Optimal Synthesis for Retrofitting Heat Exchanger Network

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ABSTRACT

During the past two decades, a lot of researches have been done on the synthesis of grassroot heat exchanger networks(HEN). However, few have been dedicated to retrofit of existing heat exchanger networks, which usually use more amount of utilities (i.e. steam and/or cooling water) than the minimum requirements. This excess gives motivation of trades-off between energy saving and rearranging investment.

In this paper, an algorithmic-evolutionary synthesis procedure for retrofitting heat exchanger networks is proposed. It consists of two stages. First, after the amount of maximum energy recovery(MER) is computed, a grass-root network featuring minimum number of units(MNU) is synthesized. In this stage, a systemetic procedure of synthesizing MNU networks is presented. It is based upon the concept of pinch, from which networks are synthesized in a logical way by the heuristics verified by the pinch technology.

In the second stage, since an initial feasible network is synthesized based on the pre-analysis result of MER and must-matches, an assignment problem between new and existing units is solved to minimize total required additional areas. After the existing units are assigned, the network can be improved by switching some units. For this purpose, an improvement problem is formulated and solved to utilize the areas of existing units as much as possible. An example is used to demonstrate the effectiveness of the proposed method.

1. Introduction

Recently, the necessity of the energy recovery process is highly evaluated in Korea according to The Middle East situation. Even though enormous quantity of energy has been discarded so far, we lay it alone because of the absence of high technology. The synthesis of heat recovery process synthesis has been developed in the direction of maximum energy recovery with minimum cost for past two decades. But these efforts can not be applied to the existing processes because it is not optimal to apply new optimum process to the existing process without making full use of the existing equipment. Consequently, when we retrofit the existing heat recovery process to recover the maximum energy, utmost use of the existing equipment is limiting factor and thus a new design method must be presented.

For this kind of problem, general qualitative interpretation about remodeling and repairing of existing heat recovery process and synthesis method through computer were presented. However, the absence of theoretical background and quantitative numerical model made it impossible to find the optimal solution from these trial and error methods.

In 1986, Jones et al. [3] made several designs through simulation runs and then presented a retrofitting method by adding the area of existing heat exchanger little by little. Later Tjoe and Linnhoff [5] removed the heat exchanges crossing the pinch point by pinch technology and proposed the procedures from a retrofit design philosophy. But when process restriction conditions are severe their approach method becomes extremely complicated to fit formal procedures and seems to be difficult to find the best retrofit.

Recently, MILP (mixed integer linear programming) model through a systematic two-stage approach was proposed by Ciric and Floudas [2]. It considered possible modification combination and included the using of existing area among targets, and also considered the increase and decrease of potentials in other heat exchangers.

Consequently, based on these theoretical backgrounds, we present a synthesis procedure of recovering maximum energy with minimum investment from a mahtematical model. Then we develope computer program for the procedure and solve the optimal solution. Namely, first of all we estimate how much more energy can be recovered from the existing process by calculating maximum heat recovery and then synthesize maximum heat recovery processes. Since there are many maximum heat recovery processes we find one similar to the existing one. Then we express the required cost which is consumed in retrofitting the existing process to maximum heat recovery process in a mathematical form. The required cost mainly consists of the installation cost of new heat exchangers, the cost resulted from the increase of effective heat exchangers area, and the moving and repiping cost.

2. Literature Review

Since many process flows consist of hot and cold streams which have known input temperatures, target temperatures, flow rates, and heat capacities, with steam and cooling water as utilities, the synthesis of heat exchanger network (HEN) means that heat exchangers between hot streams and cold streams are arranged for the minimization of the heating and cooling requirements, and the investment cost of heat exchangers.

From a graph of hot and cold streams on the T vs. Q domain, which will be explained later, a heat recovery "pinch" (T*) is easily detected.

For the maximum energy recovery, the following rules must be conserved around the pinch.

- No cold utility above the pinch
- No hot utility below the pinch
- No process heat recovery across the pinch

As the concept of pinch point is introduced, the researches on retrofitting have been in action. Here, we have summarized several methods briefly. The first one is the Pinch Technology by Tjoe and Linnhoff [5]. Design procedure finds heat exchange crossing any the pinch from existing HEN and eliminate heat exchanger associated with this heat exchange. And then the eliminated heat exchangers are relocated.

