The Thesis entitled

SYNTHESIS AND OPTIMIZATION OF A THERMAL SYSTEM NETWORK IN A CHEMICAL PLANT USING GENETIC ALGORITHMS

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by

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CERTIFICATE

This is to certify that the thesis entitled **"Synthesis and Optimization of a Thermal System Network in a Chemical Plant Using Genetic Algorithms"** is prepared and submitted by **Mr. Neerajkumar Kabirdin Chavda** (Roll No. : 322) in fulfillment of the requirement for the award of the degree of "**Doctor of Philosophy in Mechanical Engineering"** of The Maharaja Sayajirao University of Baroda, Vadodara.

The Thesis is a record of his own work carried out under my supervision and guidance. The matter embodied in the thesis, to the best of my knowledge, has not been submitted for the award of any other degree or diploma of any institute or university.

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CERTIFICATE OF THESIS APPROVAL

Thesis entitled **"Synthesis and Optimization of a Thermal System Network in a Chemical Plant Using Genetic Algorithms"** by **Mr. Neerajkumar Kabirdin Chavda** is approved for the degree of "**Doctor of Philosophy in Mechanical Engineering**".

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ABSTRACT

One of the most frequent problems in industrial plants is the excessive energy consumption. It represents the most important contribution to the composition of the global cost of industrialized products. Although heat recovery systems are frequently studied in synthesis problems, great attention was drawn after the first energetic world crisis, during the seventies. Therefore, the study of alternatives to minimize the consumption of energy has increased.

Optimum and efficient use of energy through conservation and management is vital in any energy intensive industry. As there are many heat exchangers in a given chemical process plant, it is important to build the heat exchanger network optimally. The problem of synthesis of heat exchanger network may be defined as the determination of a cost effective network to exchange heat among a set of process streams, where external utilities may be used for any unfulfilled heat load.

To synthesize a heat exchanger network, process and cost parameters like set of hot streams to be cooled and set of cold streams to be heated with their inlet and outlet temperatures, flow rates, specific heats and heat transfer coefficients, available utilities with all the above mentioned parameters and cost law for heat exchanger area, with plant life and rate of interest are required.

Pinch Technology is one of the oldest and efficient tools to optimize the heat exchanger network of the chemical process plant. It is the state of the art technique for designing energy efficient processing plants. This technique is used to compute the theoretically minimum utilities consumption, area, units and total annual cost of production. It establishes key options for process modifications, energy recovery and targets for multiple utilities. There are two approaches of pinch technology viz., minimum temperature approach and minimum flux approach. Generally minimum temperature approach is applied to the heat exchanger networks having same values of heat transfer coefficients of the streams (exceptions are many) while the minimum flux approach is used for the heat exchanger network having different values of heat transfer coefficients. But, the application of minimum temperature approach is significant in case of same as well as different values of heat transfer coefficients of the streams as compared to minimum flux approach as found in literature. This aspect is also examined in the present work.

Modification analysis of any existing chemical plant demonstrates different alternative heat exchanger network configuration of the chemical plant to identify the configuration at which total annual cost is less than that of the existing chemical plant. Modification techniques in heat exchanger network can be classified into four broad categories like computer search, mathematical programming, inspection and pinch technology. The modifications in existing HEN using pinch analysis can be carried out by two methods, viz. (1) Network Pinch Method and (2) Retrofitting Analysis.

Pinch technology undoubtedly forms the core of process optimization by energy & resource analysis. However, Pinch technology supplemented with optimization methods offer an efficient and practical method for synthesis and optimization of thermal system network of a chemical plant for both new and modification projects. There are many optimization methods available to optimize

different problem domains. Broadly they are classified as traditional and non-traditional optimization techniques. Generally linear problems are easily optimized using any traditional optimization techniques. While non-linear problems, basically complex in nature are difficult to optimize using the traditional optimization techniques and chances to obtain local optimum value rather than global optimum value are more. To optimize non-linear problems, generally non-traditional optimization techniques are used. Genetic Algorithms is a relatively recent non-traditional optimization technique.

The synthesis and optimization using a combined approach of two methods of pinch technology, viz., minimum temperature approach and minimum flux approach and genetic algorithms and modifications using two methods of pinch analysis viz., network pinch method and retrofitting analysis can be considered as a unified approach to optimize a thermal system network of a chemical plant. To develop such a unified code, a case study is undertaken. Ammonia production process is a good example of a thermal system network consisting of a large number of heat exchanger networks in which heat exchangers are arranged in series and parallel carrying out heating and cooling of process fluids, apart from components dedicated for both exothermic and endothermic chemical reactions. Thus, an ammonia production plant which is a part of a fertilizer industry situated in Gujarat is selected and a typical set of online data is acquired during a normal operation. The stream data of the network consists of 33 numbers of heat exchangers having 5 different types of heat exchanger configuration, 32 hot and 26 cold streams. Though, the plant must have been designed and commissioned using a proven synthesis and

optimization technique, it may be beneficial to look into its total annual cost through the present unified code developed with reference to synthesis, optimization and modification analysis.

As a first step, existing heat exchanger network of the ammonia plant is optimized using genetic algorithms for two approaches of pinch technology. The maximum possible saving in total annual cost of production of ammonia using minimum temperature approach and minimum flux approach are found to be 3.14 % and 15.73 % respectively. However, it is found that the pinch temperature using minimum flux approach is very high at 985.75 ^{O}C while that obtained using minimum temperature approach is only 128 ^{O}C. Based on the above results, the possibility of modification is identified.

Two modification techniques based on pinch analysis, viz., network pinch method and retrofitting analysis are employed to modify the existing heat exchanger network of the ammonia plant. Using network pinch method along with minimum temperature approach, it is seen that there is a scope for reduction in both hot and cold utilities by 1758 kW and reduction in area of heat exchanger network by 368 m^2 which results in decrease of total annual cost by 1.71 %. Further using retrofitting analysis along with minimum temperature approach, it is possible to reduce the hot and cold utility requirements by 507 kW and 292 kW for existing area efficiency and ideal area efficiency with a pay back period of 1.69 years and 0.80 years respectively.

Using network pinch method with minimum flux approach indicates the same level of reduction in utility requirements with substantial reduction in area of heat exchanger network by 136 m^2. However, the reduction in total annual cost is by 1.30 %. Retrofitting analysis with minimum flux approach indicates the reduction in the utility requirements with respect to existing area efficiency and ideal area efficiency with a pay back period of 38.68 years and 13.49 years respectively, which is very high.

The outcomes of the present work are as follows:

(1) The optimized value of area and TAC of HEN is minimum using Q_{min} approach which agrees well with the earlier studies. But, the limitation of Q_{min} approach observed is that, it yields very high practically unrealistic value of pinch temperature as compared to ΔT_{min} approach which limits the application of the approach to carry out further modification analysis.

(2) Modification using network pinch method reduces total annual cost of heat exchanger network for the ammonia plant. Thus, modification using network pinch method is preferable over retrofitting analysis for the case under investigation.

(3) Based on the present study, the unified approach of synthesis and optimization using genetic algorithms through minimum temperature approach and modification using network pinch method is proposed for the case under investigation.

CONTENTS

NOMENCLATURE

a	Cost law co-efficient for calculating total annual cost
a_r	Cost law co-efficient of reference type heat exchanger for calculating total annual cost
a_s	Cost law co-efficient of special type heat exchanger for calculating total annual cost
A	Area of HEN
$A_{additional}$	Requirement of additional area for the HEN
$A_{c,ti}$	Area of HEN for counter current specification of heat exchanger in the temperature interval, ti
A_{exist}	Area of HEN in existing HEN
A_f	Annualization factor
A_{ideal}	Area of HEN at existing utility requirement
A_{ideal1}	Area of HEN at various utility values other than existing utility requirement
A_m	Modified area of HEN
$A_{max,retr}$	Maximum area for retrofitting
A_{ti}	Area of HEN for shell and tube heat exchanger specification of heat exchanger in the temperature interval, ti
A_{GA}	HEN area required after optimization through GA
A_{HX}	Area of the heat exchanger
A_{NPM}	HEN area after modification using NPM
A_{RA}	HEN area after modification using RA
b	Cost law co-efficient for calculating total annual cost
b_r	Cost law co-efficient of reference type heat exchanger for calculating total annual cost
b_s	Cost law co-efficient of special type heat exchanger for calculating total annual cost
c	Cost law co-efficient for calculating total annual cost
c_r	Cost law co-efficient of reference type heat exchanger for calculating total annual cost
c_s	Cost law co-efficient of special type heat exchanger for calculating total annual cost
cu_{exist}	Cold utility needed in existing HEN
cur	cold utility required
cur_{GA}	Cold utility requirement after optimization through GA
cur_{NPM}	Cold utility required after modification using NPM
cur_{RA}	Cold utility required after modification using RA
C	Capacity flow rate of the stream
C_c	Capacity flow rate of cold process stream
C_{cu}	Cost of cold utility
C_h	Capacity flow rate of hot process stream

C_{hu}	Cost of hot utility
C_{ti}	Net capacity flow rate in the temperature interval, ti
CC	Capital cost of HEN
CC_{exist}	Capital cost of existing HEN
CR_{cu}	Capacity flow rate of cold utility stream
CR_{hu}	Capacity flow rate of hot utility stream
CC_{GA}	Capital cost after optimization through GA
CC_{NPM}	Capital cost of HEN after modification using NPM
CC_{RA}	Capital cost of HEN after modification using RA
$CumQ_{h,ti}$	Cumulative enthalpy of hot process and utility stream in the temperature interval, ti
$CumQ_{h,ti-1}$	Cumulative enthalpy of hot process and utility stream in the previous temperature interval, ti-1
$CumQ_{ti}$	Cumulative enthalpy of hot process and utility and cold process and utility streams arranged in ascending order at the temperature interval, ti
$CumQ_{ti-1}$	Cumulative enthalpy of hot process and utility and cold process and utility streams arranged in ascending order at the previous temperature interval, ti-1
$(C/h)_{c,ti}$	Ratio of capacity flow rate to heat transfer coefficient of cold process stream in the temperature interval, ti
$(C/h)_{h,ti}$	Ratio of capacity flow rate to heat transfer coefficient of hot process stream in the temperature interval, ti
$C_{cp,ti}$	Capacity flow rate of cold process stream in the temperature interval, ti
$C_{hp,ti}$	Capacity flow rate of hot process stream in the temperature interval, ti
F_{ti}	Correction factor for the temperature interval, ti
h	Heat transfer co-efficient of stream
h_c	heat transfer co-efficient of cold process stream
h_{cu}	Heat transfer co-efficient of cold utility stream
h_h	heat transfer co-efficient of hot process stream
h_{hu}	Heat transfer co-efficient of hot utility stream
h_j	Heat transfer co-efficient of a stream
$h_{m,j}$	Modified heat transfer co-efficient of a stream
hu_{exist}	Hot utility needed in existing HEN
hur	hot utility required
hur_{GA}	Hot utility requirement after optimization through GA
hur_{NPM}	Hot utility required after modification using NPM
hur_{RA}	Hot utility required after modification using RA
i	Number of generation
$LMTD_{ti}$	Logarithmic mean temperature difference in the temperature interval, ti
maxgen	Maximum number of generation

$MinQ_{cas}$	Minimum value of cascaded heat among all the temperature interval
N_a	Number of process and utility streams in above pinch region
N_b	Number of process and utility streams in below pinch region
$N_{s,ti}$	Number of stream present in the temperature interval, ti
$N_{u,mer}$	Minimum number of unit
$N_{variable}$	Number of variable
NS_{ti}	Rounded up value of number of shell required per match in the temperature interval, ti
OC	Operating cost of HEN
OC_{exist}	Operating cost of existing HEN
OC_{GA}	Operating cost after optimization through GA
OC_{NPM}	Operating cost of HEN after modification using NPM
OC_{RA}	Operating cost of HEN after modification using RA
popsize	Population Size
P_{cross}	Crossover probability
$P_{e,ti}$	Temperature effectiveness for individual shell and tube heat exchanger for the temperature interval, ti
$P_{mutation}$	Mutation probability
P_{ti}	Temperature effectiveness for the temperature interval, ti
Q_c	Heat load of cold process stream
Q_{cu}	Heat load of cold utility stream
Q_h	Heat load of hot process stream
Q_{hu}	Heat load of hot utility stream
$Q_{cas,ti}$	Cascaded heat in the temperature interval, ti
$Q_{cas,ti-1}$	Cascaded heat in the previous temperature interval, ti-1
$Q_{h,ti}$	Enthalpy of hot process and utility stream in the temperature interval, ti
Q_{ti}	Net enthalpy in the temperature interval, ti
$Q_{cu,min}$	Minimum requirement of cold utility.
$Q_{hu,min}$	Minimum requirement of hot utility.
Q_{HX}	Heat load of the heat exchanger
r	rate of interest
$R_{cas,ti}$	Revised cascaded heat in the temperature interval, ti
R_{ti}	Capacity flow ratio for the temperature interval, ti
$R_{variable}$	Range of variable
S_{min}	Minimum number of shell
$S_{m,ti}$	Number of shell required per match in the temperature interval, ti
S_{ti}	Number of shell needed in the temperature interval, ti
$Sum(Q/h)_{ti}$	Summation of ratio of heat to heat transfer coefficient in the temperature interval, ti
SCF_{ti}	Shift compensating factor for the temperature interval, ti
$t_{c,in}$	Inlet temperature of cold process stream

$t_{c,in,shifted}$	Shifted inlet temperature of cold process stream
$t_{c,out}$	Outlet temperature of cold process stream
$t_{c,out,shifted}$	Shifted outlet temperature of cold process stream
$t_{cu,in}$	Inlet temperature of cold utility stream
$t_{cu,out}$	Outlet temperature of cold utility stream
$t_{h,in}$	Inlet temperature of hot process stream
$t_{h,in,shifted}$	Shifted inlet temperature of hot process stream
$t_{h,out}$	Outlet temperature of of hot process stream
$t_{h,out,shifted}$	Shifted outlet temperature of hot process stream
$t_{hu,in}$	Inlet temperature of hot utility stream
$t_{hu,out}$	Outlet temperature of hot utility stream
ti	Temperature interval
$T_{c,ti}$	Temperature interval for cold process and utility stream at the temperature interval, ti
$T_{c,ti-1}$	Temperature interval for cold process and utility stream at the previous temperature interval, ti-1
$T_{h,ti}$	Temperature interval for hot process and utility stream at the temperature interval, ti
$T_{h,ti-1}$	Temperature interval for hot process and utility stream at the previous temperature interval, ti-1
T_{in}	Inlet temperature of stream
T_{out}	Outlet temperature of stream
T_{ti}	Temperature in the temperature interval, ti
TAC	Total annual cost of HEN
TAC_{exist}	Total Annual cost of existing HEN
TAC_{GA}	Total Annual cost of HEN after optimization through GA
$TAC_{min,i}$	Minimum TAC of HEN in i^{th} generation.
$TAC_{min,i+1}$	Minimum TAC of HEN in $i+1^{th}$ generation.
TAC_{NPM}	Total annual cost of HEN after modification using NPM
TAC_{RA}	Total annual cost of HEN after modification using RA
$TAC_{\%saving}$	Percentage saving in TAC of HEN
U_{exist}	Utility needed in the existing HEN
U_{GA}	Utility requirement after optimization using GA
U_{saving}	Saving in utility requirement

Greek Letters

α_{exist}	Existing area efficiency of HEN
Δ	Difference
$\Delta\alpha$	Incremental value of area efficiency
τ	plant life
φ_j	Weighting factor for a special type heat exchanger
Σ	Summation

ABBREVIATIONS

BFW	Boiler feed water
CPSN	Cold process stream number
DMW	De-mineralized water
GA	Genetic algorithms
HEN	Heat exchanger network
HENS	Heat exchanger networks
HPAC	High pressure ammonia compressor
HPFV	High pressure flash vessel
HPSGC	High pressure synthesis gas compressor
HPSN	Hot process stream number
HTSC	High temperature shift converters
ILP	Integer linear programming
KDCR	Knockout drum condensate remover
KDRGS	Knockout drum raw gas separator
LMTD	Logarithmic mean temperature difference
LP	Linear programming
LPAC	Low pressure ammonia compressor
LPFV	Low pressure flash vessel
LPSGC	Low pressure synthesis gas compressor
LTSC	Low temperature shift converters
LTSGR	Low temperature shift guard reactor
MDEA	Methyl-diethanolamine
MILP	Mixed integer liner programming
MINLP	Mixed integer non-linear programming
NG	Natural gas
NLP	Non-linear programming
NPM	Network pinch method
PG	Process gas
PR	Primary reformer
PT	Pinch technology
Q_{min} approach	Minimum flux approach
RA	Retrofitting analysis
R_{cas}	Revised cascaded heat
SG	Synthesis gas
SR	Secondary reformer
ΔT_{min}	Minimum approach temperature
ΔT_{min} approach	Minimum temperature approach

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Chapter 1

INTRODUCTION

One of the most frequent problems in industrial plants is the excessive energy consumption. It represents the most important contribution to the composition of the global cost of industrialized products. Although heat recovery systems are frequently studied in synthesis problems, great attention was drawn after the first energetic world crisis, during the seventies. Therefore, the study of alternatives to minimize the consumption of energy has increased.

The past decade has seen significant industrial and academic efforts devoted to the development of process design methodologies that target energy conservation for a large variety of chemical process industries/plants. These efforts shifted from a unit-based to a system level approach, generally named as process integration. Process integration can be described as a holistic approach to the process design, modification and operation which emphasizes the unity of the process. The main researches in the field of process integration were focused towards the energy conservation in any industrial processes. These researches resulted in development of energy integration or heat integration technology. The application of these techniques enables the comprehensive view on the thermal interactions between chemical processes and the utility systems that surrounds them. The optimization of thermal interaction between chemical processes and the utility systems is possible through proper synthesizing, which is known as synthesis and optimization of thermal system network of a chemical plant.

One of the most extensively studied and single most important application area for thermal system network is synthesis of heat exchanger networks (HENS). The principle aspect of HENS can be found in the fact that most industrial processes involve the transfer of heat, either from one process stream to another or from a utility stream to a process stream. Consequently, the target in any industrial process design is to maximize the process-to-process heat recovery and to minimize the utility requirements. To meet this goal, industrial cost-effective heat exchanger network (HEN) is of particular importance.

The problem of HENS may be defined as the determination of a cost – effective network to exchange heat among a set of process streams, where any heating and cooling not satisfied by exchange among these streams must be provided by using external utilities (e.g., steam, hot oil, cooling water, refrigerants etc.). Additional constraints like plant layout, safety, flexibility, operability and controllability must also be accounted for. HENS of a chemical plant is not only important with respect to cost point of view, but also important with respect to the energy conservation point of view. In global scenario of energy deficit, proper synthesis not only reduces the energy requirement but it provides the better opportunities to utilize the same energy for another production leading to reduce overall energy requirements.

In industrial processes, there are streams that need cooling, and streams that need heating, usually achieved by using cold and hot utilities respectively. HENS is a mean to obtain heating and cooling by process streams energetic integration by using hot streams to heat cold streams, and cold streams to cool hot streams.

Much more effort has been put on research within this area to minimize the total annual cost considering mathematical model with grass root design only, but most practical cases today seem to be in modification situations. In addition, these models are likely to be either rigorous but not solvable for bigger or deficient and solvable for large-scale problems.

Pinch technology (PT) [1] is one of the oldest techniques available to optimize the process by energy and resource analysis and is one of the tools for solving the

HENS problem. It recognizes the setting targets, i.e. predicting, what is the best performance that can possibly be achieved by the process, before actually attempting to achieve it. Thus the use of PT allows the process design engineer to determine the minimum utility requirements, area, units, number of shells and total annual cost (TAC) prior to actual design of HEN. Along with such design, process designer can also consider the various constrains like size of a plant, piping requirements, availability of the utilities as on today as well as in future etc. Thus, while designing a HEN of a chemical plant at initial stage, if the fundamentals of PT are utilized, it will ensure the minimization of energy requirement for that HEN.

In the past, the HEN of a chemical plant was designed product line wise. While designing a HEN for a product, it is fixed that a feed has to pass from different stages like heating, cooling, distillation and some chemical reaction which will lead to increase or decrease of temperatures, concentrations etc. and as per requirements of the chemical product, the exchangers, furnaces, steams, circulating waters etc. were utilized and placed accordingly. It does not ensure the minimum energy utilization. In the chemical plant, fundamentals of PT can also be applied in order to reduce the energy requirement which is known as modification.

The modification of a chemical plant is a tedious and time consuming task. In the HEN, heat exchangers are a part of complex flow sequence for any chemical product which also has distillation columns, reactors, furnaces, steam generators etc. They are also placed in such a way that piping requirements in the HEN is less at that point of time. While suggesting modifications according to the fundamentals of PT, it may require the removal of some heat exchangers, adding of some heat exchangers, some piping modifications, utilizing hot utilities (i.e. steams, furnace gases) with other streams as compared to the match in existing condition. In actual scenario, it may not be possible to change matches between some streams considering the product sequence, space limitation etc.

PT undoubtedly forms the core of process optimization by energy & resource analysis. However, it can also be supplemented with structural optimization technique to create a powerful hybrid design tool. There are many optimization methods available to optimize different problem domains. Broadly they are classified as traditional and non-traditional optimization techniques.

Generally linear problems are easily optimized using any traditional optimization techniques. While non-linear problems, basically complex in nature are difficult to optimize using the traditional optimization techniques and chances to obtain local optimum value rather than global optimum value are more. This is because of the fact that, traditional optimization techniques work on finite deterministic rules. While locating optimum value using traditional optimization methods, they also require the additional data like value of first derivation, second derivation etc. Some of the traditional optimization techniques like Unidirectional Search Method, Direct Search Method, Gradient Search Method etc. can be used only for unconstrained objective function while some can be used for constrained objective functions.

To optimize non-linear problems, generally non-traditional optimization techniques are used. Non-traditional optimization techniques can locate the global optimum value and chances of being trapped in local optimum values are comparatively very less as they work on the probabilistic rule. Over the last decade, non-traditional optimization techniques have been extensively used as search and optimization tools in various problem domains including science, commerce and engineering. Now-a-days, many non-traditional optimization techniques like Simulated Annealing, Genetic Algorithms, Ant Colony Algorithm etc. are developed which verifies all the local optimum values and then locates the global optimum value.

Genetic Algorithms (GA) is a relatively recent non-traditional optimization technique. GA is a search algorithm based on the mechanics of natural selection and natural genetics. GA works on the survival of the fittest principle. GA efficiently exploits historical information to speculate on new search points with expected improved performance. It has been seen that due to the inherent capacity of GA to handle the complex objective function, its application in the real field problem has increased.

From a comprehensive review of literatures, it is seen that a large number of investigations are carried out to synthesize and optimize and then modify energy intensive plants such as chemical, petrochemical, thermal etc. using traditional optimization tools. However, few investigations using non-traditional optimization tools on HENS of energy intensive plants in general and chemical plants in particular are reported in open literature. A unified approach of combining the two methods of PT using GA, a non-traditional optimization tool and two methods of modification analysis appears to have not reported in open literature. The present research is to develop such a unified approach and apply it to an existing ammonia production plant which is a part of a fertilizer industry.

The Thesis is organized in the following manner. A comprehensive literature review and the problem identified for research is presented in Chapter 2. Different methods available for production of ammonia, description of the ammonia plant under study and steady state data captured online from the plant are presented in Chapter 3. Chapter 4 describes the proposed unified approach of synthesis and optimization of HEN of a chemical plant using GA through two approaches of PT and modification in the existing HEN of the plant using two methods of pinch analysis. Results and discussions, on a case study based on the online steady state data acquired from the normal operation of the ammonia production plant of a fertilizer industry, carried out using the proposed unified approach is given in Chapter 5. Conclusions derived from the present study are presented in Chapter 6.

1.1 Theme of the Doctoral Work

The work proposed to be done for the doctoral work is planned as under.

(1) To study pinch technology as a tool of synthesizing the thermal system network and combining it with Genetic Algorithms, a non-traditional optimization method to optimize the heat exchanger network and to study the various methods of modification of existing heat exchanger network.

(2) To develop a unified approach of combining the two methods of PT using GA, a non-traditional optimization tool and two methods of modification analysis.

(3) To capture the steady state online data of an existing chemical plant located in Gujarat.

(4) To apply unified approach to an existing chemical plant to synthesize, optimize and modify the thermal system network and to propose the best combination to synthesize, optimize and modify the thermal system network under study.

Chapter 2

LITERATURE REVIEW

The different techniques developed by various investigators over a period of time for synthesis and optimization of a thermal system network of chemical plants are reviewed in this chapter. The earlier development in the HENS is PT and later on it is supplemented with the structural optimization techniques to obtain better results. Besides the designing of the HEN of a chemical plant prior to installation, the PT is also useful to synthesize and modify the HEN of an existing chemical plant.

The concept of “pinch technique” is introduced by Linnhoff and Flower [1], in 1978 to determine the minimum utility requirements in a HEN. However, the concept of HENS was initiated much earlier than the pinch technique is introduced. Broadly, the review may be divided as (1) Review of open literature before the introduction of pinch technology, (2) Introduction of Pinch Technology and (3) Review of open literature after the introduction of pinch technology. The following sections deal with the above broad division of literature.

2.1 Development before the Introduction of “Pinch Technology”

There are twenty two studies reported in open literature earlier to the introduction of the concept of the PT. They can further be sub divided into synthesis as well as optimization of HEN. There are a number of techniques developed during this period. The chronological order of a number of relevant published literatures is given in Table 2.1.

Table 2.1 Publications During Pre-Pinch Technology Era on Synthesis and Optimization of HEN

Sr. No.	Nature of Work	Type	Year wise number of published literature															
			1944	1961	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	Total
1	Synthesis	Article	1	1	-	-	-	-	-	-	1	-	-	-	1	-	1	5
		Thesis	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	1
2	Optimization	Article	-	-	1	-	-	1	2	1	1	1	1	1	2	1	3	15
		Thesis	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	1

From historical point of view, the HENS problem appears to have been introduced by Broeck [2], in 1944. The first attempt to systematically solve the HENS problem is reported by Westbrook [3], in 1961 by dynamic programming. In 1965, Hwa [4] used the separable programming and a superstructure including promising configuration to solve the problem of HENS. However, the real pioneers in the area are Rudd and coworkers at the University of Wisconsin and Hohmann and Lockhart at the University of Southern California. Rudd [5], in 1968 applied the decomposition theory for HENS. In 1969, Kesler and Parker [6] divided each stream into small heat duty elements of equal size and posed the matching between hot and cold elements as an assignment problem. The first rigorous definition of HENS is made by Masso and Rudd [7], in 1969. Lee et al. [8], in 1970 narrated the branch and bound synthesis of integrated process design. In 1971, Kobayashi et al. [9] improved the approach proposed by Kesler and Parker [6] by using the heat content diagram to allow for stream splits and cyclic matches. In the same year, Nishida et al. [10] introduced matching rules for minimizing total area.

Hohmann [11], in 1971 and Hohmann and Lockhart [12], in 1976 explained the feasible table, which is the first rigorous way to establish the minimum utility target using the Hohmann – Lockhart composite curves. A model to determine the minimum area of HEN in case of same overall heat transfer coefficients is presented. They also framed a rule which gives a close target to the minimum number of heat exchangers in a network. A very important part of their work is the feasible network solution space demonstrated by the area versus energy diagram for various values of minimum approach temperature (ΔT_{min}). The curve divided the space in feasible and infeasible solutions. They pointed out that the line actually defines an effective maximum number of units necessary to reach the area target. The same diagram has been used to discuss the threshold situation. When decreasing the value of ΔT_{min}, the energy consumption decreases while required heat transfer area increases. For some stream systems, there is a limiting value of ΔT_{min} where energy remains constant and the curve turns vertical.

Menzies and Johnson [13], in 1972 used branch and bound for the synthesis of optimal energy recovery networks including mechanical energy. In 1973, Pho and Lapidus [14] used partial enumeration and their synthesis matrix to synthesize the cost optimal HEN. Ponton and Donaldson [15], in 1974 and Donaldson [16], in 1976 suggested to match the hot stream with the highest supply temperature and the cold stream with highest target temperature. The general approach for dealing with different heat transfer coefficients is suggested by Nishimura [17], in 1975. Shah and Westerberg [18] in the same year explained the evolutionary HENS in order to minimize the TAC of HEN. Again in the same year, Rathore and Powers [19] used forward branching to avoid the generation and evaluation of infeasible solutions. Nishida et al. [20], in 1977 refined the approach proposed by Nishida et al. [10] by including the utilities in the minimum area algorithm. During the same year, Cena et al. [21] introduced the rules for constraints and multiple utilities, Kelhan and Gaddy [22] used the synthesis matrix proposed by Pho and Lapidus [14] for adaptive random search and Wells and Hodgkinson [23] presented an extensive list of heuristic rules for general process synthesis consideration. Based on the above mentioned studies, the concept of pinch technology evolved in 1978 due to Linnhoff and his associates.

2.2 Introduction of "Pinch Technology"

Linnhoff and Flower [1], in 1978 and Linnhoff [24], in 1979 introduced for the first time the concept of heat integration and developed the pinch technique. The technique is used for determining the minimum utility requirements for a process and identifying the best possible degree of heat recovery as a function of the ΔT_{min}. They selected the value of ΔT_{min} based on designers' experience and developed a problem table algorithm. Using the algorithm, pinch point and the minimum utility requirement of HEN are estimated for a specific value of ΔT_{min}. Since then, the PT based techniques have found application in a wide range of energy system designs, including distillation column profiling, low temperature process design, batch process integration and waste water minimization. The introduction of PT thus widened the area of process integration.

2.3 Development after the Introduction of "Pinch Technology"

Since the pioneering work of Linnhoff and associates, PT has been refined from time to time and supplemented with structural optimization techniques to optimize various thermal systems in general. In particular, various optimization techniques are employed to optimize HEN. Also modification techniques are introduced to modify HEN of existing chemical plant.

The progress in the synthesis, optimization and modification without and with GA as an optimization tool can be grouped as follows:

(i) Refinement in PT

(ii) Optimization of HEN using techniques other than GA

(iii) Development in GA

(iv) Application of GA in thermal engineering field

(v) Application of GA in HEN

(vi) Development in modification techniques

(vii) Modification in chemical plant excluding ammonia plant using techniques other than GA

(viii) Modification in ammonia plant excluding GA

(ix) Modification in chemical plant using GA

Table 2.2 gives a chronology of the progress in number of research literature covering the above groups. The detailed review of literature pertaining to each one of the groups is given in the following sections.

Table 2.2 Progress in Publications in Various Groups (I) To (IX)

Sr. No.	Topic	Type	Year wise publications available in open literature																																			
			1967	1969	1973	1975	1978	1979	1980	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	**Total**
1	Refinement in pinch technology	Article					1	2		2	3	5	2	5		1	5	4	1				2	1					1		2				1		3	1	**42**
		Thesis											2				1																						**3**
2	Optimization of HEN using techniques other than GA	Article						2			3	2	2	3		2	2	6	1	1	1	2	2	4	7	1	4	2	4	1	2	4	2	2	2	5	1	1	**71**
		Thesis																																	1				**1**
		Review																1																					**1**
3	Development in GA	Article				2								1	1		1		2	1		2	5	2	1			2	2	1	1	1			1				**26**
		Thesis	1																																				**1**
4	Application of GA in thermal engineering field	Article																						3				3			2	1	1	3	5	4	5	2	**29**
5	Application of GA in HEN	Article																								2							2	1	3	3	4		**15**
		Review																																			1		**1**
6	Development in modification techniques	Article							1			1	3	4			1	1	1							1													**13**
7	Modification in chemical plant excluding ammonia plant using techniques other than GA	Article							1	1		1	2	1			3	1			1	2	1	1	2	3	2	3	2	2			2		2		4	1	**38**
8	Modification in ammonia plant excluding GA	Article		1	1																				2	1		1			1					1	1		**9**
		Review																																		1			**1**
9	Modification in chemical plant using GA	Article																															1	1			1		**3**

2.3.1 Refinement in PT

Many researchers have contributed towards the refinement in pinch technology since its pioneering introduction by Linnhoff and his associates in 1978 and 1979. Initially, reducing the energy consumption was the objective of the research. This created necessity to discover the important and fundamental concept like heat recovery pinch. The single most important concept for HENS is the heat recovery pinch that is discovered independently by Umeda et al. [25], in 1978 and Linnhoff et al. [26], in 1979. In 1979, Umeda et al. [27] in another paper presented the thermodynamic approach for the synthesis of heat integration systems in chemical processes. They proposed a principle to modify the process in such a way that heat is added to the heat sink above pinch and removed form the heat source below pinch. In the same year, the fundamental understanding of the heat recovery pinch, including the decomposition effect is presented by Linnhoff et al. [26]. Closely linked to the heat recovery pinch is the plus/minus principle, which is defined by Linnhoff and Parker [28] and Linnhoff and Vredeveld [29], in 1984 which was previously used by Umeda et al. [27]. Linnhoff et al. [30], in 1982 presented a user guide on process integration for the efficient use of energy, which included the application of multiple utility targeting, flue gas optimization, utility pinches and to some extent process modification. In the same year, Itoh et al. [31] introduced the heat demand and supply diagram to find the load and level for the utilities, to observe options for steam generation and how to integrate different processes on a site.

The design procedure for HENS after the discovery of the heat recovery pinch is the pinch design method which is presented by Linnhoff and Hindmarsh [32], in

1983. Cerda and Westerberg [33], in the same year formulated a mixed integer liner programming (MILP) method for the target which is transformed to a linear programming (LP) transportation problem by relaxation in order to avoid solving the original MILP problem. The minimum utility problem is solved by the LP transportation model by Cerda et al. [34], in 1983 and the minimum number of units by an MILP model that is transformed and solved repeatedly as LP problem. In 1978, Umeda et al. [35] modified the general approach dealing with different heat transfer coefficient introduced by Nishimura [17], in 1975. Townsend and Linnhoff [36], in the same year introduced a new target for area taking into account the individual film transfer coefficients for the streams. Townsend [37], in 1989 extended the work of Nishimura for the cases of different film coefficients. All the above investigations used either equal and/or unequal heat transfer coefficients for different streams. According to Townsend and Linnhoff [38] (1984) and Linnhoff and Ahmad [39] (1990), this approach yields true minimum area only when heat transfer coefficients of all the streams are same. A rigorous target for heat transfer area, even in the case of different film transfer coefficients, can be found by the LP transportation model put forward by Saboo et al. [40], in 1986b.

Wood et al. [41], in 1985 discussed the application of splitting, mixing and bypassing, including non-isothermal mixing to reduce the number of units. In the same year, Jones and Rippin [42] used LP to find all heat load distributions with the global minimum number of units, but still achieve maximum energy recovery. Also in the same year, Hall [43] and Ahmad [44] discussed how to incorporate exchanger type and material of construction into the capital cost target. Their suggestion is to adjust the film transfer coefficients to account for exotic materials of construction and exchanger configurations different from 1-2 shell and tube. The most extensive work on capital cost targeting and also on how to design for the capital cost is due to Ahmad [44]. The objective of his research is to add capital cost guidance to the pinch design method which steers the designer towards maximum energy recovery. He pointed out that the energy target will be violated if matches occur that transfer more heat across an interval temperature than cascaded by the problem table algorithm and introduced remaining problem analysis for energy and area. A similar statement is made by Rev and Fonyo [45], in 1986, who encountered hidden or pseudo-pinches when designing away from the pinch. The value of ΔT_{min} is obtained from experience, but if the elaborate trading off area, energy and units in the optimization stage indicates that the chosen ΔT_{min} is adequate or inadequate. If inadequate, a new ΔT_{min} is used at the targeting and the synthesis stage. The pinch point may change, resulting in a possible very different network. Even with experience in designing a certain type of process, the chosen value of ΔT_{min} may not be optimal. The idea of establishing the optimum value of ΔT_{min} ahead of design is presented by Ahmad [44], Ahmad and Linnhoff [46], in 1986 and Linnhoff and Ahmad [47, 48], in 1986. The philosophy taken is that the annual cost targeting to find a close to optimal ΔT_{min} is the crucial task. The network development may then be done by hand.

Engel and Morari [49], in 1988 discussed the limitations of the primary loop breaking method for HENS. Trivedi et al. [50, 51], in 1989 described a new dual temperature and multi pinch point design method for the HENS. In 1989, Ahmad and Smith [52] presented targets and design for minimum number of shells in HEN. Fraser [53, 54], in 1989 demonstrated the minimum flux approach (Q_{min} approach) for dealing with different film coefficients based on industrial practice. Linnhoff and Ahmad [39], in 1990 presented targets for minimum energy and capital cost in cost optimum HEN in case of different values of overall heat transfer coefficients of streams based on minimum temperature approach (ΔT_{min} approach). In the same year, Ahmad et al. [55] discussed targets and design for detailed capital cost model in cost optimum HEN, Hall et al. [56] explained the capital cost targets for HEN comprising mixed materials of construction, pressure ratings and exchanger types while Colberg and Morari [57] presented the model for area and capital cost targets for HENS with constrained matches and unequal heat transfer coefficients. Rev and Fonyo [58], in 1991 proposed a new concept, the diverse pinch concept for total cost targeting and the synthesis of realistic initial HEN for different heat transfer coefficients.

