A Heat Exchanger Networks Synthesis Approach Based on Inherent Safety

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Abstract: An approach to incorporate inherent safety in the synthesis of heat exchanger networks (HEN) based on optimal layouts is given in this work. Hot and cold streams are produced in a set of facilities and some of these facilities may release toxic gas. The geographical allocation where each produced hot and cold stream is then incorporated in the conventional HEN synthesis problem. The number of heat exchangers, area requirement, energy consumption and energy configuration are thus optimally determined. Given are flows, inlet and outlet temperatures for each cold and hot stream as well as sufficient information on cooling and heating services. The annual cost is minimized while allowing for specification of constraints on matches, heat loads and streams splitting. The underlined idea is that inherent safety is achieved when simultaneously producing HEN and optimal facility layouts where risk due to toxic releases is also minimized. The numerical evidence indicates that inclusion of safety layouts with allocations of hot/cold streams can modify conventional HEN synthesis. The resulting model is a highly nonlinear mixed integer program (MINLP).

Keywords: HEN synthesis, inherent safety, facility layout, MINLP.

1. INTRODUCTION

In the chemical and process industry, large amounts of energy and operating costs can be saved through properly optimized heat exchanger networks (HEN). The design and synthesis of HEN has been largely explored and a broad research has been published in the chemical engineering literature. An early method for synthesis of minimum area networks proposed by Hohmann [1] called the attention of several researchers. His work included a strategy to assess feasibility of streams assuming suitable approach temperature and given utility supplies. This technology eventually evolved into what became known as the pinch design method [2]. From a mathematical programming point of view, Grossmann and Sargent [3] gave the first step into the MINLP developments by using an algorithm for discrete variables to solve the HEN problem with incorporated integer variables in the mathematical model. This algorithm was an extension of the method by Ponton & Donaldson [4]. An interesting work has increased stages in previous superstructures by calculating the number of stages based on the inlet temperatures of the hot and cold streams as well as on the exchanger minimum approach temperature [5].

The operation of heat exchangers have been also included in the optimization model to provide flexibility and resilience in HEN designs [6]. Optimal operation of HEN has complemented the typical synthesis problem since the conditions in real plants might be different to those assumed in the design [7-11]. Some of the difficulties to solve during operations due to bad designs have been explored recently [12]. Both online and offline optimization approaches have been implemented to solve optimal process operations [8]. Another operational problem refers to the cleaning of heat exchangers during plant maintenance shutdown. A mixed-integer linear model to detect the optimal set of units to be cleaned during this stage has been recently developed [13].

In general, the main purpose of HEN synthesis became the finding of optimal solutions in an efficient way, and several models were proposed to solve different conditions or scenarios. The proposed approaches have ended up in large mixed integer optimization problems. However, safety has been aside the main goals. More recently, environmental issues based on the eco-indicator 99 have been incorporated [14].

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In this work we retake the HEN synthesis problem to include the effect of safety during the design stage. The location of each hot/cold stream is incorporated in the optimization. The HEN synthesis model is based on the superstructure proposed by Yee and Grossmann [15,16], modified by [5]. The involved cold and hot streams are produced in process units belonging to facilities, which either have been already installed in the plant or will be installed. It is also considered that some of the process units may release toxic gas. The proposed formulation incorporates effects of stochastic variables such as wind speed, wind direction and atmospheric stability through Monte Carlo simulations to estimate gas dispersion. Risk of death is then estimated *via* probit functions. This layout model is taken from a previous work by Vázquez-Román *et al*. [17]. The proposed approach developed combines this layout model and the HEN model by Zamora and Grossmann [18].