It increases compatibility of existing network to decrease utility loads from a heater and a cooler and reuse existing heat exchanger area as much as possible through the use of heat load loops and paths.

The loop is started from a heat exchanger and ended at the one, thus making the design flexible. The path connects stream and heat exchanger between two utilities. If we choose these paths and connect equipments properly we can acquire a new HEN which has much energy saving.

On the contrary, another method was introduced, which retrofits HEN using a mathematical formulation of process flow, variable, the number of equipments, and so on. As mentioned earlier, this method has been studied by Ciric and Floudas [2]. This method applies two-stage approach using MILP and nonlinear programming (NLP). In the first stage, it defines objective function of optimization model as

a) minimization of cost of buying heat exchangers
b) minimization of cost of appending area
c) minimization of cost of piping

and the constraints as heat flow model, estimation of heat exchange area, calculation of adding area, assignment of heat exchangers. With maximum information, we can evaluate matches of process streams, their heat loads, place selection of new or existing heat exchangers, assignment of them, area calculation required at each match, and variation of area required at each heat exchanger.

Second stage is a step that selects the most appropriate network through the design of heat exchanger using imaginary data obtained from the whole calculated by the NLP method. At this time, the objective function is the minimization of total modification cost.

3. Retrofit of HEN Synthesis

For the optimal retrofitting design, MER is first computed and a grass-root synthesis of HEN is invented. Then we apply the evolutionary algorithmic method to find out the optimal retrofit design.

The MER network synthesis problem can be conveniently partitioned into the following three major steps. In the preanalysis step, we obtained the amounts of heating and cooling and the pinch point. In the network invention step, we determined initial feasible network structure of both side of the pinch point by selecting stream/stream matches. In the evolution for optimal retrofitting HEN step, we obtained the optimal network structure by searching over the more attractive network structure.

3-1. Preanalysis for MER

Preanalysis involves establishing targets for the network to be designed. These targets are the least amount of utilities which are needed; the probable, but not guaranteed, fewest investment cost for HEN.

For the heat exchange between hot stream and cold stream, it is necessary to exist the temperature difference between two streams. And if the temperature difference is too close, heat exchange is hard to occur. So we must define the minimum temperature differences (ΔT_{min}) to occur the heat exchange between two streams.

We divided minimum temperature differences (ΔT_{min}) into hot and cold stream forms, ΔTh_i and ΔTc_j, for hot (h_i) stream and cold (c_j) stream and applied them to each stream. And then, we construct the network.

In the whole range of temperature, it is basically possible to synthesize the network if the temperatures of hot streams are greater than those of cold streams without violation of minimum approach temperature. This idea leads to the merging of all hot streams into a single hot super stream and all cold into a single cold super stream. Plotting these two super streams on a temperature vs. enthalpy (T-Q) diagram, one can move the cold super stream just below the hot super stream. The intersection point of two super streams will be the pinch point and the unmatched portions of each of the super streams represent the minimum heating and cooling required.

These quantities and the pinch point can also be computed numerically by using the cumulative deficit concept. First let us define the minimum and maximum temperatures in the network on the shifted scale.

$$T_m = \min (T_{th_i}, T_{ci_j};\ i=1, \ldots n_h,\ j=1, \ldots n_c)$$
$$T_M = \max (T_{hi_i}, T_{tc_j};\ i=1, \ldots n_h,\ j=1, \ldots n_c)$$

Next define the following total heat capacity flowrates :

Total hot stream capacity flowrate

$$C_h(T) = \sum_{i=1}^{i=n_h} C_{hi}(T)$$

Total cold stream capacity flowrate

$$C_c(T) = \sum_{j=1}^{j=n_c} C_{cj}(T)$$

Net capacity flowrate

$$C(T) = C_c(T) - C_h(T)$$

Then the cumulative deficit h(T) is defined as

$$h(T) = \int_{T}^{T_M} C(\theta)\, d\theta$$

h(T) represents the minimum heat requirement of the network above the temperature T.

Using h(T) it is easy to compute the minimum heat requirement (H) for the network.

$$H = \max h(T)$$

The associated cooling requirement (C) is obtained from an overall energy balance.

$$C = H - \int_{T_m}^{T_M} C(T)\, dT$$

The pinch point T* is defined as the temperature where h(T) reaches its global maximum. From the definition of h(T) we know that H = h(T*) is the minimum amount of heat to be put into the network above T* for all the streams to reach their targets.