In 1995, Zhu et al. [59, 60] proposed a new method for HENS using area targeting procedure and applied the new method for the direct HENS with un-equal film coefficients based on the approach proposed by Rev and Fonyo. Rev and Fonyo [58], in 1991 and Shenoy [61], in 1995 illustrated that the Q_{min} approach is preferable over the ΔT_{min} approach for the cases of widely differing heat transfer coefficients. In 1996, Marechal and Kalitventzeff [62] proposed a new graphical technique for targeting the minimum cost of energy requirements. Jezowski et al. [63], in 2001 applied mathematical programming for loop breaking in HEN. In 2003, Brodowicz and Markowski [64] proposed the calculation of HEN for limiting fouling effects in petrochemical industry. In the same year, Ruyck et al. [65] widened the capabilities of pinch analysis through virtual HEN. Castier [66], in 2007 re-examined the pinch analysis and formulated new rules for utility targeting. In 2009, Costa and Queiroz

[67] extended the problem table algorithm for multiple utility targeting while Raskovic and Stoiljkovic [68] modified the pinch design method in the case of a limited number of process streams. In the same year, Gulyani et al. [69] established new approach for shell targeting of a HEN. In 2010, Serna-Gonzalez et al. [70] included the pumping cost in targeting TAC of HEN.

From above review, it is seen that the application of PT is based on the values of heat transfer coefficients of streams. It is also seen that the PT has been customized to incorporate the latest requirements of the industry. Along with enriching the PT, studies are also carried out to develop methods of optimization of HEN using different optimization techniques.

2.3.2 Optimization of HEN Using Techniques other than GA

During the period from 1979 to 2010, seventy two research publications [71-142] are available that deals with synthesis and optimization of HEN using different techniques other than GA. A critical review on the synthesis of cost optimal HEN related to industry is presented by Gundersen and Naess [143], in 1990. Though it is not possible to discuss all these research publications in the Thesis, it is necessary to discuss few chosen studies based on the application of PT using ΔT_{min} and Q_{min} approaches.

Thus, comparative study of thirty eight chosen research publications is carried out and presented in Table 2.3. It should be noted that literature on PT may be grouped into two, viz., systems of HEN with equal heat transfer coefficients on both the sides of stream and with unequal heat transfer coefficients on both the sides of stream. Each of the above may either employ ΔT_{min} or Q_{min} approach. From a review of thirty eight relevant published papers, it is found that thirty four papers are concerned with analysis through ΔT_{min} approach while the remaining four papers are that with Q_{min} approach. Further, it is seen that the total number of case studies carried out on various systems are eighty four and out of which fifty nine case studies are having unequal heat transfer coefficients of various streams. Out of fifty nine case studies, fifty two have been optimized using ΔT_{min} approach while only seven cases have been optimized using Q_{min} approach. These observations raise a question as to why number of studies using Q_{min} approach is insignificant as compared to that with ΔT_{min} approach with unequal heat transfer coefficients in various streams especially in the light of the observation made by Rev and Fonyo [58] and Shenoy [61]. Further, it is seen that a number of solution methodologies are developed for the synthesis and optimization of HEN.

Table 2.3 Classification of Literature Based on Steam Characteristics and Solution Methodologies other Than GA for PT

Sr. No	Name of Investigator	Year of Publication	Case Study Number	Number of Streams		Heat Exchanger Specifications	Heat Transfer Coefficients of various streams are	HENS Solution Methodology	Initial Solution Approach
				Process	Utility				
1	Linnhoff and Ahmed [39]	1990	1	9	2	U	Unequal	PDM	ΔT_{min}
2	Ciric and Floudas [91]	1990	1	4	2	U	Unequal	Simultaneous Match-Network Optimization Approach	ΔT_{min}
			2	4	2				
3	Gunderssen and Grossmann [90]	1990	1	5	2	U	Unequal	Heuristic Approach	ΔT_{min}
			2	4	2		Equal		
			3	6	2		Equal		
4	Lee et al. [87]	1990	1	4	2	U	Unequal	Simultaneous Optimization with NLP	ΔT_{min}
			2	10	2		Unequal		

5	Lee et al. [88]	1990	1	4	2	U	Unequal	Simultaneous Optimization with NLP	ΔT_{min}
			2	4	2		Unequal		
			3	6	2		Unequal		
			4	7	2		Unequal		
			5	4	2		Unequal		
6	Lee et al. [89]	1990	1	2	2	U	Equal	Simultaneous Optimization with NLP	ΔT_{min}
7	Jezowski [94]	1992	1	7	1	U	Unequal	SYNHEN Model	ΔT_{min}
			2	11	1	U	Unequal		
8	Daichendt and Grossmann [96]	1994	1	4	2	U	Equal	MINLP	ΔT_{min}
			2	10	2	U	Equal		
9	Zhu et al. [98]	1995	1	5	2	U	Unequal	Block Method	Q_{min}
			2	6	2	U	Unequal		
10	Zhu et al. [60]	1995	1	5	2	U	Unequal	Direct Synthesis	Q_{min}
			2	6	2		Unequal		
11	Athier et al. [102]	1996	1	4	2	U	Unequal	Simulated Annealing & NLP	ΔT_{min}
12	Zhu [109]	1997	1	4	2	U	Unequal	Block Decomposition Method	Q_{min}
			2	5	2				
13	Athier et al. [104]	1997	1	4	2	U	Unequal	Simulated Annealing & NLP	ΔT_{min}
14	Zamora and Grossman [105]	1997	1	4	2	U	Unequal	MINLP	ΔT_{min}
15	Kravanja and Glavic [107]	1997	1	20	2	NU	Unequal	Simultaneous Optimization	ΔT_{min}
16	Gundersen et al. [106]	1997	1	6	2	U	Unequal	Sequential Framework using MILP Transportation	ΔT_{min}
			2	6	2	U	Equal		
			3	4	2	U	Equal		
17	Zamora and Grossman [111]	1998	1	4	2	U	Unequal	MINLP	ΔT_{min}
			2	5	2	U	Unequal		
18	Athier et al. [144]	1998	1	7	2	U	Unequal	Simulated Annealing & NLP	ΔT_{min}
			2	2	2		Unequal		
19	Brioness and Kokossis [113]	1999	1	6	2	U	Unequal	Program Approach	ΔT_{min}
			2	10	2		Unequal		
			3	10	2		equal		
			4	9	2		Unequal		
20	Brioness and Kokossis [145]	1999	1	10	2	U	Equal	Program Approach	ΔT_{min}
			2	6	2		Equal		
			3	15	2		Equal		
			4	7	2		Equal		

21	Shethna et al. [116]	2000	1	41	1	U	Equal	MILP with Transportation Model	ΔT_{min}
22	Ma et al. [146]	2000	1	5	2	U	Unequal	Const. Approach Temp. Model	ΔT_{min}
			2	6	2	U	Equal		
			3	7	2	U	Equal		
23	Al- Riyani et al. [147]	2001	1	34	4	NU	Unequal	Retrofitting	ΔT_{min}
24	Ravagnani et al. [123]	2003	1	9	2	U	Equal of all PS	Detailed Heat Exchanger Design	ΔT_{min}
25	Frausto–Hernandez et al. [124]	2003	1	4	2	U	Unequal	MINLP along with Pressure Drop Effect	ΔT_{min}
			2	4	2		Unequal		
26	Lin and Miller [126]	2004	1	4	2	U	Unequal	Tabu Search Method	ΔT_{min}
			2	5	2		Unequal		
			3	10	2		Unequal		
27	Pintaric and Kravanja [125]	2004	1	7	2	U	Unequal	MINLP	ΔT_{min}
28	Hojjati et al. [128]	2004	1	4	2	NU	Equal	MINLP	ΔT_{min}
			2	4	2		Equal		
			3	9	2		Unequal		
29	Barbaro and Bagajewicz [129]	2005	1	4	2	U	Equal	MILP	ΔT_{min}
			2	7	2		Equal		
			3	10	1		Equal		
30	Pariyani et al. [132]	2006	1	4	2	U	Unequal	Randomized Algorithm	ΔT_{min}
			2	5	2		Unequal		
			3	10	2		Unequal		
31	Ravagnani and Caballero [134]	2007	1	4	2	U	Unequal	HENS along with detailed equipment design	ΔT_{min}
32	Vora and Prabhakaran [137]	2008	1	18	4	U	Unequal	Pinch Analysis and PDM	Q_{min}
33	Pettersson [136]	2008	1	4	2	U	Equal for PS	Geometric Mean Temperature Difference	ΔT_{min}
			2	5	2		Unequal		
			3	10	2		Equal		
34	Yerramsetty and Murty [138]	2008	1	4	2	U	Unequal	Differential Evolution	ΔT_{min}
			2	4	2		Unequal		
			3	10	2		Unequal		
			4	10	2		Unequal		
			5	9	2		Unequal		
35	Ravagnani et al. [139]	2008	1	4	2	U	Equal	Particle Swarm Optimization	ΔT_{min}
			2	11	2		Unequal		
36	Khorasany and Fesanghary [141]	2009	1	4	2	U	Unequal	Harmony search and sequential quadratic Programming	ΔT_{min}
			2	6	2		Unequal		
			3	10	2		Unequal		
			4	16	3		Unequal		

37	Gupta and Ghosh [142]	2010	1	4	2	U	Equal for all PS	Randomized Algorithm	ΔT_{min}
			2	5	2		Unequal		
			3	10	2		Equal		
38	Serna-Gonzalez et al. [70]	2010	1	6	2	U	Unequal	NLP along with Pressure drop	ΔT_{min}

U: Uniform, NU: Non-Uniform.

2.3.3 Development in GA

GA is a search algorithm based on the mechanics of "natural selection" and "natural genetics". It is an optimization tool based on Darwinian evolution and efficiently exploits historical information to speculate on new search points with expected improved performance. As the GA works on the "Natural Selection" and "Survival of Fittest" principle, it can handle complex and non-linear objective function with non-linear constraints. GA was mostly developed in the 1970s as an optimization toolbox, through some work had already been done in the field of evolutionary computation. In 1967, Bagley [148] introduced the words "Genetic Algorithms" and published the first application of GA. However, the first main contribution related to GA is attributed to Holland [149] and De Jong [150], in 1975. In 1975, John Holland and associates at University of Michigan developed GA to deal with the following objectives.

- To abstract and rigorously explain the adaptive processes of natural systems, and
- To design artificial system software that retains the important mechanism of natural systems.

Since its beginning, till date, it is supplemented with recent theories which make GA a powerful optimization tool. Table 2.4 gives the development in GA in chronological order while the list of few books in the field of GA is given in Table 2.5.

Table 2.4 Development in GA

Sr. No	Investigators	Year of Publication	Contribution to GA
1	Bagley, J. D. [148]	1967	The behavior of adaptive systems which employ genetic and correlation algorithms
2	Holland, J. H. [149]	1975	Adaptation in Natural and Artificial Systems
3	De Jong, K. A. [150]	1975	An analysis of the behavior of a class of genetic adaptive Systems
4	Grefenstette, J. J. [151]	1986	Optimization of control parameters for GA.
5	Baker, J. E. [152]	1987	Reducing bias and inefficiency in the selection algorithm, in GA and Their Applications
6	Krishnakumar, K. [153]	1989	Micro-genetic algorithms for stationary and non-stationary function optimization
7	Janikow, C. Z. and Michalewicz, Z. [154]	1991	An experimental comparison of binary and floating point representations in GA
8	Goldberg, D. E. and Deb, K. [155]	1991	A comparative analysis of selection schemes used in GA
9	Holland, J. H. [156]	1992	Genetic algorithms
10	Queipo, N. et al. [157]	1994	GA for thermo sciences research application to the optimized cooling of electronic components
11	Kolen, A. and Pesch, E. [158]	1994	Genetic local search in combinatorial optimization
12	Fonseca, C. M. and Fleming, P. J. [159]	1995	An overview of evolutionary algorithms in multi-objective optimization
13	Mahfoud, S. W. [160]	1995	Niching Methods for GA
14	Storn, R. and Price, K. [161]	1995	Differential evolution - a simple & efficient adaptive scheme for global optimization over continuous spaces
15	Chipperfield, A. et. al. [162]	1995	GA toolbox for use with Matlab
16	Miller B. L. and Goldberg, D. E. [163]	1995	GA, tournament selection, and the effects of noise
17	Blickle, T. and Thiele, L. [164]	1996	A comparison of selection schemes used in evolutionary Algorithms
18	Tamaki, H. et al. [165]	1996	Multi-objective optimization by GA
19	Back, T. et al. [166]	1997	Evolutionary computation: comments on the history and current state
20	Veldhuizen, D. A. V. and Lamont, G. B. [167]	2000	Multi-objective evolutionary algorithms: analyzing the state-of-the-art
21	Deb, K. [168]	2000	An efficient constraint handling method for GA
22	Schmitt, L. M. [169]	2001	Theory of GA
23	Deb, K. and Beyer, A. G. [170]	2001	Self-adaptive GA with simulated binary Crossover
24	Deb, K. et al. [171]	2002	A fast and elitist multi-objective GA: NSGA-II
25	Xue, F. et al. [172]	2003	Pareto-based multi-objective differential Evolution
26	Kim, K. W. and Baek, S. W. [173]	2004	Inverse surface radiation analysis in an axi-symmetric cylindrical enclosure using a hybrid GA
27	Lobo, F. G. et al. [174]	2007	Parameter Setting in Evolutionary Algorithms

Table 2.5 List of Few Books Published in GA

Sr. No	Authors	Year of Publication	Title of the Book
1	Goldberg, D. E. [175]	1989	GA in Search, Optimization and Machine Learning
2	Davis, L. [176]	1991	Handbook of Genetic Algorithms
3	Michalewicz, Z. [177]	1992	GA + Data Structures = Evolution Programs
4	Mitchell, M. [178]	1996	An Introduction to GA
5	Deb., K. [179]	2001	Multi-objective Optimization Using Evolutionary Algorithms
6	Goldberg, D. E. [180]	2002	The Design of Innovation: Lessons from and for Competent GA
7	Sivanandam, S. N. and Deepa, S. N. [181]	2008	Introduction to Genetic Algorithms

Over the last two decades, GA has evolved as a strong optimization tool that it can be applied to any kind of real field problem for optimization. GA is not only used in production/manufacturing field but it has found applications in thermal engineering field also.

2.3.4 Application of GA in Thermal Engineering Field

The year wise publication out of twenty nine research papers [182-210] available in open literature is presented in Table 2.6. It can be seen that the application of GA as an optimization tool in various thermal engineering problems emerged after 1996, and its application increased after 2005 not only in heat exchanger field but also in nuclear technology and fuel cell systems. But for the present study, it is essential to identify the application of GA as an optimization tool in the field of HEN.

Table 2.6 Application of GA in Thermal Engineering Field

Type of Application in Thermal Engineering Field	Year wise number of published literature										Total
	1996	2000	2003	2004	2005	2006	2007	2008	2009	2010	
Distillation System	1	1		1							3
Cogeneration	1	1							1		3
Reactor	1		1						1		3
Energy Integration		1									1
Diesel Engine			1								1
HVAC System					1						1
Heat Exchangers						3	2	4	3		12
Crystallization							1				1
Electrolysis							2				2
Nuclear Technology										1	1
Fuel Cell System										1	1
	TOTAL										29

2.3.5 Application of GA in HEN

There are fifteen research publications available in open literature related to the application of GA in HEN. The first attempt to synthesize the HEN using GA reported in open literature is by Lewin et al. [211], in 1998. They synthesized the HEN using the GA for maximum energy recovery. The problem is solved in two parts: (1) the structure of the HEN is determined by GA and (2) the heat loads of the units are fixed by the simplex algorithm to meet maximum energy recovery which is used by GA to rate the fitness. In the same year, Lewin [212] modified the previous algorithm for obtaining cost optimum HEN in which stream splitting is supported and both the objective function and constraints are non-linear.

Ravagnani et al. [213] and Ravagnani et al. [214], in 2005 developed a strategy for the synthesis and optimization of HEN using GA. First of all, they optimized ΔT_{min} using GA using pinch analysis. By using ΔT_{min}, found in previous stage, problem is divided into two regions, below and above pinch. Thus, using GA, optimal networks above and below pinch are obtained. Xiao et al. [215], in 2006 and Xiangkum et al. [216], in 2007 synthesized the large scale and flexible multi stream HEN to obtain cost optimum HEN respectively. Chen et al. [217], in 2007 synthesized the superstructure of HEN for explicit solution for thermal calculation using GA. In the same year, Jezowski et al. [218] addressed systematic simultaneous approaches to design two process systems: HEN and water network. They applied adaptive random search for water network and GA for HEN.

Ponce-Ortega et al. [219], in 2008 presented a methodology based on GA for optimal synthesis of multi-pass HEN. Their methodology allowed for proper handling of trade-offs involving energy consumption, number of units, and number of 1-2 shell and tube network area to provide a network with minimum TAC. In the same year, Ma et al. [220] extended the approach proposed by them in 2007 and synthesized multi-stream HEN for multi-period operation with genetic and simulated annealing algorithms. Dipama et al. [221], again in the same year, synthesized HEN using GA to optimize the TAC.

In 2009, Allen et al. [222] presented a procedure to design the components of HEN. They first used the pinch analysis to maximize heat recovery for a given ΔT_{min} and then using GA, each exchanger of the network is designed in order to minimize its TAC. In the same year, Luo et al. [223] and Luo et al. [224], developed a hybrid GA and monogenetic algorithm for optimal design of HEN respectively while, Fieg et al. [225] developed an explicit analytical solution of stream temperatures for the superstructure HEN. Based on the solution, a mathematical model for HENS is formulated by Fieg et al. for searching the optimal configuration of heat recovery system by a hybrid genetic algorithm.

It is also observed that out of total 15 research publications in the field of application of GA in HEN, 13 are published after 2005, which shows that the application of GA in HEN increased in the last five years. The comparative study of few chosen case studies based on the application of PT using GA as optimization tool is carried out and is given in Table 2.7. From a review of eight relevant published papers, it is found that all are concerned with analysis through ΔT_{min} approach. Further it is seen that the total number of case studies carried out on various systems are twenty one and out of which nineteen case studies are having unequal heat transfer coefficients. All the case studies having unequal heat transfer coefficients are optimized using ΔT_{min} approach.

Table 2.7 Classification of Literature Based on Stream Characteristics Using GA as an Optimization Tool for PT

Sr. No	Name of Investigator	Year of Publication	Case Study Number	Number of Streams		Heat Exchanger Specifications	Heat Transfer Coefficients of various streams are	HENS Solution Methodology	Initial Solution Approach
				Process	Utility				
1	Lewin [212]	1998	1	6	2	Uniform	Unequal	GA and MINLP	ΔT_{min}
			2	9	2		Unequal		
			3	10	2		Unequal		
			4	21	2		Unequal		
2	Ravagnani et al. [213]	2005	1	4	2	Uniform	Unequal	GA	ΔT_{min}
			2	10	2		Equal		
3	Ravagnani et al. [214]	2005	1	10	2	Uniform	Equal	Hybrid GA	ΔT_{min}
4	Bjork and. Nordman [226]	2005	1	15	2	Uniform	Unequal	GA alongwith MINLP	ΔT_{min}
5	Ponce-Ortega et al. [227]	2007	1	6	2	Uniform	Unequal	GA with detailed Heat Exchanger Design	ΔT_{min}

6	Luo et al. [223]	2009	1	6	2	Uniform	Unequal	Hybrid GA	ΔT_{min}
			2	6	2		Unequal		
			3	9	2		Unequal		
			4	20	2		Unequal		
7	Fieg et al. [225]	2009	1	6	2	Uniform	Unequal	Mono GA	ΔT_{min}
			2	9	2		Unequal		
			3	15	2		Unequal		
			4	23	18		Unequal		
8	Rezaei and Shafiei [228]	2009	1	4	2	Uniform	Unequal	GA with NLP	ΔT_{min}
			2	4	2		Unequal		
			3	6	2		Unequal		
			4	7	2		Unequal		

Comprehensive review papers are also available covering all the aspects of the development of synthesis and optimization applied to the field of thermal engineering in general and heat transfer in particular using GA as optimization tool. Gosseli et al. [229], in 2009 after reviewing seventy six papers in the field of heat transfer found intensification in the application of GA in heat transfer problems recently. They opined that due to the inherent capacity of GA to handle the complex objective function, its application in the real field problem has increased. Using GA, the HEN is theoretically optimized to obtain the theoretically possible optimized TAC. After having the ideal of theoretically possible optimized TAC, it is essential to modify the configuration of existing HEN to achieve the optimized TAC.

2.3.6 Development in Modification Techniques

Now-a-days, PT is also used for modification of existing HEN of chemical plant for minimizing TAC. The development in various modification techniques commenced in early 1980s. According to Van-Gool [230] (1980), issues involved in energy conservation should be fundamentally analyzed in any energy intensive program. The major choice, however, is between producing the present mix of materials, commodities, and services more efficiently and decreasing demand for them. The first option is referred to as the “technical fix” and the second one as “change of lifestyle”. As a measure of technical fix, energy conservation in any energy intensive chemical plant can be achieved by redesigning the plant through synthesis and optimization. Since 1984, important new developments have taken place within PT. The specific areas are capital cost targeting and design, modification targeting and design, flexibility consideration at design stage and finally total site heat and power integration.

Tjoe and Linnhoff [231], in 1984 defined the HENS problem for modification. In this case, the optimal minimum approach temperature is a function of the energy/capital trade-off and in addition the existing structure of the network and the expected payback period. They outlined a modification procedure where heat exchangers transferring heat across the pinch are removed and that compatibility with the existing network is searched by manipulating heat load loops and paths. They introduced the application of PT in modification. According to them, the modification by PT provides a promising alternative based on the concept of area efficiency and plotting investment versus saving to obtain a target for modification. Reay [232], in 1985 has also considered the problem of energy conservation by comparing two alternatives viz. (1) to redesign the chemical plant or (2) to modify the chemical plant. According to him, the sectors where energy usage is significant, conservation measures may be implemented without recourse to extensive plant or building redesign. This applies to heat recovery in the industry. For a design engineer, however, has considerably greater incentive to redesign his process when faced with the opportunity to incorporate heat recovery equipment. Modifying an existing chemical plant is another alternative. Both can lead to cost savings, the second-one generating a more rapid return of possibly lower magnitude. Both provide the engineer with challenges to his technical and managerial skills.

In 1985, Linnhoff and Tjoe [233] presented a procedure for targeting the modification based on the idea that new exchangers or shell installed will be utilized with the same area efficiency. They presented a graph relating investment cost and utility savings. Depending on expected payback period or an upper limit on the investment, one may obtain an estimate for ΔT_{min} to be used in the network manipulation together with target for energy reductions. Doldan et al. [234] in the same year, when modifying a process with a given utility system for heat and power introduced a secondary bottleneck often encountered in energy studies. This means that there is little incentive for reducing the hot utility consumption below the amount available from back pressure turbine, unless power system is modified. A small non-linear program is used to obtain this modified energy target.

Tjoe and Linnhoff [235], in 1986 presented a complete methodology for targeting modification and design. An existing network is usually non-optimal in both structure and area/energy trade-offs. They pointed out that the smallest approach temperature only indicates wrong use of driving forces, and that this value should not be used in the modification design procedure. In the same year, Saboo et al. [236, 40] described procedures for finding the most economic way to add area to installed exchangers. A new trade-off introduced is the number of exchangers to be modified versus the total additional area. Jones et al. [237], in the same year studied practical synthesis techniques for modifying heat recovery systems. According to them, computer search technique can be used to choose from a number of simulated maximum energy recovery networks with the most favorable economics and with minimal change.

In 1989, Lee et al. [238] carried out the heat integration analysis of refinery using pinch analysis. Ciric and Floudas [239], in 1990 proposed MILP model for modification at a level of matches based on a classification of the possible structural modifications. While Yee and Grossman [240], in 1991 proposed mixed integer non-linear programming (MINLP) model for modifying an existing plant. In1998, Lakshmanan and Banares-Alcantara [241] described visualization tool for developing modification solutions by inspection. According to them, this method relies heavily on the ingenuity of the designer but has proved to be very flexible-handling a wide variety of problem formulations.

From the above, it is seen that modification techniques may be classified into four broad categories like computer search, mathematical programming, inspection and PT. Table 2.8 gives the investigations reported using various modification techniques. The computer search method may not prove efficient in many cases due to three reasons: The element of chance in hitting or missing the best network, the large amount of computational effort involved in simulating many networks and the difficulty in modification to identify a design having a structure reasonably close to the existing one and simultaneously transferring zero heat across the pinch. The methods of modifying by inspection and computer search carry the potential risk of the network not being the optimum. While the use of mathematical programming makes strong computational demands, retrofitting by pinch analysis provides a promising alternative.

Table 2.8 Development in Modification Techniques

Sr. No.	Name of Investigator	Year of Publication	Modification Technique	Detailed Methodology
1	Van-Gool [230]	1980	----	Issues involved in energy conservation
2	Tjoe and Linnhoff [231]	1984	PT	ΔT_{min} Approach
3	Reay [232]	1985	----	Energy conservation by comparing two alternatives viz., redesign and modify chemical plant
4	Linnhoff and Tjoe [233]	1985	PT	Targeting based on existing area efficiency and expected payback period
5	Doldan et al. [234]	1985	Mathematical Programming	Non-linear programming model
6	Tjoe and Linnhoff [5]	1986	PT	ΔT_{min} Approach
7	Saboo et al. [236, 40]	1986	----	Procedure to add area to the installed exchangers
8	Jones et al. [237]	1986	Computer Search Method	----
9	Lee et al. [238]	1989	PT	Heat integration analysis
10	Ciric and Floudas [239]	1990	Mathematical Programming	Mixed integer linear programming model
11	Yee and Grossmann [240]	1991	Mathematical Programming	Mixed integer non-linear programming model
12	Banares-Alcantara [241]	1998	Inspection	----

2.3.7 Modification in Chemical Plant Excluding Ammonia Plant Using Techniques other than GA

This section deals with the specific research literature available in the utilization of various modification techniques employed to chemical plant excluding ammonia plant. Various optimizing techniques other than GA are employed in modification techniques presented by various investigators. Thirty eight publications

[29, 144-147, 242-274] related to the modification in existing chemical plants excluding ammonia plant using techniques other than GA are available in open literature. A review of few chosen literatures among them is given in Table 2.9 and is explained in following paragraphs.

Table 2.9 Modification in Chemical Plant Excluding Ammonia Plant Using Techniques other than GA

Sr. No.	Name of Investigator	Year of Publication	Modification Technique	Case Study
1	Linnhoff and Turner [242]	1980	PT	ICI plant
2	Dyson and Kenny [243]	1982	Pinch Design Method	Chemical plant, 'Davy McKee'
3	Linnhoff and Vredeveld [29]	1984	PT	Distillation Columns
4	Steinmetz and Chaney [244]	1985	PT and Westerberg's heat path diagram	Total site energy integration
5	Hindmarsh et al. [245]	1985	----	ICI plant
6	O'Reilly [246]	1986	PT	----
7	Nilsson and Sunden [253]	1994	PT and the "MIND" method	Crude distillation system
8	Al-Riyani et al. [147]	2001	PT	Fluid catalytic cracking plant
9	Matijaseviae and Otmaeiae [265]	2002	PT	Nitric acid plant
10	Zhaolin-Gu et al. [268]	2007	PT	Five column alcohol distillation section
11	Yoon et al. [269]	2007	PT	Industrial ethyl benzene plant
12	Sujo-Nava et al. [270]	2009	----	Sour water network in a petroleum refinery

Linnhoff and Turner [242], in 1980 reported applications within ICI and concluded that three beliefs often encountered in industry when it comes to heat integration are quite unfolded. They are (1) to design better processes, one needs more design time, (2) process integration for energy conservation leads to control problems and (3) energy conservation always costs money. Most processes are highly integrated and PT is only a tool to make sure that this integration is done properly. In 1982, Dyson and Kenny [243] reported how the pinch design method can be used within the chemical plant, 'Davy McKee', with special emphasis on crude preheat trains. Some interesting practical aspects of using such systematic methods are given.

Linnhoff and Vredeveld [29], in 1984 stated that PT has come of age, referring to a complete methodology for the design of HEN, utility systems, heat and power systems and integration of distillation columns with the back-ground process. They also pointed out the importance of considering process modifications to improve heat recovery before the HEN problem is addressed. Steinmetz and Chaney [244], in 1985 discussed total site energy integration by using PT and Westerberg's heat path diagram. The importance of the relative positions of the single process pinch points for the total plant integration is discussed. In the same year, Hindmarsh et al. [245] described how the Tensa Group in ICI addresses the integration of diesel engines, turbines and refrigeration systems into the overall process. In 1986, O'Reilly [246] reported his experiences with the PT by warning against in-discriminate use of systematic methods. He stated that design constraints will be encountered and must be properly dealt with.

In 1994, Nilsson and Sunden [253] analyzed crude distillation system using PT and the “MIND (a method of optimization developed by Nilsson in 1990)”, method. They have optimized the HEN using the PT first and the results from the pinch analysis are given as input to the MIND optimization. Their result showed that the steam demand from the boiler unit in the energy supply part of the system can be reduced by 20 % in the optimized HEN and by 21 % when a heat pump is added to the system.

Al-Riyani et al. [147], in 2001 carried out the modification analysis of a fluid catalytic cracking plant using pinch analysis and showed the energy saving potential in the plant. In 2002, Matijaseviae and Otmaeiae [265] studied the HEN of a nitric acid plant using the PT. They found the possibility of reduction in requirements for cooling water and medium pressure steam. They also found that utility saving is associated with the replacement of three heat exchangers. Thus, energy consumption increases slightly but final result is reduction of energy cost with a payback period of 14.5 months.

In 2007, Zhaolin-Gu et al. [268] pointed out some improper heat exchanger settings and modifications by the process integration using PT, studying the case of the five column alcohol distillation section, which is broadly used in new distilleries in China. Yoon et al. [269], in the same year modified the HEN for an industrial ethyl benzene plant by pinch analysis. They achieved the alternative HEN by adding a new heat exchanger and changing operating conditions. It reduces the annual energy cost by 5.6%. In order to achieve it, the capital investment is necessary but the annual cost saving will be enough to recover the cost in less than one year. Sujo-Nava et al. [270], in 2009 presented a case study of the modification of a sour water network in a petroleum refinery. After modification, they found that 83 % of freshwater and 52 % of energy can be saved.

2.3.8 Modification in Ammonia Plant Excluding GA

There are nine research publications [275-283] reported in open literature concerned with modification carried out on ammonia plants. They are compared in Table 2.10. Nand and Goswami [284], in 2008 carried out an overview of research literature on energy conservation initiatives on ammonia and urea plants.

Table 2.10 Modification in Ammonia Plant Excluding GA

Sr. No.	Name of Investigator	Year of Publication	Modification Methodology
1	Shah and Weisenfelder [275]	1969	Computerized control of a single train, large capacity plant
2	Stemphens and Richards [276]	1973	Steady state and dynamic analysis
3	Radgen [277]	1997	Exergy analysis of ammonia and urea plant of the fertilizer complex
4	Penkuhn et al. [278]	1997	Modification in an existing ammonia plant using non-linear optimization model and ASPEN PLUS software
5	De Wit and Riezebos [279]	1998	Revamping of a 25 year old plant
6	Haitham et al. [280]	2000	Energy retrofit of the front end of the plant using recent advances in PT
7	Wang et al. [281]	2003	Total process energy integration in retrofitting using modified pinch analysis
8	Panjeshahi et al. [282]	2008	Pinch and exergy analysis
9	Singh [283]	2009	Recovering waste heat by raising high pressure steam in boiler

One of the earlier studies on ammonia plant is due to Shah and Weisenfelder [275], in 1969. They studied the computerized control of a single train, large capacity ammonia plant. Computers are used to perform supervisory, interfacing control for various control loops in the plant as well as periodic on-line and off-line optimization of the profit function. They observed that the economic benefits achieved with the use of computer control because of improved plant performance and profit, on a monthly basis, easily justified the cost associated with the computer. Stemphens and Richards [276], in 1973 described steady state and dynamic analysis of an ammonia synthesis plant. According to them, the analysis help in (1) better understanding of the operation of the plant, (2) designing a simple experimental scheme for optimizing and (3) indicating criteria which ensures optimization never enters in inoperable regions.

An Exergy analysis of the ammonia plant and the urea plant of the fertilizer complex is carried out by Radgen [277], in 1997. They found that existing overall exergetic efficiency is 60 % which includes 68.83% and 87.89% exergetic efficiency of ammonia and urea plant respectively. They further observed that the possible improvements are mainly equipment based and not due to the unfavorable positioning or matching of individual unit. In the same year, Penkuhn et al. [278] presented a model that enlarges the well known linear optimization model for joint production planning problems. The model is based on thermodynamic equilibrium calculations and therefore formulated as a non-linear optimization model. The implementation of the model is carried out with the help of process simulation system ASPEN PLUS and applied as an example to an existing ammonia synthesis plant. The results showed that it is possible to improve the operating margin of the AMV ammonia process.

De Wit and Riezebos [279], in 1998 revamped a 25 year old ammonia plant which resulted in a lower energy consumption and higher production capacity by identifying the areas of higher energy consumption. In 2000, Haitham et al. [280]

studied the energy retrofit of the front end of the ammonia plant using advances in PT. The Front end of ammonia production plant consists of sections in which gases needed for production of ammonia is prepared, viz., sections from desulphurization to carbon dioxide removal and methanation. They inspected the front end of the ammonia plant and combined it with problem table algorithm. Wang et al. [281], in 2003 have performed the total process energy integration in retrofitting an ammonia plant using modified pinch analysis. The ammonia production plant is analysed using grid diagram and pinch design method.

Panjeshahi et al. [282], in 2008 have performed a retrofit study of an ammonia plant to improve the energy efficiency. The combined pinch and exergy analysis is employed and found reasonable saving of 15 % in power consumption without the need for the new investment. In 2009, Singh [283] reported that more than hundred and fifty KBR technology based ammonia plants installed globally between 1960 and 1980. In these plants, ammonia synthesis converter with an internal heat exchanger is used for energy recovery. He observed that these plants still consume high energy and one key reason for this inherent deficiency is that all the waste heat in the synthesis loop of these plants is recovered by preheating boiler feed water (BFW) rather than by producing high pressure steam. Recovering waste heat by raising medium pressure steam or by only preheating BFW makes these plants inherently energy deficit. Modification in the existing ammonia converter by incorporating a high pressure steam raising boiler in the synthesis loop and found that depending upon current specific configuration, plant energy consumption can be reduced by 0.18 to 0.30 Gcal/MT of Ammonia.

An overview of published literature is carried out by Nand and Goswami [284], in 2008 regarding the developments in the energy conservation efforts in ammonia and urea industries. They found that energy consumption is reduced from 12.48 GCal/MT in 1987-1988 to 8.97 GCal/MT in 2007-2008 for ammonia plant.

2.3.9 Modification in Chemical Plant Using GA

Review of literature related to chemical plants, in general, excluding ammonia plant is carried out in Section 2.3.7. Section 2.3.8, on the other hand focused on literature related to only ammonia plants and the modification techniques employed. Both the above sections deal with studies employing optimization tools other than GA. There are only three research publications available in open literature using GA as optimization tool in modifying existing chemical plants excluding ammonia plants. Bjork and Nordman [226], in 2005 modified the HEN problem with mathematical programming method combined with GA for ΔT_{min} approach. Bochenek and Jeżowski [285], in 2006 applied GA for retrofitting HEN with standard heat exchangers. Rezaei and Shafiei [228], in 2009 retrofitted HEN by coupling GA with non-linear programming (NLP) and integer linear programming (ILP) methods.

From the comprehensive review, there appears to be no open literature available that deals with unified method of synthesis and optimization of HEN of ammonia plant using GA as optimization tool and its modification.

2.4 Outcome of the Review

The optimization of HEN of any existing chemical plant/process ensures minimum TAC and maximum energy recovery and will help to save the energy. Different investigators have developed their model and optimized HEN for various chosen case studies. Similarly many investigations are reported in open literature for synthesizing HEN using LP, ILP, MILP, NLP, MINLP and other traditional optimization techniques. Very few investigations are found for HENS and modification analysis of an existing chemical plant using GA as optimization tool. There appears to be no study reported in open literature that deals with synthesis and optimization of HEN of an ammonia production plant using GA as optimization tool and subsequent modification using pinch analysis of HEN based on the minimum TAC and maximum energy recovery. The present study is an attempt in this direction.

2.5 Objectives of the Present Study

The objectives of the proposed research study are as follows:

1. To study genetic algorithms as an optimization tool for thermal system network, in general and heat exchanger network, in particular.
2. To capture the steady state online data of heat exchanger network of an ammonia production plant which is a part of a fertilizer industry.
3. To carry out network synthesis and optimization of HEN of the ammonia plant using genetic algorithms.
4. To carry out the modification analysis of HEN of the ammonia plant and suggest modifications, if applicable.

Chapter 3

AMMONIA PRODUCTION PROCESS

This chapter describes ammonia production process in an ammonia plant, which is a part of a fertilizer industry producing urea. Section 3.1 deals with various processes involved in ammonia production based on the method of steam reforming process. The network of heat exchangers in various stages of ammonia production process is discussed in Section 3.2. Section 3.3 gives the acquired online steady state process data of the ammonia production plant of a fertilizer industry situated in Gujarat, India. The data acquired are heat exchanger area, hot and cold process fluid streams and hot and cold utility fluid streams, under a normal operating condition of the plant.

3.1 Steam Reforming Process

Ammonia production plant is an essential sub chemical system in any fertilizer plant producing urea. Ammonia production process may be Herber-Bosch, coal based partial oxidation, heavy hydrocarbon based partial oxidation and steam reforming process. Appendix-I describes the basic four processes used in ammonia production. Most of the ammonia production plants follow steam reforming process as it possesses few distinct advantages over other processes. Natural gas (NG) is the raw material widely used in the steam reforming process as it posses the highest hydrogen to carbon ratio.

