



### 3. METHODOLOGY

#### 3.1 Materials and Equipment

##### Software:

1. Microsoft Excel spreadsheet.
2. Mathematical programming software (GAMS).
3. Commercial process simulation software.

#### 3.2 Stage-wise MILP model for grassroots design of HEN

The stage-wise superstructure model from Yee and Grossmann [10] is applied to do HEN retrofit design with network structural modifications as well as new exchanger areas by setting a minimum approach temperature (HRAT) to control the energy consumption in order to avoid the non-linearity of exchanger area calculation. The details of the mathematical programming formulation is presented as follows:

##### 3.2.1 Overall heat balance for each stream

$$(T_{out_j} - T_{in_j})F_j = \sum_{k \in ST} \sum_{i \in HP} q_{ijk} + q_{hu_j} \quad j \in CP \quad (\text{eq.1})$$

$$(T_{in_i} - T_{out_i})F_i = \sum_{k \in ST} \sum_{j \in CP} q_{ijk} + q_{cu_i} \quad i \in HP \quad (\text{eq.2})$$

##### 3.2.2 Heat balance of each stream at each stage

$$(t_{j,k} - t_{j,k+1})F_j = \sum_{i \in HP} q_{ijk} \quad j \in CP, k \in ST \quad (\text{eq.3})$$

$$(t_{i,k} - t_{i,k+1})F_i = \sum_{j \in CP} q_{ijk} \quad i \in HP, k \in ST \quad (\text{eq.4})$$

##### 3.2.3 Assignment of superstructure inlet temperature

$$T_{in_j} = t_{j,N+1} \quad j \in CP \quad (\text{eq.5})$$

$$T_{in_i} = t_{i,1} \quad i \in HP \quad (\text{eq.6})$$

### 3.2.4 Feasibility of temperature

$$t_{j,k} \geq t_{j,k+1} \quad j \in \text{CP} \quad k \in \text{ST} \quad (\text{eq.7})$$

$$T_{out_j} \geq t_{j,1} \quad j \in \text{CP} \quad (\text{eq.8})$$

$$t_{i,k} \geq t_{i,k+1} \quad i \in \text{HP} \quad k \in \text{ST} \quad (\text{eq.9})$$

$$T_{out_i} \leq t_{i,N+1} \quad i \in \text{HP} \quad (\text{eq.10})$$

### 3.2.5 Hot and cold utility load

$$(T_{out_j} - t_{j,1})F_j = qhu_j \quad j \in \text{CP} \quad (\text{eq.11})$$

$$(t_{i,N} - T_{out_i})F_i = qcu_i \quad i \in \text{HP} \quad (\text{eq.12})$$

### 3.2.6 Logical constraints

$$q_{ijk} - \Omega_p Y_{ijk} \leq 0 \quad i \in \text{HP} \quad j \in \text{CP} \quad k \in \text{ST} \quad (\text{eq.13})$$

$$qhu_j - \Omega_p Y_{hj} \leq 0 \quad j \in \text{CP} \quad (\text{eq.14})$$

$$qcu_i - \Omega_c Y_{ic} \leq 0 \quad i \in \text{HP} \quad (\text{eq.15})$$

\*\*\*  $Y_{ijk}$ ,  $Y_{hj}$ ,  $Y_{ic}$  are binary variables for process utility exchanger matching

### 3.2.7 Feasible driving force

$$dt_{ijk} \leq t_{i,k} - t_{j,k} + \Gamma_{ij}(1 - Y_{ijk}) \quad i \in \text{HP}, j \in \text{CP}, k \in \text{ST} \quad (\text{eq.16})$$

$$dt_{ijk} \leq t_{i,k+1} - t_{j,k+1} + \Gamma_{ij}(1 - Y_{ijk}) \quad i \in \text{HP}, j \in \text{CP}, k \in \text{ST} \quad (\text{eq.17})$$

$$dthu_j \leq T_{out_{HU}} - t_{j,1} + \Gamma_{hj}(1 - Y_{hj}) \quad j \in \text{CP} \quad (\text{eq.18})$$

$$dtcu_i \leq t_{i,N+1} - T_{out_{CU}} + \Gamma_{ic}(1 - Y_{ic}) \quad i \in \text{HP} \quad (\text{eq.19})$$

$$dt_{ijk+1}, dthu_j, \text{ and } dtcu_i \geq EMAT \quad i \in \text{HP}, j \in \text{CP}, k \in \text{ST} \quad (\text{eq.20})$$