3-2. Network Invention

For the selection of hot and cold stream to be matched, the HEN synthesis problem can be regarded as a transportation problem. There are n_h hot streams that contain various amounts of heat must be shipped to n_c cold streams to meet demand requirements for the target conditions.

The simplest method for inhibit the heat exchange across the pinch point is partitioned the hole problem into two subproblems, upper the pinch problem and below the pinch problem. And then solve the problem under the constraints of the highest temperature of below the pinch problem and the lowest temperature of upper the pinch problem and the pinch point temperature (T*) are same.

In order not to violate the temperature approach, at above the pinch (AP) zone, the hot stream capacity flowrate (Cp_{ha}) always less than the cold stream capacity flowrate (Cp_{ca}) and inversely at below the pinch (BP) zone, the hot stream capacity flowrate (Cp_{hb}) always greater than the cold stream capacity flowrate (Cp_{cb}).(see Fig. 1) It is noted that at T vs. Q diagram, pinch point temperature (T*) is the smallest temperature difference between hot stream and cold stream among the every temperature differences between hot streams and cold streams. Then at the Ap as well as Bp, the temperature difference between hot streams and cold streams is larger than temperature of T*. Therefore, network invention starts from the pinch.

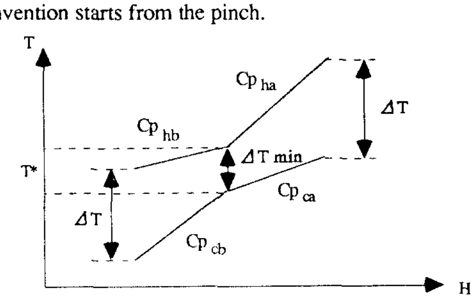

Fig 1. Temperature difference at the pinch point

The solution procedure is conducted directly on the solution array. The individual elements of the array appear in cells and represent the amounts of heat exchanged between source and sink streams. Each nonempty cell denotes a heat exchanger. Beginning with all empty cells, the procedure is defined in terms of the following steps :

(1) Check the pinch point condition for stream splitting. If splitting is needed, determine the optimal split ratio of the stream using the golden section method.

(2) Make a unit by selecting the cold stream with max (T_{c}) and the hot stream with max (T_{hi}). This is equivalent to the cell in the upper left-handed corner of the solution array.

(3) Determine the quantity of heat transferred in this unit.

(4) If $Q_{HE} = HC_{cj}$, processing of the cold stream is complete and stream j is deleted from the problem. Hence compute the outlet temperature of hot stream T_{ho} and set $HC_{hi} = HC_{hi} - Q_{HE}$ and $T_{hi} = T_{ho}$ then go to step (2). Otherwise go to step (5).

(5) If $Q_{HE} = HC_{hi}$, similarly delete hot stream i and calculate the output temperature of cold stream T_{co}. Then set $HC_{cj} = HC_{cj} - Q_{HE}$ and $T_{c} = T_{co}$

(6) Repeat from step (2) until no further matches can be made.

3-3. Retrofitting HEN

3-3-1. Presentation of problems

As shown in Fig. 2., when heat flows across the pinch point by the amount X, total utility require ments are (H + X) and (C + X), respectively. Thus we have to add the amount of heat X to the heater and remove the same amount of heat X from the cooler, resulting in the double penalties.

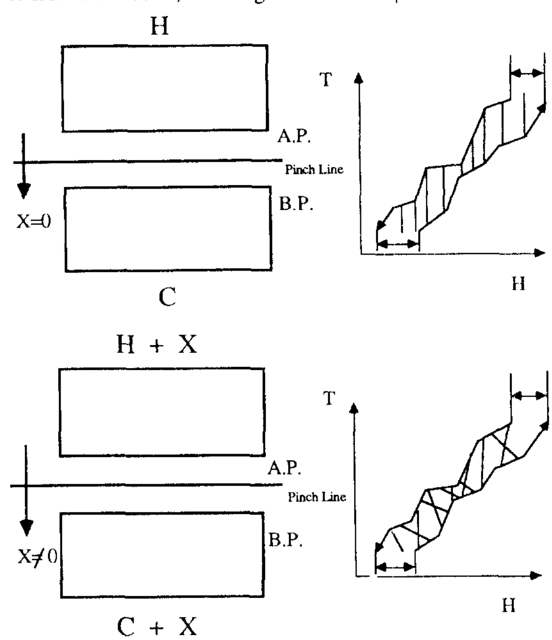

Fig 2. Heat exchange crossing the pinch

Then a retrofit problem can be stated as follow :

Given is an existing heat exchanger network with hot and cold utilities which are used more than the minimum usage. The objective is to redesign the network using existing exchangers of known area, while minimizing total modification cost.