Nitrogen and hydrogen are chemically combined in 1:3 proportions to produce ammonia. For this purpose, large quantities of nitrogen and hydrogen must be produced. Fortunately, large quantity of nitrogen is available in atmospheric air while hydrogen is extracted from NG. Thus purification and extraction procedure are needed to be carried out on atmospheric air and NG during ammonia production process.

An ammonia production plant which is a part of a fertilizer industry situated in Gujarat is selected for the present study. The flow diagram of the plant is given in Figure 3.1. The following are the various processes involved in the production of ammonia using the method of steam reforming process employed in the plant.

3.1.1 Desulfurization Process

Pure hydrogen needed in the manufacture of ammonia can be extracted by various treatment of NG available as raw material. The removal of sulfur content from NG is the first step in the extraction process. All sulfur in NG is assumed to be reactive type which can be absorbed by zinc oxide. Thus, desulfurization is process of passing preheated NG through a bed of zinc oxide. At the end of the process, the sulfur content is found to be less than 0.25 ppm in NG.

3.1.2 Reforming Process

The next process in the extraction of hydrogen from NG is known as reforming process. Desulfurized NG is mixed with superheated steam. The mixture is preheated using flue gases from primary reformer (PR). It is then allowed to react to form hydrogen, carbon monoxide, carbon dioxide and residual methane in PR. As this process is endothermic, heat energy is supplied using flue gas generated by the combustion of externally supplied fuel (again NG) in the PR.

Figure 3.1 Flow Diagram of Ammonia Production Plant of a Fertilizer Industry

The reaction in the PR takes place in the catalytic tube packed with nickel catalyst operated at elevated temperature of about 800 - 813 ^{O}C and pressure of 40 bar. Externally supplied NG is burnt in the combustor of PR to achieve the elevated temperature in the nickel catalyst tube. The flue gas from PR is used to preheat the desulfurized NG.

The partially reformed process gas (PG) consisting of H_2, CO, CO_2 and small quantity of CH_4 from PR is further treated in secondary reformer (SR) where the PG is mixed with a stochiometric quantity of compressed preheated air. The oxygen from the air is used up in combustion with the partially reformed PG. The heat energy from combustion is used in completing the methane reforming that takes place in nickel catalyst bed in the SR. The completed reformed PG consisting of H_2, CO, CO_2 and traces of CH_4 is then treated to convert CO into CO_2 and to remove CO_2 respectively in CO convertor and CO_2 absorber.

3.1.3 Process for Removal of CO and CO_2

The reformed gas from SR is then cooled in an array of heat exchanger before entering the high temperature shift converter. The processes of conversion of CO into CO_2 from PG are carried out in high and low temperature shift converters (HTSC and LTSC) and subsequently CO_2 is absorbed in CO_2 absorber.

HTSC, consisting of copper promoted iron catalyst, converts CO into CO_2 by allowing the cooled PG to react with steam to form CO_2 and H_2. As the reaction is exothermic, large amount of heat is generated. Therefore, another heat exchanger train is needed to cool down the resulting PG consisting of CO_2 and H_2 along with small amount of CO to about 200 ^{O}C before being sent to LTSC. Water gas shift reaction, then, takes place in the presence of Cu-Zn catalyst in LTSC and as result of which the CO content in PG reduces to a negligible amount of about 0.3 %.

The PG leaving CO conversion unit consisting of HTSC and LTSC contains mainly H_2, N_2, CO_2, residual steam and traces of other constituents of air. In between HTSC and LTSC, a series of heat exchangers cool down PG using either BFW or synthesis gas (which is a form of PG). A low temperature shift guard reactor (LTSGR) installed in between these heat exchangers, removes impurities like arsenic, chloride etc. from PG.

Heat exchangers in parallel and series arrangement between SR and HTSC and in series arrangement between HTSC and LTSGR are primarily meant for cooling down PG. The heat energy thus released is used to generate steam by preheating saturated water and return condensate, thus recovering heat energy of reactions in PR, SR and LTSGR.

PG then enters CO_2 absorber through a series – parallel network of heat exchangers and a knockout drum raw gas separator (KDRGS). Between LTSGR and LTSC, recovery of heat energy is possible due to cooling down of PG. Function of KDRGS is to remove condensate and other traces of gases. CO_2 absorber consisting of an alkali absorbent like methyl-diethanolamine (MDEA) absorbs CO_2. CO_2 is absorbed by MDEA in the CO_2 absorber. The absorbed CO_2 is recovered in the CO_2 recovery unit and sent to urea plant. Thus, PG coming out of CO_2 absorber contains mainly N_2 and H_2 with negligible amount of CO, CO_2 and CH_4. PG coming out of CO_2 absorber is known as synthesis gas (SG). SG is heated in series of heat exchangers before it enters the methanator.

3.1.4 Methanation Process

The traces of CO and CO_2 present in SG are converted into CH_4 by reacting with H_2 present in SG during the methanation process. The oxides of carbon in SG are eliminated during methanation process in the presence of nickel catalyst.

The SG is then cooled in a series of heat exchangers using BFW, circulating water and liquid NH_3 from ammonia flash drum and passes through a knockout drum condensate remover (KDCR) before entering the compression system.

3.1.5 Synthesis Gas Compression Process

The pressure and temperature of SG needed at the ammonia reactor are about 140 – 145 bar and 140 – 145 ^{O}C respectively. A two stage SG compressor system with series of heat exchangers at intermediate stages ensures not only the requirement of the condition of SG at methanator but also at first and second stage of reactions at ammonia reactors.

3.1.6 Ammonia Synthesis Process

High pressure and high temperature SG consisting of H_2, N_2 and small amount of CH_4 compressed in two stages, enters the first stage of ammonia reactor wherein nitrogen and hydrogen are chemically combined to form ammonia gas. About 15 % of conversion takes place in the first reactor. Similar reaction takes place in second stage reactor wherein 8 % of the conversion takes place. Thereafter, ammonia gas is cooled in a series of heat exchangers using cooling water in two exchangers and liquid ammonia from NH_3 flash drums in three heat exchangers thereby converts NH_3 gas into liquid NH_3 having temperature of about -33 ^{O}C. After the separation of unconverted H_2, N_2 and CH_4, ammonia is stored in product storage tank.

Ammonia flash drums are used to flash ammonia gas and liquid ammonia is used as coolant in number of heat exchangers. Ammonia gas from flash chamber is compressed in multistage compressor and is sent to urea plant through an array of heat exchangers.

3.1.7 Ammonia Liquefaction Process

Ammonia gas from product storage is liquefied in flash drums. In the first flash drum, ammonia gas and ammonia liquid are separated. Liquid ammonia is circulated into one of the heat exchanger to recover the heat and converted into ammonia gas. Ammonia gas is then compressed in low pressure and high pressure ammonia compressor (LPAC and HPAC) and sent to Urea plant. The ammonia gas from first flash drum is taken to second and third ammonia flash drums where the saturation temperatures corresponding to pressure is higher than the first and second flash drums. From second and third ammonia flash drums also liquid ammonia is circulated to the heat exchangers and converted into ammonia gas. Ammonia gas from second stage flash drum is mixed with the ammonia gas from LPAC before it is taken to the HPAC. Ammonia gas from third ammonia flash drum is mixed with the intercooled ammonia gas from first stage of HPAC and compressed again in second stage of HPAC and after cooling, ammonia gas is taken to the urea plant.

3.1.8 CO_2 Recovery Process

PG enters the CO_2 absorber from bottom and lean mixture of MDEA and CO_2 (lean MDEA) from low pressure flash vessel (LPFV). Recycled CO_2 from high pressure flash vessel (HPFV) after compression, also enters the CO_2 absorber. In the CO_2 absorber, lean MDEA absorbs CO_2 present in PG and becomes rich mixture of MDEA and CO_2 (known as rich MDEA). Rich MDEA is then used to operate the hydraulic turbine and at exhaust, rich MDEA enters HPFV. In HPFV, CO_2 gas is separated partly and is taken to CO_2 absorber after compression. Rich MDEA then enters LPFV where majority of CO_2 is separated and after cooling in heat exchangers, is sent to urea plant.

Semi-lean mixture of MDEA and CO_2 (known as semi-lean MDEA) from LPFV is sent to CO_2 stripper after heating in different heat exchangers and subsequently to CO_2 absorber. In CO_2 stripper, CO_2 and MDEA are separated. CO_2 from CO_2 stripper is taken to the LPFV and lean MDEA from CO_2 stripper is returned to CO_2 absorber.

3.2 Network of Heat Exchangers in Ammonia Production Process

This section describes the network of heat exchangers employed in the ammonia production plant. These exchangers are used for preheating of NG, heating and cooling of PG and SG. Some of them act as heating and cooling systems of CO_2 gas and ammonia gas. The network is so designed that maximum recycling and recovery of heat energy could be possible and effective utilization of recovered heat energy for reuse where needed, thus making HEN energy efficient. The complete network of heat exchangers is described in the order of its appearance in the production process flow line. Figure 3.1 may be referred for the specific network. All heat exchangers are referred with tag numbers.

1. Desulfurized NG enters HX 150C at 27 ^{O}C and is heated to 74 ^{O}C using steam at a temperature of 147 ^{O}C from heat recovery boiler drum. Here steam is considered as hot utility since steam is used to heat the NG.
2. NG is further heated in a heat recovery unit using flue gases coming out of PR. Steam is injected at about 245 ^{O}C into NG in such a way that the resulting mixture at the exit is at a temperature of 451 ^{O}C.
3. The next array of heat exchangers is installed between SR and HTSC. The temperature of PG coming out of SR is at 998 ^{O}C. HX 101CA and HX 101CB are similar heat exchangers installed parallel to the incoming PG and another exchanger HX 102C is installed taking the exit PG from both the exchangers HX 101CA and HX 101CB. HX 101CA , HX 101CB and HX 102C use saturated water from boiler as coolant whose boiling temperature is at 313 ^{O}C while the temperature of PG decreases from 998 ^{O}C to 483 ^{O}C in both HX 101CA and HX 101CB and from 482 ^{O}C to 371 ^{O}C in HX 102C.
4. A series of heat exchangers, viz., HX 103C, HX 104C and HX 112 operate between HTSC and LTSGR, cooling PG in steps. The temperature of PG decreases from 430 ^{O}C to 333 ^{O}C in HX 130C, from 332 ^{O}C to 241 ^{O}C in HX 104C and from 240 ^{O}C to 204 ^{O}C in HX 102C. The cold process stream for HX 103C is saturated water drawn from heat recovery boiler at a pressure such that the saturation temperatures during latent heat absorption is 313 ^{O}C and gets converted into saturated steam. HX 104C utilizes SG as cold process stream whose inlet and outlet temperatures across the exchanger are 114 ^{O}C and 316 ^{O}C respectively. HX 112C utilizes condensate as cold process stream whose temperature increases from 50 ^{O}C to 155 ^{O}C in the exchanger.

5. PG leaving LTSGR at 128 ^{O}C is cooled in two heat exchangers installed in series, viz., HX 142 CA and HX 142 CB from 228 ^{O}C to 190 ^{O}C before it enters LTSC. The PG coming out from LTSC is at 194 ^{O}C and enters HX 143C where its temperature decreases from 194 ^{O}C to 169 ^{O}C. The cold process stream from the 104J condensate pump flows through HX 143C to HX 142CA and to HX 142CB, the temperature of BFW increases from 113 ^{O}C to 180 ^{O}C in HX 143C and further increases to 211 ^{O}C in HX 142CA and HX 142 CB.
6. There are four heat exchangers, viz., HX 143C, HX 105CA, HX 105CB and HX 106C operating between LTSC and CO_2 absorber. HX 105CA and HX 105CB operate in parallel in between HX 143C and HX 106C. BFW consisting of condensate as coolant from HX 112C mixed with de-mineralized water (DMW) is used as cold process stream in HX 106C and after de-aeration is used in HX 143C as coolant before allows to further use in HX 142CA and HX 142CB. The temperature of BFW increases from 52 ^{O}C to 120 ^{O}C in HX 106C and subsequently increases from 113 ^{O}C to 180 ^{O}C in HX 143C. The temperature of PG decreases from 194 ^{O}C to 169 ^{O}C in HX 143C and further decreases from 168 ^{O}C to 128 ^{O}C in both HX 105CA and HX 105CB using MDEA from CO_2 stripper. The temperature rise in MDEA in HX 105CA is from 116 ^{O}C to 121 ^{O}C while that in HX 105CB is from 118 ^{O}C to 123 ^{O}C.

7. SG from CO_2 absorber passes through HX 136C and HX 104C as cold process fluid before entering the methanator (106D Reactor). The temperature of SG increases from 48 ^{O}C to 117 ^{O}C in HX 136C and then from 114 ^{O}C to 316 ^{O}C in HX 104C. In the methanator, the temperature increases further to 360 ^{O}C. SG is cooled subsequently to 8 ^{O}C using three heat exchangers in series between methanator and knockout drum condensate remover, viz., HX 114C, HX 115C and HX 141C. The temperature drop in three heat exchangers are respectively from 360 ^{O}C to 145 ^{O}C, from 144 ^{O}C to 38 ^{O}C and from 37 ^{O}C to 8 ^{O}C. BFW from de-aerator is partially used as cold process stream in HX 114C, the temperature increase being from 115 ^{O}C to 311 ^{O}C. Cooling water is circulated in HX 115C with temperature rise from 32 ^{O}C to 46 ^{O}C. Liquid NH_3 from NH_3 flash drum, 110F is circulated in HX 141C and its temperature increases from -8 ^{O}C to 15 ^{O}C.

8. There are three heat exchangers, viz., HX 136C, HX 116C and HX 129C between low pressure and high pressure synthesis gas compressor (LPSGC and HPSGC) which handles SG at a pressure of 60 bar. HX 136C is a SG – SG heat exchanger in which SG from CO_2 absorber is heated from 48 ^{O}C to 117 ^{O}C with the help of compressed SG from LPSGC whose temperature decreases from 159 ^{O}C to 86 ^{O}C. SG from LPSGC is subsequently cooled in HX 116C and HX 129C from 85 ^{O}C to 41 ^{O}C and from 40 ^{O}C to 7 ^{O}C using cooling water and liquid NH_3 respectively. Cooling water temperature increases from 34 ^{O}C to 46 ^{O}C while that of liquid NH_3 from flash drum 110F decreases from -10 ^{O}C to 2 ^{O}C.

9. SG from HPSGC is partly re-circulated through an intercooler HX 137C which cools SG to 23 ^{O}C at a pressure of 143 bar. Being an intercooler, it is not considered in the analysis and also not shown in the flow diagram. HX 121C heats SG from 23 ^{O}C to 141 ^{O}C at the inlet to first stage NH_3 reactor using the NH_3 gas from second stage reactor passing the HX 107C and HX 123C. The NH_3 gas is cooled from 377 ^{O}C to 278 ^{O}C in HX 107C using the mixture of BFW outlet of HX 123C and the heat exchanger train between LTSGR and LTSC, viz., HX 143C, HX 142CA and HX 142CB. HX 123C further cools NH_3 gas from 277 ^{O}C to 166 ^{O}C while HX 121C cools NH_3 gas further from 164 ^{O}C to 68 ^{O}C and HX 124 from 67 ^{O}C to 47 ^{O}C using cooling water.

10. SG from HX 121C enters the annular space located in periphery of first stage of NH_3 reactor (105D). SG then enters HX 122C located internally in first stage reactor where it is heated from 140 ^{O}C to 427 ^{O}C. Heated SG then passes through the different stages of catalyst bed i.e. Fe, where N_2 and H_2 are combined to form NH_3. In fist stage reactor, 15 % of conversion takes place through an exothermic reaction. The output of the first stage reactor, mixture of NH_3 gas and unconverted N_2, H_2 and small amount of CH_4 having temperature of 471 ^{O}C enters HX 122C, where it is cooled to 284 ^{O}C with the help of SG, before being allowed to enter the second stage reaction.

11. Mixture of NH_3 gas and unconverted N_2, H_2 and CH_4 enters the second stage reactor where again in presence of catalyst, 8 % conversion takes place and temperature of NH_3 gas increases to 377 ^{O}C.

12. HX 117C, HX 118C and HX 119C arranged in series cools NH_3 gas from 45 ^{O}C to 22 ^{O}C, from 21 ^{O}C to 1 ^{O}C and from -4 ^{O}C to -24 ^{O}C respectively using liquid NH_3 from NH_3 flash drum 110F, 111F and 112F respectively operated at different saturation pressure with corresponding saturation temperatures at 13 ^{O}C, -7 ^{O}C and -32 ^{O}C respectively. NH_3 gas from HX 124C is divided into two streams and supplied to HX 120C and HX 117C. In HX 120C NH_3 gas is cooled from 46 ^{O}C to -11 ^{O}C using the recycled SG partly from 106F separator and heat the same from -22 ^{O}C to 25 ^{O}C before allowed to enter HPSGC. The remaining recovered SG is allowed to enter LPSGC after drying and cryogenic separation. In HX 117C, NH_3 gas is cooled from 45 ^{O}C to 22 ^{O}C using liquid NH_3 from NH_3 flash drum, 110F.

13. A LP NH_3 compressor raises the pressure of flashed NH_3 gas from flash drums 112F before mixes with high pressure NH_3 gas from flash drum 111F and further raises the pressure before storing in 109F storage drum. Similarly, flashed NH_3 gas from flash drum 110F enters the storage drum after compressed in HP compressor along with that flowing from other flash drums. An intercooler HX 128C decreases the temperature of NH_3 gas in between compression stages from 106 ^{O}C to 36 ^{O}C using cooling water circulation. Heat exchangers HX 127CA and HX 127CB operates parallel between HP compressor and 109F storage tank thereby cools the NH_3 gas from 133 ^{O}C to 44 ^{O}C using cooling water circulation. High pressure NH_3 gas from flash drum 110F directly enters the storage tank after passing through HX 126C in which flash gas is cooled from 35 ^{O}C to 3 ^{O}C using liquid NH_3 at 9 ^{O}C.

14. The recovered CO_2 gas from LPFV used for urea plant is cooled in series of HX 110CA and 110CB from 96 ^{O}C to 57 ^{O}C. Cooling water circulation in HX 108CA and HX 108CB cools the lean MDEA from CO_2 stripper and flows to CO_2 absorber. Semi-lean MDEA is heated using lean MDEA from 71 ^{O}C to 99 ^{O}C in an array of heat exchangers HX 109CA1, HX 109CA2, HX 109CB1 and HX 109CB2 arranged parallel and series which simultaneously decreases temperature of lean MDEA from 122 ^{O}C to 90 ^{O}C.

From the above description of various networks of heat exchangers, it is clear that the various process streams are so arranged not only to achieve the target of ammonia production but also to achieve the same with maximum utilization of heat energy. This will enable the plant to operate at minimum possible operating and capital cost (OC and CC). To achieve this, a number of synthesis and optimization techniques are available from earlier investigation as discussed in Chapter 2.

The present study intends to focus on an ammonia production plant which is a part of a fertilizer industry situated in Gujarat. Though, the plant must have been designed and commissioned using a proven synthesis and optimization technique, it may be beneficial to look into its TAC with reference to a unified synthesis and optimization tool using GA and a modification technique incorporated. For this purpose, online steady state process data is captured during a normal operation of the plant.

3.3 Online Steady State Data of Ammonia Production Plant

As seen from the process description of the production of ammonia, the plant consists of a large number of networks of heat exchangers with requirements of three types of utility streams and non-uniform specification of heat exchangers. Table 3.1 gives the on line steady data acquired during normal operation of the ammonia plant. It can be seen that 32 hot process and 26 cold process streams are needed in the plant.

Table 3.1 Online Steady State Data Acquired During Normal Operation of the Ammonia Plant

Sr. No	Heat Exchanger			Process Parameters				Stream Number	
	Tag Number	Configuration	Fluid	T_{in} °C	T_{out} °C	h kW/m²-K	C kW/K		
1	HX 150C	T	NG	27.0	74.0	1.088	19	CP	1
		S	Steam	147.0	147.0	0.120	2	HU	1
2	HX 101 CA	T	Saturated Water	313.0	313.0	2.230	44694	CP	2
		S	PG	998.0	483.0	0.254	87	HP	1
3	HX 101 CB	T	Saturated Water	313.0	313.0	2.230	44694	CP	3
		S	PG	998.0	483.0	0.253	86	HP	2
4	HX 102C	T	PG	482.0	371.0	0.365	86	HP	3
		S	Saturated Water	313.0	313.0	0.692	9601	CP	4
5	HX 103C	T	PG	430.0	333.0	0.346	86	HP	4
		S	Saturated Water	313.0	313.0	0.461	8370	CP	5
6	HX 104C	T	PG	332.0	241.0	0.198	89	HP	5
		S	SG	114.0	316.0	0.089	40	CP	6
7	HX 112C	T	PG	240.0	204.0	1.130	87	HP	6
		S	Condensate	50.0	155.0	0.387	30	CP	7

8	HX 142 CA/ CB	T	BFW	179.0	211.0	0.201	114	CP	8
		S	PG	228.0	190.0	0.169	96	HP	7
9	HX 143C	T	BFW	113.0	180.0	0.241	114	CP	9
		S	PG	194.0	169.0	0.646	307	HP	8
10	HX 105 CA	T	MDEA	116.0	121.0	5.261	5973	CP	10
		S	PG	168.0	128.0	0.658	746	HP	9
11	HX 105 CB	T	MDEA	118.0	123.0	5.261	5973	CP	11
		S	PG	168.0	128.0	0.642	728	HP	10
12	HX 106C	T	PG	127.0	63.0	0.377	200	HP	11
		S	DMW	52.0	120.0	0.355	188	CP	12
13	HX 136C	T	LPSGC SG	159.0	86.0	0.315	40	HP	12
		S	SG	48.0	117.0	0.334	42	CP	13
14	HX 116C	T	LPSGC SG	85.0	41.0	0.319	43	HP	13
		S	CW	34.4	46.1	0.788	162	CU	1
15	HX 129C	T	LPSGC SG	40.0	7.0	0.454	41	HP	14
		S	NH_3	-10.0	2.0	1.248	114	CP	14
16	HX 114C	T	SG	360.0	145.0	0.099	40	HP	15
		S	BFW	115.0	311.0	0.110	44	CP	15
17	HX 115C	T	SG	144.0	38.0	0.166	45	HP	16
		S	CW	32.0	46.0	0.616	344	CU	2
18	HX 141C	T	SG	37.0	8.0	0.053	7	HP	17
		S	NH_3	-8.0	15.0	0.067	9	CP	16
19	HX 121C	T	HPSGC SG	23.0	141.0	0.187	222	CP	17
		S	108D Output	164.0	68.0	0.230	273	HP	18
20	HX 122C	T	105D Output	471.0	284.0	0.434	223	HP	19
		S	HPSGC SG	140.0	427.0	0.283	145	CP	18
21	HX 107C	T	108D Output	377.0	278.0	0.721	152	HP	20
		S	BFW	220.0	252.0	2.232	472	CP	19
22	HX 123C	T	108D Output	277.0	166.0	0.570	230	HP	21
		S	BFW	117.0	231.0	0.555	224	CP	20

23	HX 124C	T	108D Output	67.0	47.0	0.889	282	HP	22
		S	CW	32.1	46.1	0.868	401	CU	3
24	HX 117C	T	108D Output	45.0	22.0	0.690	192	HP	23
		S	NH_3	13.0	13.0	0.166	4425	CP	21
25	HX 118C	T	108D Output	21.0	1.0	0.919	323	HP	24
		S	NH_3	-7.0	-7.0	0.206	6462	CP	22
26	HX 120C	T	Recycle Gas	-22.0	25.0	0.342	232	CP	23
		S	108D Output	46.0	-11.0	0.282	191	HP	25
27	HX 119C	T	108D Output	-4.0	-24.0	1.556	809	HP	26
		S	NH_3	-32.0	-32.0	0.179	16193	CP	24
28	HX 128C	T	CW	31.7	43.3	0.358	201	CU	4
		S	MP NH_3	106.0	36.0	0.126	33	HP	27
29	HX 127 CA/ CB	T	CW	31.7	34.4	0.971	23341	CU	5
		S	HP NH_3	133.0	44.0	0.120	315	HP	28
30	HX 108 CA/ CB	T	CW	34.4	46.8	0.871	3567	CU	6
		S	Lean MDEA	88.0	42.0	0.401	961	HP	29
31	HX 109 CA1/CA2/ CB1/CB2	T	Semi-lean MDEA	71.0	99.0	0.471	923	CP	25
		S	Lean MDEA	122.0	90.0	0.412	807	HP	30
32	HX 110C	T	CW	42.8	47.5	0.915	4979	CU	7
		S	CO_2	96.0	57.0	0.824	600	HP	31
33	HX 126C	T	NH_3	9.0	9.0	0.085	285	CP	26
		S	Flash Gas	35.0	3.0	0.483	9	HP	32

T = Tube Side, S = Shell Side, CW = Circulating Water, Lean MDEA = Lean Mixture of MDEA and CO_2, Semi-lean MDEA = Semi Lean Mixture of MDEA and CO_2, HP = Hot Process Stream, CP = Cold Process Stream, HU = Hot Utility Stream, CU = Cold Utility Stream.

Chapter 4

SYNTHESIS, OPTIMIZATION AND MODIFICATION

This chapter deals with the theoretical aspects of the proposed unified approach of synthesis and optimization using PT for synthesis, GA for optimization and network pinch method (NPM) and retrofitting analysis (RA) for modification. The proposed unified approach of synthesis and optimization is a combination of two approaches of PT, viz., either ΔT_{min} or Q_{min} approach with GA as an optimization tool. The two approaches of PT are separately employed along with GA to synthesize and optimize HEN of ammonia production plant to predict the optimum TAC. If the synthesis using PT and optimization using GA leads to a possibility of modifying the plant for saving in TAC, modification techniques using either NPM or RA can be employed.

Section 4.1 describes the two approaches of PT, viz., ΔT_{min} and Q_{min} approach. Synthesis and optimization of an existing HEN using GA is given in Section 4.2. Section 4.3 describes the two methods of modifications, viz., NPM and RA. Section 4.4 gives the details of the unified approach adopted for the synthesis, optimization and modification of HEN.

4.1 Pinch Technology

PT is the state of the art technique for designing the HEN of chemical plant for maximum energy recovery. The use of the method allows one to determine minimum utility requirements, number and area of heat exchangers required based on the thermal data of process streams i.e. their temperatures and heat duties in the process. Although a powerful technique for process synthesis, pinch technology may be supplemented with one of the structural optimization technique to create a hybrid design tool.

4.1.1 Comparison between ΔT_{min} and Q_{min} Approaches

As discussed earlier, PT is employed for HEN to estimate heat exchanger area needed, minimum number of exchanger shell and units needed for maximum energy recovery. For this purpose, one can employ either ΔT_{min} or Q_{min} approach. The basic difference between the two approaches lies in the manner in which the pinch point temperature is determined. The shift in the inlet and outlet temperature of cold and hot process/utility steams are by an amount of $\frac{\Delta T_{min}}{2}$ for ΔT_{min} approach, while that for process/utility streams are by an amount of $\frac{Q_{min}}{h}$ in case of Q_{min} approach. There is possibility of uniform temperature shift in ΔT_{min} approach while temperature shift is non-uniform in Q_{min} approach. In Q_{min} approach, the temperature shift of all the streams are inconsistent since the heat transfer coefficient, h will be different for different streams. This poses difficulty in the estimation of logarithmic mean temperature difference (LMTD) for each temperature interval using Q_{min} approach. However, a shift compensating factor defined takes care of the determination of LMTD when Q_{min} approach is employed. The another difference between ΔT_{min} and

Q_{min} approaches is that, all the calculations except the calculation of pinch point temperature are carried out using un-shifted temperatures in case of ΔT_{min} approach, while all the calculations are carried out using shifted temperatures in case of Q_{min} approach.

4.1.2 Estimation of Area, Number of Units and Shell for HEN

As stated earlier, PT is a technique for designing the HEN for maximum energy recovery. The minimum utility requirements, number, area of heat exchangers required and TAC of HEN can be estimated using PT. The following step by step procedure can be adopted for the estimation of the above. The procedure is almost similar for both the approaches of PT, viz., ΔT_{min} and Q_{min} approaches. However, the difference between them is explained simultaneously. The various contributions in the development of PT are compiled in a systematic manner by Shenoy [61] and used in present work.

4.1.2.1 Minimum Requirement of Utilities

Minimum requirement of utilities are estimated based on the laws of thermodynamics and also it should be thermodynamically minimum. According to energy balance, the energy available in hot process and hot utility streams should be equal to energy required by cold process and cold utility streams. Mathematically,

$$\sum Q_h + \sum Q_{hu} = \sum Q_c + \sum Q_{cu} \tag{4.1}$$

Heat transfer can occur only from higher temperature streams to lower temperature streams. There must be a positive temperature difference to provide an adequate driving force for heat transfer between hot and cold streams. Thus, to calculate practical energy targets, the maximum amount of heat transfer possible with a stipulated minimum positive temperature difference must be determined and the remaining heat must be supplied by external utilities.

4.1.2.2 Pinch Point

Pinch point is calculated on the basis of the fact that, the stream with higher temperature level can give heat to that stream with lower temperature level. The steps to calculate the pinch point for ΔT_{min} and Q_{min} approaches are as under:

Step 1. (a) ***ΔT_{min} Approach***

Shift the inlet and outlet temperatures of cold and hot process streams using the following equations.

$$t_{h,in,shifted} \text{ or } t_{h,out,shifted} = (t_{h,in} \text{ or } t_{h,out}) - (\Delta T_{min} / 2) \quad (4.2)$$

$$t_{c,in,shifted} \text{ or } t_{c,out,shifted} = (t_{c,in} \text{ or } t_{c,out}) + (\Delta T_{min} / 2) \quad (4.3)$$

Step 1. (b) ***Q_{min} Approach***

Shift the inlet and outlet temperatures of cold and hot process streams using following equations.

$$t_{h,in,shifted} \text{ or } t_{h,out,shifted} = (t_{h,in} \text{ or } t_{h,out}) - (Q_{min} / h) \quad (4.4)$$

$$t_{c,in,shifted} \text{ or } t_{c,out,shifted} = (t_{c,in} \text{ or } t_{c,out}) + (Q_{min} / h) \quad (4.5)$$

Step 2. Sort the shifted temperatures in descending order omitting the common temperatures to both hot and cold process streams. The temperatures arranged in descending order are known as temperature interval (ti).

Step 3. Calculate Net Capacity Flow Rate for each temperature interval using

$$C_{ti} = \sum C_{cps,ti} - \sum C_{hps,ti} \quad (4.6)$$

Step 4. Calculate Net Enthalpy in each temperature interval using

$$Q_{ti} = C_{ti} * \Delta T_{ti} \quad (4.7)$$

Step 5. Calculate the cascaded heat using

For First Temperature interval, viz. ti = 0,

$Q_{cas,ti} = 0$ (4.8)

For Other Temperature intervals, i.e. ti > 0,

$Q_{cas,ti} = Q_{cas,ti-1} - Q_{ti}$ (4.9)

Step 6. Calculate revision of cascaded heat using

$R_{cas,ti} = Q_{cas,ti} + MinQ_{cas,ti}$ (4.10)

Step 7. Note the temperature interval at zero R_{cas} value. This is the "pinch point temperature" or simply "pinch point".

Step 8. Identify the R_{cas} at first temperature interval as $Q_{hu,min}$ and R_{cas} at last temperature interval as $Q_{cu,min}$.

4.1.2.3 Cumulative Enthalpy for Hot Process Stream and Cold Process Stream

For hot process steams, cumulative enthalpies are calculated as follows:

Similar steps are used in the calculation of cumulative enthalpy for cold process streams also.

Step 1. Sort out $T_{h,in}$ and $T_{h,out}$ in ascending order, omitting the repeated values for ΔT_{min} approach and sort out $T_{h,in,shifted}$ and $T_{h,out,shifted}$ in ascending order, omitting the repeated values for Q_{min} approach. The temperatures arranged in descending order are known as temperature interval (ti).

Step 2. Calculate, for each interval of temperatures, the summation of capacity flow rate of hot streams present in the interval and store in next to the temperature interval. Note that, for first temperature interval, the value of capacity flow rate is zero.

Step 3. Multiply the sum of the capacity flow rate value in each temperature interval by the temperature difference for that interval to obtain the enthalpy ($Q_{h,ti}$) for that temperature interval. Note that, for first temperature interval, the value of enthalpy is zero.

Step 4. Calculate for each temperature interval, cumulative enthalpy using

For First Temperature interval, viz. ti = 0,

$$CumQ_{h,ti} = 0 \tag{4.11}$$

For Other Temperature intervals, i.e. ti > 0,

$$CumQ_{h,ti} = CumQ_{h,ti-1} + Q_{h,ti} \tag{4.12}$$

For cold process steams, cumulative enthalpies are calculated in similar way mentioned above in step1 to step 4 for hot process streams.

4.1.2.4 Area of HEN for Counter Current Heat Exchanger

Heat transfer area of HEN for counter current specification of heat exchangers can be calculated as follows:

Step 1. Calculate capacity flow rates for utility streams.

Case I Single Utility i.e. one hot and /or one cold utility

- Use the same step-by-step procedure to calculate pinch point given in Section 4.1.2.2 for the estimation of requirement of minimum hot and cold utility.
- Calculate the capacity flow rate for hot and cold utility

$$CR_{hu} = (Q_{hu,min}) / (t_{hu,in} - t_{hu,out}) \tag{4.13}$$

$$CR_{cu} = (Q_{cu,min}) / (t_{cu,out} - t_{cu,in}) \tag{4.14}$$

Case II Multi Utility i.e. more than one hot and /or one cold utility

In the case of more than one hot and/or one cold utility present, which utility is to be used first must be decided properly. The following step-by-step procedure is used.

- Determine the priority to the each utility based on the two criterion, viz., lowest cost and inlet temperature of utilities.
    (1) Select first the lowest cost utilities.
    (2) Give priority to hottest cold utility and coldest hot utility in the absence of cost data or same cost.
- Calculate the revised cascaded heat (R_{cas}) by applying the interpolation between the temperature interval and R_{cas} at the inlet temperature of the utility.
- Determine the usage level of individual utilities based on their priority number and minimum utility requirements.
- Calculate flow rates for utilities using

$$CR_{hu} = (\text{Individual Usage Level}) / (t_{hu,in} - t_{hu,out}) \qquad (4.15)$$

$$CR_{cu} = (\text{Individual Usage Level}) / (t_{cu,out} - t_{cu,in}) \qquad (4.16)$$

Step 2. Calculate cumulative enthalpies for hot streams (process and utility both) and cold streams (process and utility both)

- Calculate cumulative enthalpies for hot process and hot utility streams in similar way mentioned in Section 4.1.2.3 for only hot process streams. The basic difference is that, in this step hot utility is considered along with hot process streams.

- Calculate cumulative enthalpies for cold process and cold utility streams in similar way given in Section 4.1.2.3.

Step 3. Determine cumulative enthalpies for each intervals

- Merge cumulative enthalpies of hot process and utility streams with the cumulative enthalpies of cold process and utility streams.
- Omit common values from the merged cumulative enthalpies and sort in ascending order.

Step 4. Calculate temperature intervals for hot process and utility streams i.e. $T_{h,ti}$

Step 5. Calculate temperature intervals for cold process and utility streams i.e. $T_{c,ti}$

Step 6. Calculate $\Sigma(C/h)_{h,ti}$ and $\Sigma(C/h)_{c,ti}$ for each interval of $T_{h,ti}$ and $T_{c,ti}$.

Step 7. Calculate Sum(Q/h) in each interval using the following equations:

For First Temperature interval, viz. ti = 0,

$$Sum\left(Q/h\right)_{ti} = 0 \tag{4.17}$$

For Other Temperature intervals, ti > 0

$$\mathrm{Sum}\left(\mathrm{Q}/\mathrm{h}\right)_{ti} = \left(\mathrm{T_{h,ti}} - \mathrm{T_{h,ti-1}}\right) \times \sum\left(\mathrm{C}/\mathrm{h}\right)_{\mathrm{h,ti}} + \left(\mathrm{T_{c,ti}} - \mathrm{T_{c,ti-1}}\right) \times \sum\left(\mathrm{C}/\mathrm{h}\right)_{\mathrm{c,ti}} \tag{4.18}$$

Step 8. Calculate LMTD for each interval using the following for the two approaches, of, ΔT_{min} and Q_{min}.

For ΔT_{min} Approach:

For First Temperature interval, viz. ti = 0,

$$LMTDti = 0 \tag{4.19}$$

For Other Temperature intervals, ti > 0

$$LMTD_{ti} = \frac{\left(T_{h,i} - T_{c,i}\right) - \left(T_{h,i-1} - T_{c,i-1}\right)}{\ln\left[\frac{\left(T_{h,i} - T_{c,i}\right)}{\left(T_{h,i-1} - T_{c,i-1}\right)}\right]} \tag{4.20}$$

For Q_{min} Approach:

Calculate the Shift Compensating Factor (SCF) in order to compensate for non-uniform temperature shift.

For First Temperature interval, viz. ti = 0,

$$\mathrm{SCF_{ti}} = 0 \tag{4.21}$$

For Other Temperature intervals, ti > 0

$$\mathrm{SCF_{ti}} = \frac{\mathrm{Q_{min}}}{\mathrm{CumQ_{ti}} - \mathrm{CumQ_{ti-1}}} \times \mathrm{Sum}(Q/h)_{\mathrm{ti}} \tag{4.22}$$

For First Temperature interval, viz. ti = 0,

$$LMTDti = 0 \tag{4.23}$$

For Other Temperature intervals, ti > 0

$$LMTD_{ti} = \frac{\left(T_{h,i} - T_{c,i}\right) - \left(T_{h,i-1} - T_{c,i-1}\right)}{\ln\left[\dfrac{\left(T_{h,i} - T_{c,i}\right) + SCF_{ti}}{\left(T_{h,i-1} - T_{c,i-1}\right) + SCF_{ti}}\right]} \tag{4.24}$$

Step 9. Calculate heat transfer area of HEN using the following relation

$$A_{c,ti} = \frac{\left[Sum\left(Q/h\right)_{ti}\right]}{LMTD_{ti}} \tag{4.25}$$

Step 10. Divide, at the pinch point temperature, heat transfer area of HEN for counter current heat exchanger into two parts viz., area above pinch and area below pinch.