The above constraints are used to model HEN of stage-wise superstructure and restricted all HRAT of the required matches to be larger or equal to the exchanger minimum approach temperature (EMAT).

The unreasonable result from stage model showed up from eq.16 and 17.

$$dt_{ijk} \leq t_{i,k} - t_{j,k} + \Gamma_{ij}(1 - Y_{ijk}) \quad (\text{eq.16})$$

$$dt_{ijk} \leq t_{i,k+1} - t_{j,k+1} + \Gamma_{ij}(1 - Y_{ijk}) \quad (\text{eq.17})$$

**and**  $dt_{ijk} \geq \mathbf{EMAT}$

GAMS leads  $dt_{ijk}$  to EMAT value. This reason means that  $dt_{ijk}$  is not the real approach temperature. To calculate exchanger area,  $dt_{ijk}$  is designed as

$$dtt_{ijk} = t_{i,k} - t_{j,k} \quad (\text{eq.18})$$

The exact value of approach temperature as shown in eq.18 will be taken to compute heat exchanger area with these equations below:

$$\text{LMTD} \approx \left[ (dtt1 \times dtt2) \times \frac{(dtt1 + dtt2)}{2} \right]^{\frac{1}{3}} \quad (\text{eq.19})$$

$$\text{Area} = \left( \frac{1}{h_i} + \frac{1}{h_j} \right) \times \left( \frac{Q}{\text{LMTD} \times F_T} \right) \quad (\text{eq.20})$$

Eq.18, 19 and 20 are used to calculate heat exchanger area separately by Microsoft visual C++ 6.0 and then approach temperature, heat capacity flow rate, film heat transfer coefficient, number of hot and cold stream and heat load from stage model in GAMS are used to calculate. This stage-wise superstructure model is suitable for grassroots-design of HEN. For the retrofit design of HEN, there are three steps including tuning, retrofit and relocation step to be added the stage-wise superstructure model.

### 3.3 Retrofit Procedure for HEN design

The retrofit procedure for HEN consists of three steps, tuning step, retrofit step, and relocation step as shown in Figure 3.1

