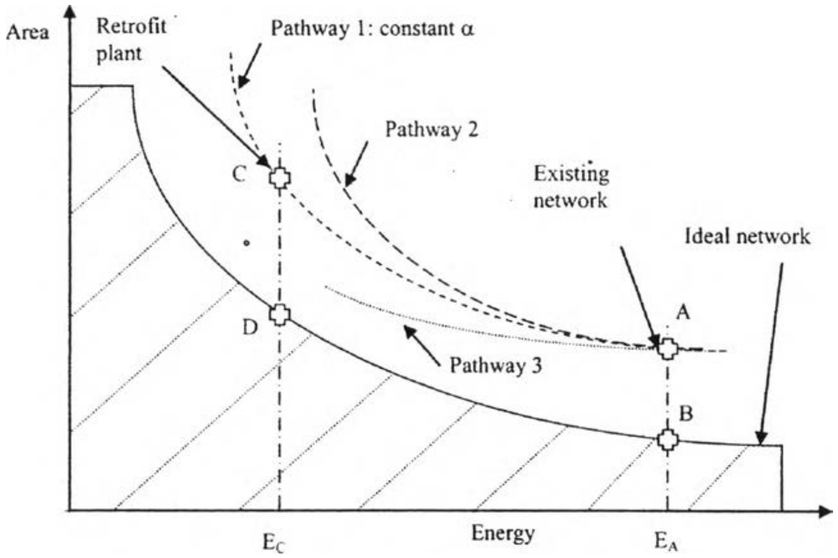

Figure 2.1 Energy versus area curves (Bagajewicz *et al.*, 2013).

(i) Retrofit targeting: The graph of energy and area indicates (A) the existing network (usually having some heat transfer crossing the pinch), (B) the minimum-area network without heat crossing the pinch (ideal network) resulting from vertical heat transfer at the same energy consumption as (A). Point (C) is the retrofitted plant with the reduce energy consumption and point (D) is the retrofitted plant with the reduced energy consumption of the minimum area network. As shown in this graph, there are three different pathways, pathway 1 ($\alpha_r = \alpha_e$), pathway 2 ($\alpha_r<\alpha_e$) and pathway 3 ($\alpha_r>\alpha_e$); $\alpha_e = (A_A/A_B)_{\text{same energy at A}}$,$\alpha_r= (A_D/A_C)_{\text{same energy at C}}$. Both the estimated capacity investment and energy saving increase along with the moving on the pathway 1 (constant α). However, the net present value is used to evaluate the trade-off between energy saving and investment cost.

(ii) Retrofit design: Bagajewicz *et al.* summarized the retrofit design methodologies from Kemp (2007) as the following: (1) Obtain a grassroots design for targeted energy consumption. (2) Start with the existing network and the remove the cross-pinch and complete the HEN design. (3) Start with the existing network and identify the most critical changes required in the network structure to give a substantial energy reduction. However, it is difficult to obtain the optimal retrofit design since this task relies on the user experience, insightful knowledge about process and some guesses.

In contrast to heat exchanger synthesis, heat exchanger network retrofitting is a promising solution to decrease current energy consumption in existing process industries. It can be enhanced by using some algorithm or/and mathematical programming based methods to solve problems. In this work, Sreepathi and Rangaiah (2014) concentrated on techniques to solve HEN retrofitting problems and then study the effect of exchanger reassignment on the solution of HEN retrofitting problems. They also propose and use various exchanger reassignment strategies (ERS) based on mathematical programming methods to reduce complexity and computational load of the problems. The limitation on area addition is more practical, therefore, their proposed strategy limit on area addition to an existing exchanger. Due to considering on none of additional area above their limit, a new heat exchanger will be installed to meet the retrofit requirement and thus the investment cost may be higher than the strategies with no restriction on additional area. After formulating, the proposed exchanger reassignment strategies are performed by single objective optimization (SOO) using the recent integrated differential evolution (IDE). The single objective optimization usually provides an optimal solution, total annualized cost. Apart from single objective optimization, multi-objective optimization (MOO) provides many solutions and obtains Pareto-optimal solutions which one can be selected for practical implementation. NGPM, which is an implementation of non-dominated sorting genetic algorithm II (NSGA-II), is used to solve heat exchanger retrofitting problems for multi-objective optimization.

In 2012, Siemanond and Kosol developed pinch-technology retrofit procedure to lower utility consumption levels whereas minimize the capital investment cost. To retrofit the existing HEN of Crude Distillation Unit (CDU), they applied pinch analysis in targeting step to estimate the optimal HRAT, followed by design step at below and above pinch using stagewise model.

To determine the optimum approach temperature for HEN, Sharifah (2012) applied the Stream Temperature vs. Enthalpy Plot Supertargeting (STEPS) method instead of composite curves to eliminate the simplified assumption of single level utility, one type of exchanger and single heat transfer coefficient.

In 2014, Liu et al. proposed an effective technique based on stage-wise superstructure to fully utilize existing exchangers in the retrofitted HEN. To retrofit

HEN, the hybrid genetic algorithm was applied to the MINLP problem which is difficult to solve.

In practical, HEN retrofitting through the structure changes of existing HEN is uneconomic; therefore, Jiang et al. 2014 proposed an approach to improve level of heat transfer enhancement without any modification of network topology. In contrast to mathematical based optimization, an improved sensitivity analysis the optimizers can interact with the procedure and make a decision by considering the importance of practical constraints and user preference.