4.1.2.5 Heat Transfer Area of HEN for Shell and Tube Heat Exchanger

Step 1. Calculate the temperature effectiveness, P for each temperature interval using

$$P_{ti} = \frac{\left(T_{h,i} - T_{h,i-1}\right)}{\left(T_{h,i} - T_{c,i-1}\right)} \tag{4.26}$$

Step 2. Calculate the capacity flow rate ratio, R for each temperature interval using

$$R_{ti} = \frac{\left(T_{c,i} - T_{c,i-1}\right)}{\left(T_{h,i} - T_{h,i-1}\right)} \tag{4.27}$$

Step 3. Calculate the temperature effectiveness of an individual 1-2 shell and tube heat exchanger, $P_{e,ti}$ for each temperature interval using

$$P_{e,ti} = 0.9 \times P_{max} \tag{4.28}$$

Where, $P_{max} = \dfrac{2}{\left(R_{ti} + 1 + \left(R_{ti}^{\ 2} + 1\right)^{\frac{1}{2}}\right)}$

Step 4. Calculate the number of shells needed in series, S for each temperature interval

$$S_{ti} = \frac{\ln\left[\dfrac{(1 - R_{ti}P_{ti})}{(1 - P_{ti})}\right]}{\ln\left[\dfrac{\left(1 - R_{ti} \times P_{e,ti}\right)}{\left(1 - P_{e,ti}\right)}\right]} \quad \text{for } R_{ti} \neq 1 \tag{4.29}$$

$$S_{ti} = \frac{\left[\dfrac{P_{ti}}{(1 - P_{ti})}\right]}{\left[\dfrac{\left(P_{e,ti}\right)}{\left(1 - Pe, ti\right)}\right]} \quad \text{for } R_{ti} = 1 \tag{4.30}$$

Step 5. Calculate correction factor, F for each temperature interval

$$F_{ti} = \left(\frac{\ln\left[\dfrac{\left(1 - P_{r,ti}\right)}{1 - R_{ti} \times P_{r,ti}}\right]}{N_{ti} \times \left(R_{ti} - 1\right)}\right) \quad \text{for } R_{ti} \neq 1 \tag{4.31}$$

$$F_{ti} = \left(\frac{P_{r,ti}}{N_{ti} \times \left(R_{ti} - 1\right)}\right) \quad \text{for } R_{ti} = 1 \tag{4.32}$$

Where,

$$N_{ti} = \left(\frac{1}{\sqrt{R_{ti}^{\ 2} + 1}}\right) \ln\left[\frac{2 - P_{r,ti} \times \left(R_{ti} + 1 - \sqrt{R_{ti}^{\ 2} + 1}\right)}{2 - P_{r,ti} \times \left(R_{ti} + 1 + \sqrt{R_{ti}^{\ 2} + 1}\right)}\right] \quad \text{and}$$

$$P_{r,ti} = \frac{(1-Y_{ti})}{(R_{ti}-Y_{ti})}\ ,\ Y_{ti} = \left[\frac{(1-R_{ti}P_{ti})}{(1-P_{ti})}\right]^{\frac{1}{NS_{ti}}} \quad \text{for } R_{ti} \neq 1$$

$$P_{r,ti} = \frac{P_{ti}}{(NS_{ti} - NS_{ti} \times P_{ti} + P_{ti})} \qquad \text{for } R_{ti} = 1$$

Step 6. Calculate area of HEN for shell and tube heat exchanger

$$A_{ti} = \frac{A_{c,ti}}{F_{ti}} \tag{4.33}$$

Step 7. Divide, at the pinch point temperature, heat transfer area of HEN for shell and tube heat exchanger into two parts viz., area above pinch and area below pinch.

4.1.2.6 Minimum Number of Unit for Maximum Energy Recovery

Step 1. Note the number of process streams and utility streams above pinch point (N_a) and number of process and utility streams below pinch point (N_b) from step by step calculation of pinch point given in Section 4.1.2.2.

Step 2. Calculate minimum number of units for an maximum energy network, $N_{u,mer}$ using following relationship:

$$N_{u,mer} = (N_a - 1) + (N_b - 1) \tag{4.34}$$

4.1.2.7 Number of Shell for Maximum Energy Recovery

Rough Estimation of Shells

Step 1. Calculate of number of shells required per match, $S_{m,ti}$.

The number of shells required per match, $S_{m,ti}$ is exactly same as that obtained using Equations (4.29) and (4.30) in Step 4 of calculation of area of HEN for shell and tube heat exchanger given in Section 4.1.2.5

Step 2. Calculate number of streams in each interval, $N_{s,ti}$

The number of streams (hot and cold) present in each temperature is counted during the calculation of cumulative enthalpy for hot and cold process streams as mentioned in Section 4.1.2.3.

Step 3. Calculate of number of shells in each interval

Calculate the minimum number of shells in each interval using following equation.

$$S_{min} = S_{m,ti} * (N_{s,ti} - 1) \tag{4.35}$$

Step 4. Determine the number of shells in intervals below pinch and above pinch regions and sum separately after rounding off to the next higher integer.

Accurate Determination of Shells

Step 1. Calculate of shell contribution on a stream-wise basis.

Calculate the numbers of shells required on a stream-wise basis for the region above pinch and below pinch. Determine the contribution of shells of all the streams.

Step 2. Sum up and round it off to the nearest integer, the number of shells above pinch and below pinch.

Step 3. Calculate the area per shell below pinch and above pinch and check for shell size violation.

At the pinch point temperature, heat transfer area of HEN for shell and tube heat exchanger calculated in Section 4.1.2.5 is divided into two parts viz., area above pinch and area below pinch. Area above pinch and below pinch are divided by number of shells above pinch and below pinch calculated in above step to obtain area per shell above pinch and below pinch. This area per shell above and below pinch should not be more than the standard area per shell. In case of violating the area per shell above or below pinch, number of shell required above or below pinch should be increased respectively until the area per shell above or below pinch reaches to the standard value.

4.1.3 Estimation of Total Annual Cost of HEN

The TAC of a HEN basically comprises the operating cost and the capital cost. The operating cost is a function of the energy requirements and the capital cost is the cost of heat exchangers.

4.1.3.1 Operating Cost (OC)

The operating cost is calculated using the equation,

$$OC = \left(C_{hu} \times Q_{hu,min}\right) + \left(C_{cu} \times Q_{cu,min}\right) \tag{4.36}$$

4.1.3.2 Capital Cost (CC)

The capital cost for a network of Shell and Tube heat exchangers can be calculated using the equation,

$$CC = a \times N_{u,mer} + b \times S_{min} \times \left({}^{A}/_{S_{min}}\right)^{c} \tag{4.37}$$

In the above equation, a, b and c are the cost coefficients. Their values depend on the material of construction, the pressure rating and the type of heat exchangers. The coefficient, a, represents the fixed cost.

4.1.3.3 Total Annual Cost (TAC)

As the energy cost is a recurring expense and the capital cost is a one-time investment, the expected life of the plant must be considered while calculating TAC. Thus, TAC is given by,

$$\mathrm{TAC} = \mathrm{OC} + (\mathrm{CC} \times \mathrm{A_f}), \tag{4.38}$$

$$Where, A_f \text{ is the annualization factor} = \frac{(1+r)^{\tau}}{\tau}$$

4.1.3.4 TAC of HEN with Non-Uniform Heat Exchangers

The following step by step procedure is followed for the calculation of cost of a HEN consisting of Non-Uniform heat exchangers.

Step 1. Determine reference heat exchanger for a network of non-uniform heat exchangers and specify its values as a_r, b_r and c_r.

Step 2. Specify the values of cost law constants for specific heat exchangers as a_s, b_s and c_s.

Step 3. Calculate the weighting factor (ϕ_j) for a specific heat exchanger using a_r, b_r and c_r and its a_s, b_s and c_s using

$$\phi_j = \left(\frac{b_r}{b_s}\right)^{1/c_r} + \left(\frac{A}{S_{min}}\right)^{1-\left(c_s/c_r\right)} \tag{4.39}$$

Step 4. Determine the modified heat transfer co-efficient of the stream ($h_{rr,j}$) for the specific heat exchangers using

$$h_{rr,j} = \phi_j \times h_j \tag{4.40}$$

Step 5. Determine the modified area (A_{rr}) using the modified heat transfer co-efficient of the stream, $h_{rr,j}$.

Calculate the area of HEN for counter current heat exchanger and shell and tube heat exchangers using $h_{rr,j}$ instead of h_j in similar way mentioned in Sections 4.1.2.4 and 4.1.2.5 respectively.

Step 6. Determine CC for a network of 1-2 Shell and Tube heat exchangers using the following cost equation

$$CC = a_r \times N_{u,mer} + \{ b_r \times S_{min} \times ({A_{rr}}/{S_{min}})^{c_r} \} \qquad (4.41)$$

Step 7. Determine TAC for a network of 1-2 Shell and Tube heat exchangers using the equation (4.38).

4.2 Genetic Algorithms

The methodology of GA developed by Goldberg [175] is adopted in this work. The step by step procedure to optimize the existing HEN using GA for both the approaches is as follows.

Step 1. Input the process parameters, cost parameters and data of existing HEN. Process parameters include terminal temperatures, heat transfer coefficients and mass capacity flow rate of streams; while cost parameters include cost of utilities, rate of interest, plant life and cost law coefficients. Data of existing HEN consists of utilities needed, area of HEN, OC, CC and TAC.

Step 2. Select the approach, either ΔT_{min} or Q_{min} approach.

Step 3. Input GA parameters which include number of variable, range of variable, crossover probability, mutation probability and maximum number of generation. Along with the crossover probability and mutation probability, the GA parameters like population size and number of generation are critical. Population size determines number of points across the solution space from where search starts simultaneously and number of generation defines that how many times loop can be continued.

Step 4. Execute the subroutine for GA.

1. Random Population Generation

   GA begins with a population of string structures, created at random. The term string is referred as binary string (binary coded variable) in GA literature. Each string stores the value of variable i.e. ΔT_{min} or Q_{min} in binary form.

2. Evaluate Randomly Generated Population

   Thereafter, each binary string is decoded to get its real value of variable. Using real value of variable, TAC of HEN is calculated using steps presented in Section 4.1.2 and Section 4.1.3 for ΔT_{min} and Q_{min} approach. TAC of HEN corresponding to each string is compared and minimum among them is stored in $TAC_{min,i}$.

3. The population is then operated by three main operators known as Reproduction, Crossover and Mutation to create a hopefully better population. The population is further evaluated and tested for termination. The termination criterion is generally the number of generation. If termination criteria are not met, the population is again operated by above three operators and evaluated. This procedure is continued until the termination criteria are met. One cycle of these operators and the evaluation procedure is known as a Generation.

4. Reproduction of Binary Strings

   Reproduction is the selection of binary strings having minimum value of TAC of HEN. There are many methods available for operating binary strings for reproduction like Tournament Selection, Biased Roulette Wheel selection etc. The biased roulette wheel selection method selects binary strings having minimum values of TAC of HEN. In the present work, the biased roulette wheel selection process for reproduction is used. Selected binary strings which are known as parent strings then undergo crossover.

5. Crossover of Parent Strings

The different methods available for crossover is single point, double point and multi point crossover. In single point crossover, parent strings and crossover site are selected randomly and subsequently the right hand portions from the crossover site of the selected parent strings are interchanged. In the present work, single point crossover method is employed. Parent strings then undergo mutation operator.

6. Mutation of Parent Strings

The different methods for mutation are change of single bit, change of two bit and change of multi bit. In change of single bit mutation method, parent strings and mutation site are selected based on random number. At the mutation site of the selected parent string, value of bit is changed from 0 to 1 or 1 to 0. For mutation, change of single bit method for is employed in the present work. The new binary coded strings thus obtained after applying three operators are known as child strings. Each child string also represents value of variable i.e. ΔT_{min} or Q_{min} in binary form.

7. Evaluation of Child Strings

Child strings are decoded to obtain the real value of variable and related TAC of HEN is calculated using steps presented in Section 4.1.2 and Section 4.1.3 for ΔT_{min} and Q_{min} approach. TAC of HEN corresponding to each child string is compared and minimum among them is stored in $TAC_{min,i+1}$. $TAC_{min,i}$ is compared with $TAC_{min,i+1}$ and hence the binary string having minimum value of objective function is selected and stored. Thus, one generation of operation in GA is completed. The program continues in the loop until required number of generation is reached. Finally, the binary sting having minimum value of TAC is captured. The binary string is further decoded to calculate the optimized TAC of HEN and stored.

Step 5. The TAC of HEN obtained using GA (TAC_{GA}) is compared with TAC of the existing HEN (TAC_{exist}). If TAC_{GA} is less than TAC_{exist}, modification in the existing HEN is possible.

4.3 Modification Analysis

Modifications in existing HEN of the ammonia plant using NPM and RA with ΔT_{min} and Q_{min} approaches are carried out. Different modification analyses are applied to existing HEN to identify the feasible configuration of HEN due to which TAC of HEN after modification reaches closer to the TAC_{GA}. The TAC of HEN consists of CC and OC. CC is the cost of heat exchangers used in HEN, while OC is the cost of utilities. There is an inverse relationship between CC and OC. Hence, two routes of modifications, either to reduce CC or OC have been identified. At this stage, it becomes essential to verify both the routes of modifications. There are two methods of HEN modification using pinch analysis viz., NPM and RA. NPM starts with the value of ΔT_{min} or Q_{min} at which TAC of HEN is minimum, while RA starts with the value of ΔT_{min} or Q_{min} at which the utilities are same as the utilities needed in the existing HEN. Generally, NPM modifies the HEN to reduce CC, while RA modifies HEN to reduce OC. The methodologies of NPM and RA developed by Linnhoff and Hindmarsh

[32] and Tjoe and Linnhoff [235] and presented in Shenoy [61] are adopted in this work. The different steps for modification in existing HEN using NPM and RA are given below.

4.3.1 Network Pinch Method

The steps to modify HEN using NPM are as follows:

(1) Identify the Target ΔT_{min} or Q_{min}

Analyze the variation of TAC of HEN at different values of ΔT_{min} or Q_{min} to select the value of ΔT_{min} or Q_{min} (Target ΔT_{min} or Q_{min}) at which TAC of HEN is minimum. For the present work, targeted ΔT_{min} or Q_{min} is same as ΔT_{min} or Q_{min} obtained using GA.

(2) Plot the Grid Diagram of the Existing HEN

Prepare the grid diagram of the existing HEN of ammonia plant at targeted ΔT_{min} or Q_{min} value. In the grid diagram, temperatures are shown on the top and the bottom. Identify pinch temperature for hot and cold streams at the top and the bottom respectively. Connect both the pinch temperatures by dark dotted line. Show each process stream by a line which represents the inlet and outlet temperature of each stream at the start and end of the line. Mark heat exchanger tag number on the circle which is placed on the line. Represent the heat load of the heat exchanger with rectangle near the line. Mention the process stream numbers at the left and right ends of the diagram.

(3) Analyze the Grid Diagram

Analyze critically the grid diagram using the criteria. There should not be use of hot utility below pinch and cold utility above pinch in the existing HEN, and there should not be the cross pinch heat transfer.

(4) Decide the alteration in existing HEN configuration

Decide the alterations depending upon the analysis of grid diagram based on the criteria mentioned above.

(5) Calculate the hot and cold utility required (hur_{NPM} and cur_{NPM}), area of HEN (A_{NPM}), CC (CC_{NPM}), OC (OC_{NPM}) and TAC of HEN (TAC_{NPM}) after modifying the HEN using NPM using steps presented in Section 4.1.2 and Section 4.1.3 for ΔT_{min} and Q_{min} approach and percentage saving in TAC.

4.3.2 Retrofitting Analysis

The first step in modification using RA is to calculate the existing area efficiency of the HEN and establish the relationship between area of HEN and utility. The area-utility relationship then is used to build the relationship between an investment and saving. The payback period is determined for each relationship between investment and saving. The procedure to modify the existing HEN using RA is given below in steps.

(1) Select the Appropriate Value of ΔT_{min} or Q_{min}

Select the value of ΔT_{min} or Q_{min} at which the hot and cold utilities required are same as the hot and cold utilities needed in the existing HEN. Identify area of HEN at the selected value of ΔT_{min} or Q_{min}. Consider the area of HEN at selected ΔT_{min} or Q_{min} as A_{ideal} at that utility.

(2) Calculate Existing Area Efficiency (α_{exist}), of HEN, using

$$\alpha_{exist} = A_{ideal}/A_{exist} \quad (4.42)$$

(3) Select the Various Utility Values

Select some of the utility (hot and cold) values which are less than the utilities needed in the existing plant along with corresponding values of ΔT_{min} or $Q_{min.}$ This is mainly due to the fact that RA mainly aims to reduce the usage of utility and OC. Consider the area of HEN at each selected utility values as $A_{ideal,1}$.

(4) Calculate the maximum area for retrofitting for each selected utility values. RA also aims to sustain the use of the area of HEN while the usage of utilities is reduced. So, it is seen that the area efficiency at any stage should not be less than α_{exist}. Obtain the maximum area for retrofitting, ($A_{max,retr}$), to be used in designing the new HEN using,

$$A_{max,retr} = (A_{ideal} - A_{ideal,1})/\Delta\alpha + A_{exist} \quad (4.43)$$

When α_{exist} is low (i.e., $\alpha_{exist} < 0.9$), the value of $\Delta\alpha$ is considered as 1 which represents ideal area efficiency. At each selected utility values, Calculate $A_{max,retr}$ for both the cases, viz., $\Delta\alpha = 1$ which represents ideal area efficiency and $\Delta\alpha = \alpha_{exist}$ which represents existing area efficiency of HEN. Plot the relationship between $A_{max,retr}$ and utility which is known as the Area – Energy plot for RA.

(5) Calculate the Saving in Utility and Additional Area of HEN Required at each selected utility requirements using:

$$U_{saving} = U_{exist} - U_{GA}. \text{ (Based on Hot or Cold Utility)} \quad (4.44)$$

$$A_{additional} = A_{max,retr} - A_{exist}. \text{ (Based on } \Delta\alpha = 1 \text{ and } \Delta\alpha = \alpha_{exist}) \quad (4.45)$$

(6) Calculate additional investment in additional area of HEN and annual savings in OC for different values of ΔT_{min} or Q_{min}.

(7) Estimate the Payback Period for different values of ΔT_{min} or Q_{min}, using

Payback Period = Additional Investment / Annual Saving (4.46)

(8) Calculate the hot and cold utility required (hur_{RA} and cur_{RA}), area of HEN (A_{RA}), CC (CC_{RA}), OC (OC_{RA}) and TAC of HEN (TAC_{RA}) after modifying the HEN using RA using steps presented in Section 4.1.2 and Section 4.1.3 for ΔT_{min} and Q_{min} approach and percentage saving in TAC.

4.4 Unified Approach

The proposed unified approach of synthesis and optimization of an existing HEN of ammonia production plant using GA and modification using NPM and RA is given in this Section. Figure 4.1 represents main flow chart for the proposed unified approach. A detailed computer code in C++ programming language based on the scheme given in flow charts is developed. The detailed procedure to run the program is presented in Appendix III and program is available in the CD enclosed in the Thesis.

The main flow chart consists of five major units viz., input parameters of HEN, selection of approach for PT, optimization using GA, comparison of optimization results with the details of existing HEN and possibility of modification in the existing HEN of the ammonia plant. Subroutine flow charts are presented in Figure 4.2 for optimization using GA and Figure 4.3 for modification using NPM and RA.

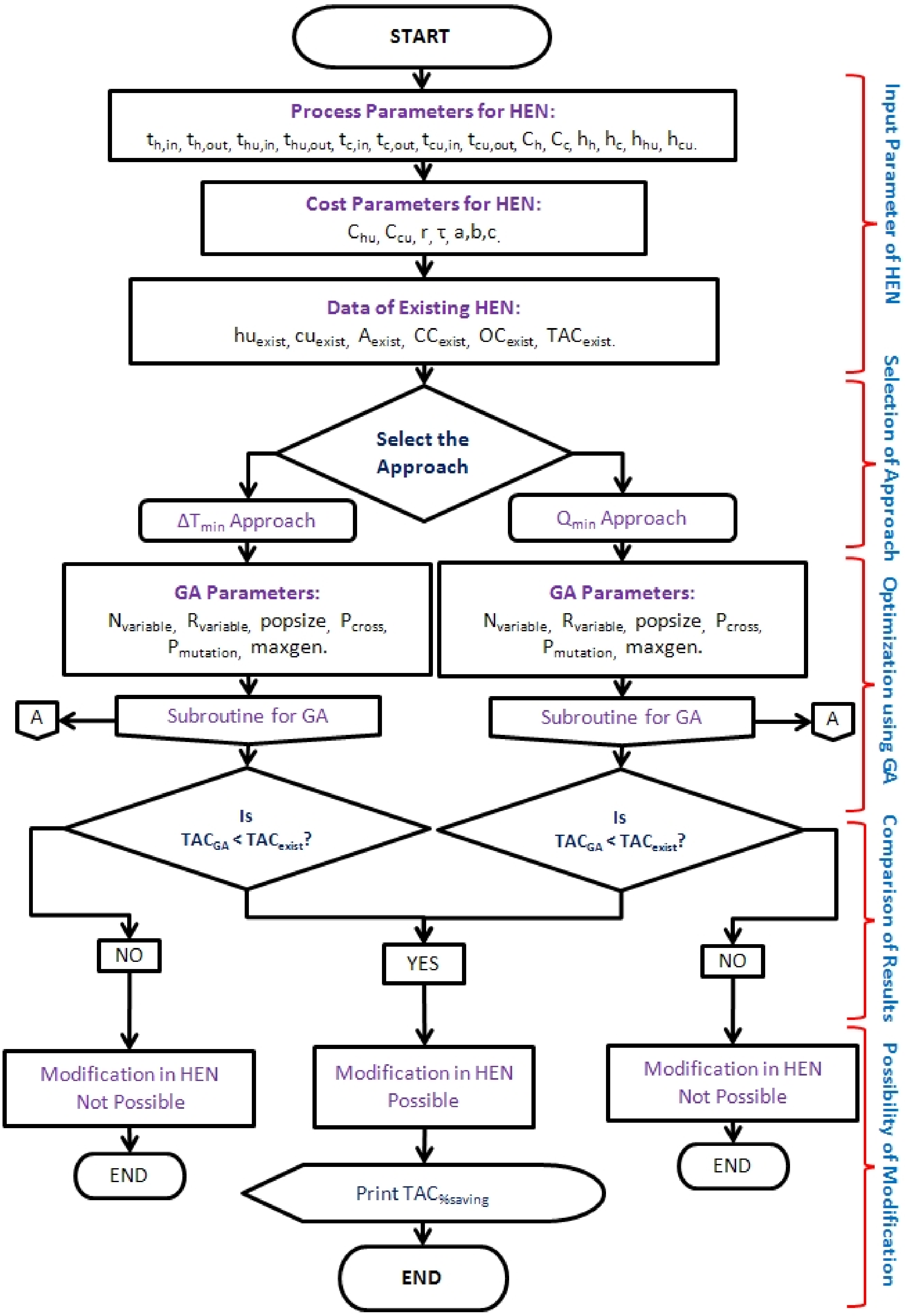

Figure 4.1 Main Flow Chart

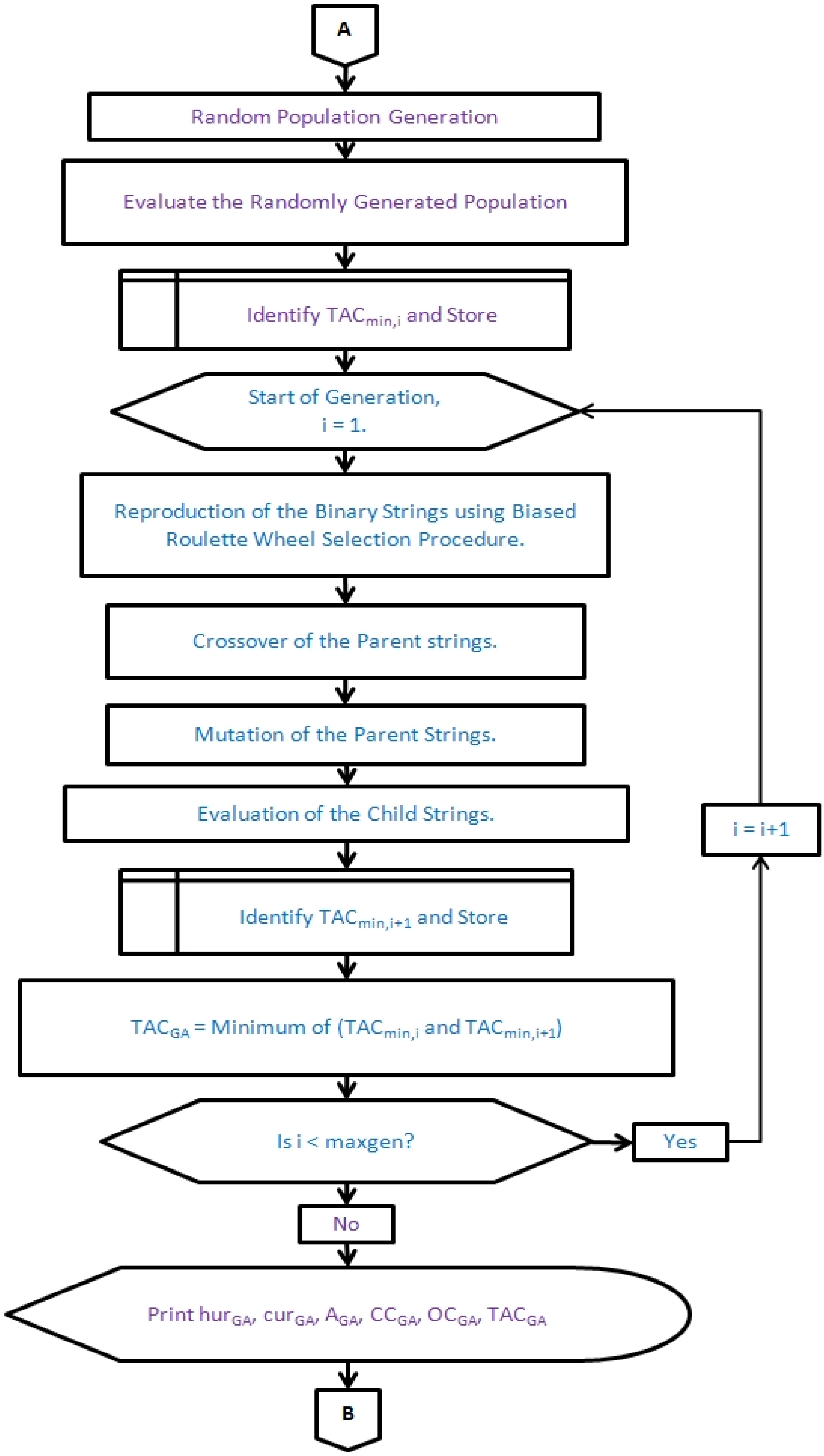

Figure 4.2 Subroutine Flow Chart for GA

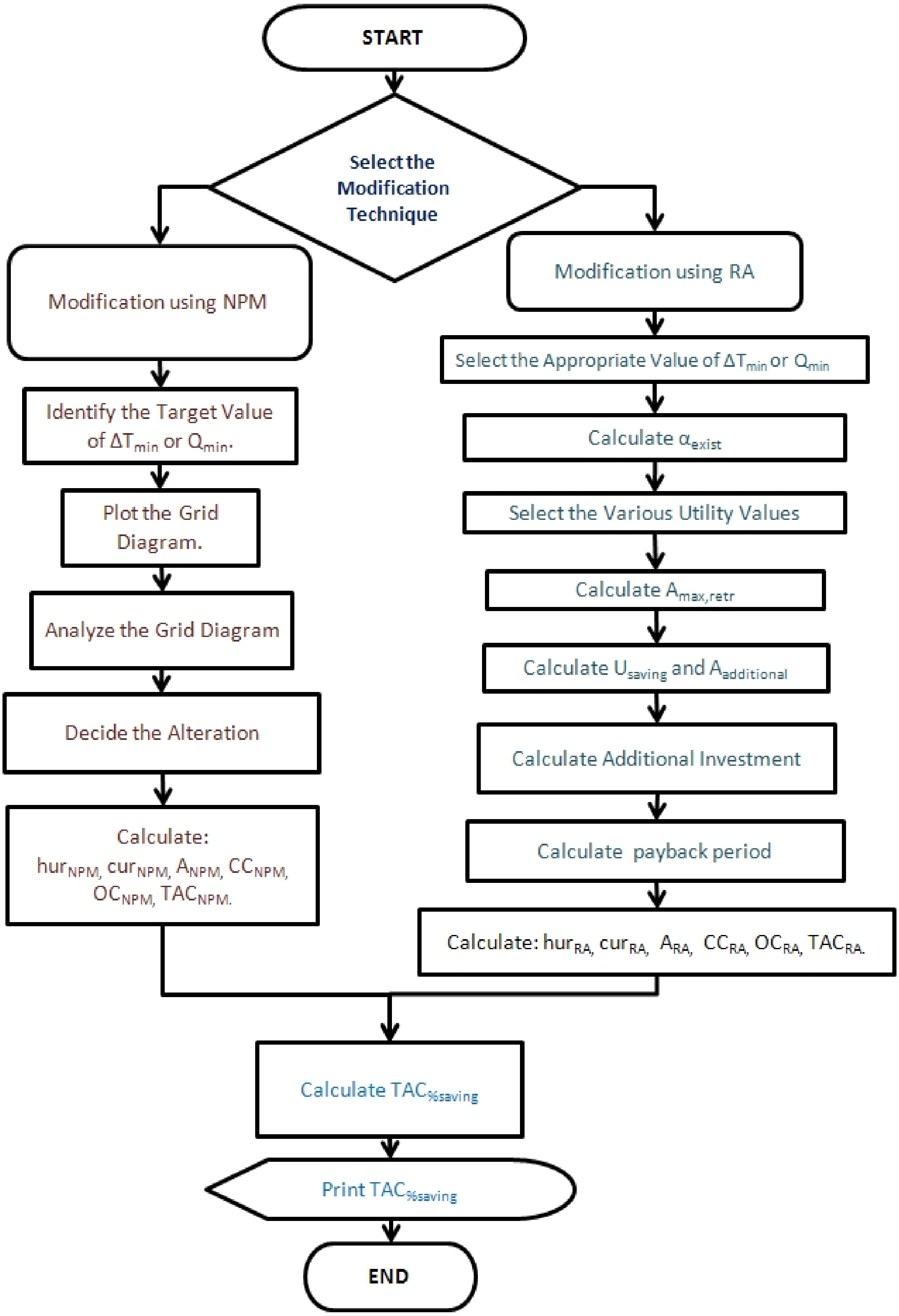

Figure 4.3 Subroutine Flow Chart for Modification

The different steps for synthesis and optimization using GA are as below.

Step 1. Input parameters needed for the analysis are stream data, cost data and GA data. Stream data includes terminal temperatures at inlet and outlet sections of heat exchangers, heat capacity, flow rate and average heat transfer coefficient for all the fluid streams. A typical steady state on line stream data during the normal operation of the existing ammonia plant of the fertilizer industry is used as input data as given in Table 3.1 of Chapter 3. The stream data and cost parameters for hot process and utility streams are arranged and given in Table 4.1, while Table 4.2 presents the rearranged data for cold process and utility streams. Utility cost, plant life, rate of interest and cost law coefficient for different types of heat exchangers used in the HEN are the cost data. Cost law coefficients for various heat exchanger types are estimated using the 1-2 shell and tube exchanger as the basis and are given in Table 4.3. [61]

Table 4.1 Stream Data and Cost Parameters for Hot Process and Utility Streams

Stream	Type	Process Parameters			
		T_{in} (^OC)	T_{out} (^OC)	h (kW/m^2-K)	C (kW/K)
HP1	Hot Process	998.0	483.0	0.254	86.95
HP2	Hot Process	998.0	483.0	0.253	86.45
HP3	Hot Process	482.0	371.0	0.365	86.50
HP4	Hot Process	430.0	333.0	0.346	86.29
HP5	Hot Process	332.0	241.0	0.198	89.92
HP6	Hot Process	240.0	204.0	1.130	87.11
HP7	Hot Process	228.0	190.0	0.169	96.41
HP8	Hot Process	194.0	169.0	0.646	307.50
HP9	Hot Process	168.0	128.0	0.658	746.64
HP10	Hot Process	168.0	128.0	0.642	728.43
HP11	Hot Process	127.0	63.0	0.377	200.39
HP12	Hot Process	159.0	86.0	0.315	39.99
HP13	Hot Process	85.0	41.0	0.319	43.30

HP14	Hot Process	40.0	7.0	0.454	41.74
HP15	Hot Process	360.0	145.0	0.099	40.76
HP16	Hot Process	144.0	38.0	0.166	45.21
HP17	Hot Process	37.0	8.0	0.053	6.88
HP18	Hot Process	164.0	68.0	0.230	273.54
HP19	Hot Process	471.0	284.0	0.434	223.65
HP20	Hot Process	377.0	278.0	0.721	152.72
HP21	Hot Process	277.0	166.0	0.570	230.24
HP22	Hot Process	67.0	47.0	0.889	282.82
HP23	Hot Process	45.0	22.0	0.690	192.41
HP24	Hot Process	21.0	1.0	0.919	323.12
HP25	Hot Process	46.0	-11.0	0.282	191.40
HP26	Hot Process	-4.0	-24.0	1.556	809.69
HP27	Hot Process	106.0	36.0	0.126	33.37
HP28	Hot Process	133.0	44.0	0.120	315.47
HP29	Hot Process	88.0	42.0	0.401	961.80
HP30	Hot Process	122.0	90.0	0.412	807.79
HP31	Hot Process	96.0	57.0	0.824	600.13
HP32	Hot Process	35.0	3.0	0.483	8.93
HU1,Steam	Hot Utility	147.0	147.0	0.120	---
C_{hu} = 120 $/kW/year, r =10 % and τ = 50 years.					

Non Uniform Heat Exchanger Specifications

For Streams HP1 and HP2:

Bayonet Type Heat Exchanger with a =30000, b = 1050, c = 0.81.

For Streams HP4, HP6, HP7, HP8, HP14, HP23, HP24 and HP26:

Split Type Heat Exchanger with a =30000, b = 975, c = 0.81.

For Streams HP27 and HP31:

Divided Type Heat Exchanger with a =30000, b = 900, c = 0.81.

For Stream HP17:

Kettle Type Heat Exchangers with a=30000, b= 1125, c = 0.81.

For Other Streams :

Shell & Tube Type with a =30000, b = 750, c = 0.81.

Table 4.2 Stream Data and Cost Parameters for Cold Process and Utility Streams

Stream	Type	Process Parameters			
		T_{in} (^{O}C)	T_{out} (^{O}C)	h (kW/m^2-K)	C (kW/K)
CP1	Cold Process	27.0	74.0	1.088	18.71
CP2	Cold Process	313.0	313.0	2.230	44694.00

CP3	Cold Process	313.0	313.0	2.230	44694.00
CP4	Cold Process	313.0	313.0	0.692	9601.17
CP5	Cold Process	313.0	313.0	0.461	8370.25
CP6	Cold Process	114.0	316.0	0.089	40.51
CP7	Cold Process	50.0	155.0	0.387	29.87
CP8	Cold Process	179.0	211.0	0.201	114.48
CP9	Cold Process	113.0	180.0	0.241	114.74
CP10	Cold Process	116.0	121.0	5.261	5973.15
CP11	Cold Process	118.0	123.0	5.261	5973.15
CP12	Cold Process	52.0	120.0	0.355	188.60
CP13	Cold Process	48.0	117.0	0.334	42.31
CP14	Cold Process	-10.0	2.0	1.248	114.79
CP15	Cold Process	115.0	311.0	0.110	44.71
CP16	Cold Process	-8.0	15.0	0.067	8.68
CP17	Cold Process	23.0	141.0	0.187	222.54
CP18	Cold Process	140.0	427.0	0.283	145.72
CP19	Cold Process	220.0	252.0	2.232	472.47
CP20	Cold Process	117.0	231.0	0.555	224.18
CP21	Cold Process	13.0	14.0	0.166	4425.45
CP22	Cold Process	-7.0	-7.0	0.207	6462.33
CP23	Cold Process	-22.0	25.0	0.342	232.13
CP24	Cold Process	-32.0	-32.0	0.179	16193.82
CP25	Cold Process	71.0	99.0	0.471	923.19
CP26	Cold Process	9.0	10.0	0.085	285.13
CU1	Cold Utility	30.0	39.0	1.495	---
CU2	Cold Utility	36.0	48.0	1.121	---
C_{cu}= 25 \$/kW/year, r =10 % and τ = 50 years.					

Non Uniform Heat Exchanger Specifications

For Streams CP2 and CP3:

Bayonet Type Heat Exchanger with a =30000, b = 1050, c = 0.81.

For Streams CP5, CP7, CP8, CP9, CP14, CP21, CP22 and CP24:

Split Type Heat Exchanger with a =30000, b = 975, c = 0.81.