For the non-MER HEN, saving /year vs. investment curve was thought to have a logarithmic shape by Linhoff et al. If the minimum payback period is the objective function there is no optimum point because the payback year increases as the investment increases. However, from the actual point of view, saving/year vs. investment curve may be S-shaped because there will be no energy recovery until investment reaches to some extent.

After all, the object function can be the minimization of patback year t, where t(yr) = investment cost / U (utility savings) and there exists optimum t(yr) as shown in Fig. 3. Then since the payback year is the reciprocal of the of the slope of tangent line the optimum occurs at the largest slope, ie. line 3 in Fig. 3. and the point (A, B) is the optimal retrofitting point.

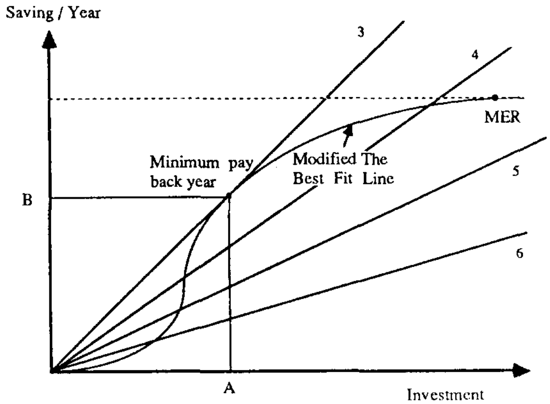

Fig 3. Modified the best curve for saving year/investment

The investment cost can be expressed as follows :

$$I = \sum_{i}^{N_{unit}} \gamma C_{rep} + \beta A_{add} + \alpha C_{fix} \qquad (1)$$

where

- α : 0 if a new unit has two same streams of the assigned existing one
  1 if a new unit has only one same stream
  2 if a new unit has totally different streams
- C_{rep} : repiping cost
- β : equipment cost per unit of heat exchanger area
- A_{add} : required additional area, which is max (A_{new}, -A_{old}, 0)
- γ : 0 if a new unit is assigned to one of the existing units
  1 otherwise
- C_{fix} : fixed cost of a new installed unit

For this equation, the second term is dominant.
and the same data are used as in Floudas et al. [2]

$\alpha\ C_{rep}$ = 400 * (0, 1, 2)
$\beta\ A_{add}$ = 171.4 * A_{add}
$\gamma\ C_{fix}$ = 3460 * (0, 1)
where unit is $

3-3-2. Propositions for Optimal Retrofitting HEN

The assumptions made in this paper are

1. A minimum temperature approach is prespecified.
2. The heat capacity flow rates are constant.
3. The heat transfer coefficients for each match are known and fixed.
4. The existing network uses more than minimum utility usage.

The first assumption is required to compute the maximum energy recovery. The second one is introduced for simplicity of calculation. To evaluate the heat transfer area, fixed heat transfer coefficients are assumed. From the economic point of view, return on investment should be expected. Thus possible energy savings are prerequisite for retrofit problems.

The objective function is formulated

$$\min T = \frac{I}{U} \qquad (2)$$

where T is payback year, while I and U denote investment cost and utility savings, respectively. If we confine retrofitting problems to MER networks, the energy savings are constant. Then the objective function of minimizing the payback time is equivalent to minimizing the investment cost to modify the existing network for MER.

The existing networks tend to have fewer units because of much more utility usage, compared to MER networks featuring minimum number of units (MNU). It should be noted that one degree of freedom exists to optimize the initial network if it has an extra unit or stream splitting. For extra unit, the initial network has a heat load loop (HLL). Heat loads can be redistributed among the units in the HLL. If a network has stream splitting, optimal split ratio can be also determined.

