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New Heat Exchanger Network Design Model

Pitak Jongsuwat[a], Uthaiporn Suriyapraphadilok*[a], Miguel Bagajewicz[b]

[a]ThePetroleum and Petrochemical College, Chulaongkorn University, 254 Soi Chula 12, Phyathai Road, Wangmai, Patumwan, Bankok 10330 Thailand
[b]School of Chemical, Biological and Material Engineering, University of Oklahoma, USA
uthaiporn.s@chula.ac.th

A new heat exchanger network model is presented consisting of an extension of the stage-wise superstructure approach that was proposed by Yee et al. (1990). Motivated by systems where splitting of large FCP stream is needed to match with several smaller FCP streams (like crude fractionation units), we add several matches per branch (Figure 1). Given the non-convex nature of the resulting MINLP and the associated difficulties to solve it without good initial points, we propose a new initialization strategy for generating feasible starting points. We demonstrate the successful application of our approach using examples from literature.

1. Introduction

Heat Integration and HEN synthesis, which is a heuristic approach to utilize energy efficiently and economically, has been widely used either in the petroleum or petrochemical industries. Likewise, there are many innovations, and a lot of research effort to develop the models for network synthesis problem. Extensive works have been done to modify and apply the HEN synthesis design such as the work from Jarusarn et al. (2013) who applied the HEN synthesis design to improve the heat recovery efficiency on a Gas Separation Plant in Thailand. Another recent work by Peipichetakul et al. (2013) also applied this concept to obtain an optimal HEN design that suited the operation in a refinery to respond to the uncertainty in crude oil quality.

Among the superstructure-based models for HEN design, the most popular one is the stage-wise superstructure approach that was proposed by Yee and Grossmann (1990), namely the SYNHEAT model. One interesting feature of this model is that all constraints are linear due to the assumption of isothermal mixing. However, the model does not address multiple matches in the same branch, a phenomenon that is common in crude units. The absence of these multiple matches may cause good solutions being excluded from the feasible space.

Huang and Karimi (2012) proposed an extension of the model by Yee and Grossmann (1990) by adding recycle/bypasses and non-isothermal mixing. They also improved the bounds of the branch temperature by not limiting them to be within the initial and final temperatures of their parent streams, hence, upon mixing, the temperatures of the branches can be lower or higher than their parent stream. In our model we add sub-stages and we also allow non-isothermal mixing.

Solving the MINLP problem using DICOPT without a good set of initial feasible points does not render a solution, whereas, solving the MINLP using BARON can obtain a solution without providing a feasible initial points. But BARON generally obtains the result slowly (Huang et al., 2013). In this work, we propose a strategy to obtain good initial values for the MINLP by using a heuristic initialization strategy.

The paper is organized as follows: We present the new model first. We then discuss the difficulties in solving the model and our initialization procedure. Finally, examples are presented.

2. Model

In the original formulation by Yee and Grossmann (1990), the feasible space is defined by strict linear constraints. Nonetheless, the stage-wise model in this work is non-convex due to the presence of non-

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linear, non-convex terms in the objective function related to the area costs. In our work we make the following changes:

- The areas of heat of heat exchangers are used explicitly in the objective function (The original SYNHEAT model uses the ratio of the heat transferred to the log mean temperature difference).
- The area costs are assumed to be linearly dependent on the areas, thus making the objective function linear.
- Because the areas of heat exchangers are explicitly defined in the objective function, new constraints to calculate them are incorporated.

In addition, to allow multiple matches per branch stage and stream splitting, the original stage-wise superstructure of Yee and Grossmann (1990) is modified as depicted in Figure 1. Following a hot (cold) stream, each hot *i* (cold *j*) streams is split into a fixed number of branch Bh's (Bc's). After entering the main stage *MK*, a fixed number of sub-stage *K*'s is added inside each main stage. A potential heat exchanger match between hot (*i*) and cold (*j*) streams can be taken place in each sub-stage. If no match of hot and cold stream is selected, this sub-stage is bypassed and the next sub-stage *MK+1* is entered. By this, we allow multiple matches per branch stream in each main stage *MK*. After passing all heat exchangers in the main stage *MK*, the hot (cold) branch streams are recombined to their parent stream *i* (*j*). The stream then enters the next main stage, splits into branch streams, enters the sub-stage *K*'s and recombines until it leaves the last main stage. Finally a cold (hot) utility is used to cooled (heated) the hot (cold) stream at the extreme of the superstructure to adjust the final temperature.