For Stream CP16:

Kettle Type Heat Exchangers with a=30000, b= 1125, c = 0.81.

For Other Streams:

Shell & Tube Type with a =30000, b = 750, c = 0.81.

Table 4.3 Comparison of Cost Law Coefficients for Different Type of Heat Exchangers

Type of Heat Exchanger	Cost Law Coefficient	a	b	c
1-2 Shell and Tube Type Heat Exchanger (Reference Type)	Cost Law Coefficient Comparison	1	1	1
	Actual Value of Cost Law Coefficient	30000	750	0.81
Divided Type Heat Exchanger	Cost Law Coefficient Comparison	1	1.2	1
	Actual Value of Cost Law Coefficient	30000	900	0.81
Split Type Heat Exchangers	Cost Law Coefficient Comparison	1	1.3	1
	Actual Value of Cost Law Coefficient	30000	975	0.81
Bayonet Type Heat Exchanger	Cost Law Coefficient Comparison	1	1.4	1
	Actual Value of Cost Law Coefficient	30000	1050	0.81
Kettle Type Heat Exchanger	Cost Law Coefficient Comparison	1	1.5	1
	Actual Value of Cost Law Coefficient	30000	1125	0.81

Step 2. The data of the existing HEN of ammonia plant like hot and cold utility needed and area of HEN are the captured online data while, CC, OC and TAC are calculated using the procedure mentioned in Section 4.1.3. The data of the existing HEN of ammonia plant of the fertilizer industry are given in Table 4.4.

Table 4.4 Data of Existing HEN

hu_{exist}	cu_{exist}	A_{exist}	CC_{exist}	OC_{exist}	TAC_{exist}
kW	kW	m^2	$/year	$/year	$/year
879	145359	31633	8677553	3739482	24112814

Step 3. Select the approach of PT viz., ΔT_{min} or Q_{min} for the analysis.

Step 4. Assign values for the relevant parameters needed. GA parameters are number of variables, range of variables, population size, cross over probability and number of generation. For the present work, number of variable for GA parameter is one and is ΔT_{min} for ΔT_{min} approach and Q_{min} for Q_{min} approach. The remaining GA parameters are selected based on the range reviewed by Gosseli et al. [229]. GA parameters used in the analysis are presented in Table 4.5.

Table 4.5 GA Parameters

Sr. No.	GA Parameter	Optimization using PT and GA for ΔT_{min} Approach	Optimization using PT and GA for Q_{min} Approach
1	Number of Variable ($N_{variable}$)	1 (ΔT_{min})	1 (Q_{min})
2	Range of Variable ($R_{variable}$)	ΔT_{min} = 10 to 40	Q_{min} = 3 to 4
3	Population Size (popsize)	10	10
4	Maximum Number of Generation (maxgen)	50	10
5	Crossover Probability (P_{cross})	0.675	0.250
6	Mutation Probability ($P_{mutation}$)	0.164	0.150

Step 5. Execute the subroutine for GA as presented in Figure 4.2 for selected approach of PT.

Step 6. Generate the random population using the input parameters as given in Step 2 of Section 4.2.

Step 7. Evaluate the random population as mentioned in Step 3 of the Section 4.2. Compare TAC of HEN corresponding to each string and store the minimum among them as $TAC_{min,i}$.

Step 8. Operate the randomly generated population in loop for number of generation. In each number of generations, operate the population using three main operators as mentioned in Step 4 to Step 7 of the Section 4.2 and generate child strings.

Step 9. Evaluate each child string as mentioned in Step 8 of the Section 4.2. Compare TAC of HEN corresponding to each child string and store minimum among them as $TAC_{min,i+1}$. Compare $TAC_{min,i}$ with $TAC_{min,i+1}$ and hence select and store the binary string having minimum value of objective function.

Thus, one generation of operation in GA is completed. The program continues in the loop until required number of generation is reached. Finally, capture the binary sting having minimum value of TAC. Decode and store further binary string to calculate the optimized value of hot and cold utility required (hur_{GA} and cur_{GA}), Area of HEN (A_{GA}), CC (CC_{GA}), OC (OC_{GA}) and TAC of HEN (TAC_{GA}).

Step 10. Compare TAC_{GA} with TAC_{exist}. End the program, if $TAC_{GA} > TAC_{exist}$, as modification in the existing HEN is not possible. If $TAC_{GA} < TAC_{exist}$, modification in the existing HEN is possible. Calculate and store theoretical possible percentage saving in TAC ($TAC_{\%saving}$).

Step 11. Execute the subroutine for modification as presented in Figure 4.3 in case of the possibility of modification in the existing HEN of the ammonia plant.

Step 12. Select the modification technique viz., NPM or RA.

Step 13. In case of NPM, identify the target value of ΔT_{min} or Q_{min} based on the analysis of the variation of TAC of HEN at different values of ΔT_{min} or Q_{min} as mentioned in Step 1 of the Section 4.3.1.

Step 14. Construct the grid diagram at target value of ΔT_{min} or Q_{min} and analyze it critically as mentioned in Step 2 and Step 3 of the Section 4.3.1 respectively.

Step 15. Decide the alterations in existing HEN and calculate the data of the HEN after modification using NPM viz., hur_{NPM}, cur_{NPM}, A_{NPM}, CC_{NPM}, OC_{NPM}, TAC_{NPM} and $TAC_{\%saving}$ as mentioned in Step 4 and Step 5 of the Section 4.3.1 respectively.

Step 16. In case of RA, select the appropriate value of ΔT_{min} or Q_{min} at which the hot and cold utilities required are same as the hot and cold utilities needed in the existing HEN as mentioned in Step 1 of the Section 4.3.2.

Step 17. Determine the existing area efficiency of HEN as mentioned in Step 2 of the Section 4.3.2.

Step 18. Calculate the maximum area for retrofitting at existing and ideal area efficiency for each selected utility values which are less than the utilities needed in the existing plant as mentioned in Step 3 and Step 4 of the Section 4.3.2.

Step 19. Calculate the saving in utility, additional area required, annual saving in OC and payback period as mentioned in Step 5 to Step 7 of the Section 4.3.2.

Step 20. Calculate the data of the HEN after modification using RA viz., hur_{RA}, cur_{RA}, A_{RA}, CC_{RA}, OC_{RA}, TAC_{RA} and $TAC_{\%saving}$ as mentioned in Step 8 of the Section 4.3.2.

The unified approach of synthesis and optimization using GA is employed to the existing HEN of an ammonia production plant using both the approaches of PT viz., ΔT_{min} and Q_{min} approach. Based on the results of synthesis and optimization, modifications in the existing HEN of the ammonia plant has been carried out using two methods based on pinch analysis viz. NPM and RA. Based on the steady state on-line data captured from the normal running of the plant given in Table 4.1, Table 4.2 and Table 4.3, sample calculation to estimate the TAC of HEN for ΔT_{min} approach at a ΔT_{min} of 10 ^{O}C is given in Appendix IV.

Chapter 5

RESULTS AND DISCUSSIONS

The unified approach presented in chapter 4 is used to synthesize, optimize and modify with respect to minimization of TAC of the existing HEN of an ammonia production plant of a fertilizer industry manufacturing urea. As the first step, HEN of the ammonia plant is synthesized and optimized using GA for two approaches of PT viz., ΔT_{min} and Q_{min} approaches and the scope for the modification is identified. In the second step, modification in existing HEN of the ammonia plant is carried out using two methods based on pinch analysis viz., NPM and RA.

Sections 5.1 and 5.2 deal with the results obtained during the synthesis and optimization carried out on the HEN of the ammonia production plant using GA for two approaches of PT viz., ΔT_{min} and Q_{min} approaches respectively. Comparison of the results of the two approaches is given in Section 5.3. Sections 5.4 and 5.5 discuss the results of two modification techniques employed viz., NPM and RA respectively based on the ΔT_{min} approach. The comparison of the results obtained using NPM and RA is given in Section 5.6. The results of modification through NPM and RA with Q_{min} approach are presented respectively in Sections 5.7 and 5.8. The comparison of both the modification techniques implemented for the Q_{min} approach of PT is given in Section 5.9. The comparison of data of modified HEN using NPM and RA for ΔT_{min} and Q_{min} approaches with that of existing HEN is given in Section 5.10. A summary of outcome of the synthesis, optimization using GA and modification analysis of the HEN of ammonia plant which is a part of a fertilizer industry is given in Section 5.11.

5.1 Optimization Using GA with ΔT_{min} Approach

The synthesis and optimization of existing HEN of ammonia plant is carried out using GA. Table 5.1 gives the initial output of the GA program, consisting of GA parameters and the randomly generated initial population like binary strings, their decoded and real values (ΔT_{min}) and fitness function (TAC of HEN) corresponding to each string. Then, the initial population is operated through a loop for generation. The GA output for one such generation is presented in Table 5.2 which consists of reproduction, crossover and mutation report, child string in binary form generated after reproduction, crossover and mutation, real value and fitness function corresponding to each child string and statics after each generation.

Table 5.1 Initial Output of Optimization of HEN for TAC Using GA with ΔT_{min} Approach

MINIMIZATION PROBLEM		
No. of Variables	=	1
Lower & Upper bound for Varaiable-1	=	[10.00, 40.00]
Chromosome Length for Varaiable-1	=	15
Total Population size	=	10
Total Chromosome length	=	15
Maximum No. of generations (maxgen)	=	50
Crossover probability (pcross)	=	0.675
Mutation probability (pmutation)	=	0.164

INITIAL POPULATION			
Initial Binary String	Decoded Value	Real Value of Variable (ΔT_{min})	Fitness Function (TAC of HEN)
011100101011011	14683	23.00	23498734
000110101100000	3424	13.00	24524261
110011100011111	26399	34.00	23870090
000100101111011	2427	12.00	24588598
010100100101010	10538	19.00	23626708
000011001011010	1626	11.00	24652364
001101010001110	6798	16.00	24115364
100110100010000	19728	28.00	23397854
111101100111011	31547	38.00	24395600
110010000010000	25616	33.00	23775602

Table 5.2 Output of a Typical One Generation Using GA with ΔT_{min} Approach

Reproduction, Crossover and Mutation Report								
Generation 0				Generation 1				
No.	Parent String	Real Value (ΔT_{min})	Fitness Function (TAC of HEN)	Parent String	Crossover Site	Child String	Real Value (ΔT_{min})	Fitness Function (TAC of HEN)
1	011100101011011	23.00	23498734	(4, 5)	0	000000101111011	10.00	24678582
2	000110101100000	13.00	24524261	(4, 5)	0	001100100100000	15.00	24446877
3	110011100011111	34.00	23870090	(5, 7)	0	001000110001000	14.00	24524319
4	000100101111011	12.00	24588598	(5, 7)	0	001001011001111	14.00	24524319
5	010100100101010	19.00	23626708	(3, 1)	6	110010100011011	33.00	23775602
6	000011001011010	11.00	24652364	(3, 1)	6	111000000010011	36.00	24091253
7	001101010001110	16.00	24115364	(2, 6)	0	<u>011110001100100</u>	<u>24.00</u>	<u>23355687</u>
8	100110100010000	28.00	23397854	(2, 6)	0	000011001011000	11.00	24652364
9	111101100111011	38.00	24395600	(4, 3)	12	000011101100111	11.00	24652364
10	110010000010000	33.00	23775602	(4, 3)	12	100100011111011	27.00	23422822

Generation 1 Accumulated Statistics:

Total Crossovers = 2, Total Mutations = 33,

Global Best Individual so far, Generation 0: Fitness(TAC of HEN) = 23355687,

011110001100100, X[1] = 24.00, Fitness(x1,x2..) = 23355687.

The data of existing HEN and the optimized data obtained using GA are compared in Table 5.3. The existing HEN is operated using less quantity of hot utility compared to the optimized data using GA. Thus, OC of the existing HEN is found to be less than that of the optimized data using GA. However, the existing HEN requires more area of HEN compared to that of the optimized data using GA. Thus, CC of existing HEN is more than that of the optimized data using GA. It is seen, therefore, that the existing HEN operates at lesser OC but higher CC as compared to that of the optimized data using GA. Hence, ΔT_{min} approach of PT coupled with GA as optimization predicts that TAC_{exist} is more than TAC_{GA}. For the HEN of the ammonia plant synthesized and optimized using ΔT_{min} approach and GA respectively, the percentage saving in TAC is found to be 3.14 %. As TAC_{GA} is less than TAC_{exist}, there exists a possibility to reduce further TAC_{exist} by employing various modification techniques.

Table 5.3 Comparison Between Optimized HEN Using GA and Existing HEN

	ΔT_{min}	**Pinch Temp.**	**hur**	**cur**	**A**	**CC**	**OC**	**TAC**
	^oC	**^oC**	**kW**	**kW**	**m^2**	**$/year**	**$/year**	**$/year**
Existing HEN	--	--	879	145358	31633	8677553	3739482	24112814
Optimized HEN Using GA	24.00	128.00	15572	125045	23430	7820407	4994781	23355687
	Theoretical Possible Saving in TAC							757127
	Theoretical Possible Percentage Saving in TAC							3.14 %

5.2 Optimization Using GA with Q_{min} Approach

Q_{min} approach of PT is also used in the synthesis with optimization through GA of the existing HEN of ammonia plant. The initial output of the optimization through GA is presented in Table 5.4 consisting of GA parameters and the randomly generated initial population like binary strings, their decoded and real values (Q_{min}) and fitness function (TAC of HEN) corresponding to each string similar to that carried out in case of ΔT_{min} approach discussed in Section 5.1. Then, the initial population is operated through a loop for generation. The GA output for one such generation is given in Table 5.5 consisting of reproduction, crossover and mutation report, child string in binary form generated after reproduction, crossover and mutation, real value and fitness function corresponding to each child string and statics after each generation.

Table 5.4 Initial Output of Optimization of HEN for TAC Using GA with Q_{min} Approach

MINIMIZATION PROBLEM		
No. of Variables	=	1
Lower & Upper bound for Varaiable-1	=	[3.00, 4.00]
Chromosome Length for Varaiable-1	=	14
Total Population size	=	10
Total Chromosome length	=	14
Maximum No. of generations (maxgen)	=	10
Crossover probability (pcross)	=	0.25
Mutation probability (pmutation)	=	0.15

INITIAL POPULATION			
Initial Binary String	Decoded Value	Real Value of Variable (Q_{min})	Fitness Function (TAC of HEN)
00001110000101	901	3.00	25607850
01001010000111	4743	3.20	25804902
01010101111000	5496	3.30	21435616
11001000000000	12800	3.70	26197533
00110100000000	3328	3.20	25804902
01110100000011	7427	3.40	26648263
00111110011000	3992	3.20	25804902
00011100100000	1824	3.10	20319884
00111000001000	3592	3.20	25804902
01011110101010	6058	3.30	21435616

Table 5.5 Output of a Typical One Generation Using GA with Q_{min} Approach

Reproduction, Crossover and Mutation Report								
Generation 0				Generation 1				
No.	Parent String	Real Value (Q_{min})	Fitness Function (TAC of HEN)	Parent String	Crossover Site	Child String	Real Value (Q_{min})	Fitness Function (TAC of HEN)
1	01001010000111	3.20	25804902	(7, 7)	0	00111111001100	3.20	25804902
2	01001010000111	3.20	25804902	(7, 7)	0	00111111001100	3.20	25804902
3	01010101111000	3.30	21435616	(3, 7)	0	01010101111000	3.30	21435616
4	11001000000000	3.70	26197533.44	(3, 7)	0	00111110011000	3.20	25804902
5	00110100000000	3.20	25804902	(10, 2)	0	01011110101000	3.30	21435616
6	01110100000011	3.40	26648263	(10, 2)	0	01101110000111	3.40	26648263
7	00111110011000	3.20	25804902	(8, 4)	0	00011110100000	3.10	20319884
8	00011100100000	3.10	20319884	(8, 4)	0	11001000001000	3.70	26197533
9	00111000001000	3.20	25804902	(7, 6)	3	01110111011011	3.40	26648263
10	01011110101010	3.30	21435616	(7, 6)	3	01111100101100	3.40	26648263

Generation 1 Accumulated Statistics:

Total Crossovers = 1, Total Mutations = 18,

Global Best Individual so far, Generation 0: Fitness (TAC of HEN) = 20319884,

00011110100000 X[1] = 3.10 Fitness(x1,x2..) = 20319884.

Table 5.6 compares the data of existing HEN and the optimized data obtained using GA using Q_{min} approach. It is to be noted that the existing HEN operates using more quantity of utilities (hot and cold both) and requires more area of HEN as compared to that of the optimized data using GA with Q_{min} approach. Thus, OC and CC of the existing HEN are found to be more than that of the optimized data using GA. Therefore, TAC_{exist} is found to be more than TAC_{GA}. However, the corresponding pinch temperature is 985.75 ^{O}C which is too high for any practical systems of network of exchangers. It should be noted that the theoretical possible saving in TAC using optimization through GA with Q_{min} approach of PT as compared to the TAC of existing HEN is 15.73 % which is significant reduction in TAC. Therefore, there is still a possibility to reduce TAC_{GA} through a suitable modification technique, not withstanding a very high pinch temperature. It may also be possible that the modification analysis can lead to a manageable level of pinch temperature under optimized condition of area and TAC.

Table 5.6 Comparison Between Optimized HEN Using GA and Existing HEN

	Q_{min}	Pinch Temp.	hur	cur	A	CC	OC	TAC
	kW/m^2	^{O} C	kW	kW	m^2	$/year	$/year	$/year
Existing HEN	--	--	879	145359	31633	8677553	3739482	24112814
Optimized HEN Using GA	3.10	985.75	0.00	109473	22274	7489091	2736848	20319884
	Theoretical Possible Saving in TAC							3792930
	Theoretical Possible Percentage Saving in TAC							15.73 %

5.3 Comparison

Table 5.7 compares the existing HEN with the optimized HEN using GA with both the approaches of PT, viz., ΔT_{min} and Q_{min} approach.

Table 5.7 Comparison Between Optimized HEN Using GA with ΔT_{min} Approach, Q_{min} Approach and Existing HEN

	ΔT_{min}, ^oC / Q_{min}, kW/m^2	Pinch Temp.	hur	cur	A	CC	OC	TAC	Theoretical Percentage Saving in TAC
		^oC	kW	kW	m^2	\$/year	\$/year	\$/year	
Existing HEN	--	--	879	145358	31633	8677553	3739482	24112814	---
Optimized HEN Using GA with ΔT_{min} Approach	24.00	128.00	15572	125045	23430	7820407	4994781	23355687	3.14
Optimized HEN Using GA with Q_{min} Approach	3.10	985.75	0.00	109473	22274	7489091	2736848	20319884	15.73

A comparison of outcome of the synthesis and optimization of HEN of the ammonia plant using GA with the two approaches of PT, viz., ΔT_{min} and Q_{min} approach gives the following:

1. Optimization of the HEN using GA decreases TAC by 3.14% and 15.73% respectively using ΔT_{min} and Q_{min} approaches. The reduction is small in case of ΔT_{min} approach due to the increase in OC although CC decreases. However,

both CC and OC decreases using Q_{min} approach which significantly decreases TAC.

2. Area of HEN required is found to be less using Q_{min} approach in comparison with that estimated using ΔT_{min} approach which agrees well with the earlier studies of Rev and Fonyo [58] and Shenoy [61]. Thus, both area and TAC required are predicted to be less using Q_{min} approach. However, the value of pinch temperature predicted using the approach is very high as compared to that of ΔT_{min} approach. The reason for this may be attributed to the non-uniform shifts in temperatures observed using Q_{min} approach. This poses a question regarding the appropriateness of employing Q_{min} approach for synthesis and optimization of HEN although both area of heat transfer and TAC needed are predicted lower than that using ΔT_{min} approach. Further, modification analysis using both the approaches of PT may be carried out to examine the possibility of favourable reduction in the values of area and TAC required in the cases of both the approaches of PT as compared to the existing HEN.

5.4 Modification Using NPM in Existing HEN with ΔT_{min} Approach

The modification using NPM starts with the identification of target ΔT_{min}. To identify the target ΔT_{min}, the variation of TAC of HEN at different values of ΔT_{min} is calculated and plotted in Figure 5.1. It is seen that TAC of HEN is nearly constant for the values of ΔT_{min} from 10 ^{O}C to 15.8 ^{O}C and then decreases in the range of values of ΔT_{min} from 15.9 ^{O}C to 24 ^{O}C and further increases in the range of values of ΔT_{min} from 25 ^{O}C to 40 ^{O}C. It is seen that, TAC of HEN is minimum at ΔT_{min} of 24 ^{O}C. Thus, the selected value of ΔT_{min} for NPM is 24 ^{O}C.

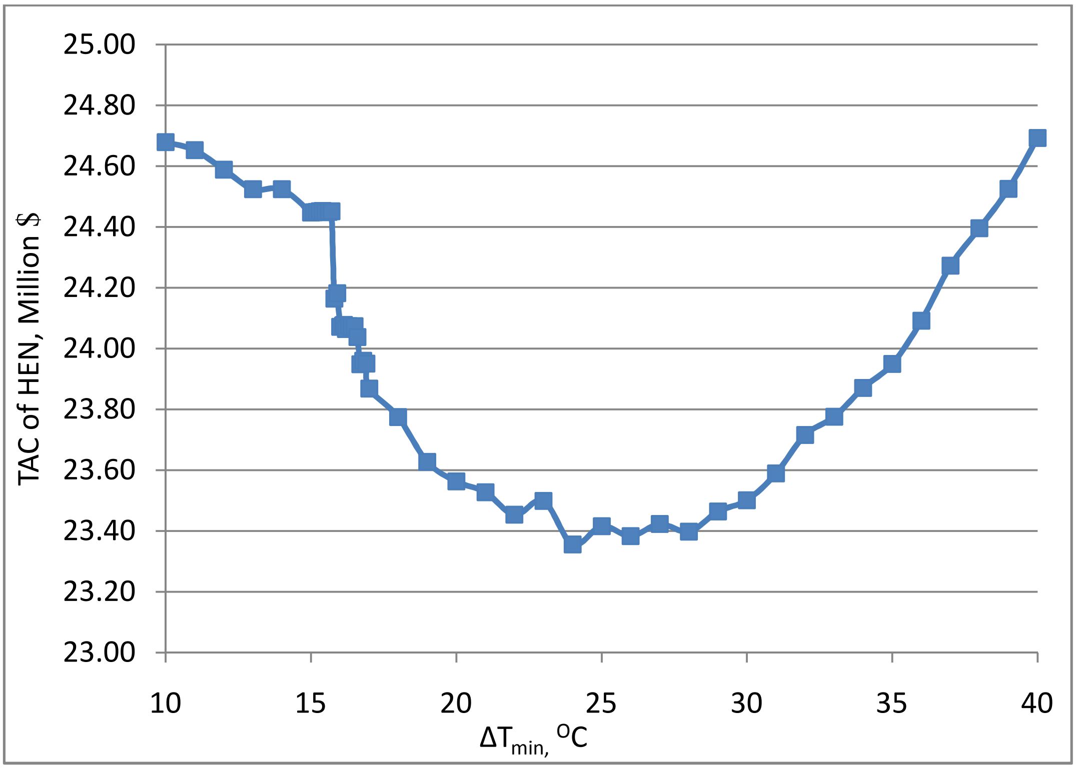

Figure 5.1 Variation of TAC of HEN with ΔT_{min}

Figure 5.2 gives the variation of the area of HEN and quantity of hot and cold utilities required at different values of ΔT_{min}. It can be seen that the area of HEN is nearly constant in the range of the values of ΔT_{min} from 10 ^{O}C to 15.8 ^{O}C and decreases subsequently. Further, the quantity of hot and cold utilities required is nearly constant in the range of the values of ΔT_{min} from 10 ^{O}C to 15.8 ^{O}C and subsequently increases. The trend of the variation is due to the fact that the pinch temperature reduces from a very high value of 990 ^{O}C to feasible value of 124 ^{O}C at the ΔT_{min} of 15.8 ^{O}C. However, for further analysis the value of ΔT_{min} selected is 24 ^{O}C due to the fact that TAC is minimum at this ΔT_{min}.

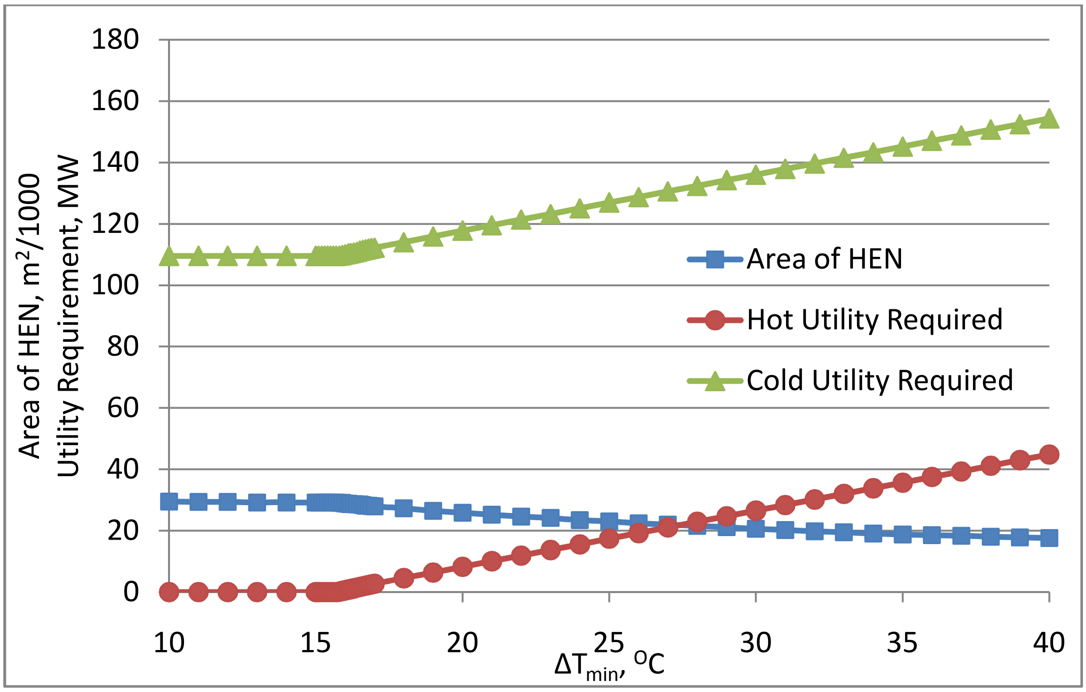

Figure 5.2 Variation of Area of HEN and Utilities Required with ΔT_{min}

Using the selected value of ΔT_{min} at 24 ^{O}C, the grid diagram of the existing HEN constructed is given in Figure 5.3. The pinch temperature line is shown by dotted red vertical line. The right and left hand side portion of the pinch temperature line is known as region below and above pinch respectively. From the grid diagram, the following are observed: (1) There is a use of hot utility below pinch with the cold process stream number 1, which is not desirable and (2) There is a cross pinch heat transfer in hot process stream number (HPSN) 9, 10, 12, 16 and 18, and in cold process stream number (CPSN) 6, 7, 9, 12, 13, 15 and 17; which is also not desirable. The modifications in existing HEN for the usage of hot utility below pinch and cross pinch heat transfer in twelve numbers of streams are given in the following Sections.

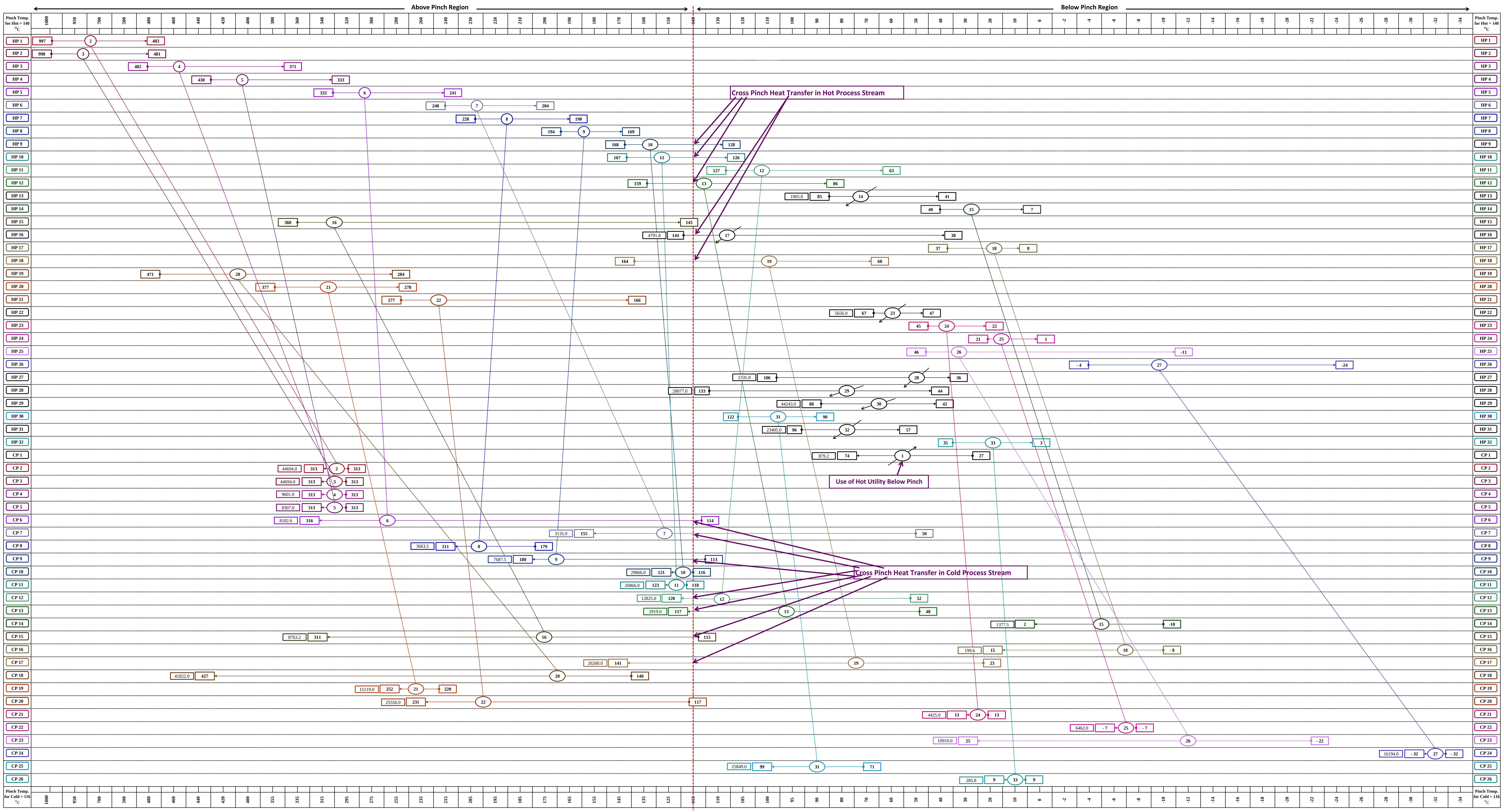

Figure 5.3 Grid Diagram of the Existing HEN for ΔT_{min} Approach

5.4.1 Modification for the Usage of Hot Utility below Pinch

There is a match between hot utility and CPSM 1 at heat exchanger HX150C located in below pinch region as shown in Figure 5.3. The heat load for the match is 879 kW. To eliminate the use of hot utility below pinch, CPSN 1 can be matched with any of the hot process streams using utility. HPSNs 13, 16, 27, 28, 29 and 31 use the utility, out of which HPSN 16 transfer the heat across the pinch, so it cannot be selected. The heat load of HPSN 27, 28, 29 and 31 are more compared to the heat load of CPSN 1, so their use is not feasible. Hence, it is desirable to match CPSN 1 with HPSN 13. Thus heat exchanger HX116 C can be removed from the existing HEN, which reduces the existing area of HEN by 136 m^2. This modification reduces area of HEN and utility requirement also which results in the reduction of TAC of HEN. Table 5.8 gives the comparison of the results obtained after the modification for usage of hot utility below pinch through NPM with that of the existing HEN. It can be seen that the elimination of hot utility below pinch and cold utility lead to decrease in area of HEN, OC, CC and hence TAC in comparison with that of the existing HEN.

Table 5.8 Comparison of NPM Modified HEN with Existing HEN

	hur	cur	A	CC	OC	TAC
	kW	kW	m^2	\$/year	\$/year	\$/year
Existing HEN	879	145358	31633	8677553	3739482	24112814
Modification for Usage of Hot Utility below Pinch	0	144479	31497	8598552	3611994	23799846
Saving in TAC after Modification for usage of hot utility below pinch						312968
Percentage Saving in TAC						1.30 %

5.4.2 Modification For Cross Pinch Heat Transfer

There is a cross pinch heat transfer in HPSN 9, 10, 12, 16 and 18, and in CPSN 6, 7, 9, 12, 13, 15 and 17 as the line showing each above mentioned stream crosses the vertical, pinch temperature dotted line, in red colour as shown in Figure 5.3.

The inlet and outlet temperatures of HPSN 16 are 144 ^{O}C and 38 ^{O}C, respectively and the pinch temperature of hot process stream is 140 ^{O}C. The cross pinch heat transfer of HPSN 16 takes place in between temperatures 144 ^{O}C to 140 ^{O}C. Similarly, inlet and outlet temperatures of CPSN 6 are 113 ^{O}C and 180 ^{O}C, respectively, and the pinch temperature for cold process stream is 116 ^{O}C. Hence, the cross pinch heat transfer of CPSN 6 takes place in between 113 ^{O}C to 116 ^{O}C. As the cross pinch heat transfer in HPSN 16 and CPSN 6 are in very narrow range, it can be neglected in large systems of network of exchangers. CPSN 9, 12, 13 and 15 also transfers heat across the pinch. The transfer of heat across the pinch is found in between inlet temperatures of CPSN 9 (113 ^{O}C) and CPSN 15 (115 ^{O}C) and outlet temperatures of CPSN 12 (120 ^{O}C) and CPSN 13 (117 ^{O}C) and pinch temperature (116 ^{O}C). These transfers of heat across pinch are very nearer to the pinch temperature region. This may be due to the fluctuations in the ammonia production plant which runs continuously. Thus, they are also not considered for the analysis.

HPSN 9 and 10 and CPSN 7 transfer heat across the pinch and also they form a loop of heat exchangers as

HX-112C $\rightarrow$ HX-142CA/CB $\rightarrow$ HX-143C $\rightarrow$ HX-105CA $\rightarrow$ HX-105CB $\rightarrow$ HX-106C $\rightarrow$ HX-112C

As there is a cross pinch transfer, it is essential to modify the existing HEN. The original and modified values of terminal temperatures, heat load and area for the heat exchangers are presented in Table 5.9. After the modifications, there is no cross pinch heat transfer for HPSN 9, 10 and CPSN 7, the utility requirement remains unchanged and area of HEN reduces by 232 m^2. So, OC remains unchanged while CC decreases.

Table 5.9 Comparison of Original and Modified Values for Cross Pinch Heat Transfer

Heat Exchanger Tag Number	Stream Number	Original Values				Modified Values				Change in Area of HEN
		T_{in}	T_{out}	Q_{HX}	A_{HX}	T_{in}	T_{out}	Q_{HX}	A_{HX}	
		^oC	^oC	kW	m^2	^oC	^oC	kW	m^2	m^2
HX 112C	CP7	50	155	3135	77	50	120	2090	51	(-)25.71
	HP6	240	204			240	216			
HX 142 CA/ CB	HP7	228	190	3663	570	240	202	3663	441	(-)128.45
	CP8	179	211			179	211			
HX 143C	HP8	194	169	7687	476	206	181	7683	310	(-)165.51
	CP9	113	180			113	180			
HX 105 CA	HP9	168	128	29865	1135	180	140	29865	1140	(+)4.76
	CP10	116	121			116	121			
HX 105 CB	HP10	168	128	29865	1135	180	140	29865	1112	(-)23.05
	CP11	118	123			118	123			
HX 106C	HP11	127	63	12825	531	140	63	15430	637	(+)106.31
	CP12	52	120			52	120			
Net Change in Area of HEN										(-)231.65

Table 5.10 gives the comparison of the results obtained after the modification for cross pinch heat transfer through NPM with that of the existing HEN. It can be seen that the reduction in area of HEN leads to decrease in CC and hence TAC in comparison with that of existing HEN by 0.94 %.

Table 5.10 Comparison Between Modified HEN Using NPM and Existing HEN

	hur	cur	A	CC	OC	TAC
	kW	kW	m^2	\$/year	\$/year	\$/year
Existing HEN	879	145358	31633	8677553	3739482	24112814
Modification for Cross Pinch Heat Transfer	879	145358	31401	8581123	3739482	23886415
Saving in TAC after Modifications for Cross Pinch Heat Transfer						226399
Percentage Saving in TAC						0.94 %

It should be noted that there is also cross pinch heat transfer for the HPSN 12 and 18 and CPSN 17. These streams also require modifications. While modifying these streams, the other stream terminal temperatures change and they transfer the heat across the pinch. So, it is not considered here.

5.4.3 Comparison

A comparison is made between the data obtained for HEN using the modifications for usage of hot utilities below pinch, for cross pinch heat transfer and NPM considering both the above modification with the data of existing HEN. Table 5.11 compares the hot utility, cold utility, area of HEN, CC, OC and TAC. It can be seen that hot and cold utilities required and area of HEN after implementing modification for usage of hot utility below pinch are less which in turn decreases OC and CC of HEN as compared to that of existing HEN. Thus, percentage saving in TAC is found to be 1.30 %. The percentage saving in TAC of HEN after implementing modification for cross pinch heat transfer as compared with the existing HEN is 0.94 %. If both the modifications are implemented, the percentage saving in TAC can be reduced to 1.71%.