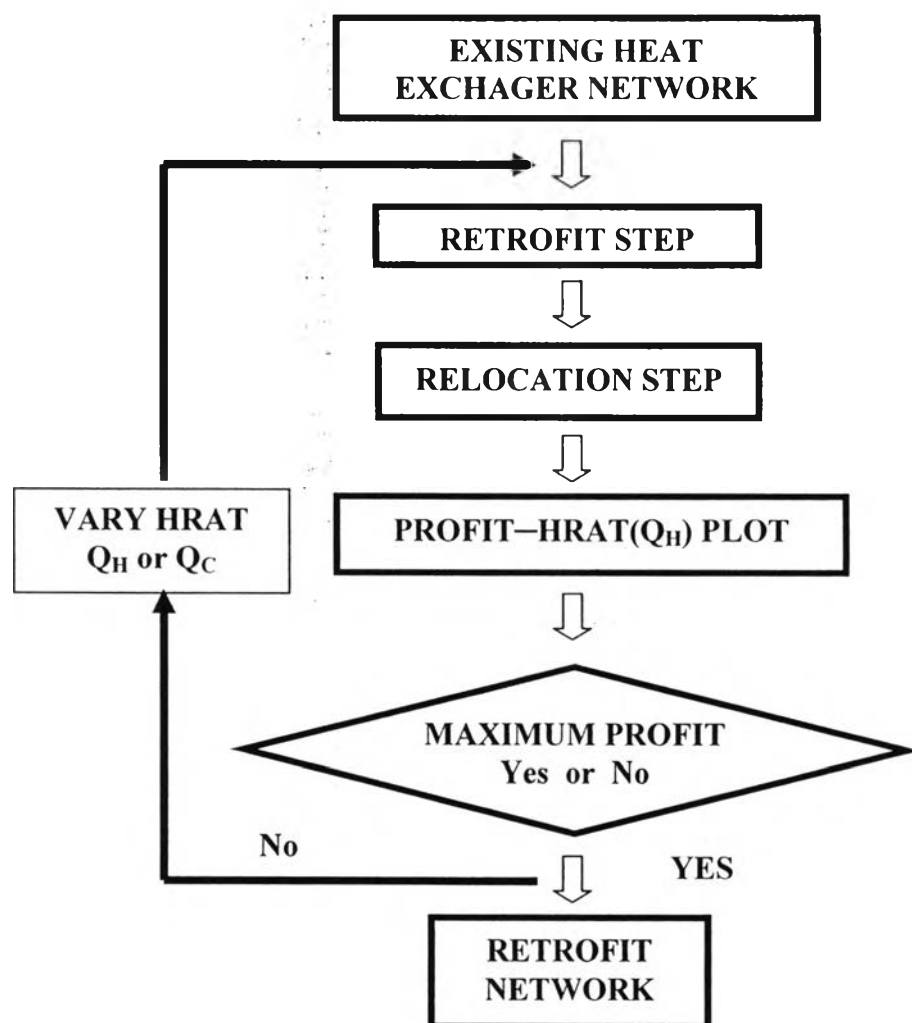


Figure 3.1 Flow chart of finding final retrofit heat exchanger.

### 3.3.1 Retrofit Step

Retrofit step is the second procedure next to the tuning step. This step reduces the HRAT or overall hot/cold utility and generates the retrofit—design HEN structure. This step also finds the best HEN structure for minimum utility cost and fixes the position of heat load before doing relocation to find minimum relocation cost.

#### Constraint in Retrofit Step

$$Z_{ijk} \geq 1$$

*ijk is hot, cold and stage number index, respectively.*

### 3.3.2 Relocation Step

From retrofit step, HEN structure is generated but how HEN structure changes from base case to retrofit network is not specified. So this step can tell how HEN changes. There are two relocation concepts in this research; which are

*Concept 1* The relocation in this concept tries to relocate all base case heat exchangers for the retrofit case.

*Concept 2* The relocation in this concept relocates the same base case heat exchangers for the retrofit case by fixing the location of heat exchanger as the base case.

#### 3.3.2.1 *Relocation with concept 1*

The relocation of an existing exchanger from the base case to the new location of the retrofit occurs when the area differences between an exchanger from the base case and ones from the retrofit case are calculated and compared to each other to find the minimum area difference and do relocation. The relocated procedure will be preceded with other existing exchanger for relocating them to new location of retrofit case. This technique is trying to reuse all existing heat exchangers with/without added/removed area (area-difference) for the retrofit case. The relocation is a program from Microsoft Visual C++ and a diagram of this concept is shown in Figure 3.2

#### 3.3.2.2 *Relocation with Concept 2*

If two things are compared each other between moved heat exchanger and fixed heat exchanger, the important thing which is considered is the first one. Moving method has a cost to pay and It may causes more payback period. Therefore

some existing heat exchangers are not moved to the other matching from retrofit step but in the case of additional or removal area and adding new heat exchanger are carried out. Diagram of this concept is shown in Figure 3.3