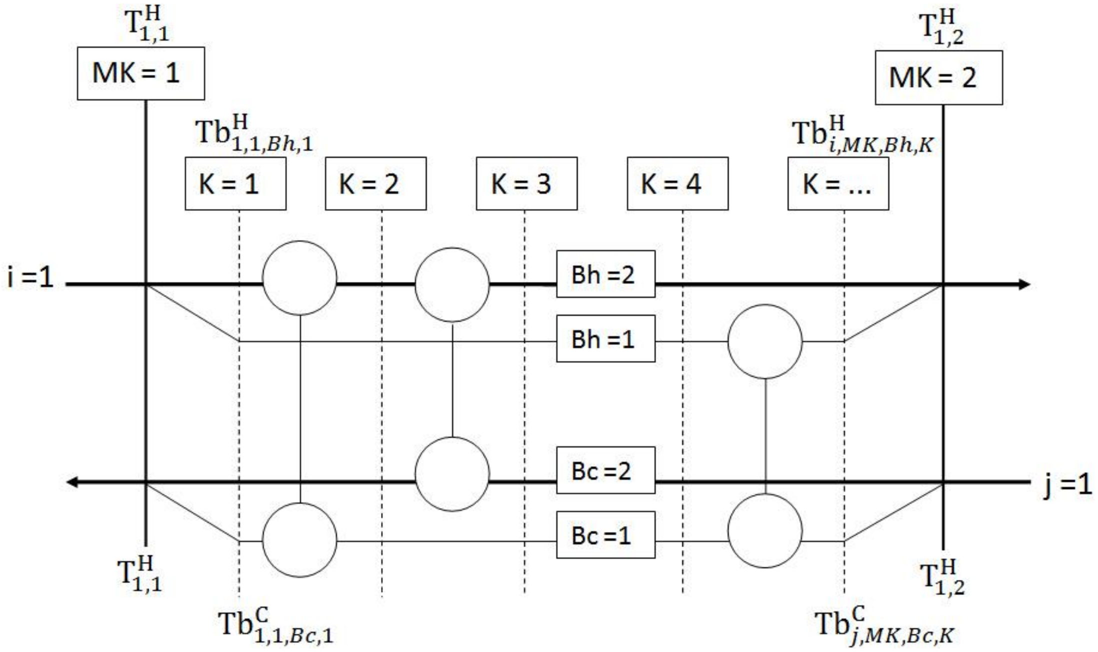

Figure 1: New stage-wise superstructure configuration

We now present some of the new model equations. The reader is referred to the paper by Yee and Grossmann (1990) for others.

Objective function:

$$\begin{aligned}\text{TAC} = {} & C_{CU}\sum_{i\in HP} qCU_i + C_{hu}\sum_{j\in CP} qhu_j \\ & + C_{HE}\sum_{i\in HP}\sum_{j\in CP}\sum_{MK\in ST}\sum_{Bh\in HP}\sum_{Bc\in CP}\sum_{K\in ST} Z_{i,j,MK,Bh,Bc,K} + C_{HE}\sum_{i\in HP} Zcu_i + C_{HE}\sum_{j\in CP} Zhu_j \\ & + C_{Aij}\sum_{i\in HP}\sum_{j\in CP}\sum_{MK\in ST}\sum_{Bh\in HP}\sum_{Bc\in CP}\sum_{K\in ST} A_{i,j,MK,Bh,Bc,K} + C_{Ai}\sum_{i\in HP} Acu_i + C_{Aj}\sum_{j\in CP} Ahu_j\end{aligned} \tag{1}$$

Overall energy balance:

$$\sum_{MK\in ST}\sum_{j\in CP}\sum_{B\in FB}\sum_{K\in ST} q_{i,j,MK,Bh,Bc,K} + qcu_i = (TIN_i - TOUT_i)CF_i^H\ , i \in HP \tag{2}$$

$$\sum_{MK \in ST} \sum_{i \in HP} \sum_{B \in FB} \sum_{K \in ST} q_{i,j,MK,Bh,Bc,K} + qhu_j = \left(TOUT_j - TIN_j\right) CF_j^C \text{ , } j \in CP \tag{3}$$