Table 5.11 Comparison Between Modified HEN Using NPM and Existing HEN

	hur	cur	A	CC	OC	TAC
	kW	kW	m^2	\$/year	\$/year	\$/year
Existing HEN	879	145358	31633	8677553	3739482	24112814
Modification for Usage of Hot Utility below Pinch	0	144479	31497	8598552	3611994	23799846
Modification for Cross Pinch Heat Transfer	879	145358	31401	8581123	3739482	23886415
Modification using NPM (Considering Both the above modifications)	0	144479	31265	8556413	3611994	23700912
Saving in TAC after Modifications using NPM						411902
Percentage Saving in TAC after Modifications using NPM						1.71 %

Thus, modifications using NPM leads to a decrease in TAC due to the reduction of area of HEN. The other possibility to reduce TAC of HEN is by attempting to reduce OC. This can be possible by implementing modification through RA.

5.5 Modification Using RA in Existing HEN with ΔT_{min} Approach

The modification using RA begins with the selection of the ΔT_{min} at which hot and cold utilities required are same as the utilities needed in the existing HEN. It is seen that hot and cold utilities needed in existing HEN are, respectively, 879 and 145359 kW. At the approximately same utility requirement, the value of ΔT_{min} is found to be 16.14 ^{O}C and the corresponding area of HEN is 28763 m^2 which is considered as $A_{ideal.}$ The area of the existing HEN (A_{exist}) is 31633 kW. Thus, α_{exist} at which the existing HEN operates is 0.90 which indicates that the existing HEN uses the area reasonably efficiently. From Table 5.3, it is seen that, as existing HEN needs more quantity of cold utility as compared to that of the optimized data using GA, the requirement of utility can be reduced using RA which may lead to reduce the TAC of HEN.

The various hot and cold utility values which are below the existing utility values are identified and presented in Table 5.12 along with of ΔT_{min}, pinch temperature and area of HEN. At each selected utility value, the maximum area for retrofitting, $A_{max,retr}$, is calculated using two cases, viz. (1) at existing area efficiency of 0.9 and (2) at ideal area efficiency of 1. At each selected utility value, area of HEN, $A_{max,retr}$ at existing area efficiency and $A_{max,retr}$ at ideal area efficiency represents theoretical ideal area of HEN, possible area of HEN maintaining the existing area efficiency and possible area of HEN at ideal area efficiency respectively. Table 5.12 gives the overall idea of possible reduction in utility and corresponding increase in the area of heat exchanger. The next step in RA is to calculate the annual saving in OC.

Table 5.12 Maximum Area for Retrofitting for Each Selected Utility

hur	cur	ΔT_{min}	Pinch Temp.	A	$A_{max,retr}$	
					$\Delta\alpha = 1$	$\Delta\alpha = \alpha_{exist}$
kW	kW	^{o}C	^{o}C	m^2	m^2	m^2
878	110352	16.14	124.07	28763	31633	31633
801	110274	16.10	124.05	28783	31653	31655
586	110059	16.00	124.00	28844	31713	31722
371	109844	15.90	123.95	29058	31928	31961
156	109629	15.80	123.90	29088	31958	31994
0	109473	15.70	990.15	29147	32017	32060

The estimated values of savings in utilities and annual saving in OC at each selected utility requirement are given in Table 5.13. Table 5.13 signifies the possible saving in utility based on hot and cold utility and corresponding annual saving in OC at each selected utility requirement. Annual saving in OC at each selected utility requirement is possible with additional investment in requirement of additional area of HEN. The next step in RA is to calculate the additional area required, investment in additional area and corresponding payback period at each selected utility value.

Table 5.13 Annual Saving in OC for Each Selected Utility

hur	cur	ΔT_{min}	Pinch Temp.	U_{saving} Based on		Annual Saving in OC
				Hot Utility	Cold Utility	
kW	kW	^{O}C	^{O}C	kW	kW	$/year
878	110352	16.14	124.07	0	0	0
801	110274	16.10	124.05	77	77	11204
586	110059	16.00	124.00	292	292	42367
371	109844	15.90	123.95	507	507	73533
156	109629	15.80	123.90	722	722	104713
0	109473	15.70	990.15	878	878	127351

The requirement of additional area of HEN in comparison with existing area of HEN is estimated at each selected utility requirement for both the cases. The additional investment required in additional area of HEN and payback period at each selected utility requirement are also estimated and is given in Table 5.14. It is seen that if HEN is considered to operate at existing area efficiency, the maximum payback period of investment is 1.69 years, the associated investment in additional area of 328 m^2 is $123942 and annual saving in OC due to decrease in utility by 507 kW is

\$73533. On the other hand, if HEN is operated at ideal area efficiency, the minimum payback period of investment is only 0.8 years, the associated investment in OC in additional area of 80 m^2 is \$33882 and annual saving in OC due to the in decrease in utility by 292 kW is \$42367.

Table 5.14 Additional Area, Investment and Payback Period for Each Selected Utility

$\Delta T_{min.}$	$A_{max,retr}$		$A_{additional}$		Investment		Payback Period	
	$\Delta\alpha = 1$	$\Delta\alpha = \alpha_{exist}$	$\Delta\alpha = 1$	$\Delta\alpha = \alpha_{exist}$	$\Delta\alpha = 1$	$\Delta\alpha = \alpha_{exist}$	$\Delta\alpha = 1$	$\Delta\alpha = \alpha_{exist}$
^{O}C	m^2	m^2	m^2	m^2	\$	\$	years	years
16.14	31633	31633	0	0	0.00	0.00	0.00	0.00
16.10	31653	31655	20	22	10434	11404	0.93	1.02
16.00	31713	31722	80	89	33882	37067	0.80	0.87
15.90	31928	31961	295	328	102668	123942	1.40	1.69
15.80	31958	31994	325	361	123026	134654	1.17	1.29
15.70	32017	32060	384	427	142066	155512	1.12	1.22

Table 5.15 gives a comparison of data of modified HEN using RA for the two cases of existing area efficiency and ideal area efficiency with that of existing HEN. It is seen that after modification using RA for existing and ideal area efficiency, the payback periods are 1.69 years are 0.80 years respectively. But TAC of HEN is found to be more than the TAC of existing HEN. The modification using RA reduces the utility requirements and OC, but increases the area of HEN and CC. Thus, TAC is more than that of existing HEN. It is not possible to reduce TAC of HEN by reducing the utility requirements for the ammonia plant.

Table 5.15 Comparison Between Modified HEN Using RA and Existing HEN

	hur	cur	A	CC	OC	TAC
	kW	kW	m^2	\$/year	\$/year	\$/year
Existing HEN	879	145359	31633	8677553	3739482	24112814
Modified HEN Using RA for Existing Area Efficiency	372	144851	31961	8791469	3665948	24306734
Modified HEN Using RA for Ideal Area Efficiency	587	145066	31713	8716325	3697112	24161474

5.6 Comparison of Data of Modified HEN Using NPM and RA with ΔT_{min} Approach

Table 5.16 gives comparison of data of modified HEN using NPM and RA for the two cases of existing area efficiency and ideal area efficiency. On comparing TAC of HEN obtained by implementing NPM and RA, it is found that TAC of HEN decreases when NPM is employed while it increases when RA is employed.

Modification analysis of the existing HEN of the ammonia plant using NPM indicate the possibility of a saving of 1758 kW of utility, which leads to the removal of one heat exchanger from the existing HEN and reduction of area of HEN by 367 m^2. The modifications also show the possibility of partial reduction and addition of area to the existing heat exchangers. However, it is not practically possible either to reduce or to add partial areas to the existing heat exchangers. The addition of partial area, however, can be compensated by introducing the heat transfer enhancement techniques.

Modification in the existing HEN of the ammonia plant using RA reduces OC but increases area of HEN and CC. This leads to increase in TAC of HEN.

Table 5.16 Comparison Between Modified HEN with NPM, RA with Existing HEN

	hur	cur	A	CC	OC	TAC
	kW	kW	m^2	$/year	$/year	$/year
Existing HEN	879	145358	31633	8677553	3739482	24112814
Modification using NPM	0	144479	31265	8556413	3611994	23700912
Modified HEN Using RA for Existing Area Efficiency	372	144851	31961	8791469	3665948	24306734

5.7 Modification Using NPM in Existing HEN with Q_{min} Approach

For modification using NPM, target value of Q_{min} is identified by plotting the variation of TAC of HEN at different values of Q_{min} which is given in Figure 5.4. It is seen that TAC of HEN varies continuously and to some extend arbitrarily for the entire range of Q_{min}. The reasons for the fluctuation in TAC of HEN may be the non-uniform shift in temperatures, use of non-uniform shift temperatures in the entire calculations etc. The minimum TAC predicted with the modification analysis carried out using NPM in the existing HEN with Q_{min} approach is found to be 3.1 kW/m^2.

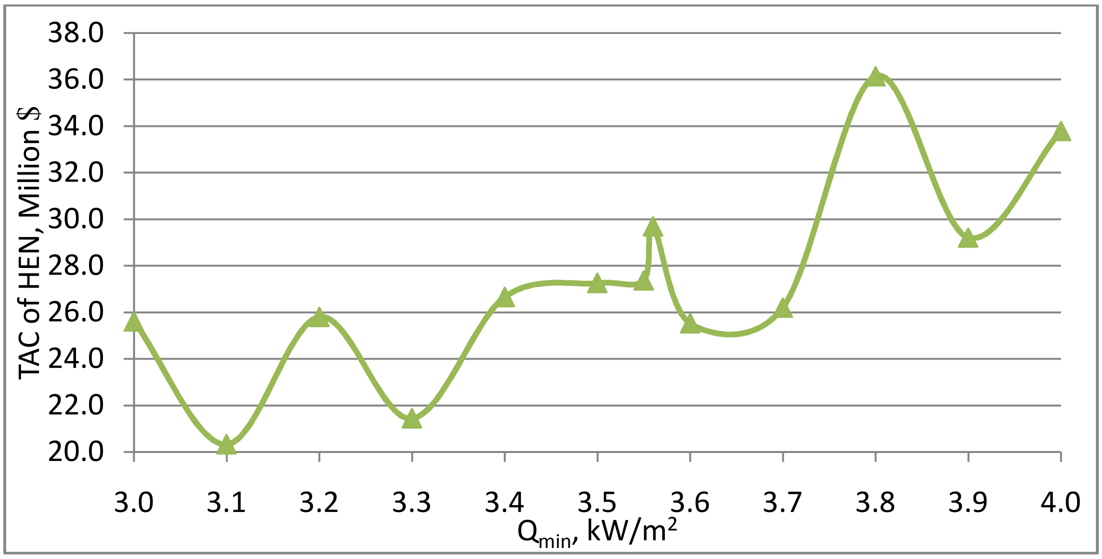

Figure 5.4 Variation of TAC of HEN with Q_{min}

Figure 5.5 illustrates the variation of the area of HEN and quantity of utilities required at different values of Q_{min}. The area of HEN also varies continuously while the quantity of hot and cold utilities required remains nearly constant for the entire range of Q_{min}. Further, it is seen that beyond the value of Q_{min} of 3.4 kW/m^2, there is no significant increase in utility requirements. On the other hand, there is a significant variation in area of HEN.

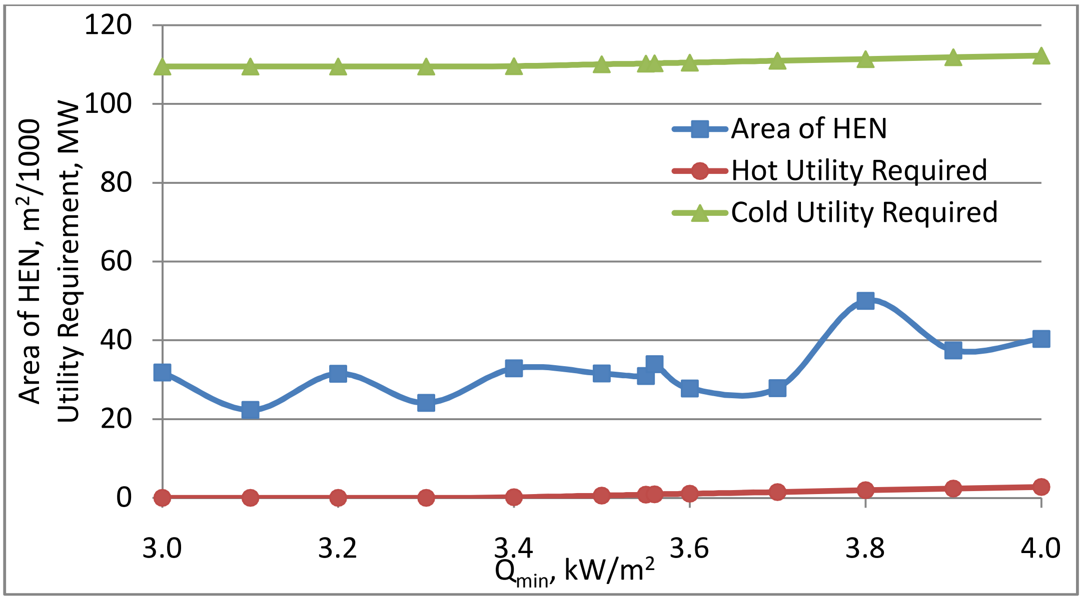

Figure 5.5 Variation of Area of HEN and Utilities Required with Q_{min}

The variation of pinch temperature for different values of Q_{min} is given in Figure 5.6. The pinch temperature decreases from 985.75 ^{O} C to feasible value of 116.5 ^{O}C at Q_{min} of 3.4 kW/m^2 and thereafter remains unchanged. However, TAC is found to be higher for any values of Q_{min} beyond 3.4 kW/m^2. As, TAC of HEN is minimum at the Q_{min} of 3.1 kW/m^2, the value of Q_{min} for NPM is selected as 3.1 kW/m^2.

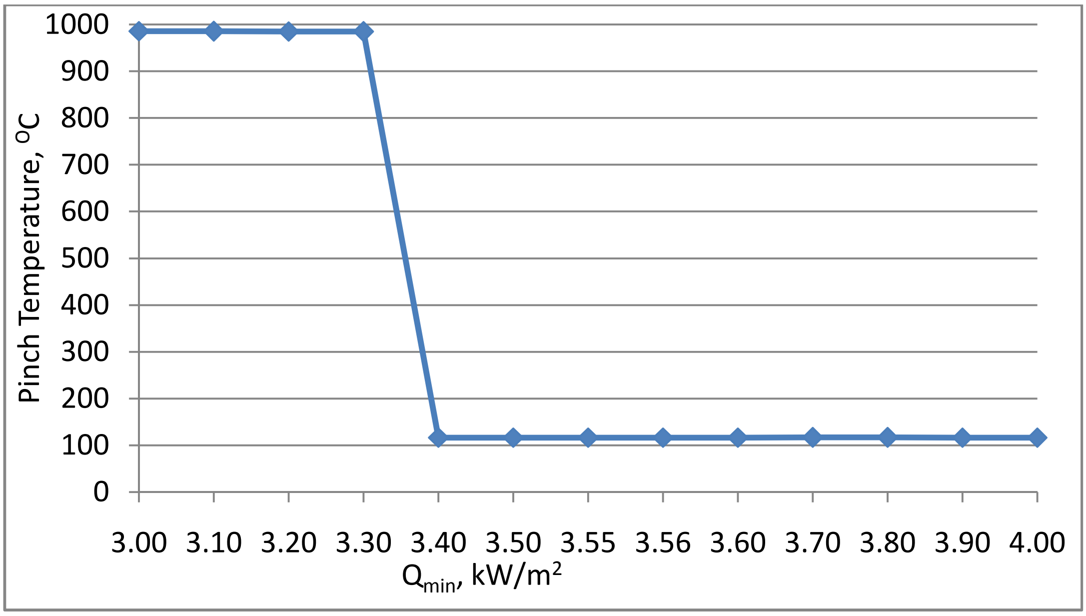

Figure 5.6 Variation of Pinch Temperature with Q_{min}

At this selected value, the grid diagram of the existing HEN is developed and is given in Figure 5.7. As the pinch temperature at the selected Q_{min} of 3.1 kW/m^2 is 985.75 ^{O}C, the entire HEN is located below pinch in the grid diagram. At this condition, HEN is not feasible to operate. Analyzing the grid diagram, it is seen that there is a use of hot utility below pinch with the CPSN 1 and there is a cross pinch heat transfer in HPSN 1 and 2, which is not desirable. The modifications in existing HEN are given in the following sections.

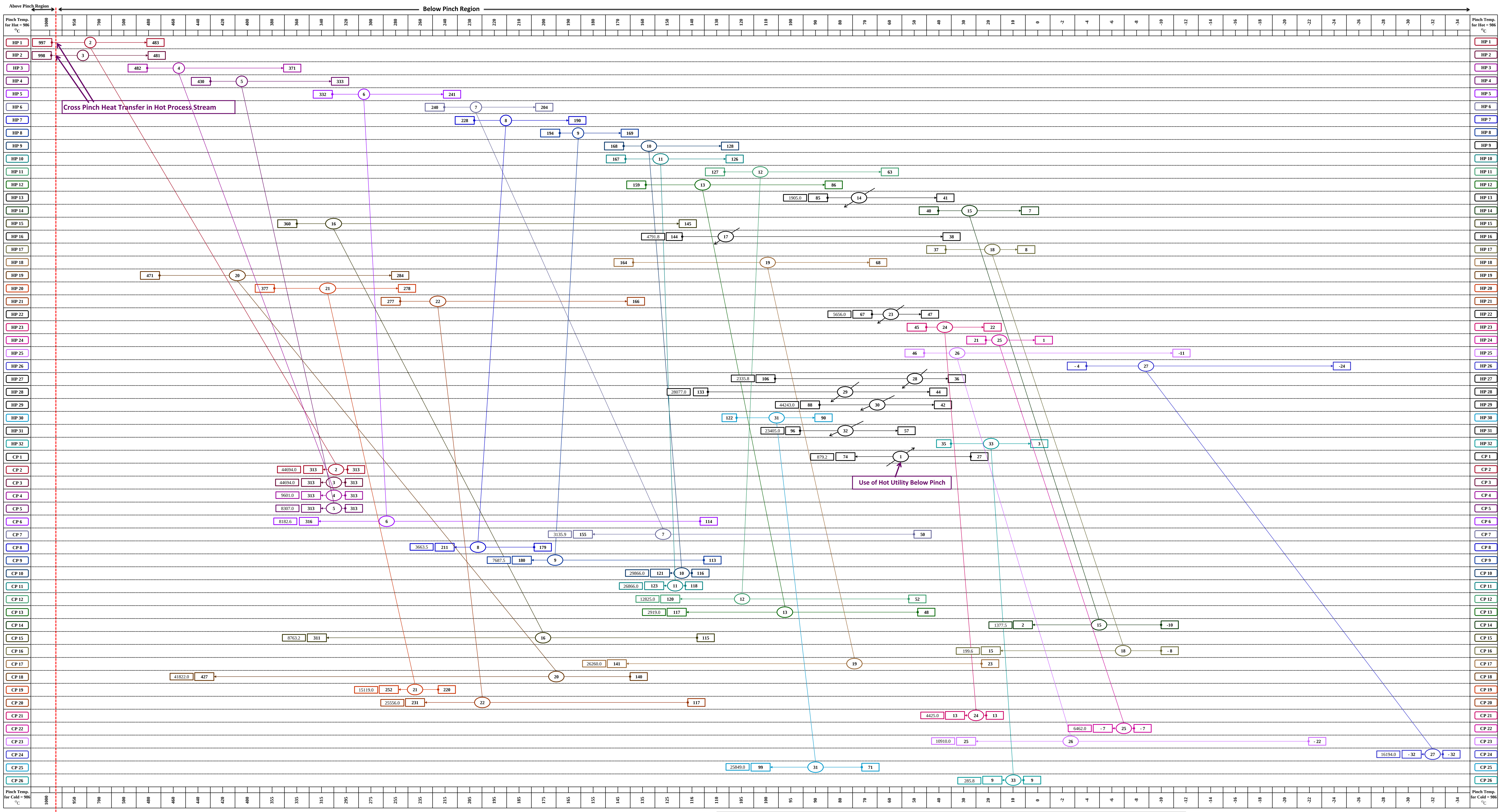

Figure 5.7 Grid Diagram of the Existing HEN for Q_{min} Approach

5.7.1 Modification for the Usage of Hot Utility Below Pinch

There is a match between hot utility and CPSN 1 at heat exchanger HX150C. The heat load for the match is 879 kW. To eliminate the use of hot utility below pinch, CPSN 1 can be matched with any of the hot process streams using utility. HPSN 13, 16, 27, 28, 29 and 31 use the utility. The heat load of HPSN 16, 27, 28, 29 and 31 are more compared to the heat load of CPSN 1. Therefore, their use is not feasible. Hence, it is desirable to match CPSN 1 with HPSN 13. Thus heat exchanger HX116 C can be removed from the existing HEN, which reduces the existing area of HEN by 136 m^2. This modification reduces utility requirement and heat exchanger area both, resulting in reduction of TAC of HEN. The results are compared in Table 5.17.

Table 5.17 Comparison of the Data of Modified HEN Using NPM with Existing HEN

	hur	cur	A	CC	OC	TAC
	kW	kW	m^2	$/year	$/year	$/year
Existing HEN	879	145359	31633	8677553	3739482	24112814
Modified HEN using NPM	0	144479	31497	8598552	3611994	23799846
Saving in TAC after Modifications using NPM						312968
Percentage Saving in TAC after Modifications using NPM						1.30 %

It is seen that area of HEN, utilities required, CC and OC estimated after modification using NPM are less than that of existing HEN. The percentage saving in TAC is found to be 1.30 %. The other possibility is to reduce TAC of HEN by attempting to reduce OC for which modifications using RA is employed in the next section.

5.7.2 Modification For Cross Pinch Heat Transfer

There is a cross pinch heat transfer in HPSN 1 and 2. The inlet and outlet temperatures of HPSN 1 are 997 and 483 ^{O}C and the same for HPSN 2 are 998 and 481 ^{O}C respectively. The pinch temperature of hot process stream is 985.75 ^{O}C. The cross pinch heat transfer of HPSN 1 is in between temperatures 997 ^{O}C and 985.75 ^{O}C and the same for HPSN 2 is in between temperatures 998 ^{O}C and 985.75 ^{O}C respectively. As the cross pinch heat transfer in HPSNs 1 and 2 is in very narrow range and can be neglected in large HEN, the modifications for cross pinch heat transfer are not considered in the analysis.

5.7.3 Comparison

A comparison is made between the data obtained for HEN using the modification for usage of hot utilities below pinch, for cross pinch heat transfer and NPM considering both the above modifications with the data of existing HEN. Table 5.18 compares the hot utility, cold utility, area of HEN, CC, OC and TAC. It can be seen that hot and cold utilities required and area of HEN after implementing modification for usage of hot utility below pinch are less which in turn decreases OC and CC of HEN as compared to that of existing HEN. Thus, percentage saving in TAC is found to be 1.30 %. As the cross pinch heat transfer in HPSNs 1 and 2 is in very narrow range, the modification for cross pinch heat transfer is not considered. Thus, after implementation of both the modifications, the percentage saving in TAC is found to be same at 1.3 % as the modification for usage of hot utility below pinch.

Table 5.18 Comparison Between Modified HEN Using NPM and Existing HEN

	hur	cur	A	CC	OC	TAC
	kW	kW	m^2	\$/year	\$/year	\$/year
Existing HEN	879	145358	31633	8677553	3739482	24112814
Modification for Usage of Hot Utility below Pinch	0	144479	31497	8598552	3611994	23799846
Modification for Cross Pinch Heat Transfer	Not considered					
Modification using NPM (Considering Both the above modifications)	0	144479	31497	8598552	3611994	23799846
Saving in TAC after Modifications using NPM						312968
Percentage Saving in TAC after Modifications using NPM						1.30 %

5.8 Modification Using RA in Existing HEN with Q_{min} Approach

The modification using RA begins with the selection of the Q_{min} at which utilities required are same as the utilities needed in the existing HEN. It is seen that hot and cold utilities needed in existing HEN are, respectively, 879 and 145359 kW. At the approximately same utility requirement, the value of Q_{min} is found to be 3.6 kW/m^2 and corresponding pinch temperature is found to be 116.68 ^{O}C which is in feasible range. The corresponding value of area of HEN is found to be 27720 m^2 at Q_{min} of 3.6 kW/m^2. α_{exist} at which the HEN operates is 0.88. The various utility values which are below the existing utility are selected and at each selected utility values,

Q_{min}, pinch temperature and area of HEN are given in Table 5.19. At each selected utility value, $A_{max,retr}$ is calculated using two cases, viz., existing area efficiency of 0.88 and ideal area efficiency of 1.

Table 5.19 Maximum Area for Retrofitting for Each Selected Utility Values

hur	cur	Q_{min}	Pinch Temp.	A	$A_{max,retr}$	
					$\Delta\alpha = 1$	$\Delta\alpha = \alpha_{exist}$
kW	kW	kW/m^2	^oC	m^2	m^2	m^2
1012	110486	3.60	116.68	27720	31633	31633
788	110262	3.55	116.67	30871	34783	35213
565	110038	3.50	116.67	31529	35441	35961
100	109574	3.40	116.50	32812	36724	37418

The next step in RA is to calculate the additional area required at each selected utility values. The saving in utilities at each selected utility is estimated. Based on the saving in utilities, annual saving in OC is estimated. The estimated values of savings in utilities and annual saving in OC at each selected utility requirement are presented in Table 5.20.

Table 5.20 Annual Saving in OC for Each Selected Utility

hur	cur	Q_{min}	Pinch Temp.	U_{saving} Based on		Annual Saving in OC
				Hot Utility	Cold Utility	
kW	kW	kW/m^2	^oC	kW	kW	\$/year
1012	110486	3.60	116.68	0	0	0
788	110262	3.55	116.67	224	224	32473
565	110038	3.50	116.67	447	447	64945
100	109574	3.40	116.50	913	913	132354

The annual saving in OC at each selected utility requirement is possible with additional investment in requirement of additional area of HEN. The requirement of additional area of HEN, the additional investment required and payback period are estimated at each selected utility requirement for both the cases and presented in Table 5.21. It is seen that if HEN is operated at existing area efficiency, the maximum payback period of investment is 38.68 years which is very high. During this payback period, the associated investment in additional area of 3580 m^2 is \$1255910 and annual saving in the reduction of utility by 224 kW is \$32473. In similar way, if HEN is operated at ideal area efficiency, the minimum payback period of investment is 13.49 years which is also very high. During this payback period, the associated investment in additional area of 5092 m^2 is \$1785135 and annual saving in the reduction of utility by 913 kW is \$132354.

Table 5.21 Additional Area, Investment and Payback Period for each Selected Utility

Q_{min}	$A_{max,retr}$		$A_{additional}$		Investment		Payback Period	
	$\Delta\alpha = 1$	$\Delta\alpha = \alpha_{exist}$	$\Delta\alpha = 1$	$\Delta\alpha = \alpha_{exist}$	$\Delta\alpha = 1$	$\Delta\alpha = \alpha_{exist}$	$\Delta\alpha = 1$	$\Delta\alpha = \alpha_{exist}$
kW/m^2	m^2	m^2	m^2	m^2	\$	\$	years	years
3.60	31633	31633	0	0	0	0	0.00	0.00
3.55	34783	35213	3150	3580	1111432	1255910	34.23	38.68
3.50	35441	35961	3808	4328	1339443	1510890	20.62	23.26
3.40	36724	37418	5092	5785	1785135	2023936	13.49	15.29

The data of existing HEN and that after modification using RA for both the cases of existing area efficiency and ideal area efficiency are compared in Table 5.22. After modification using RA at existing and ideal area efficiency, the TAC of HEN are respectively \$ 25990602 and \$ 26800934 which are more than the TAC of existing HEN. The modification using RA reduces the utility requirements and OC but area of HEN and CC increases. It is found that the TAC of HEN cannot be decreased for the case under consideration by reducing the utility requirements.

Table 5.22 Comparison Between Modified HEN using RA and Existing HEN

	hur	cur	A	CC	OC	TAC
	kW	kW	m^2	\$/year	\$/year	\$/year
Data of Existing HEN	879	145358	31633	8677553	3739482	24112814
Modification Using RA for Existing Area Efficiency	565	110038	35961	9869518	2818750	25990602
Modification Using RA for Ideal Area Efficiency	100	109574	37418	10243368	2751350	26800934

5.9 Comparison of Data of Modified HEN Using NPM and RA with Q_{min} Approach

Table 5.23 gives a comparison of data of modified HEN using NPM and RA with Q_{min} approach adopted.

Table 5.23 Comparison Between Modified HEN with NPM, RA with Existing HEN

	hur	cur	A	CC	OC	TAC
	kW	kW	m^2	$/year	$/year	$/year
Existing HEN	879	145358	31633	8677553	3739482	24112814
Modification using NPM	0	144479	31497	8598552	3611994	23799846
Modification Using RA for Existing Area Efficiency	565	110038	35961	9869518	2818750	25990602

From Table 5.23, it is seen that there is a possibility of saving of hot and cold utility by 879 kW and area of HEN by 136 m^2 respectively after implementing the modification using NPM which leads to reduction in OC, CC and TAC of HEN as compared to that of the existing HEN. When RA is employed, there is a possibility of saving in hot and cold utility by 314 kW and 35320 kW with corresponding increase in area of HEN by 4328 m^2. This reduces OC but increases CC and TAC of HEN also.

5.10 Comparison of Data of Modified HEN Using NPM and RA for ΔT_{min} and Q_{min} Approaches with Existing HEN

Table 5.24 gives comparison of data of modified HEN using NPM and RA for ΔT_{min} and Q_{min} approaches with that of existing HEN. From Table 5.24, it is seen that out of four combinations available for modification in existing HEN of the ammonia plant of a fertilizer industry, the minimum value of TAC is obtained for the combination of modification using NPM with ΔT_{min} approach. Therefore, the unified approach of synthesis and optimization of the existing HEN of the ammonia plant using GA for ΔT_{min} approach of PT and modification using NPM is proposed.

Table 5.24 Comparison between Modified HEN Using NPM and RA for ΔT_{min} and Q_{min} Approaches with Existing HEN

	hur	cur	A	CC	OC	TAC
	kW	kW	m^2	$/year	$/year	$/year
Existing HEN	879	145358	31633	8677553	3739482	24112814
Modification using NPM with ΔT_{min} Approach	0	144479	31265	8556413	3611994	23700912
Modified HEN Using RA for Existing Area Efficiency with ΔT_{min} Approach	372	144851	31961	8791469	3665948	24306734
Modified HEN Using RA for Ideal Area Efficiency with ΔT_{min} Approach	587	145066	31713	8716325	3697112	24161474
Modification using NPM with Q_{min} Approach	0	144479	31497	8598552	3611994	23799846
Modification Using RA for Existing Area Efficiency with Q_{min} Approach	565	110038	35961	9869518	2818750	25990602
Modification Using RA for Ideal Area Efficiency with Q_{min} Approach	100	109574	37418	10243368	2751350	26800934

The flow diagram of the existing HEN of the ammonia plant is modified to incorporate the modification obtained using the proposed combination and given in Figure 5.8. From Figure 5.8, it is seen that the heat exchanger HX 116 is removed and the SG leaving tube side of HX 136C is passed through the heat exchanger HX 150C and then entered to heat exchanger HX 129C. Thus the requirements of hot and cold utility respectively at HX 150C and HX 116C are reduced. The modification requires some re-piping work. As the cost of re-piping in comparison with TAC of HEN is very less, it is not considered in the present work.

Figure 5.8 Modified Flow Diagram of the Ammonia Plant

Note: In the Heat Exchangers Tag Number, "HX" is not mentioned in the Flow Diagram, only Number is mentioned.

5.11 Summary of Outcome of the Present Study

The outcome from the synthesis, optimization and modification analysis carried out using NPM and RA with ΔT_{min} and Q_{min} approach as adopting GA as optimization tool on the existing HEN of an ammonia plant which is a part of fertilizer industry are summarized below.

1. The synthesis and optimization of the HEN of the ammonia plant using GA with ΔT_{min} approach suggests that the minimum value of ΔT_{min} and pinch temperature for the HEN of the ammonia plant are 24 ^{O}C and 128 ^{O}C respectively. Promising modification design solutions are generated using NPM which indicates that the scope for reduction in utilities and in area of HEN are respectively by 1758 kW and 367 m^2 which results in a reduction of TAC by 1.71 %.
2. Modification using RA with ΔT_{min} approach suggests that it is possible to reduce the utility requirements for both the cases viz. existing area efficiency and ideal area efficiency with a pay back period of 1.69 years and 0.80 years respectively, which is reasonably attractive. However, TAC of HEN is higher for both the cases as compared to that of the existing HEN.
3. The synthesis and optimization of the HEN of the ammonia plant using GA with Q_{min} approach suggests that the minimum value of Q_{min} and pinch temperature are 3.1 kW/m^2 and 985.75 ^{O}C respectively. Using the grid diagram, it is found that complete HEN is located below pinch and hence complete analysis is not possible. This is mainly due to very high pinch temperature. Promising modification design solutions are generated using

NPM which indicates that the scope for reduction in utilities and in area of HEN is respectively by 1758 kW and 136 m^2 which results in a reduction of TAC by 1.30 %.

4. Modification using RA with Q_{min} approach suggests that it is possible to reduce the utility requirements for both the cases of existing area efficiency and ideal area efficiency with a payback period of 38.68 years and 13.49 years respectively which is very high. TAC of HEN is also higher in both the cases as compared to that of the existing HEN. Due to the above reasons, this option is not acceptable.

Chapter 6

CONCLUSIONS

The conclusions derived from the synthesis and optimization of existing HEN of ammonia plant of a fertilizer unit carried out using GA with two approaches of PT, viz., ΔT_{min} and Q_{min} and the modification analysis of existing HEN of ammonia plant for NPM and RA are presented in this chapter.

6.1 Conclusions

(1) The optimized value of area of HEN is minimum using Q_{min} approach which agrees well with the earlier studies of Rev and Fonyo [58] and Shenoy [61]. But, the limitation of Q_{min} approach observed is that, it yields very high practically unrealistic value of pinch temperature as compared to that of ΔT_{min} approach which limits the application of the approach.

(2) The proposed unified model can verify where there is a scope for modification of the HEN.

(3) Modification using NPM reduces TAC of HEN for the ammonia plant. Thus, modification using NPM is preferable over RA for the present case.

(4) Amongst the four unified methods suggested in the present work, the combination of synthesis and optimization using GA and modification using NPM for ΔT_{min} approach of the PT is the best option for the modification in existing HEN of the ammonia production plant of the fertilizer industry.

6.2 Scope for the Future Work

(1) The proposed unified model of synthesis, optimization and modification of a thermal system network of a chemical plant be applied to similar type of Ammonia production plant of a fertilizer unit and results obtained be compared with the present work. This validation study will strengthen the use of the present unified model

(2) The application of proposed unified model may also be extended to various chemical plants of similar types and results obtained be compared.

(3) A generalized model of synthesis, optimization and modification of a thermal system network may be proposed which is applicable to all types of chemical plants.

(4) The proposed unified model may also be modified by using either other non-traditional optimization techniques or other modification methods and be applied to Ammonia production plant of a fertilizer unit and results obtained be compared with the present work.

APPENDIX I

AMMONIA

Ammonia finds a very important place in the manufacturing of many materials. It has many applications such as direct use as fertilizer, in the manufacturing of fertilizers like urea, ammonium sulfate, di-ammonium phosphate, sodium nitrate, ammonium nitrate etc., and in the manufacturing of nitric acid and chemical compounds like acrylonitrite, caprolactum, nylon 6 and nylon 6/6. It is also used as refrigerant for refrigeration systems and large scale air-conditioning systems.

Ammonia, a colourless gas at atmospheric conditions is a toxic and explosive. In liquid form, it's boiling and freezing points are respectively -33 ^{O}C and -77 ^{O}C at atmospheric pressure.

The different raw materials used for production of ammonia are Natural Gas, Naphtha, Fuel Oil, and byproducts from chemical plants like Cock Oven Gas, Refinery Gas etc. The quantity and place of byproducts like Coke Oven Gas, Refinery Gas etc. mainly depends on the production in the chemical plants. So, they are not effective to use for continuous production of ammonia. The fuel oil is heavier than natural gas and naphtha. As the molecular weight of the raw material increases, the difficulty and cost of processing in ammonia production increase. So, at present the application of fuel oil as raw material in ammonia production is negligible. The natural gas, naphtha and fuel oil are compared based on the percentages of carbon, hydrogen and sulfur present in them Table I.1.

Table I.1 Constituent Elements of Raw Materials Available for Production of Ammonia

Elements present in Raw Material	Natural Gas	Naphtha	Fuel Oil
Carbon	73.4 %	83.8 %	87.2 %
Hydrogen (required for Ammonia Production)	22.76 %	16.2 %	9.9 %
Sulfur (Impurity, To be removed)	3.25 %	5.1 %	8.8 %
Hydrogen to Carbon Ratio	0.31	0.19	0.11

Generally, it is stated that the most effective and economical raw material for production of ammonia is the one with highest Hydrogen to Carbon ratio. Thus, natural gas is the most effective and economical raw material for the production of ammonia. In places where natural gas is not available, naphtha is the next best alternative for production of ammonia. Ammonia is one of the important raw materials to manufacture Urea. Most commonly the urea manufacturing plant consists of a sub chemical unit to manufacture ammonia. Ammonia production is a highly energy consuming process requiring from 35 to 50 GJ of energy per ton of ammonia production depending on the raw material used and process involved.