2. PROBLEM STATEMENT

The problem addressed here is established in this section. The layout part in the model considers a set of already existing facilities i∈I, a set of new facilities for sitting s∈S, and a set of release types r∈R where a subset of existing facilities i∈I have a particular release r∈R. Displacement values with respect to the center are used to identify the exact releasing point of the releasing facility. Facilities are considered to have a rectangular shape with known dimensions, street sizes, and positions where hot and cold streams are generated. Facilities can be interconnected due to natural process needs and each facility has its own length, Lx, depth, Ly, and center coordinates, (x,y), are used to identify their allocations. The available land to allocate these facilities is also rectangular with dimensions Lx and Ly and each facility is surrounded by streets. Then parameters to calculate the probability of death in each facility given expected population in the facility and other parameters are included as indicated in [17]. For the HEN synthesis problem, the model solved here relies on the LP and MILP transshipment model to handle unrestricted and restricted matches [18-22]. It predicts the consumption of utilities. The networks may involve stream splitting, mixing, and bypassing. A set of cold streams *C* to be heated and a set of hot streams to be cooled are also given. The problem is thus formulated as a MINLP type where the objective function is referred to economic terms.

3. THE MATHEMATICAL MODEL

Starting with land constraints, a new facility must be installed inside the available land having dimensions $\mathrm{L}x$ and $\mathrm{L}y$:

$$\frac{Lx_s}{2} + st \le x_s \le Lx - \left(\frac{Lx_s}{2} + st\right) \tag{1}$$

$$\frac{Ly_s}{2} + st \le y_s \le Ly - \left(\frac{Ly_s}{2} + st\right) \tag{2}$$

where Lx_s and Ly_s are dimensions for facility for sitting *s*, st is the street size and the center of the facility has coordinates $\left(x_s, y\right)$.

The non-overlapping constraint is solved by assuming that an s-facility can be allocated with reference to a k-facility in 4 regions named A, L, R and D, Figure **1**. The following disjunction is used:

$$\left[\begin{array}{c} "L" \\ x_s \le x_k - D_{s,k}^{\min,x} \end{array}\right] \vee \left[\begin{array}{c} "R" \\ x_s \ge x_k - D_{s,k}^{\min,x} \end{array}\right] \vee \left[\begin{array}{c} "A","D" \\ x_s \ge x_k - D_{s,k}^{\min,x} \\ x_s \le x_k - D_{s,k}^{\min,x} \\ \left[\begin{array}{c} "A" \\ y_s \ge y_k - D_{s,k}^{\min,y} \end{array}\right] \vee \left[\begin{array}{c} "D" \\ y_s \le y_k - D_{s,k}^{\min,y} \end{array}\right] \end{array}\right] \tag{3}$$

where,

$$D_{s,k}^{\min,x} = \frac{Lx_s + Lx_k}{2} + st \tag{4}$$

Figure 1: Allocation of Facility *s* respect to Facility *k*.

$$D_{s,k}^{\min,y} = \frac{Ly_s + Ly_k}{2} + st \tag{5}$$

Wind direction, wind speed and air stability affect the dispersion of any gaseous release. These stochastic variables are estimated for the geographical allocating area to estimate average toxic concentrations on several wind directions. Monte Carlo simulation should be applied to estimate these average values. Probit functions are then used to get the dose-response; *i.e.* convert concentration of dispersed toxic gases into damage probability [23]. In the case of toxic releases, the response refers to probability of death. All possible directions, 360°, are divided in slices to estimate the probability of death in each run of the Monte Carlo method. All results are then fitted by using an exponential decay function so that the probability of death in a given facility s due to release type r in facility i, $P_{i,r,s}$ is estimated by:

$$P_{i,r,s} = a_{i,r,\alpha^*}.e^{-b_{i,r,\alpha^*} d_{i,s}} \tag{6}$$

where a_{i,r,α^*} and $b_{i,r,s}$ are fitted parameters for slice α^* and $d_{i,s}$ is the Euclidian separation distance between the releasing i-facility and the s-facility. Another disjunction emerges here to detect the values corresponding slice in which facility s belongs with respect to the i-facility.

Assuming that facilities might be interconnected *via* pipes due to natural process requirements, the piping cost C_{piping} is estimated by,

$$C_{piping} = \sum_{(i,j)\in M_{ij}} C_p d_{ij} \tag{7}$$

where C_p is the cost pipe, $\$/m, d_{ij}$ is the separation distance between facilities i and j and M_{ij} is a set whose elements indicate which pair of (i,j) facilities are interconnected.