<u>Assignment Problem</u>

Once an initial network is obtained, the existing units should be assigned to the new units of the synthesized network. From intuition, the full utilization of existing areas looks best. But all units in the newly synthesized network does not necessarily have exact areas of existing ones. Thus, from the second term of the objective function of Eq. (1), the assignment problem falls to a simple matching problem of minimizing the number of units which do not fully utilize the existing areas. Moreover, since retrofitting problems are always pinched problems, new MER networks usually require more heat transfer areas than existing areas (i.e., $\Sigma A_{new} - \Sigma A_{existing} \geq 0$). Then the assignment of existing areas to the new units can be solved by the following heuristic rule.

<u>Proposition</u> 1

Place the units of both new and existing networks in the order of decreasing area. Match each unit corresponding to the order.

This proposition makes the number of units which require negative additional area as few as possible. From the proposition 1, required additional area for each matched pair can be nonnegative (i.e., $A_{new} - A_{existing} \geq 0$). Any two nonnegative (or nonpositive) pairs can be switched without increasing additional areas, resulting in another solution if two nonnegative (nonposition) values are also guaranteed after switch. Otherwise, modification cost increases from switching. For one nonnegative and one positive pairs, no other way is possible to make both of them nonnegative.

<u>Improvement of Initial Network</u>

Since the cost of retrofitting the heat exchanger network consists of the cost of network rearrangement and the cost of setting up the heat exchangers and the cost of additional heat exchanger areas. The cost of setting up the heat exchangers is made up of repiping cost and labor cost. Since it is not taken into account that the repiping and labor cost can be reduced by exchanging the heat exchangers assigned already.

These after the existing units are assigned, the network can be improved by switching some units. For this purpose, the following proposition can be applied.

<u>Proposition</u> 2

Any two assigned existing areas to new units can be switched without affecting total additional areas if differences of areas between both original and switched matches are kept nonnegative. Otherwise, if increases required additional area. If increment of required additional area is greater than C_{rep} / β, this switching results in a worse solution. However, the objective function value can be reduced by applying the proposition 2 if switching can reduce the value of α of Eq. (1).

4. Application

In this part, we will check and compare our with Ciric and Floudas [2]'s which is solved by their optimal retrofitting result method, equivalent to modified MILP approach.

Three hot and three cold streams and two utilities are the elements of the process of this problem. The streams and economic data are in table 1 and table 2, respectively. The existing HEN consists seven heat exchanger as described in Fig. 4. and the heat exchanger areas are listed in table 3.

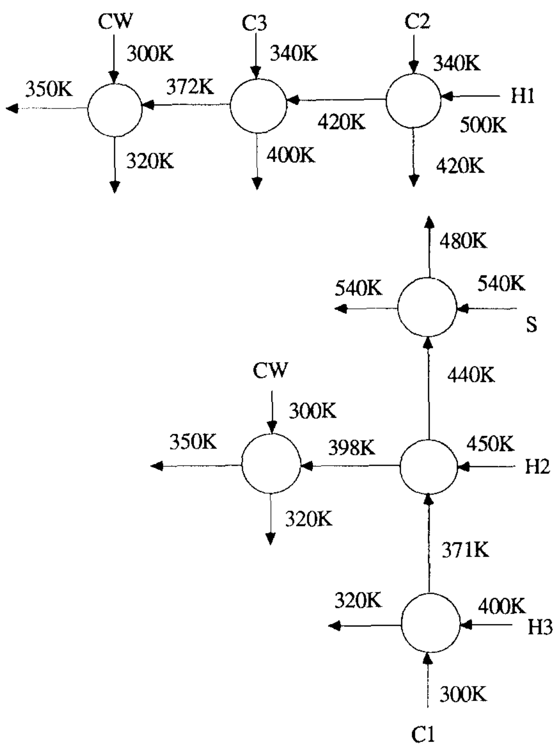

Fig 4. Existing heat exchanger network

TABLE 1: STREAM DATA FOR EXAMPLE

STREAM	T in(K)	T out(K)	FCp(kW/K)	$ /KW yr
H1	500	350	10	
H2	450	350	12	
H3	400	320	8	
C1	300	480	9	
C2	340	420	10	
C3	340	400	8	
S1	540	540		80
CW	300	320		20

$U = 0.8\ kW/m^2K$

TABLE2 : COST FACTOR FOR EXAMPLES

β = 171.4	Cost per square meter of heat transfer area
Cp^2 = 10	Relative cost for moving one exchanger
Cp^3 = 400	Relative cost of repiping one stream
Cp^4 = 800	Relative cost of repiping
Cp^5 = 3460	Fixed charge cost of a new exchanger
Cp^6 = 4260	Fixed charge cost of a new exchanger and repiping two streams