I.1 Manufacture of Ammonia

There are four basic processes to manufacture ammonia. They are Herber-Bosch process, coal based partial oxidation process, heavy hydrocarbon based partial oxidation process and steam reforming process.

I.1.1 Heber-Bosch process

In the original Heber-Bosch process, the hydrogen source was coke derived from coal. In this process, coke is first blasted with air and the heat liberated by the formation of carbon dioxide raises the coke to incandescence. The products combustion leaves the system by going to the atmosphere. Steam is added next to produce water gas containing carbon dioxide, carbon monoxide, and hydrogen. The nitrogen is usually furnished by adding a sufficient quantity of the combustion products from the blasting step to the gas is converted to hydrogen and carbon dioxide by reaction with steam over a catalyst and the converted gas is stored in another gas holder, compressed and scrubbed using an ammoniac cuprous solution to remove unconverted carbon monoxide. The resultant, relatively pure gas, consisting of three parts hydrogen to one part nitrogen, is then fed as makeup gas to the synthesis loop.

I.1.2 Coal-based partial oxidation processes

Two commercially established processes utilizing coal feeds are the Lurgi process and the Koppers-Totzek process.

In the Lurgi process, coal is gasified in a fixed bed reactor using oxygen and steam at about 2000-3000 kN/m^2 pressure. The steam and oxygen enter the gasifier through slots in a rotary grate while the coal is charged through specially designed lock hoppers and distributed evenly over the cross section of the gasifier. Ash is removed in a non-slugging operation by the rotary grates. Gasification temperatures range from about 560 ^{O}C to 620 ^{O}C depending on the feed characteristics. Because the gasification temperature is in the intermediate range and the operating pressure is relatively high, the methane and carbon dioxide content from a typical Lurgi gasifier are 10-11% and about 28% respectively. The crude gas from the Lurgi gasifier is treated in several processing steps including waste heat recovery, shift conversion, removal of tars phenols, and other by products, Retinol treatment for carbon dioxide and sulfur removal, liquid nitrogen scrubbing to produce highly purified synthesis gases.

The Koppers-Totzek dilute phase gasification takes place at low pressure and much higher temperature essentially ensuring complete hydrocarbon conversion. A homogeneous mixture of pulverized coal, oxygen and steam reacts producing a flame zone temperature of about 1925 ^{O}C. Subsequent steam and carbon endothermic reactions reduce the temperature to around 1480 ^{O}C. Residual methane levels of 0.1% and less are realized. Depending on the reactivity of the coal, up to 99% of the carbon is gasified; the bulk of the resultant gases consist of hydrogen and carbon monoxide. The crude washing, compression, sulfur removal, shift conversion, carbon dioxide removal, nitrogen scrubbing, compression and synthesis.

I.1.3 Heavy Hydrocarbon-based Partial Oxidation processes

Two major partial oxidation processes are commercially available, the Shell process and the Texaco process. Operating conditions in the gas generator vary from 1200 ^{O}C to 1370 ^{O}C and from 3100 kN/m^2 to 8270 kN/m^2.

Preheated hydrogen feed and oxygen are mixed with steam and fed to the combustion chamber of the reactor. A non-catalytic flame reaction produces the raw synthesis gas. The hot reactor effluent is cooled by generating high pressure steam is specially designed waste heat boilers. In spite of the presence of free carbon in the gas, the design ensures that heat transfer surfaces remain clean even after prolonged operation. The raw synthesis gas is then routed to the carbon removal system, consisting of a carbon catcher and gas cooler scrubber, where the carbon produced in the reactor is removed as water slurry. The carbon is transferred to the oil from carbon oil pellets in a device called a palletizer. The resultant pellets are re-slurred with oil feed in a homogenizer and recycled as dilute slurry to the reactor.

Preheated hydrogen feed along with oxygen and steam are fed to the reactor using a hot water steam from the scrubber. The water quenches cools the resultant mix tire is regenerated in the naphtha stripper. From the stripper overheads, naphtha stripper containing carbon is recycled to the reactor. The water from naphtha separator, after degassing, is routed back to the scrubber and the clean raw synthesis gas is available for further processing.

I.1.4 Steam Reforming Process

At present 75-80 % of ammonia produced in the world is produced from steam reforming operations and approximately 65-70 % of these use natural gas as feed. The feedstock, ranging from natural gas to naphtha, is first de-sulfurized, mixed with steam and reformed in the primary reformer. The remaining carbon dioxide and carbon monoxide are removed by reaction of hydrogen to produce methane and water in a methanation step. The synthesis gas is then compressed and ammonia is produced.

Advantages:

Ammonia production using steam reforming process has the following advantages:

(i) The steam reforming process generates more hydrogen than partial oxidation process.

(ii) Steam reforming process requires less feed than partial oxidation process.

(iii) Production of ammonia from coal plants is more costly than conventional gas based processes, because of the extensive solid handling and effluent treatment facilities required and

(iv) Steam reforming process generates less pollution than other processes.

APPENDIX II

OPTIMIZATION TECHNIQUES

The appendix, briefly reviews various optimization techniques available in literature which can be used in HEN optimization. As there are many methods of optimization available along with extensions and modifications, all cannot be discussed in detail, the most popular among them are briefly presented.

II.1 Classification of Optimization Methods

Optimization methods can also be subdivided as Unconstrained and Constrained type.

II.1.1 Methods of Unconstrained Function (Search Methods)

1. Unidirectional Search
2. Direct Search Methods
    - Simplex Search Method
    - Hook-Jeeves Pattern Search Method
    - Powell's Conjugate Direction Method
3. Gradient-Based Methods
    - Caunchy's Method or Steepest Descent Method
    - Newton's Method
    - Conjugate Gradient Method or Fletcher and Reeves Method
    - Variable-metric Method or Davidon, Fletcher and Powell Method

II.1.2 Methods of Constrained Function

1. Linear Programming Methods
    - Graphical Method
    - Simplex Method
    - Nelder & Mead Method

        Methods for Handling Constraints

        - Langrange Multipliers
        - Kuhn-Tucker Conditions
        - Penalty Method
        - Method of Multiplier
2. Constrained Direct Search Methods
    - Variable elimination Method
    - Complex Search Method
    - Random Search Method
    - Linearized Search Methods
    - Frank-Wolf Method
    - Separable Programming
    - Cutting Plane Method
3. Direction Generation Methods
    - Methods of Feasible Directions
    - Generalized Reduced Gradient
    - Gradient Projection Methods
4. Quadratic Approximation Methods

5. Integer Programming
    - Penalty Function Method
    - Branch and Bound Method
6. Quadratic Programming
7. Geometric Programming
8. Goal Programming
9. Non-Traditional Methods
    - Genetic Algorithms
    - Simulated Annealing
    - Tabu Search
    - Ant Algorithm
    - Particle Swarm Optimization

II.2 Genetic Algorithms

GA is relatively recently developed non-traditional optimization technique. GA is presented briefly in this section. The procedure for GA is described first and then a short overview of some frequent variations that can be implemented to modify the basic algorithm is presented. Then after mechanics of GA, the difference between GA and other optimization methods, advantages and draw backs of GA are presented.

II.2.1 Procedure of GA

GA can be implemented for mainly all kind of problems and broadly the procedure for implementing GA is classified as Single Objective and Multi Objective. Before beginning the description of the GA procedure, it is important to differentiate between single-objective and multi-objective GA. The first one aims to find a single set of input variables that will optimize one or many performance criterions synthesized into a single-objective function. The principle of the second type of GA is to find many non-dominated solutions, also called Pareto-optimal solutions, whose performances spread over the objective functions domain.

II.2.1.1 Single-objective GA

- The decision variables are coded in binary form in binary coded GA and in real coded GA; real values of variables are used.
- Each binary form is known as string structure in GA literature.
- The length of string is usually determined according to the range of decision variable and the desired solution accuracy.
- The pseudo code for operation of GAs is presented in Figure I.1.

```
Begin:
        Initialize population;
        Evaluate population;
            Repeat
                Reproduction;
                Crossover;
                Mutation;
            Until (termination criteria);
End.
```

Figure I.1 Pseudo Code for GA

- GA begins with random generation of initial population coded in string of 0 or 1. The number of strings generated initially is known as population size in GA literature. These binary coded strings represent the lower limit and upper limit of variables.
- After evaluation of binary coded strings, they are evaluated to obtain the fitness of the objective function.
- Then the strings with optimum value of fitness function are selected for next operations i.e. reproduction, crossover and mutation.
- The chances of selection of the strings with optimum values of objective function are more and they can also be selected more number of times. The selection of strings is achieved by roulette wheel selection process. These reproduced strings, known as child strings, are operated with crossover and mutation to obtain hopefully better strings.
- In crossover, two child strings are selected randomly and crossover site is selected by random number generation. The child strings are interchanged at crossover site to hopefully obtain better child strings.
- In mutation, child strings are selected randomly again to undergo mutation and mutation site is also generated randomly. The value of bit is changed either from 0 to 1 or 1 to 0 at mutation site of the selected child. In this way, new strings are obtained.
- Again they are evaluated and their fitness values are calculated.
- This is called one cycle and the cycle is repeated until a termination criterion is reached.

- One cycle is known as generation in GA terminology and cycle is continued until required number of generation is reached.
- Finally, the optimum value of objective function is printed.

II.2.1.2 Multi-objective GA

- The multi-objective GA procedure does not search for a single optimal solution. It searches for a set of solutions that represent tradeoffs between many objective functions.
- The principles on which the multi-objective GA procedure relies are the same as those of the single-objective optimization i.e. combining strongest individuals to create offspring by crossover and mutations, and repeat this scheme over many generations.
- However, the multi-objective optimization algorithm must take into account for the fact that there are many "best solutions", which modifies the selection process.
- It sorts the individuals based on the non-domination rank and on the crowding distance, to ensure a high level of performance as well as a good dispersion of the results.
- This algorithm can be implemented with real-coding as well as with binary-coding.

II.2.2 Selection of GA parameters

To implement GA, certain number of settings (GA parameters) must be selected. Unfortunately, the exact settings used for running the GA are not always provided in the reviewed publications which, in some cases, might complicate the repeatability of the results or the extension of a work to a similar problem. The choices of GA parameters have a great effect on the speed of convergence as well as on the success of the optimization. Thus population size, crossover probability, mutation probability etc. should be selected based the type of problem domain and complexity. After the introduction of GA, it has been modified time to time to make it powerful optimization tool.

II.3 Frequent variations in GA

The variations in GA are explained as under.

II.3.1 Local search

Local optimization algorithms in GAs have been introduced in the early 1990s. Their A local optimization algorithms is often included in the GA in order to overcome the disadvantage of the inability of fine local tuning. This operator replaces or follows the mutation operator. Local search is achieved by changing slightly one or some characteristics of promising or randomly selected individuals. However, unlike mutation, both designs (i.e., the initial and the slightly modified one) are evaluated. Generally, only the best one is kept in the population. Algorithms implementing this strategy in a GAs are often called hybrid genetic algorithms.

II.3.2 Elitism

Elitism strategy is frequently implemented to eliminate regression in the optimization process from one generation to the next. The most common technique used to apply elitism in single-objective algorithms is to introduce directly one or many of the best individuals of the parent generation into the offspring generation. Another technique which is employed in multi-objective algorithms consists of including the parent and offspring populations in the same mating pool in such a way that the mating population can never be weaker than the previous one.

II.3.3 Niching

The main aim behind introducing niching is that when two extremely different individuals perform well, we do not want to lose the specificities of each individual by mixing their chromosomes. In niching, when two individuals competing for a place in the mating pool are too “morphologically far” the second competitor is changed for another one and so on until the two competitors are sufficiently similar. This reduces risks of eliminating very unique individuals through the tournament selection.

II.3.4 Micro GA

When GA require more computations time, micro-GA is a quick alternative. It generally uses less than 10 individuals per population and basically applies the same scheme as GA, except that it does not use the mutation operator. However, the fact is that the small population size leads faster to local optima. To preserve diversity, when the algorithm restarts with new random populations, the best individual found before is inserted. This algorithm leads to a smaller number of populations to evaluate than GA and so, it is faster.

II.4 Mechanics of GA

The mechanics of GA is surprisingly simple, involving nothing more complex than copying binary strings and swapping the part of the binary strings. Three operators of GA are Reproduction, Crossover and Mutation. [175]

II.4.1 Reproduction

Reproduction is usually the first operator applied on a population. Reproduction selects good binary strings in a population and forms a mating pool. There exists a number of reproduction operators in GA literature, but the essential idea is that, above average strings are picked from the current population and duplicates of them are inserted in the mating pool.

The commonly used reproduction operator is the proportionate selection operator, where a string in the current population is selected with a probability proportional to the string's fitness(f). Thus, the i^{th} string in the population is selected with a probability proportional to its fitness. Since, the population size is usually kept fixed in a simple GA; the cumulative probability for all strings in the population must be one. Therefore, the probability for selecting i^{th} string is fi/∑f (1 to N), where, N is the population size. One way to achieve this proportionate selection is to use a roulette wheel with the circumference marked for each string proportionate to the string's fitness. Another method for reproduction is Tournament selection. Biased roulette wheel selection method is used.

II.4.2 Crossover

Crossover operator is applied next to the reproduction operator. Like reproduction operator, there exists a number of crossover operators in GA literature but in almost all crossover operators, two strings are picked from the mating pool at random and some portion of the strings are exchanged between the strings.

In single point crossover operator, this is performed by randomly choosing a crossing site among the string and by exchanging all bits on the right side of the crossing site as shown in Figure II.2.

0 0 | 1 0 1	⇒	0 0 | 0 1 1
1 1 | 0 1 1		1 1 | 1 0 1

Figure II.2 Working Principle of Single Point Crossover Operator

In two point crossover operator, two random sites are chosen and the contents bracketed by these sites are exchanged between two strings. This idea can be extended to create multi – point crossover operator also. It is shown in Figure II.3. In the present algorithm, the single point crossover is used.

0 0 | 1 0 1 | 0 1 ⇒ 0 0 | 0 1 1 | 0 1

1 1 | 0 1 1 | 0 0 ⇒ 1 1 | 1 0 1 | 0 0

Figure II.3 Working Principle of Two Point Crossover Operator

The two stings participating in the crossover operation are known as parent strings and the resulting strings are known as children strings. It is intuitive form this construction that good substrings from parent strings can be combined to form a better child string, if an appropriate site is chosen. Since the knowledge of an appropriate site is usually not known beforehand, a random site is often chosen. With a random site selection, the children strings produced may or may not have a combination of good sub-strings form of parent strings. Good Sub-string forms depend on whether or not the crossing site falls in the appropriate place. This is not the point of worry, because if good strings are created by crossover, there will be more couples of them in the next mating pool generated by the reproduction operator. But if good strings are not created by crossover, they will not survive too long, because reproduction will not select again those strings in subsequent generations.

It is clear from the above discussion that, the effect of crossover may be detrimental or beneficial. Crossover needs to be performed in a way that the information stored in the parent strings is maximally preserved.

II.4.3 Mutation operator

Crossover operator is mainly responsible for the search aspect of GA, even though mutation operator is also used for this purpose. Mutation operator changes the single bit from 1 to 0 and vice versa with a small mutation probability, Pm. The need for the mutation is to keep diversity in the population. For example, consider at a particular position of bit along the string length of all the strings in the population have a value “0”, and the value “1” is needed in that position to obtain the optimum value, then neither reproduction nor crossover operator described above will be able to create the value “1” in that position. The inclusion of mutation operator includes some probability of turning that 0 into 1. Furthermore, for local improvement of a solution, mutation may be found useful.

These three operators are simple and straight forward. Reproduction operator selects good strings and crossover operator creates good sub-strings from two good strings together to hopefully form a better sub-string. Mutation operator alters a string locally to hopefully create a better string.

II.4.4 Objective Function

As GA work on the survival of the fittest principle of nature to develop the search process, it is naturally suitable for soling maximization problems. However, minimization problems can also be converted into maximization problems by using suitable transformation rule. The transformation of objective function can be achieved by two methods as described below.

First Method:

Minimization $f(x)$, can be transformed to standard form as

Maximization $1/[1+f(x)]$.

Second Method:

Minimization C, can be transformed as

Maximization CONSTANT – C.

Where, CONSTANT = Higher Value Compared to Cost Value.

II.5 How Genetic Algorithm Differs?

Genetic algorithms are different from more normal optimization and search procedures mainly in four ways. [175]

(1) GA work with coding of the parameter set, not the parameters themselves.

The advantage of working with a coding of variables is that the coding discritizes the search space, even though the function may be continuous. On the other hand, since GA requires only function values at various discrete points, a discrete or discontinuous function can be handled with no extra cost. This allows GA to be applied to a wide variety of problems.

(2) GA searches from a population of points, not a single point.

As more than one string being processed simultaneously, it is very likely that the expected GA solution may be global solution. Even though some traditional algorithms are population–based, like complex search methods, those methods do not use previously obtained information efficiently. In GA, previously found good information is emphasized using reproduction operator and propagated adaptively through crossover and mutation operators.

Another advantage with a population–based search algorithm is that multiple optimal solutions can be captured in the population easily, thereby reducing the effort to use the same algorithm many times.

(3) GA use payoff (objective function) information, not derivatives or other auxiliary knowledge.

GA does not require any auxiliary information except the values of objective function. Some methods work under the assumption that the function to be optimized is uni-modal and continuous. In GA, there are no such assumptions.

(4) GA use probabilistic transition rules, not deterministic rules.

In many optimization methods, we move gingerly from a single point in the decision space to the next using some transition rules to determine the next point. This point to point method is dangerous because it is perfect prescription for locating false peak in multi-modal (many peak) search spaces. While GA does not use any rule and need any auxiliary information. Simply stating, GA is blind.

II.6 Advantages and Drawbacks

GA works with coding of decision variables instead of using the original variables. The advantage of working with coding of variables is that the coding discretizes the search space, even though the objective function is continuous.

Since GA requires only the values of objective function at various points, a discontinuous function can also be handled easily.

GA works with a population of points instead of a single point. Thus, it is very likely that the expected GA solution may be a global solution.

GA does not require any auxiliary information except the value of objective function.

One of the disadvantages of GA is that they can be slow to converge compared to other optimization methods that have been developed specifically for a problem. This is especially true for the cases of larger and hard-to-solve problems such as synthesis of heat exchanger network, retrofitting conditions, topology optimization or inverse problems. GA may also be less efficient and slower than traditional methods when dealing with very simple problems, especially those for which an analytical optimum is known. Finally, it is important to note that several runs of a GA with the exact same settings could potentially converge to different nearly-optimal results because of their probabilistic nature. Therefore, repeatability is not always perfect.

APPENDIX III

PROCEDURE TO OPERATE COMPUTER PROGRAM

The program is prepared in C++ programming language. For synthesis an optimization of ammonia plant using GA through ΔT_{min} and Q_{min} approach, separate programs are prepared and copied on the CD. The programs are copied in two formats, viz. (1) “exe” format which can be run directly and (2) “cpp” format which requires the software Turbo C++.

The CD contains two folders named (1) Program in EXE format and (2) Program in CPP format. The folder “program in EXE format” contains the programs named (1) GADEMIN.exe and (2) GAMINFLUX.exe. The folder named “program in CPP format” contains the programs named (1) GADTMIN.cpp, (2) GAMINFLUX.cpp and two header files required for executing the program named (1) DEC_BIN.H and (2) RANDON.H. The procedure to run the programs for both the formats is as under.

II.1 Procedure to Run the Program which is in “exe” format

(i) Open the CD.

(ii) Open the folder named “Program in EXE format”.

(iii) There are two programs named “GADTMIN.exe” and “GAMINFLUX.exe”.

(iv) Double click on any of the programs to start executing.

(v) Program will ask the “File name with out giving extension for storing output”. Any file name is to be entered in which output of the program is to be stored.

(vi) Then program will ask the GA parameters like population size, maximum number of generation, crossover probability, mutation probability and any random number.

(vii) Once above GA parameters are entered, program will run and store the output in the particular file.

(viii) Output of the program can be read from the file.

II.2 Procedure to Run the Program which is in “cpp” format

(i) This requires to install “Turbo C++ program” in the root directory of the computer.

(ii) In the subdirectory, “C:\TC\INCLUDE”, copy the files “DEC_BIN.H” and “RANDOM.H” available on the CD.

(iii) Open the CD and the folder named “Program in CPP format”.

(iv) Copy the required program either GADTMIN.cpp or GAMINFLUX.cpp on the desktop of the computer.

(v) Run the program Turbo C++ and open the program to be executed.

(vi) Press the “Ctrl+F9” keys on the keyboard and the program will start executing.

(vii) Program will ask the “File name with out giving extension for storing output”. Any file name is to be entered in which output of the program is to be stored.

(viii) Then program will ask the GA parameters like population size, maximum number of generation, crossover probability, mutation probability and any random number.

(ix) Once above GA parameters are entered, program will run and store the output in the particular file.

(x) Output of the program can be read from the file.

APPENDIX IV

SAMPLE CALCULATION

Based on the calculation steps explained in Section 4.1.2 and Section 4.1.3, sample calculation to estimate the TAC of HEN is given in this appendix for ΔT_{min} approach at a ΔT_{min} of 10 ^{O}C.

IV.1 Minimum Requirement of Utilities

Using equation 4.1,

$\sum Q_h + \sum Q_{hu} = \sum Q_c + \sum Q_{cu}$

Where,

$\sum Q_h \quad = \quad Q_{h1} + Q_{h2} + Q_{h2} + \ldots\ldots\ldots\ldots\ldots + Q_{h32}$

$\quad = \quad C*(T_{h1,in} - T_{h1,out}) + \ldots\ldots\ldots\ldots\ldots + C*(T_{h32,in} - T_{h32,out})$

$\quad = \quad 86.95*(997\text{-}483) + \ldots\ldots\ldots\ldots\ldots + C*(T_{h32,in} - T_{h32,out})$

$\quad = \quad 44692.30 + \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots + C*(T_{h32,in} - T_{h32,out})$

$\quad = \quad 498329$ kW and,

$\sum Q_c \quad = \quad Q_{c1} + Q_{c2} + Q_{c2} + \ldots\ldots\ldots\ldots\ldots + Q_{c26}$

$\quad = \quad 389608.2$ kW

According to equation 4.1,

$\sum Q_h + \sum Q_{hu} = \sum Q_c + \sum Q_{cu}$

$498329 + \sum Q_{hu} = 389608.2 + \sum Q_{cu}$

To balance the above equation,

Minimum $\sum Q_{hu} = 0$ and

Minimum $\sum Q_{cu} = \sum Q_h - \sum Q_c = 498329 - 389608.2 = 108720.8$ kW

The results are given in Table IV.1

Table IV.1 Minimum Requirement of Utilities

ΔT_{min}, ^{O}C	Minimum Hot Utility Required, kW	Minimum Cold Utility Required, kW
10	0	108720

IV.2 Pinch Point

Step 1 Shift the inlet and outlet temperatures of cold and hot process and utility streams using equations 4.2 and 4.3

$t_{h,in,shifted}$ or $t_{h,out,shifted}$ = ($t_{h,in}$ or $t_{h,out}$) - (ΔT_{min} / 2)

For HP1, $t_{h,in,shifted}$ = ($t_{h,in}$) - (ΔT_{min} / 2) = 997 –(10/2) = 992 ^{O}C.

For HP1, $t_{h,out,shifted}$ = ($t_{h,out}$) - (ΔT_{min} / 2) = 483 –(10/2) = 478 ^{O}C.

$t_{c,in,shifted}$ or $t_{c,out,shifted}$ = ($t_{c,in}$ or $t_{c,out}$) + (ΔT_{min} / 2)

For CP1, $t_{c,in,shifted}$ = ($t_{c,in}$) + (ΔT_{min} / 2) = 27 + (10/2) = 33 ^{O}C.

For CP1, $t_{c,out,shifted}$ = ($t_{c,out}$) + (ΔT_{min} / 2) = 74 + (10/2) = 79 ^{O}C.

In similar way, shifted value of inlet and out temperatures of hot and cold process and utility streams are calculated and given in Table IV.2.

Table IV.2 Shifted Inlet and Outlet Temperatures of Hot and Cold Process and Utility Streams

Stream	Shifted Inlet Temperature, ^{O}C	Shifted Outlet Temperature, ^{O}C
H 1	992	478
H 2	993	478
H 3	477	366
H 4	425	328
H 5	327	236
H 6	235	199
H 7	223	185
H 8	189	164
H 9	163	123
H 10	162	121
H 11	122	58
H 12	154	81
H 13	80	36
H 14	35	2

H 15	355	140
H 16	139	33
H 17	32	3
H 18	159	63
H 19	466	279
H 20	372	273
H 21	272	161
H 22	62	42
H 23	40	17
H 24	16	-4
H 25	41	-16
H 26	-9	-29
H 27	101	31
H 28	128	39
H 29	83	37
H 30	117	85
H 31	91	52
H 32	30	-2
C 1	33	79
C 2	317	318
C 3	55	160
C 4	317	318
C 5	123	128
C 6	119	321
C 7	319	320
C 8	184	216
C 9	118	185
C 10	121	126
C 11	319	320
C 12	57	125
C 13	53	122
C 14	-5	7
C 15	120	316
C 16	-3	20
C 17	28	146
C 18	18	19
C 19	225	257
C 20	122	236
C 21	145	432
C 22	-2	-1
C 23	-17	30
C 24	76	104
C 25	-28	-27

C 26	14	15
HU1	143	142
CU1	35	44
CU2	41	53

Step 2 Shifted temperatures are arranged in descending order omitting the common temperatures to both hot and cold process streams and given in Table IV.3

Step 3 Calculate Net Capacity Flow Rate for each temperature interval using equation 4.6

$C_{ti} = \sum C_{cps,ti} - \sum C_{hps,ti}$

For first temperature interval, viz., ti = 0, net capacity flow rate is zero.

For other temperature intervals, ti > 0

For first temperature interval, ti =1, temperature rage is 993 to 992^{O}C.

$\sum C_{cps,ti}$ = 0 {The range of any cold process stream (Shifted inlet temperature of cold process stream to shifted outlet temperature of cold process stream) does not fall in the temperature range 993 to 992 ^{O}C}

$\sum C_{hps,ti}$ = 86.45 (As the range of only HP1 fall in the temperature range 993 to 992 ^{O}C)

Hence, $C_{ti} = \sum C_{cps,ti} - \sum C_{hps,ti} = 0 – 86.45$

= - 86.45 kW/K

In similar way, net capacity flow rate for all temperature intervals are calculated and given in Table IV.3.

Step 4 Calculate Net Enthalpy in each temperature interval using equation 4.7

$Q_{ti} = C_{ti} * \Delta T_{ti}$

For first temperature interval, viz., ti = 0, net enthalpy is zero.

For other temperature intervals, ti > 0

For first temperature interval, ti =1, temperature rage is 993 to 992^{O}C.

$Q_{ti} = C_{ti} * \Delta T_t = -86.45 * (993 - 992)$

$= -86.45$ kW

In similar way, net enthalpy for all temperature intervals are calculated and given in Table IV.3.

Step 5 Calculate the cascaded heat using equations 4.8 and 4.9

For first temperature interval, viz., ti = 0, cascaded heat is zero.

For other temperature intervals, ti > 0

For first temperature interval, ti =1,

$Q_{cas,ti} = Q_{cas,ti-1} - Q_{ti}$

= Cascaded Heat for ti=0 – Net Enthalpy for ti=1

$= 0 - (-86.45)$

$= 86.45$ kW

In similar way, cascaded heat for all temperature intervals are calculated and given in Table IV.3.

Step 6 Calculate revision of cascaded heat using equation 4.10

$R_{cas,ti} = Q_{cas,ti} + MinQ_{cas,ti}$

Minimum cascaded heat among all the cascaded heat is identified and added to the cascaded heat. As seen from Table IV.3, minimum cascaded heat is zero. Hence, revised cascaded heats for all temperature intervals are similar to the cascaded heat. Revised cascaded heats are given in Table IV.3

Table IV.3 Pinch Point Calculations

Temperature Interval, ti	Sorted Shifted Temperature in Descending Order, ^{O}C	Net Capacity Flow Rate, kW/K	Net Enthalpy, kW	Cascaded Heat, kW	Revised Cascaded Heat, kW
0	993	0	0	0	0
1	992	-86	-86	86	86
2	478	-173	-89129	89215	89215
3	477	-86	-86	89302	89302
4	476	-173	-173	89474	89474
5	466	-86	-865	90339	90339
6	432	-310	-10545	100884	100884
7	425	-164	-1151	102035	102035
8	372	-251	-13288	115323	115323
9	366	-403	-2421	117743	117743
10	355	-317	-3486	121230	121230
11	328	-358	-9658	130887	130887
12	327	-271	-271	131159	131159
13	321	-361	-2168	133327	133327
14	320	-321	-321	133647	133647
15	319	17651	17651	115997	115997
16	318	-321	-321	116318	116318
17	317	89067	89067	27250	27250
18	316	-321	-321	27571	27571
19	279	-276	-10216	37787	37787
20	273	-52	-315	38102	38102
21	272	100	100	38001	38001
22	257	-130	-1950	39951	39951
23	236	342	7192	32759	32759
24	235	657	657	32102	32102
25	225	569	5695	26407	26407
26	223	97	194	26213	26213
27	216	1	4	26209	26209
28	199	115	1957	24252	24252
29	189	202	2022	22231	22231
30	185	-105	-421	22652	22652
31	184	106	106	22546	22546
32	164	-9	-173	22719	22719
33	163	299	299	22420	22420
34	162	-448	-448	22868	22868
35	161	-1176	-1176	24044	24044
36	160	-946	-946	24990	24990
37	159	-916	-916	25906	25906
38	154	-1190	-5948	31854	31854

39	146	-1230	-9837	41691	41691
40	145	-1007	-1007	42698	42698
41	140	-1153	-5764	48462	48462
42	139	-1112	-1112	49574	49574
43	128	-1157	-12730	62304	62304
44	126	4500	9001	53304	53304
45	125	10474	10474	42830	42830
46	123	10662	21324	21506	21506
47	122	5436	5436	16070	16070
48	121	5053	5053	11017	11017
49	120	-191	-191	11208	11208
50	119	-236	-236	11444	11444
51	118	-277	-277	11721	11721
52	117	-391	-391	12112	12112
53	104	-1199	-15588	27700	27700
54	101	-276	-828	28527	28527
55	91	-309	-3092	31620	31620
56	85	-909	-5456	37076	37076
57	83	-102	-203	37279	37279
58	81	-1063	-2127	39406	39406
59	80	-1023	-1023	40429	40429
60	79	-1067	-1067	41496	41496
61	76	-1048	-3144	44640	44640
62	63	-1971	-25625	70265	70265
63	62	-1698	-1698	71963	71963
64	58	-1980	-7922	79885	79885
65	57	-1780	-1780	81665	81665
66	55	-1969	-3937	85602	85602
67	53	-1999	-3997	89599	89599
68	52	-2041	-2041	91640	91640
69	42	-1441	-14407	106047	106047
70	41	-1158	-1158	107205	107205
71	40	-1349	-1349	108554	108554
72	39	-1542	-1542	110096	110096
73	37	-1226	-2452	112549	112549
74	36	-264	-264	112813	112813
75	35	-221	-221	113034	113034
76	33	-263	-526	113560	113560
77	32	-218	-218	113778	113778
78	31	-243	-243	114021	114021
79	30	-210	-210	114231	114231
80	28	13	27	114204	114204
81	20	-209	-1674	115878	115878
82	19	-201	-201	116079	116079

83	18	4225	4225	111854	111854
84	17	-201	-201	112054	112054
85	16	-8	-8	112062	112062
86	15	-331	-331	112394	112394
87	14	-46	-46	112439	112439
88	7	-331	-2319	114758	114758
89	3	-216	-866	115624	115624
90	2	-210	-210	115834	115834
91	-1	-168	-504	116337	116337
92	-2	6294	6294	110043	110043
93	-3	-159	-159	110202	110202
94	-4	-168	-168	110369	110369
95	-5	156	156	110214	110214
96	-9	41	163	110051	110051
97	-16	-766	-5362	115413	115413
98	-17	-575	-575	115987	115987
99	-27	-807	-8067	124054	124054
100	-28	15387	15387	108667	108667
101	-29	-807	-807	109474	109474

Step 7 Pinch Point

Note the temperature interval at zero R_{cas} value. This is the “pinch point temperature” or simply “pinch point”. At zero cascaded heat value, the value of sorted shifted temperature is 993 ^{O}C. Hence, pinch point temperature is 993 ^{O}C for ΔT_{min} = 10 ^{O}C.

Step 8 Minimum Hot and Cold Utility Requirements

Identify the R_{cas} at first temperature interval as $Q_{hu,min}$ and R_{cas} at last temperature interval as $Q_{cu,min}$. At first temperature interval, viz., ti=0, revised cascaded heat is zero and at last temperature interval, revised cascaded heat is 109474. Minimum hot and cold utility requirements are given in Table IV.4.

Table IV.4 Minimum Hot and Cold Utility Requirements

ΔT_{min} , ^{O}C	Minimum Hot Utility Required, $Q_{hu,min}$	Minimum Cold Utility Required, $Q_{cu,min}$
10	0	109474

IV.3 Cumulative Enthalpy for Hot and Cold Process Stream

The calculation steps for calculating cumulative enthalpy for hot and cold process streams and for hot and cold process and utility streams are similar. Hence, sample calculation for calculating cumulative enthalpy for hot and cold process and utility streams are carried out and given in Step 2 of Section IV.4.

IV.4 Area of HEN for Countercurrent Heat Exchanger Specification

Heat transfer area of HEN for counter current specification of heat exchangers is estimated as follows:

Step 1 Calculate Capacity Flow Rates for Utility Streams

(1) As there is only hot utility, as per the case of single utility using equation 4.13

$$CR_{hu} = (Q_{hu,min}) / (t_{hu,in} - t_{hu,out})$$

$$Q_{hu,min} = 0 \text{ (From Table IV.4)}$$

$$t_{hu,in} = 148\ ^{O}C \quad \text{and} \quad t_{hu,out} = 147\ ^{O}C$$

$$\text{Hence, } CR_{hu} = (Q_{hu,min}) / (t_{hu,in} - t_{hu,out})$$

$$= 0 / (148\text{-}147) = 0$$

(2) As there are two cold utilities, as per the case of multi utility,

(i) Giving priority to hottest cold utility based on inlet temperature of cold utility. The priority numbers of cold utility streams are given in Table IV.5.

Table IV.5 Priority Numbers of Cold Utility Streams

Cold Utility Priority Number	Cold Utility Inlet Temperature, ^{O}C	Cold Utility Outlet Temperature, ^{O}C
0	36	48
1	30	39

(ii) Revised cascaded heat (R_{cas}) by applying the interpolation between the temperature interval and R_{cas} at the inlet temperature of the utility. For first cold utility, at inlet temperature of 36 ^{O}C, revised cascaded heat is 112813 (from Table IV.3) and based on the priority and minimum utility requirements revised cascaded heat (Individual usage level) for first cold utility stream is 107205.1 kW.

(iii) For second cold utility stream, revised cascaded heat (Individual Usage Level) is

= $Q_{cu,min}$ – Revised Cascaded Heat for First Cold Utility

= 109473.7 – 107205.1 = 2268.6 kW/K

(iv) Capacity flow rates for cold utility streams are calculated using equation 4.16 and given in Table IV.6.

CR_{cu} = (Individual Usage Level) / ($t_{cu,out}$ – $t_{cu,in}$)

For first cold utility, CR_{cu} = 107205.1 / (48 – 36)

= 8933.76 kW/K

Table IV.6 Capacity Flow Rate of Cold Utility Streams

Cold Utility Priority Number	Cold Utility Inlet Temperature, ^{O}C	Cold Utility Outlet Temperature, ^{O}C	Revised cascaded heat (Individual Usage Level, Cold Utility Required), kW	Capacity Flow Rate of Cold Utility, kW/K
0	36	48	107205	8934
1	30	39	2268	252

Step 2 Cumulative Enthalpies for Hot and Cold Process and Utility Streams

Step 2.1 Cumulative Enthalpies for Hot Process and Utility Streams

(i) As per Step 1 of Section 4.1.2.3:

- Sort out $T_{h,in}$ and $T_{h,out}$ in ascending order, omitting the repeated values for ΔT_{min} approach. Sorted inlet and outlet temperatures of hot process and utility streams in ascending order are given in Table IV.7.

(ii) As per Step 2 of Section 4.1.2.3:

- Calculate, for each interval of temperatures, the summation of capacity flow rate of hot streams.

  For first temperature interval, viz., ti=0, capacity flow rate is zero.

  For other temperature intervals, viz., ti>0,

  For temperature interval, ti=1,

  As the range of only one hot process stream, viz., HP 26 (inlet and outlet temperatures of HP 26 are -4 ^{O}C and -24 ^{O}C), falls between temperatures -24 ^{O}C to -11 ^{O}C , capacity flow rate for first temperature interval is 806.69 kW/K.

- In similar way, capacity flow rate for all temperature intervals are calculated and given in Table IV.7.

(iii) As per Step 3 of Section 4.1.2.3:

- Multiply the sum of the capacity flow rate value in each temperature interval by the temperature difference for that interval to obtain the enthalpy for that temperature interval.

  For first temperature interval, viz., ti = 0, enthalpy is zero.

  For other temperature intervals, viz., ti>0,

  For first temperature interval, ti=1,

  Enthalpy = capacity flow rate * (temperature different for ti=1)

  = 806.69 * (-11 – (-24))

  = 10486.98 kW

- In similar way, capacity flow rate for all temperature intervals are calculated and given in Table IV.7.