The total occupied land cost, C_{land}, is:

$$C_{land} = c_l AxAy \tag{8}$$

where c_l is the cost of land per m^2, and Ax and Ay define the dimensions of the minimum rectangular area containing all facilities, i.e.

$$A_x = \max\left\{\frac{x_s + Lx_s}{2}\right\} \tag{9}$$

$$A_y = \max\left\{\frac{y_s + Ly_s}{2}\right\} \tag{10}$$

The cost of risk, C_{risk}, is calculated by

$$C_{risk} = c_{pp} t_l \sum_s \sum_{ri(i,r)} f_{i,r} p_s \mathrm{Pr}_{i,r,s} \tag{11}$$

where c_{pp} is the compensation cost to pay per fatality, t_l is the expected life time of the plant, $f_{i,r}$ is the frequency of the type of release r in facility *i*, and p_s is the expected population in facility *s*. Using Equation (6) and incorporating a binary variable, $B_{i,ri,\alpha}$, to indicate what angular slice contains an affected facility for sitting with respect to a releasing facility , Equation (11) becomes,

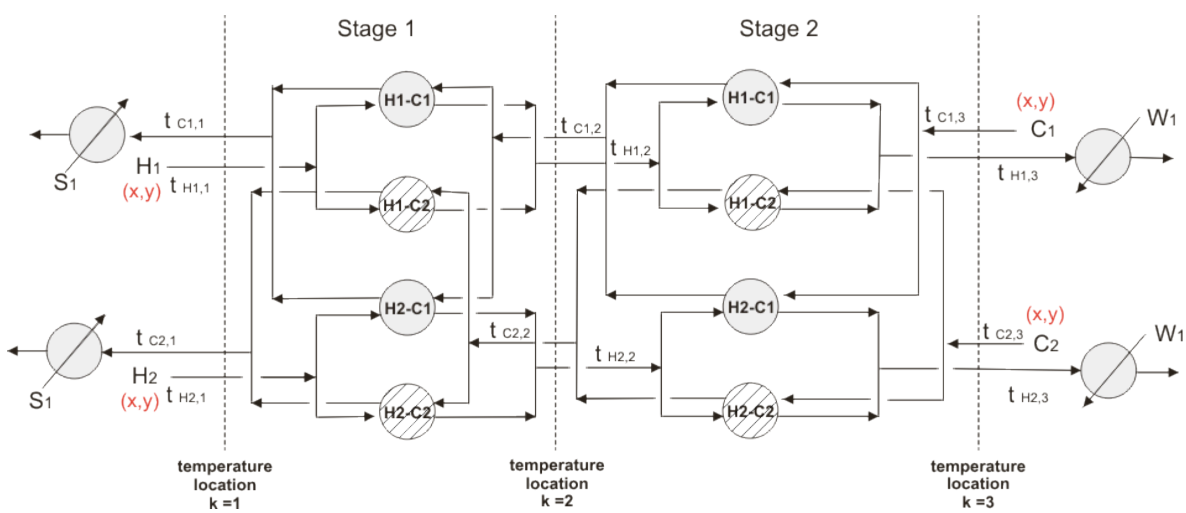

Figure 2: HEN superstructure.

$$C_{risk} = c_{pp} t_l \sum_s \sum_{ri(i,r)} f_{i,r} p_s \sum_\alpha B_{i,ri,\alpha} a_{i,r,\alpha} e^{-b_{i,r,\alpha^*} d_{i,s}} \quad (12)$$

The above described model includes disjunctions which have to be converted in equations to use a conventional solver. The convex-hull method was used to achieve this conversion. For details of this model, where other numerical difficulties were also resolved, it is suggested to see Vázquez-Román *et al*. [17].

For the HEN synthesis problem, the model presented by Zamora and Grossmann [18] is modified to include the geographical point where the hot/cold stream is generated. This point remains constant when the generated stream belongs to an already installed facility; otherwise, the allocation is a part to be determined by solving the optimization problem. It is considered that heating and cooling services already exist in each facility that no installation cost is considered in the HEN synthesis. A piping cost, additional to the cost indicated in Equation (9), is included when a hot stream exchanges heat with a cold stream and it is estimated as the Manhattan separation distance multiplied by the pipe cost/m^2. The concept of superstructure has been typically used to provide a graphical representation for the simultaneous synthesis problem. Considering a two hot-two cold stream synthesis problem, Figure **2** shows a two-stage superstructure for the synthesis problem. Streams are split at each stage to allow potential streams matching to indicate the existence of a heat exchanger. It should be observed that this superstructure is also indicating the coordinates where each stream is generated.