Energy balance at each sub-stage:

$$\sum_{Bh \in HP} \sum_{K \in ST} \left(Tb_{i,MK,Bh,K}^H - Tb_{i,MK,Bh,K+1}^H\right) CFb_{i,MK,Bh}^H = \left(T_{i,MK}^H - T_{i,MK+1}^H\right) CF_i^H \text{ , } i \in HP, MK \in ST \tag{4}$$

$$\sum_{Bc \in CP} \sum_{K \in ST} \left(Tb_{i,MK,Bc,K}^C - Tb_{i,MK,Bc,K+1}^C\right) CFb_{j,MK,Bc}^C = \left(T_{j,MK}^C - T_{j,MK+1}^C\right) CF_j^C \text{ , } j \in CP, MK \in ST \tag{5}$$

$$\sum_{j \in CP} \sum_{Bc \in CP} q_{i,j,MK,Bh,Bc,K} = \left(Tb_{i,MK,Bh,K}^H - Tb_{i,MK,Bh,K+1}^H\right) CFb_{i,MK,Bh}^H, i \in HP, MK \in ST \text{ , } Bh \in HP, K \in ST \tag{6}$$

$$\sum_{i \in HP} \sum_{Bh \in HP} q_{i,j,MK,Bh,Bc,K} = \left(Tb_{i,MK,Bc,K}^C - Tb_{i,MK,Bc,K+1}^C\right) CFb_{j,MK,Bc}^C, j \in CP, MK \in ST \text{ , } Bc \in CP, K \in ST \tag{7}$$

As in the original model, each match is represented by a binary variable and the corresponding temperature inequalities. We omit them. In addition, we prefer to use the approximated LMTD terms by Chen (1987) for comparing result with the exiting HENS formulation with literature.

3. Solution Strategy

The solving strategy includes four models as presented in Figure 2 to help tuning the initial values for the MINLP solver. The initial values explored are the flow rates of the branches and the results after solving each model are used as the initial values of the next model.
The role of each model is presented below.

- **First MILP.** It finds the minimum number of matches and utility consumption by fixing the branch flow variables (CFb). In this model, the area costs are not included. Because the flow in the branches is fixed, then all bilinearities vanish.
- **First NLP**. Using the solution from the first MILP, we fix the matches (Z) and obtain the minimum utility cost by adjusting the branch flows.
- **Second MILP.** This model is used to synthesize the network by minimizing the number of matches and the utility consumption. Again, the branch flow variables (CFb) are fixed while solving this step. This second MILP provides a solution with a better set of branch flows.
- **Second NLP.** We again adjust the branch flows minimizing utility and investment cost by fixing the heat exchanger location (Z) obtained from the Second MILP.
- **Final MINLP**. The initial values for this model are those obtained by the Second NLP and the Second MILP. If the Second NLP returns an infeasible result, the results are still useful since the moving direction towards convergence of the results is in the desired direction. However, if all results from the Second NLP are used as the initial values for MINLP model, these initial values can cause the MINLP to fail. Therefore, all of the initial values for the MINLP are obtained from the Second NLP model except the branch flow variable which are obtained from Second MILP, as illustrated in Figure 2.

  After solving the first iteration of all models (First MILP → First NLP →Second MILP → MINLP), results obtained from MINLP are used as the initial point of the next iteration in the First MILP model and re-run all models. There are some exceptions of using the initial values from the MINLP: If the value of branch flow variable is zero, a non-zero number has to be reassigned as initial value. At least five percent of its parent stream is to be assigned to that zero branch flow variable. If any value of the branch flow stream in First MILP is zero, that branch flow stream will be eliminated in the next solving model and this can cause missing other plausible network configuration.
  One key strategy to minimize the total annualized cost (TAC) is to set the upper bound TAC (TAC^U) constraint. After the first feasible result, if the new TAC result is lower than the previous TAC from last iteration (TAC*), the new TAC will be set as a new bound TAC^U. On the other hand, if the new TAC result is larger than TAC* or if infeasible solution was obtained from that iteration, the TAC* will still be set as a TAC^U.