(iv) As per Step 4 of Section 4.1.2.3:

- Calculate for each temperature interval, cumulative enthalpy using equations 4.11 and 4.12

  For First Temperature interval, viz. ti = 0, $CumQ_{h,ti} = 0$

  For Other Temperature intervals, i.e. ti > 0,

  $$CumQ_{h,ti} = CumQ_{h,ti-1} + Q_{h,ti}$$

  For first temperature interval, ti=1,

  $CumQ_{h,ti}$ = cumulative enthalpy for ti=0 + Enthalpy for ti=1

  = 0 + 10486.98 = 10486.98 kW

- In similar way, cumulative enthalpy for all temperature intervals are calculated and given in Table IV.7.

Table IV.7 Cumulative Enthalpy at Each Temperature Interval for Hot Process and Utility Streams

Temperature Interval, ti	Sorted Inlet and Outlet Temperature of Hot Process and Utility Streams in Ascending Order, ^{O}C	Capacity Flow Rate, kW/K	Enthalpy, kW	Cumulative Enthalpy, kW
0	-24	0	0	0
1	-11	807	10487	10487
2	-4	998	6987	17474
3	1	191	957	18431
4	3	515	1029	19460
5	7	523	2094	21554
6	8	565	565	22119
7	21	572	7437	29556
8	22	249	249	29805
9	35	441	5738	35542
10	36	432	432	35975
11	37	466	466	36441
12	38	459	459	36900
13	40	504	1008	37908
14	41	462	462	38370
15	42	506	506	38876
16	44	1467	2935	41811

17	45	1783	1783	43594
18	46	1591	1591	45184
19	47	1399	1399	46583
20	57	1682	16820	63403
21	63	2282	13693	77096
22	67	2482	9930	87025
23	68	2200	2200	89225
24	85	2473	42044	131269
25	86	2430	2430	133699
26	88	2470	4940	138639
27	90	1508	3016	141655
28	96	2316	13895	155551
29	106	1716	17158	172708
30	122	1682	26918	199626
31	126	875	3498	203125
32	127	1603	1603	204728
33	128	1403	1403	206130
34	133	2149	10746	216877
35	144	1834	20172	237048
36	145	1789	1789	238837
37	147	1829	3659	242496
38	148	1829	1829	244325
39	159	1829	20123	264448
40	164	1789	8947	273395
41	166	1516	3032	276427
42	167	1746	1746	278173
43	168	1018	1018	279190
44	169	271	271	279461
45	190	578	12148	291610
46	194	675	2700	294309
47	204	367	3674	297983
48	228	455	10908	308891
49	240	358	4297	313189
50	241	271	271	313460
51	277	361	12993	326453
52	278	131	131	326583
53	284	283	1700	328284
54	332	507	24338	352622
55	333	417	417	353039
56	360	503	13592	366631
57	371	463	5089	371720
58	377	549	3295	375015
59	430	396	21011	396026
60	471	310	12716	408742

61	481	86	865	409607
62	482	173	173	409780
63	483	86	86	409866
64	997	173	89129	498995
65	998	86	86	499081

Step 2.2 Cumulative Enthalpies for Cold Process and Utility Streams

Cumulative enthalpies for cold process and utility streams are calculated as mentioned in Step 2.1 of Section IV.4. Cumulative enthalpy for cold process and utility streams at all temperature intervals are given in Table IV.8.

Table IV.8 Cumulative Enthalpy at Each Temperature Interval for Cold Process and Utility Streams

Temperature Interval, ti	Sorted Inlet and Outlet Temperature of Cold Process and Utility Streams in Ascending Order, ^{O}C	Capacity Flow Rate, kW/K	Enthalpy, kW	Cumulative Enthalpy, kW
0	-33	0	0	0
1	-32	16194	16194	16194
2	-22	0	0	16194
3	-10	232	2786	18979
4	-8	347	694	19673
5	-7	356	356	20029
6	-6	6818	6818	26847
7	2	356	2845	29691
8	9	241	1686	31377
9	10	527	527	31904
10	13	241	722	32626
11	14	4666	4666	37292
12	15	241	241	37533
13	23	232	1857	39390
14	25	455	909	40300
15	27	223	445	40745
16	30	241	724	41468
17	36	493	2960	44428
18	39	9427	28281	72709
19	48	9175	82575	155284
20	50	284	567	155851
21	52	313	627	156478
22	71	502	9538	166017
23	74	1425	4276	170292

24	99	1407	35163	205455
25	113	483	6766	212221
26	114	598	598	212819
27	115	639	639	213458
28	116	683	683	214141
29	117	6656	6656	220798
30	118	6838	6838	227636
31	120	12811	25623	253259
32	121	12623	12623	265882
33	123	6650	13299	279181
34	140	677	11501	290682
35	141	822	822	291504
36	155	600	8396	299900
37	179	570	13676	313577
38	180	684	684	314261
39	211	570	17658	331919
40	220	455	4096	336015
41	231	928	10203	346218
42	252	703	14772	360990
43	311	231	13625	374615
44	312	186	186	374801
45	313	89574	89574	464376
46	314	186	186	464562
47	315	18158	18158	482720
48	316	186	186	482906
49	427	146	16175	499081

Step 3 Determine cumulative enthalpies for each intervals

Merge cumulative enthalpies of hot process and utility streams with that of cold process and utility streams. Omit common values from the merged cumulative enthalpies and sort in ascending order. The cumulative enthalpies are given in Table IV.9.

Step 4 Calculate Temperature Intervals for Hot Process and Utility Streams

For first temperature interval, ti = 0, cumulative enthalpy is zero, which corresponds to -24 ^{O}C in Table IV.7 (Table of cumulative enthalpy of hot process and utility streams).

For temperature interval, ti = 1, cumulative enthalpy is 10486.98 which corresponds to -11 ^{O}C in the same table.

For temperature interval, ti = 2, cumulative enthalpy is 10193.82 which does not corresponds to any temperature in the table. Hence, using interpolation between temperatures -11 ^{O}C, -4 ^{O}C and cumulative enthalpies 10486.98, 17473.65 gives temperature of -5.28 ^{O}C for cumulative enthalpy of 10193.82 kW.

In similar way, temperature interval for hot streams for all temperature intervals are calculated and given in Table IV.9.

Step 5 Calculate Temperature Intervals for Cold Process and Utility Streams

Temperature interval for cold process and utility streams are calculated in similar way as mentioned Step 4 of Section IV.4 and given in Table IV.9.

Step 6 Calculate Σ(C/h) and Σ(C/h) for Hot and Cold Process and Utility Streams

Step 6.1 Calculate Σ(C/h) for Hot Process and Utility Streams

For first temperature interval, viz., ti=0, Σ(C/h) for Hot Streams is zero.

For other temperature intervals, viz., ti>0,

For first temperature interval, ti=1,

As the range of only one hot process stream, viz., HP 26 (inlet and outlet temperatures of HP 26 are -4 ^{O}C and -24 ^{O}C), falls between temperatures -24 ^{O}C to -11 ^{O}C, capacity flow rate for first temperature interval is 806.69 kW/K. For HP 26, heat transfer coefficient is 1.556. Hence, Σ(C/h) = 806.69/1.556 = 518.

Step 6.2 Calculate Σ(C/h) for cold process and utility streams

Σ(C/h) for cold process and utility streams are calculated in similar way as mentioned in Step 6.1 of Section IV.4.

Table IV.9 gives Σ(C/h) and Σ(C/h) for hot and cold process and utility streams.

Step 7 Calculate Sum(Q/h) in each interval using equations 4.17 and 4.18

For First Temperature interval, viz. ti = 0,

$$Sum\left(\frac{Q}{h}\right)_{ti} = 0$$

For Other Temperature intervals, ti > 0

$$\mathrm{Sum}\left(\frac{Q}{h}\right)_{ti} = \left(\mathrm{T_{h,ti}} - \mathrm{T_{h,ti-1}}\right) \times \sum\left(\frac{C}{h}\right)_{\mathrm{h,ti}} + \left(\mathrm{T_{c,ti}} - \mathrm{T_{c,ti-1}}\right) \times \sum\left(\frac{C}{h}\right)_{\mathrm{c,ti}}$$

For first temperature interval, ti=1,

$$\mathrm{Sum}\left(\frac{Q}{h}\right)_{ti} = \left((-11) - (-24)\right) \times (518.439) + \left((-32.35) - (-35)\right) \times (0)$$

$$\mathrm{Sum}\left(\frac{Q}{h}\right)_{ti} = 6739.707$$

In similar way, Sum(Q/h) for all temperature intervals are calculated and given in Table IV.9.

Step 8 Calculate LMTD for each interval using *equations 4.19 and 4. 20*

For First Temperature interval, viz. ti = 0, $LMTDti = 0$

For Other Temperature intervals, ti > 0

$$LMTD_{ti} = \frac{\left(T_{h,i} - T_{c,i}\right) - \left(T_{h,i-1} - T_{c,i-1}\right)}{\ln\left[\frac{\left(T_{h,i} - T_{c,i}\right)}{\left(T_{h,i-1} - T_{c,i-1}\right)}\right]}$$

For first temperature interval, ti=1,

$$LMTD_{ti=1} = \frac{\left((-11) - (-32.35)\right) - \left((-24) - (-33)\right)}{\ln\left[\frac{\left((-11) - (-32.35)\right)}{\left((-24) - (-33)\right)}\right]}$$

$$LMTD_{ti=1} = 14.29 = 15$$

In similar way, LMTD for all temperature intervals are calculated and given in Table IV.9.

Step 9 Calculate heat transfer area of HEN using equation 4.25

For first temperature interval, ti=0, counter current area is zero.

For other temperature intervals, ti>0,

$$A_{c,ti} = \frac{\left[Sum\left(\frac{Q}{h}\right)_{ti}\right]}{LMTD_{ti}}$$

For first temperature interval, ti=1,

$$A_{c,ti} = \frac{\left[Sum\left(\frac{Q}{h}\right)_{ti}\right]}{LMTD_{ti}}$$

$$A_{c,ti} = \frac{[6739.707]}{15} = 449.31$$

In similar way, counter current area for all temperature intervals are calculated and given in Table IV.9.

Table IV.9 Counter Current Area at Each Temperature Interval

Temperature Interval, ti	Cumulative Enthalpy, kW	Temperature Interval for Hot Streams, ^{o}C	Temperature Interval for Cold Streams, ^{o}C	Σ(C/h) for Hot Streams, m^2	Σ(C/h) for Cold Streams, m^2	Sum(Q/h) , m^2/K	LMTD, K	Countercurrent Area, m^2
0	0	-24	-33	0	0	0	0	0
1	10487	-11	-32	518	0	6740	15	449
2	16194	-5	-32	1197	90468	38727	24	1614
3	16194	-5	-22	1197	0	0	22	0
4	17474	-4	-16	1197	679	5277	15	352
5	18431	1	-12	679	679	6192	13	476
6	18979	2	-10	1030	679	2703	13	208
7	19460	3	-9	1030	900	2208	12	184
8	19673	3	-8	1049	771	902	12	75
9	20029	4	-7	1049	900	1613	12	134
10	21554	7	-7	1049	900	3256	13	250
11	22119	8	-7	1141	900	1215	15	81

12	26847	16	-6	1271	32119	32775	19	1725
13	29556	21	2	1271	900	12875	21	613
14	29691	22	2	1271	900	1037	20	52
15	29805	22	2	919	900	841	20	42
16	31377	26	9	1198	808	9546	19	502
17	31904	27	10	1198	4170	5599	17	329
18	32626	28	13	1198	808	4385	17	258
19	35542	35	14	1198	808	8420	19	443
20	35975	36	14	1179	808	1254	22	57
21	36441	37	14	1444	808	1525	23	66
22	36900	38	14	1314	808	1394	24	58
23	37292	39	14	1587	27468	3548	25	142
24	37533	39	15	1587	808	1566	25	63
25	37908	40	17	1587	679	2275	24	95
26	38370	41	19	1495	679	2847	23	124
27	38876	42	21	1630	679	3109	22	141
28	39390	42	23	4029	679	2916	21	139
29	40300	43	25	4029	1869	6234	19	328
30	40745	43	27	4029	1190	3602	18	200
31	41468	44	30	4029	1207	5609	15	374
32	41811	44	31	4029	1207	1779	14	127
33	43594	45	34	6658	1376	11631	12	969
34	44428	46	36	6658	1376	5819	11	529
35	45184	46	36	6379	1376	3143	10	314
36	46583	47	36	5700	1376	5904	11	537
37	63403	57	38	6018	9345	76858	15	5124
38	72709	61	39	6747	9345	36739	21	1749
39	77096	63	39	6747	9345	17435	23	758
40	87025	67	41	7278	9177	39045	25	1562
41	89225	68	41	6960	9177	9160	27	339
42	131269	85	45	8149	9177	180592	34	5312
43	133699	86	46	8014	9177	10444	40	261
44	138639	88	46	8141	9177	21222	42	505
45	141655	90	47	5742	9177	14501	43	337
46	155284	96	48	7703	9177	58963	46	1282
47	155551	96	49	7703	9177	9500	48	198
48	155851	96	50	7703	1334	2767	47	59
49	156478	97	52	7703	1411	5636	46	123
50	166017	102	71	6974	1942	75678	38	1992
51	170292	105	74	6974	3902	29088	31	938
52	172708	106	76	6974	3885	16493	31	532
53	199626	122	95	6710	3885	181711	29	6266
54	203125	126	97	4749	3885	28660	28	1024

55	204728	127	98	5884	3885	10312	29	356
56	205455	128	99	5884	3885	5060	29	174
57	206130	128	100	5352	1925	5267	29	182
58	212221	131	113	6487	1925	42646	23	1854
59	212819	131	114	6487	2401	4206	18	234
60	213458	131	115	6487	2856	4784	17	281
61	214141	132	116	6487	3263	5325	17	313
62	216877	133	116	6487	3263	9597	17	565
63	220798	135	117	3858	4398	10840	18	602
64	227636	139	118	3858	4675	19062	20	953
65	237048	144	119	3858	4675	23237	23	1010
66	238837	145	119	3586	4675	4238	26	163
67	242496	147	119	3997	5811	9654	27	358
68	244325	148	119	3997	5811	4827	29	166
69	253259	153	120	3997	5811	23573	31	760
70	264448	159	121	3997	5811	29600	36	822
71	265882	160	121	3997	5280	3802	39	97
72	273395	164	122	3870	4144	20934	41	511
73	276427	166	123	2681	4144	7251	43	169
74	278173	167	123	3085	4144	4173	44	95
75	279181	168	123	3085	4144	3685	45	82
76	279190	168	123	1950	4144	75	45	2
77	279461	169	123	816	4144	2476	46	54
78	290682	188	140	1292	3009	74957	47	1595
79	291504	190	141	1292	3524	5360	49	109
80	291610	190	141	1292	3524	853	49	17
81	294309	194	146	1862	2334	17953	49	366
82	297983	204	152	1386	2334	28157	51	552
83	299900	208	155	1463	2334	13633	53	257
84	308891	228	171	1463	2257	64547	56	1153
85	313189	240	178	893	2257	27729	60	462
86	313460	241	179	816	2257	1889	62	30
87	313577	241	179	1270	2257	877	63	14
88	314261	243	180	1270	2826	5234	63	83
89	326453	277	201	1270	2350	93189	70	1331
90	326583	278	202	866	2350	1405	76	18
91	328284	284	205	1078	2350	13481	78	173
92	331919	291	211	1593	2350	26419	80	330
93	336015	299	220	1593	1780	28892	80	361
94	346218	319	231	1593	1992	53969	84	642
95	352622	332	240	1593	1588	34575	91	380
96	353039	333	241	1139	1588	2081	93	22
97	360990	349	252	1388	1588	39879	95	420

98	366631	360	276	1388	1377	49179	91	540
99	371720	371	298	977	1377	41076	78	527
100	374615	376	311	1213	1377	23654	69	343
101	374801	377	312	1213	970	1382	65	21
102	375015	377	312	1213	970	474	65	7
103	396026	430	312	1002	970	53317	89	599
104	408742	471	312	752	970	30981	138	225
105	409607	481	312	237	970	2379	164	15
106	409780	482	312	579	970	581	170	3
107	409866	483	312	342	970	343	171	2
108	464376	797	313	684	41054	240012	301	797
109	464562	798	314	684	970	1705	485	4
110	482720	903	315	684	33001	104629	535	196
111	482906	904	316	684	970	1705	589	3
112	498995	997	426	684	515	120316	580	207
113	499081	998	427	684	515	989	571	2
114	499081	998	427	342	515	0	571	0

IV.5 Heat Transfer Area for Shell and Tube Heat Exchanger

Step 1 Calculate the temperature effectiveness using equation 4.26

For First Temperature interval, viz. ti = 0,

$$\text{Temperature Effectiveness} = 0$$

For Other Temperature intervals, ti > 0

$$P_{ti} = \frac{\left(T_{h,i} - T_{h,i-1}\right)}{\left(T_{h,i} - T_{c,i-1}\right)}$$

For first temperature interval, ti=1

$$P_{ti} = \frac{((-11)-(-24))}{((-11)-(-33))} = 0.5909$$

In similar way, temperature effectiveness for all temperature intervals are calculated and given in Table IV.10.

Step 2 Calculate Capacity flow rate ratio using equation 4.27

For First Temperature interval, viz. ti = 0,

$$\text{Capacity flow rate ratio} = 0$$

For Other Temperature intervals, ti > 0

$$R_{ti} = \frac{\left(T_{c,i} - T_{c,i-1}\right)}{\left(T_{h,i} - T_{h,i-1}\right)}$$

For first temperature interval, ti=1

$$R_{ti} = \frac{\left((-32.3524) - (-33)\right)}{\left((-11) - (-24)\right)} = 0.0498$$

In similar way, capacity flow rate ratio for all temperature intervals are calculated and given in Table IV.10.

Step 3 Calculate Temperature effectiveness for 1-2 Shell and Tube Heat Exchanger using equation 4.28

For First Temperature interval, viz. ti = 0,

$$P_{e,ti} = 0$$

For Other Temperature intervals, ti > 0

$$P_{e,ti} = 0.9 \times P_{\max} \quad \text{Where,} \quad P_{\max} = \frac{2}{\left(R_{ti} + 1 + \left(R_{ti}^{\ 2} + 1\right)^{\frac{1}{2}}\right)}$$

For first temperature interval, ti=1

$$P_{e,ti} = 0.9 \times P_{\max} \quad \text{Where,} \quad P_{\max} = \frac{2}{\left(R_{ti} + 1 + \left(R_{ti}^{\ 2} + 1\right)^{\frac{1}{2}}\right)}$$

$$P_{\max} = \frac{2}{\left(0.049815 + 1 + \left((0.049815)^2 + 1\right)^{\frac{1}{2}}\right)}$$

$$P_{\max} = 0.97511$$

$$P_{e,ti} = 0.9 \times 0.97511 = 0.87759$$

In similar way, temperature effectiveness for 1-2 shell and tube heat exchanger for all temperature intervals are calculated and given in Table IV.10.

Step 4 Calculate Number of Shell using equation 4.29

For First Temperature interval, viz. ti = 0, $S_{ti} = 0$

For Other Temperature intervals, ti > 0

$$S_{ti} = \frac{\ln\left[\frac{(1-R_{ti}P_{ti})}{(1-P_{ti})}\right]}{\ln\left[\frac{(1-R_{ti}\times P_{e,ti})}{(1-P_{e,ti})}\right]} \qquad \text{for } R_{ti} \neq 1$$

$$S_{ti} = \frac{\left[\frac{P_{ti}}{(1-P_{ti})}\right]}{\left[\frac{(P_{e,ti})}{(1-Pe,ti)}\right]} \qquad \text{for } R_{ti} = 1$$

For first temperature interval, ti=1 as $R_{ti} \neq 1$

$$S_{ti} = \frac{\ln\left[\frac{(1-(0.049815)(0.5909))}{(1-(0.5909))}\right]}{\ln\left[\frac{(1-(0.049815)\times(0.877597))}{(1-(0.877597)}\right]}$$

$$S_{ti} = \frac{\ln\left[\frac{0.97056}{0.4091}\right]}{\ln\left[\frac{0.95628}{0.1224}\right]} = \frac{\ln[2.3724]}{\ln[7.8126]} = \frac{0.8639}{2.0557} = 0.4202$$

In similar way, number of shells for all temperature intervals are calculated and given in Table IV.10.

Step 5 Calculate Correction factor using equations 4.31 and 4.32

For First Temperature interval, viz. ti = 0, $F_{ti} = 0$

For Other Temperature intervals, ti > 0

$$F_{ti} = \left(\frac{\ln\left[\frac{(1-P_{r,ti})}{1-R_{ti}\times P_{r,ti}}\right]}{N_{ti}\times(R_{ti}-1)}\right) \qquad \text{for } R_{ti} \neq 1$$

$$F_{ti} = \left(\frac{P_{r,ti}}{N_{ti}\times(R_{ti}-1)}\right) \qquad \text{for } R_{ti} = 1$$

Where,

$$N_{ti} = \left(\frac{1}{\sqrt{R_{ti}^{2}+1}}\right)\ln\left[\frac{2-P_{r,ti}\times\left(R_{ti}+1-\sqrt{R_{ti}^{2}+1}\right)}{2-P_{r,ti}\times\left(R_{ti}+1+\sqrt{R_{ti}^{2}+1}\right)}\right]$$ and

$$P_{r,ti} = \frac{(1-Y_{ti})}{(R_{ti}-Y_{ti})},\quad Y_{ti} = \left[\frac{(1-R_{ti}P_{ti})}{(1-P_{ti})}\right]^{\frac{1}{NS_{ti}}}$$ for $R_{ti} \neq 1$

$$P_{r,ti} = \frac{P_{ti}}{(NS_{ti} - NS_{ti}\times P_{ti} + P_{ti})}$$ for $R_{ti} = 1$

For first temperature interval, ti=1 as $R_{ti} \neq 1$

$$F_{ti} = \left(\frac{\ln\left[\frac{(1-P_{r,ti})}{1-R_{ti}\times P_{r,ti}}\right]}{N_{ti}\times(R_{ti}-1)}\right)$$

Where,

$$Y_{ti} = \left[\frac{(1-R_{ti}P_{ti})}{(1-P_{ti})}\right]^{\frac{1}{NS_{ti}}} = \left[\frac{(1-(0.049815)(0.5909))}{(1-0.5909)}\right]^{\frac{1}{1}} = 2.3724$$

$$P_{r,ti} = \frac{(1-Y_{ti})}{(R_{ti}-Y_{ti})} = \frac{(1-2.3724)}{(0.049815-2.3724)} = 0.5909$$

$$N_{ti} = \left(\frac{1}{\sqrt{R_{ti}^{2}+1}}\right)\ln\left[\frac{2-P_{r,ti}\times\left(R_{ti}+1-\sqrt{R_{ti}^{2}+1}\right)}{2-P_{r,ti}\times\left(R_{ti}+1+\sqrt{R_{ti}^{2}+1}\right)}\right]$$

$$N_{ti} = \left(\frac{1}{\sqrt{(0.049815)^{2}+1}}\right)\ln\left[\frac{2-(0.5909)\times\left(0.049815+1-\sqrt{(0.049815)^{2}+1}\right)}{2-(0.5909)\times\left(0.049815+1+\sqrt{(0.049815)^{2}+1}\right)}\right]$$

$$N_{ti} = 0.90887$$

$$F_{ti} = \left(\frac{\ln\left[\frac{(1-P_{r,ti})}{1-R_{ti}\times P_{r,ti}}\right]}{N_{ti}\times(R_{ti}-1)}\right) = \left(\frac{\ln\left[\frac{(1-(0.5909))}{1-(0.049815)\times(0.5909)}\right]}{(0.90887)\times((0.049815)-1)}\right)$$

$$F_{ti} = \frac{-0.85737}{-0.86359} = 0.992$$

In similar way, correction factors for all temperature intervals are calculated and given in Table IV.10.

Step 6 Calculate Area of HEN for Shell and Tube Heat Exchanger using equation 4.33

For First Temperature interval, viz. ti = 0, $A_{ti} = 0$

For Other Temperature intervals, ti > 0, $A_{ti} = \dfrac{A_{c,ti}}{F_{ti}}$

For first temperature interval, ti=1

$$A_{ti} = \frac{A_{c,ti}}{F_{ti}} = \frac{449.31}{0.9928} = 452.56$$

In similar way, correction factors for all temperature intervals are calculated and given in Table IV.10.

Table IV.10 Area of HEN for Shell and Tube Heat Exchanger at Each Temperature Interval

Temperature Interval, ti	Temperature Interval for Hot Streams, ^oC	Temperature Interval for Cold Streams, ^oC	Temperature Effectiveness	Capacity Flow Rate Ratio	Temperature Effectiveness for 1-2 Shell and Tube Heat Exchanger	Number of Shells	Correction Factor	Counter Current Area, m^2	Area of HEN for Shell and Tube Heat Exchanger, m^2
0	-24	-33	0.00	0.00	0.00	0.00	0.00	0	0
1	-11	-32	0.59	0.05	0.88	0.42	0.99	449	453
2	-5	-32	0.21	0.06	0.87	0.11	1.00	1614	1615
3	-5	-22	0.00	0.00	0.90	0.00	1.00	0	0
4	-4	-16	0.07	4.30	0.19	0.21	0.99	352	354
5	1	-12	0.29	0.82	0.58	0.32	0.98	476	486
6	2	-10	0.07	2.22	0.32	0.12	1.00	208	208
7	3	-9	0.07	1.48	0.42	0.09	1.00	184	184
8	3	-8	0.03	1.51	0.42	0.04	1.00	75	75
9	4	-7	0.06	1.47	0.42	0.07	1.00	134	135
10	7	-7	0.21	0.08	0.87	0.11	1.00	250	251
11	8	-7	0.07	0.08	0.86	0.03	1.00	81	81
12	16	-6	0.36	0.08	0.86	0.22	1.00	1725	1730
13	21	2	0.18	1.61	0.40	0.27	0.99	613	622
14	22	2	0.03	0.70	0.62	0.02	1.00	52	52
15	22	2	0.02	1.03	0.52	0.02	1.00	42	42
16	26	9	0.15	1.83	0.37	0.25	0.99	502	509
17	27	10	0.07	0.84	0.57	0.06	1.00	329	330

18	28	13	0.09	1.83	0.37	0.13	1.00	258	259
19	35	14	0.30	0.09	0.86	0.18	1.00	443	444
20	36	14	0.04	0.09	0.86	0.02	1.00	57	57
21	37	14	0.04	0.10	0.86	0.02	1.00	66	66
22	38	14	0.04	0.10	0.86	0.02	1.00	58	58
23	39	14	0.03	0.11	0.85	0.02	1.00	142	142
24	39	15	0.02	2.09	0.33	0.03	1.00	63	63
25	40	17	0.03	2.17	0.32	0.04	1.00	95	95
26	41	19	0.04	1.99	0.34	0.06	1.00	124	124
27	42	21	0.04	2.18	0.32	0.07	1.00	141	141
28	42	23	0.02	6.32	0.13	0.06	1.00	139	139
29	43	25	0.03	3.23	0.24	0.06	1.00	328	328
30	43	27	0.02	6.59	0.13	0.06	1.00	200	200
31	44	30	0.03	6.08	0.14	0.10	1.00	374	374
32	44	31	0.02	2.97	0.25	0.03	1.00	127	127
33	45	34	0.07	3.61	0.22	0.17	1.00	969	973
34	46	36	0.05	3.22	0.24	0.10	1.00	529	530
35	46	36	0.05	0.17	0.82	0.03	1.00	314	314
36	47	36	0.09	0.15	0.83	0.05	1.00	537	537
37	57	38	0.48	0.18	0.82	0.36	0.99	5124	5200
38	61	39	0.18	0.24	0.79	0.11	1.00	1749	1752
39	63	39	0.08	0.25	0.79	0.05	1.00	758	758
40	67	41	0.15	0.27	0.78	0.09	1.00	1562	1564
41	68	41	0.04	0.24	0.79	0.02	1.00	339	339
42	85	45	0.38	0.27	0.78	0.29	0.99	5312	5377
43	86	46	0.02	0.26	0.78	0.01	1.00	261	261
44	88	46	0.05	0.27	0.78	0.03	1.00	505	505
45	90	47	0.05	0.16	0.83	0.02	1.00	337	337
46	96	48	0.12	0.25	0.79	0.07	1.00	1282	1283
47	96	49	0.00	8.17	0.10	0.01	1.00	198	198
48	96	50	0.00	6.05	0.14	0.01	1.00	59	59
49	97	52	0.01	5.47	0.15	0.02	1.00	123	123
50	102	71	0.11	3.42	0.23	0.29	0.99	1992	2017
51	105	74	0.07	1.20	0.48	0.08	1.00	938	940
52	106	76	0.04	1.22	0.47	0.05	1.00	532	532
53	122	95	0.35	1.20	0.48	0.55	0.93	6266	6705
54	126	97	0.13	0.62	0.64	0.10	1.00	1024	1026
55	127	98	0.03	1.14	0.49	0.03	1.00	356	356
56	128	99	0.02	1.00	0.53	0.02	1.00	174	174
57	128	100	0.02	2.90	0.26	0.03	1.00	182	182
58	131	113	0.09	4.45	0.18	0.31	0.99	1854	1877
59	131	114	0.02	3.59	0.22	0.03	1.00	234	234
60	131	115	0.02	3.37	0.23	0.03	1.00	281	281
61	132	116	0.02	3.15	0.24	0.04	1.00	313	313

62	133	116	0.07	0.32	0.76	0.05	1.00	565	565
63	135	117	0.11	0.28	0.78	0.07	1.00	602	603
64	139	118	0.17	0.27	0.78	0.11	1.00	953	955
65	144	119	0.20	0.14	0.84	0.11	1.00	1010	1012
66	145	119	0.04	0.14	0.84	0.02	1.00	163	163
67	147	119	0.07	0.14	0.84	0.04	1.00	358	358
68	148	119	0.03	0.14	0.84	0.02	1.00	166	166
69	153	120	0.15	0.14	0.84	0.08	1.00	760	761
70	159	121	0.16	0.14	0.84	0.09	1.00	822	823
71	160	121	0.02	0.14	0.84	0.01	1.00	97	97
72	164	122	0.10	0.27	0.78	0.06	1.00	511	511
73	166	123	0.05	0.23	0.80	0.03	1.00	169	169
74	167	123	0.02	0.26	0.78	0.01	1.00	95	95
75	168	123	0.02	0.15	0.83	0.01	1.00	82	82
76	168	123	0.00	1.50	0.42	0.00	1.00	2	2
77	169	123	0.02	0.40	0.73	0.01	1.00	54	54
78	188	140	0.30	0.86	0.57	0.34	0.98	1595	1635
79	190	141	0.03	0.70	0.62	0.02	1.00	109	109
80	190	141	0.00	0.96	0.54	0.00	1.00	17	17
81	194	146	0.08	1.13	0.50	0.08	1.00	366	367
82	204	152	0.17	0.61	0.65	0.14	1.00	552	554
83	208	155	0.07	0.76	0.60	0.06	1.00	257	257
84	228	171	0.27	0.80	0.59	0.29	0.98	1153	1173
85	240	178	0.17	0.63	0.64	0.15	1.00	462	464
86	241	179	0.02	0.48	0.70	0.01	1.00	30	30
87	241	179	0.01	0.63	0.64	0.00	1.00	14	14
88	243	180	0.03	0.53	0.68	0.02	1.00	83	83
89	277	201	0.35	0.63	0.64	0.36	0.97	1331	1366
90	278	202	0.01	0.23	0.80	0.01	1.00	18	18
91	284	205	0.07	0.50	0.69	0.05	1.00	173	173
92	291	211	0.08	0.89	0.56	0.08	1.00	330	331
93	299	220	0.09	1.11	0.50	0.10	1.00	361	362
94	319	231	0.20	0.55	0.67	0.17	0.99	642	646
95	332	240	0.13	0.72	0.61	0.11	1.00	380	381
96	333	241	0.01	0.59	0.65	0.01	1.00	22	22
97	349	252	0.15	0.72	0.61	0.13	1.00	420	421
98	360	276	0.10	2.18	0.32	0.18	0.99	540	544
99	371	298	0.12	2.00	0.34	0.19	0.99	527	530
100	376	311	0.07	2.38	0.30	0.12	1.00	343	344
101	377	312	0.01	2.95	0.25	0.01	1.00	21	21
102	377	312	0.01	0.01	0.90	0.00	1.00	7	7
103	430	312	0.45	0.00	0.90	0.26	1.00	599	599
104	471	312	0.26	0.00	0.90	0.13	1.00	225	225
105	481	312	0.06	0.00	0.90	0.03	1.00	15	15

106	482	312	0.01	0.00	0.90	0.00	1.00	3	3
107	483	312	0.01	0.00	0.90	0.00	1.00	2	2
108	797	313	0.65	0.00	0.90	0.46	1.00	797	798
109	798	314	0.00	0.93	0.55	0.00	1.00	4	4
110	903	315	0.18	0.01	0.90	0.09	1.00	196	196
111	904	316	0.00	0.93	0.55	0.00	1.00	3	3
112	997	426	0.14	1.19	0.48	0.16	0.99	207	209
113	998	427	0.00	0.59	0.65	0.00	1.00	2	2
114	998	427	0.00	0.00	0.90	0.00	1.00	0	0

IV.6 Minimum Number of Unit

Note the number of process streams and utility streams above pinch point (N_a) and number of process and utility streams below pinch point (N_b) from step by step calculation of pinch point. Using equation 4.34, minimum number of unit is calculated and given in Table IV.11.

Table IV.11 Minimum Number of Unit

ΔT_{min}, ^{O}C	Minimum Number Unit
10	59

IV.7 Number of Shell: Accurate Determination of Shell

The numbers of shells required on a stream-wise basis for the region above pinch and below pinch is calculated and rounded off to the nearest integer.

Rounded off shell below pinch = 74

Rounded off shell above pinch = 0

Accurate Number of Shell = 74 + 0 = 74

IV.8 Estimation of Total Annual Cost of HEN with Non-Uniform Heat Exchangers

Step 1 Determine reference heat exchanger for a network of non-uniform heat exchangers and specify its values as a_r, b_r and c_r.

Reference Heat Exchanger:

Shell & Tube Type with a_r =30000, b_r = 750, c_r = 0.81.

Step 2 Specify the values of cost law constants for specific heat exchangers as a_s, b_s and c_s.

For Stream HP1:

Bayonet Type Heat Exchanger with a_s =30000, b_s = 1050, c_s = 0.81 and

Heat transfer coefficient, h_j = 0.254

Step 3 Calculate the Weighting factor using equation 4.39

For Stream HP1:

$$\emptyset_j = \left(\frac{750}{1050}\right)^{1/0.81} + \left(\frac{A}{S_{min}}\right)^{1-(0.81/0.81)}$$

$$\emptyset_j = (0.7143)^{1/0.81} + \left(\frac{A}{S_{min}}\right)^{1-1}$$

$$\emptyset_j = 0.6601 + 1 = 1.6601$$

Step 4 Modified heat transfer coefficient using equation 4.40

$$h_{\text{rr},j} = \emptyset_j \times h_j$$

For Stream HP1: $h_{\text{rr},j} = \emptyset_j \times h_j = 1.6601 \times 2.54$

$$h_{\text{rr},j} = 4.22$$

Step 5 Modified area of counter current heat exchanger, 1-2 shell and tube heat exchanger, minimum number of unit and number of shell are calculated in similar way mentioned in Section IV.4, Section IV.5, Section IV.6 and Section IV.7 respectively using modified heat transfer coefficient and given in Table IV.12.

Table IV.12 Modified Data

ΔT_{min}, ^oC	Modified Area of HEN for 1-2 Shell and Tube Heat Exchanger, m^2	Minimum Number of Unit	Number of Shell
10	29480	59	105

Step 6 Calculate capital cost, operating cost and total annual cost of HEN using equations 4.41, 4.36 and 4.38 respectively

$$\text{Capital Cost}, CC = a_r \times N_{u,mer} + \{ b_r \times S_{min} \times ({A_{rr}}/{S_{min}})^{c_r} \}$$

$$CC = 30000 \times 59 + \{ 750 \times 105 \times \left({29480.96}/{105} \right)^{0.81} \}$$

$$CC = \$\, 9345580.96$$

$$\text{Operating Cost, } OC = \left(C_{hu} \times Q_{hu,min} \right) + \left(C_{cu} \times Q_{cu,min} \right)$$

$$OC = (120 \times 0) + (25 \times 109473.6) = \$\, 2736840.75$$

$$\text{Total Annual Cost,TAC} = \mathrm{OC} + (\mathrm{CC} \times \mathrm{A_f}),$$

$$Where, A_f = \frac{(1+r)^{\tau}}{\tau} = \frac{(1+0.1)^{50}}{50} = 2.3478$$

$$\mathrm{TAC} = 2736840.75 + (9345580.96 \times 2.3478)$$

$$\mathrm{TAC} = 2736840.75 + (9345580.96 \times 2.3478)$$

$$\mathrm{TAC} = \$\, 24678576.00$$

The area of HEN for 1-2 shell and tube heat exchanger, minimum number of unit, number of shell, annualization factor, capital cost, operating cost and total annual cost for ΔT_{min} approach at ΔT_{min} 10 ^{O}C are given in Table IV.13

Table IV.13 Estimated Data for ΔT_{min} approach at ΔT_{min} 10 ^{O}C.

ΔT_{min}, ^{O}C	Area of HEN for 1-2 Shell and Tube Heat Exchanger, m^2	Minimum Number of Unit	Number of Shell	Annualization factor	Capital Cost, \$	Operating Cost, \$	Total Annual Cost, \$
10	29480	59	105	2.35	9345580	2736840	24678576

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