All equations for the HEN synthesis, considering a set of hot streams HPS and a set of cold streams CPS with a ST set of stages, are shown in Table **1**: Equations HEN1 give overall heat balances for hot streams i and cold streams j while Equations HEN2 provide heat balances at each k-stage; Equations HEN3 assign inlet temperature to streams; Equations HEN4 incorporate feasibility in temperatures; Equations HEN5 estimates the hot and cold utility loads; Equations HEN6 are logical constraints where the value of $Q_{i,j}^{\max}$ is set as the smallest heat content of the two streams involved in the match where z_{ijk}, zcu_i and zhu_j are binary variables; Equations HEN7 give the calculation of the approach temperature where $\Delta T^{\max} = \max\left\{0, TIN_i - TIN_j, TOUT_j - TOUT_i\right\}$; Equations HEN8 are minimum approach temperature constraints; and Equations HEN9 provide bounds to variables. To have the no splitting case, integer constraints are added to the formulation so that a maximum of one match can exist at each stage and for each stream:

$$\sum_j z_{i,j,k} \le 1,\ i \in HPS, k \in ST \quad (13a)$$

$$\sum_i z_{i,j,k} \le 1, \quad j \in CPS, k \in ST \quad (13b)$$

The objective function includes the combination of the utility cost, the fixed charges for exchanger and area cost for each exchanger, the LMTD terms for heat exchangers are approximated using the Chen equation [24], and the separation distances among heat exchanging streams based on their geographical coordinates:

$$\begin{aligned}
&\min \sum_{i\in HPS} CCUqcu_i + \sum_{j\in CPS} CHUqhu_j + \\
&\sum_{i\in HPS}\sum_{j\in CPS}\sum_{k\in ST} CF_{ij} z_{ijk} + \sum_{i\in HPS} CF_{i,cu} zcu_i + \sum_{j\in CPS} CF_{hu,j} zhu_j + \\
&\sum_{i\in HPS}\sum_{j\in CPS}\sum_{k\in ST} C_{ij}\left[\frac{q_{ijk}}{\left[U_{ij}\left(dt_{ijk}\right)\left(dt_{ijk+1}\right)\frac{\left(dt_{ijk}+dt_{ijk+1}\right)}{2}\right]^{1/3}}\right]^{B_{ij}} + \\
&\sum_{i\in HPS} C_{i,cu}\left[\frac{qcu_i}{\left(U_{i,cu}\left[dtcu_i\left(TOUT_i - TIN_{cu}\right)\times\frac{\left\{dtcu_i\left(TOUT_i - TIN_{cu}\right)\right\}}{2}\right]^{1/3}\right)}\right]^{B_{i,cu}} + \\
&\sum_{j\in CPS} C_{hu,j}\left[\frac{qhu_j}{\left(U_{hu,j}\left[dthu_j\left(TIN_{hu} - TOUT_j\right)\times\frac{\left\{dthu_j\left(TIN_{hu} - TOUT_j\right)\right\}}{2}\right]^{1/3}\right)}\right]^{B_{hu,j}}
\end{aligned} \quad (14)$$

Thus the objective includes determining the heat exchanger network which exhibits the least annual cost for the network. In combining the two models, the final objective function results by adding Equations (7), (8), (12), and (14).