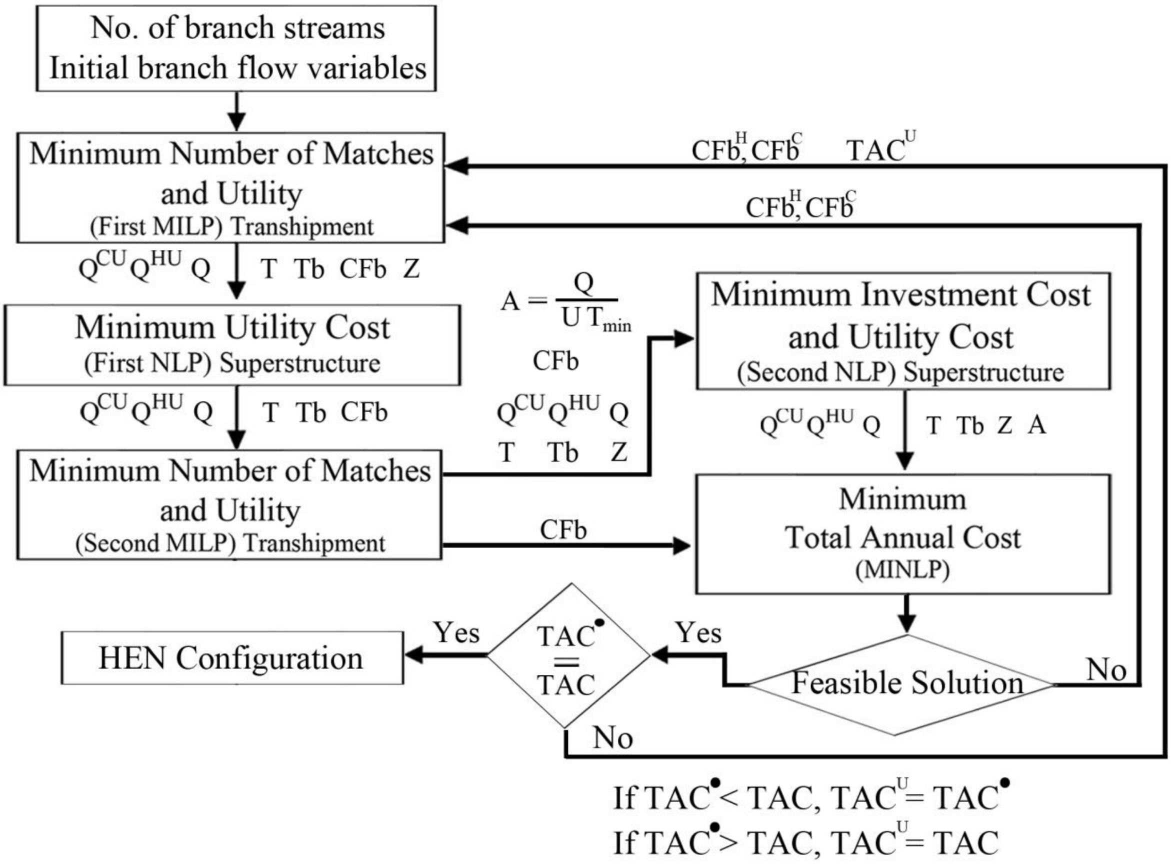

Figure 2: Step of decomposition based on HEN synthesis approach by sequential technique.Examples

A number of examples were implemented in GAMS (version 24.2.1) and solved by CPLEX v.12.6 as the LP solver, CONOPT v.3.15M as the NLP solver, and DICOPT as the MINLP solver on a PC machine (i7 2.00 GHz, 8 GB of RAM, 64-bit-operation system) by set number of maximum iteration at five. Example 1 (Table 1) was taken from Huang and Karimi (2012), Figure 3 shows our best HEN configuration. Although we obtained the same number of exchangers as the best networks reported in literature (Huang et al., 2012), our configuration is different from their HENs. Our TAC is \$73,684 with a total area of 174 m^2 which are lower than the results from Huang and Karimi (2012) (TAC \$76,327, area = 182.5 m^2). It showed that with our new proposed initialization strategy, we can obtain a different HEN configuration with a better TAC and area at the first iteration in 2,978 CPU s.

Example 2 was taken from Björk and Westerlund (2002). They used this example to illustrate the impact of non-isothermal mixing. The data for this example is presented in Table 2. Our model yields a HEN with four exchangers and a TAC of \$94,880 (see Figure 4) which is slightly lower than the best network reported by Huang and Karimi (2012) with a TAC of \$95,643 and by Björk and Westerlund (2002) with a TAC of \$96,001 by the three iteration in 3,353 cpu s.

Table 1: Data of example 1

Stream	TIN(^{o}C)	TOUT(^{o}C)	h(kW/m^2-^{o}C)	F(kW/^{o}C)	Cost(\$/kWy)
I1	167	77	2	22	-
J1	76	157	2	20	-
J2	47	95	0.67	7.5	-
CU	27	47	1	-	20
HU	227	227	1	-	120