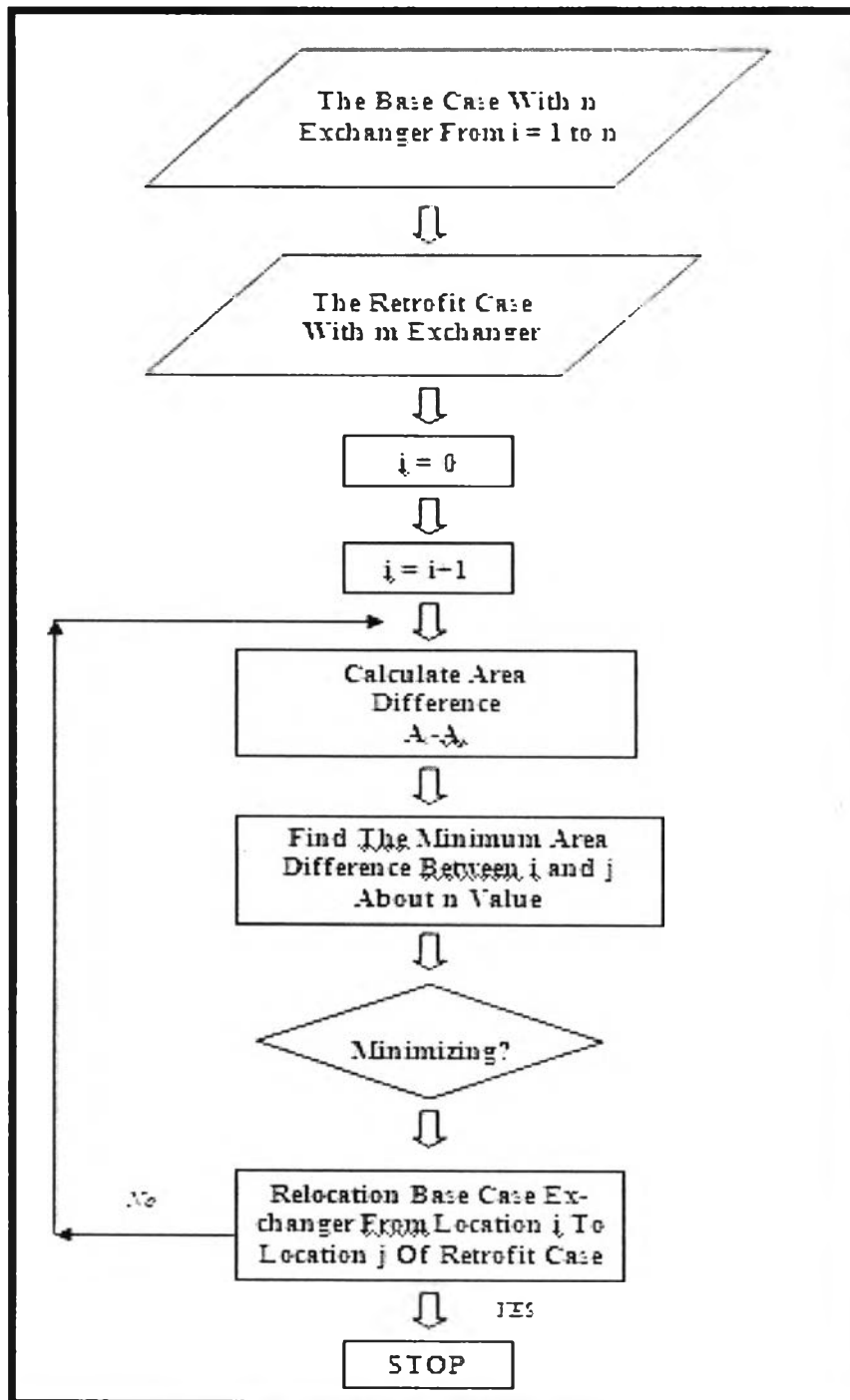


Figure 3.2 Flow chart of relocation concept 1.