4. CASE STUDY: RESULTS AND DISCUSSION

The optimization problem is solved using the GAMS package [25]. The case study was also presented in

Table 1: The HEN Synthesis Model

$\left(TIN_i - TOUT_i\right) FCp_i = \sum_{k \in ST} \sum_{j \in CPS} q_{ijk} + q_{cui}, \quad i \in HPS$	(HEN1A)
$\left(TOUT_j - TIN_j\right) FCp_j = \sum_{k \in ST} \sum_{i \in HPS} q_{ijk} + q_{huj}, \quad j \in CPS$	(HEN1B)
$\left(t_{i,k} - t_{i,k+1}\right) FCp_i = \sum_{j \in CPS} q_{ijk}, \quad k \in CPS$	(HEN2A)
$\left(t_{j,k} - t_{j,k+1}\right) FCp_j = \sum_{i \in HPS} q_{ijk},$	(HEN2B)
$TIN_i = t_{i,1}$	(HEN3A)
$TIN_j = t_{j,NOK+1}$	(HEN3B)
$t_{i,k} \geq t_{i,k+1}$	(HEN4A)
$t_{j,k} \geq t_{j,k+1}$	(HEN4B)
$TOUT_i \leq t_{i,NOK+1}$	(HEN4C)
$TOUT_j \leq t_{j,1}$	(HEN4D)
$\left(t_{i,NOK+1} - TOUT_i\right) FCp_i = qcu_i$	(HEN5A)
$\left(TOUT_j - t_{j,1}\right) FCp_j = qhu_j$	(HEN5B)
$q_{ijk} - Q_{i,j}^{\max} z_{ijk} \leq 0$	(HEN6A)
$qcu_i - Q_i^{\max} zcu_i \leq 0$	(HEN6B)
$qhu_j - Q_j^{\max} zhu_j \leq 0$	(HEN6C)
$dt_{ijk} \leq t_{ik} - t_{jk} + \Delta T^{\max}\left(1 - z_{ijk}\right)$	(HEN7A)
$dt_{i,j,k+1} \leq t_{i,k+1} - t_{j,k+1} + \Delta T^{\max}\left(1 - z_{ijk}\right)$	(HEN7B)
$dtcu_i \leq t_{i,NOK+1} - TOUT_{cu} + \Delta T^{\max}\left(1 - zhu_j\right)$	(HEN7C)
$dthu_j \leq TOUT_{hu} - t_{j,1} - + \Delta T^{\max}\left(1 - zhu_j\right)$	(HEN7D)
$dt_{ijk} \geq \Delta T_{mapp}, k \in K \cup \left(NOK + 1\right)$	(HEN8A)
$dtcu_i \geq \Delta T_{mapp}$	(HEN8B)
$dthu_j \geq \Delta T_{mapp}$	(HEN8C)
$TOUT_i \leq t_{i,k} \leq TIN_i$	(HEN9A)
$TIN_j \leq t_{i,k} \leq TOUT_j$	(HEN9B)
$q_{ijk}, qcu_i, qhu_j \geq 0, k \in K$	(HEN9C)

Vázquez-Román *et al*. [17]. The best layout is required to allocate two new facilities, *NA* and *NB*, and the control room, *CR*, in a given 250m-500m land where two facilities, *FA* and *FB*, have been already installed. Dimensions for facility *FA* are 20mX10m and it can have chlorine releases from the center point ubicated in the point (15,10). Dimension of *FB* are 15mX15m and its center point is allocated in (12.5, 27.5). The dimensions for new facilities *NA* and *NB* are 10mX30m and 30mX15m, respectively. The control room, also to

Table 2: Data for the Case Study

Stream	TIN (K)	TOUT (K)	Fcp (kW K^{-1})	Cost (\$ kW^{-1} yr^{-1})
HS1	443	333	30	-
HS2	423	303	15	-
CS1	293	408	20	-
CS2	290	413	40	-
Hot service	450	450	-	80
Cold service	293	313	-	20

$U = 0.8\left(kWm^{-2}K^{-1}\right)$ for all matches except ones involving steam.

$U = 1.2\left(kWm^{-2}K^{-1}\right)$ for matches involving stream.

$Annual\ cost = 1000 \times \left[area\left(m^2\right)\right]^{0.6}$ for all exchangers except heaters.

$Annual\ cost = 1200 \times \left[area\left(m^2\right)\right]^{0.6}$ for heaters.