TABLE 3: AREAS OF EXISTING EXCHANGERS FOR EXAMPLE

Exchanger	Area (m^2)	Original Match
1	45.06	H 2 - C1
2	12.50	H 1 - C2
3	33.09	H 3 - C1
4	23.50	H 1 - C3
5	5.75	S 1 - C1
6	5.39	H 1 - CW
7	11.49	H 2 - CW

This heat exchange network needs stream of 360 KW and 800 KW cooling water, so total cost amount to $ 44,800 / yr. According to our computation, the minimum heating and cooling power is reduced 0 KW and 440 KW, respectively from the preanalysis step. Therefore, cost for heating and cooling can be reduced to $ 8800 / yr.

In the network invention, stream H1 and C1 should be matched. Because of the possibility of the existence of the imperfect matching of H1-C1, we need seven heat exchanger. (Even if the theoretical minimum number of units is 6) We set up more unit and we can optimize the total amount of heat exchange between 360 KW (the lowest boundary of stream H2) and 700 KW (the highest boundary of stream C2). The distribution of seven heat exchanger loads is shown in table 4.

TABLE 4 ; RETROFIT NETWORK DATA FOR EXAMPLE

Match	Heat Load	Exchanger	Assignment Category	Existing Area	Estinated Area	Retrofitted Area
H 1 C 1	512	3	3	33.09	38.82	28.16
H 1 C 2	800	2	1	12.5	83.08	34.72
H 1 C 3	188	4	1	23.5	23.5	31.74
H 2 C 1	908	1	1	45.06	97.96	47.65
H 2 C 3	292	7	3	11.49	30.52	21.85
H 3 C 1	200	5	2	5.75	25.0	5.75
H 3 C W	440	6	3	5.39	15.84	12.84

And the initial network structure is shown in Fig. 5. Then we improved the network by the proposition 2. The total cost for the initial network was $ 7,644 but we accomplished reduction of cost to $ 7,244 by switching the matches between H1-C2 (assigned to H2-C3 match) and H1-C1 (assigned to H1-C3 match).

No more reduction of cost by, switching heat exchangers can not be accomplished. Compared with Ciric and Floudas's results of the additional heat exchanger area of 50.9 m^2 and the total cost of $ 30621 our additional heat exchange area is 25.9257 m^2 with total cost of $ 7243.66.

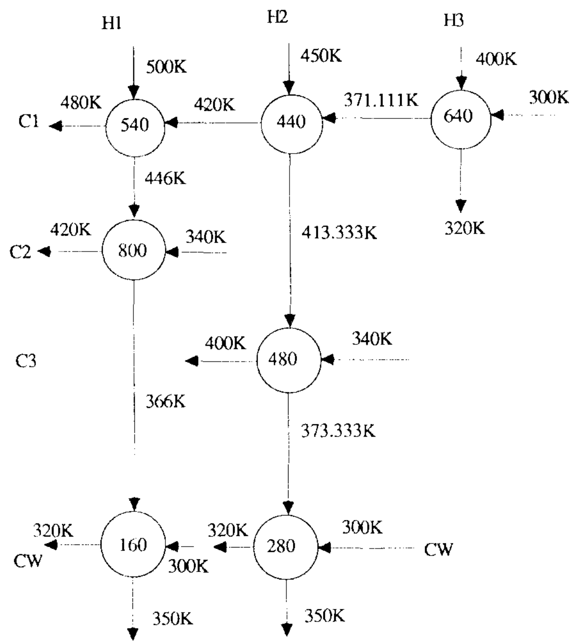

Fig 5. The initial grass-root network

5. Conclusion

In this paper, an algorithmic-evolutionary synthesis procedure for retrofitting heat exchanger networks is proposed. It consists of two stages. First, after the amount of maximum energy recovery (MER) is computed, a grassroot network featuring minimum number of units (MNU) is synthesized. After an initial feasible network is synthesized based on the pre-analysis result of MER and must-matches, an assignment problem between new and existing units is solved to minimize total required additional areas.

As a future work, a modification of the initial network structure toward smaller total required additional area seems rather to be desirable. Some work should be done on the improvement of initial network by modifying network structure to require less additional area.

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