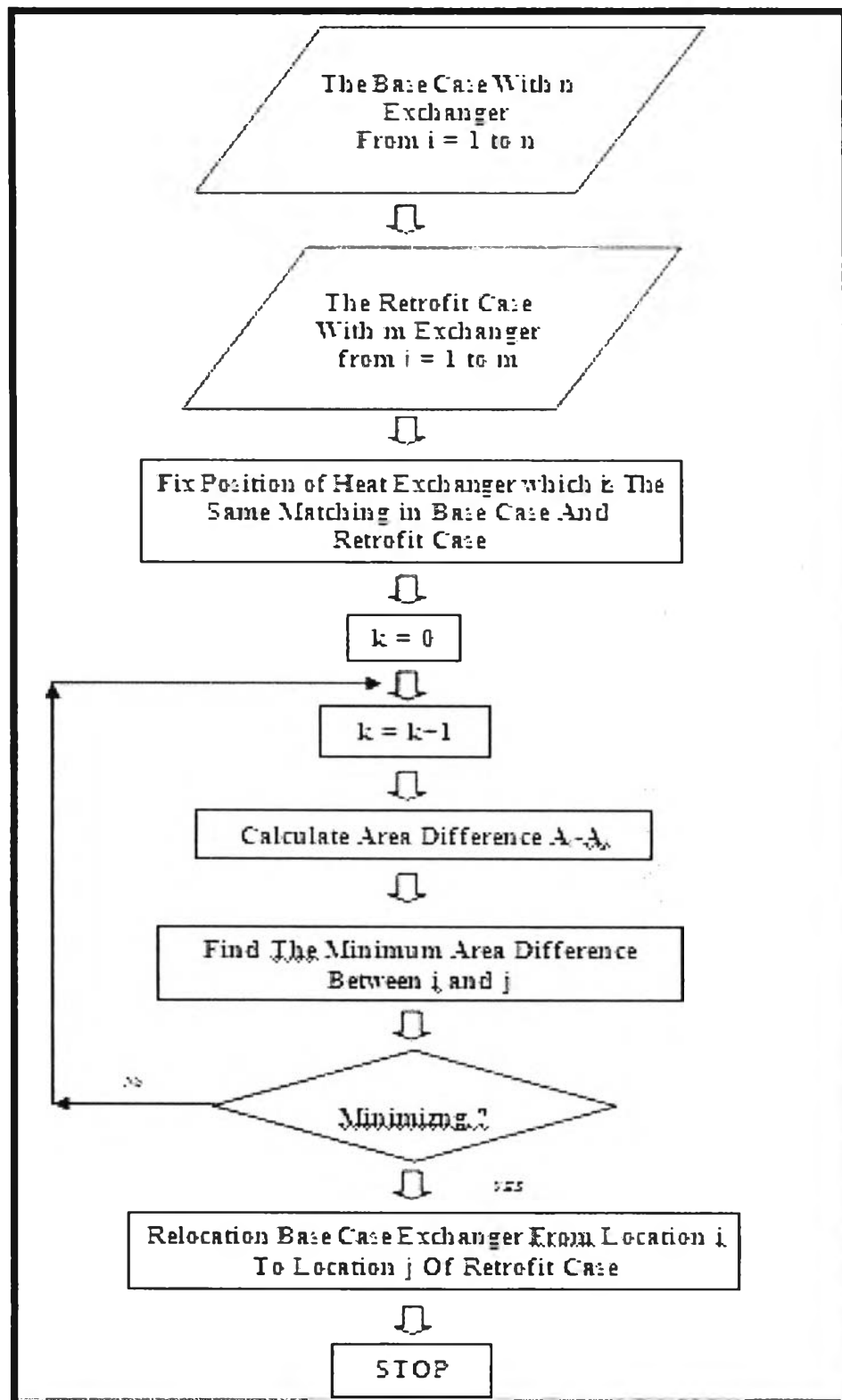


Figure 3.3 Flow chart of relocation concept 2.