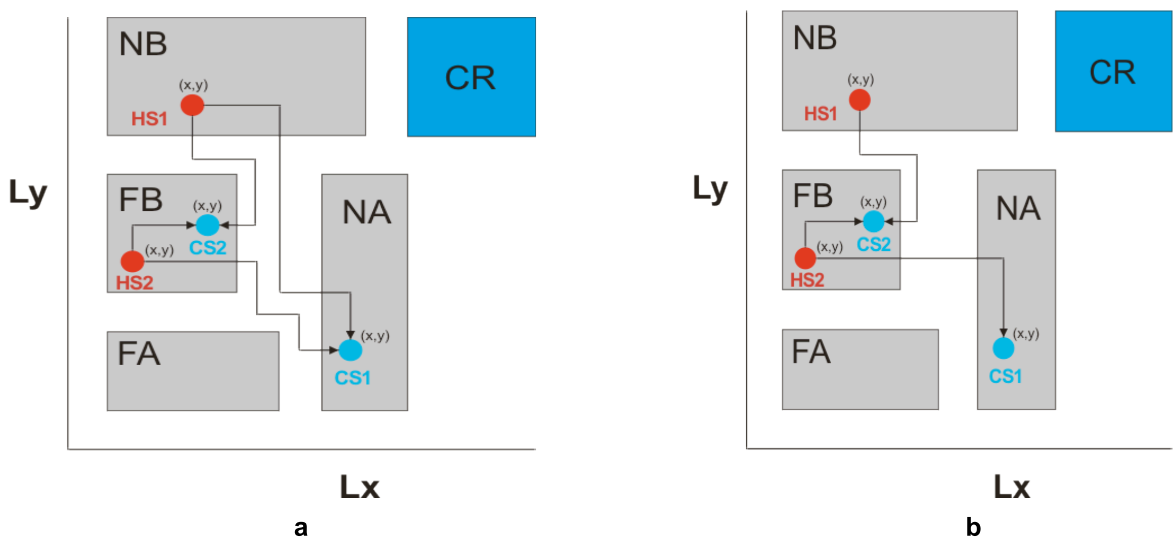

Figure 3: Results for the case study: (**a**) No geographical allocation and (**b**) with geographical allocation.

be allocated, is a square of 15m per side. Facilities *FA* and *NA* as well as *NA* and *NB* are interconnected and the estimated cost of piping is 196.8 \$/m. The cost of land is considered as \$6.00/m^2 and the wind analysis is taken from Corpus Christi, Tx. The chlorine release is considered as indicated in [26], occurring at 1 m height with a rate of 3.0 kg/s and frequency 5.8x10-4 /year following a Gaussian plume distribution. The suggested exposure time considered here is 10min with 1m as surface factor roughness. More relevant data can be found in Vázquez-Román *et al*. [17].

This example contains two hot streams, two cold streams, and one hot-cold utilities. The already installed facility *FB* contains streams *HS2* and *CS2* whereas new facility *NB* contains the hot stream *HS1* and new facility *NA* contains the cold stream CS1. The data are shown in Table **2**. When the optimization problem is solved without considering geographical allocation, the results are shown in Figure **3a**: Heat exchangers will be installed for matches HS2-CS2, HS2-CS1, HS1-CS2, and HS1-CS1 while services are required for HS1, CS1 and CS2. Figure **3b** shows the results when geographical allocations for generated streams are included in the optimization: Services are required for the same streams HS1, CS1 and CS2 but heat exchangers are for matches HS1-CS2, HS2-CS2 and HS2-CS1. Thus the optimal network is clearly affected when the corresponding geographical installation is included in the optimization procedure.

5. CONCLUSIONS

A new approach to combine safety requirements and the HEN synthesis problem has been developed in this work. Including geographical allocations of each hot and cold stream in the HEN synthesis is important to optimize the total cost. The case study has demonstrated that the final HEN strongly depends on the facilities layout. A relevant points, not included in this study, to enhance incorporating the layout in HEN designs is that wrong networks may impose extra pumps or compressors with associating pipes and valves. This result is also supported by an old observation that piping cost can be as high as 80% of delivered purchase equipment cost, see for instance [27]. The same approach can be easily extended to the retrofitting and some other synthesis problems. Safety issues must be included in all future designs.

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