EMAT = 1^{o}C, Heat exchangers cost (\$) = 6,600+670(Area)$^{0.83}$

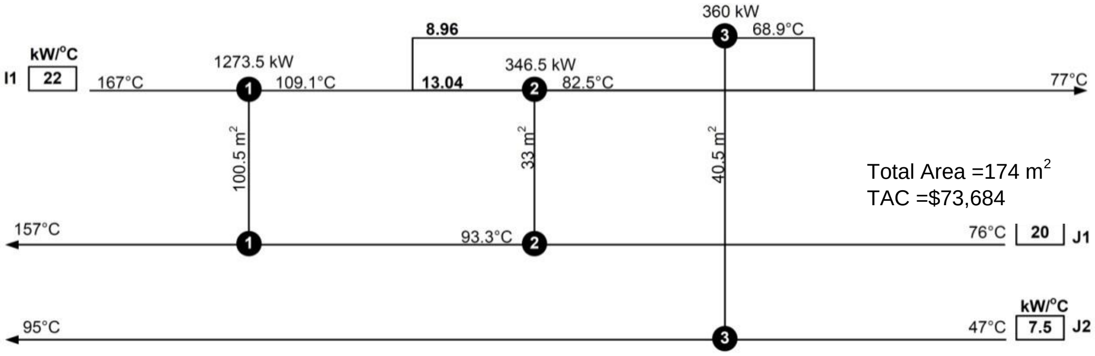

Figure 3: The best Heat exchanger Configuration result of example 1 after applying a TACU constraint.

Table 2: Data of example 2

Stream	TIN(^{o}C)	TOUT(^{o}C)	h(kW/m^2-^{o}C)	F(kW/^{o}C)	Cost($/kWy)
I1	155	30	2	8	-
I2	80	40	2	15	-
I3	200	40	2	15	-
J1	20	160	2	20	-
J2	20	100	2	15	-
CU	290	300	2	-	20
HU	680	680	2	-	120

EMAT = 1 ^{o}C, Heat exchangers cost ($) = 6,000+600(Area)$^{0.85}$

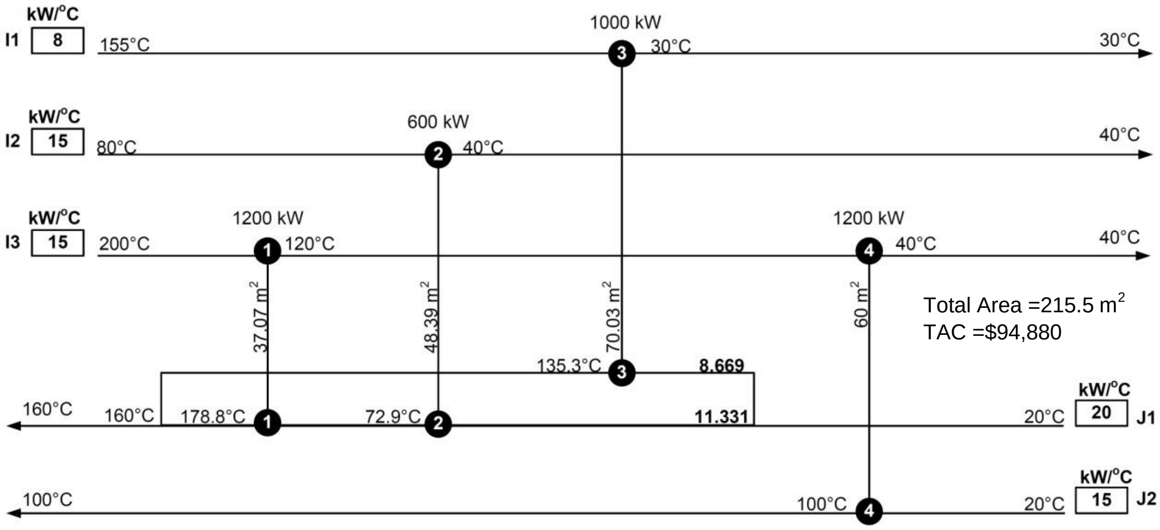

Figure 4: The best Heat exchanger Configuration result of example 2 after applying a TACU constraint.

It is noted that the outlet temperature of stream J1 leaving HE1 is 178.8^{o}C which is higher than the final temperature of the parent stream at 160^{o}C, showing that the outlet temperature of hot and cold branch streams is allowed to be cooled or heated to a temperature lower or higher than its parent stream's final temperature. This arrangement is not allowed in the original stage-wise superstructure since the original model limits the sub-stream temperature to be within the initial and final temperatures of their parent stream. In our solving strategy, we bound all temperature variable based on maximum and minimum temperatures of the two matching parent streams. From this technique, we are able to bound our sub-stream temperatures without adding any new variables in our non-isothermal mixing model.Conclusion

A modified stage-wise superstructure for solving heat exchanger network is presented. Our novel model includes the non-isothermal mixing and multiple matches per branch stream. We use a novel initialization strategy and our sub-stream temperature bounding. We introduce our sequential techniques to help tuning all variables to obtain feasible initial values since good and feasible initial points are crucial in solving complex MINLP problems using DICOPT. We illustrated our model by two examples and our HENs results are slightly better than other existing modified stage-wise superstructure models.

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