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Robust Optimization of Heat Exchanger Network with Uncertainty in Inlet Temperatures of Streams

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The methodology of heat integration has been used to optimize and satisfy the demands of external utilities and resources. In the real process plants, it can easily be observed that due to unexpected process troubles and changes in environmental and operating conditions, equipment and processes do not run on the deterministic values of parameters upon which they are designed. Variations and uncertainties developed for any reason have some impacts on the process parameters, which may affect the profitability if not optimized. To optimize the utility requirements, the use of Pinch Analysis has been integrated with robust optimization where uncertainties in source quality (inlet temperature of source) are incorporated in the nominal formulation of the mathematical programming and are converted to deterministic equivalents. In this methodology, under the conditions of parametric uncertainties, decision-makers would have the choice to make a trade-off between the protection level of the constraint and the degree of conservatism of the solution. This model will assist the planner to decide the hot and cold utility requirements under uncertain flow situations and the source temperatures and to do the essential grounding accordingly.

1. Introduction

Maximum utilization of energy available within a plant is a major concern in process plants throughout the globe. For which industries always strive to improve with process integration. Optimization of Heat Exchanger Network (HEN) is one of the popular methodologies in chemical process plants in which heat transfer occurs among process streams in a way it minimizes the use of hot and cold utilities originally proposed by Hohmann (1971).
Papoulias and Grossmann (1983) offered a linear programming version for calculating minimum utility cost with restricted matches and the MILP transhipment model for minimizing the number of units in HEN and stream matches involved in each unit. Linnhoff and Flower (1978) proposed a Problem Table Algorithm (PTA) that assists in creating a Grand Composite Curve (GCC), which helps in evaluating the external utility requirement as well as heat duties in every temperature interval. Pinch Technology has progressed substantially over the last 45 years, aided by the expanded use of mathematical modelling, simulation, and optimization for heat integration (Klemeš and Kravanja 2013). Valeekiatkul and Siemanond (2019) constructed a HEN for a variable (temperature-dependant) specific heat capacity using a partitioning technique with a stage-wise superstore model. Ravagnani et al. (2005) used a genetic algorithm together with Pinch Analysis (PA) to construct optimal heat exchangers networks and to determine the least number of heat transfer units to achieve the minimum global cost.
Though numerous methodologies for minimizing the requirements of utilities, thereby reducing their costs, have also been studied and established. Only a little about the actual troubles and disturbances of process plants have been considered and published in the literature. Parametric uncertainties may develop in the process due to disturbances and sudden changes in operating conditions and the incomplete information of the processes involved. Designing a HEN with accurate values of process parameters as input, which is rarely available in practice, may produce infeasible results and translate into the poor performance of the process. Therefore, incorporating uncertainty in the design becomes extremely important to protect the process design and actual operation against the worst-case within that set of process parameters. Hafizan et al. (2019) presented a methodology in which the plus-minus concept is applied for process modifications, and new heuristics were

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introduced to guide heat exchanger sizing and bypass location in HEN design for optimal heat recovery. A computational framework is proposed by Escobar et al. (2013) using a decentralized control system for the synthesis of controllable and flexible HEN, which is assumed to operate over a specified range of expected inlet temperatures and flow rate variations. HEN design offered by this framework guarantees to operate with the design control system under uncertain parameters ensuring optimal energy integration and stream temperature targets.

In this paper, the presented mathematical model is based on the source-sink allocation problem (Sahu and Bandyopadhyay, 2010). In general, these problems mainly account for resource targeting in water allocation networks (Kumawat and Chaturvedi, 2020). With uncertainty in parameters, methodologies have been devised to target the minimum resource required in such problems using fuzzy mathematical programming (Tan, 2011), stochastic Pinch Analysis (Arya et al., 2018), robust optimization (Kumawat and Chaturvedi, 2021). In order to determine flexible solutions with a viable alternative, robust optimization is suggested as a systematic strategy ensuring that the model is resistant to any realization of uncertainty. Although the data on uncertainty is unknown, it is constrained if the uncertainty space is convex.

In this paper, robust optimization is applied for a possible solution for the optimization of HEN. To present the robust framework in mathematical terms, the concept of robust optimization proposed by Bertsimas and Sim (2004) has closely been followed and considers the linear programming problem. The model proposed in this paper assists the decision-makers in calculating the utility requirements based on the level of uncertainty and the degree of conservatism of the solution.

2. Mathematical Formulation

The mathematical formulation involving uncertainty in the inlet temperature has been approached differently and deeply follows the formulation of WAN (water allocation network) (Sahu and Bandyopadhyay, 2010). Let's assume the inlet temperature of all the hot and the cold streams to be the source and outlet temperature be the demand and heat is flowing from source $'i'$ to demand $'j'$. Following the analogy for HEN from for every internal source and every internal demand in terms of mass flow, heat capacity is expressed in Eqs(1) and (2).

$$\sum_{j=1}^{Nd} f(i,j) = F(i), \qquad \forall i \tag{1}$$

$$\sum_{i=1}^{Ns} f(i,j) = F(j), \qquad \forall j \tag{2}$$

Here, $F(i)$ and $F(j)$ are the mass flow heat capacities of source and demand. Eq (3) represents heat balance throughout the HEN in terms of hot utility (HU) and cold utility (CU).

$$HU(j) - CU(j) = F(j) * Tout(j) - \sum_{i=1}^{Ns} f(i,j) * Tin(i) \tag{3}$$

The overall objective of the formulation is to minimize the utility requirements and be governed by
Minimize:

$$u = \sum HU + \sum CU \tag{4}$$

2.1 Robust formulation for uncertainty in the inlet temperature T_{in}

A robust counterpart formulation is presented by reformulating the above-mentioned nominal model. In a given HEN, let's assume that the degree of uncertainty in the inlet temperature of every hot and cold stream can be summarized as:

$$Tin\ (i) \in \left(\bar{T}in(i) - \hat{T}in(i), \bar{T}in(i) + \hat{T}in(i)\right) \tag{5}$$

$$y\ (i) = \frac{Tin\ (i) - \bar{T}in(i)}{\hat{T}in(i)} \qquad \forall\ i \tag{6}$$

where, $y(i)$ is the scaled deviation of the parameter $Tin(i)$ and will always have values in the -1 ≤ $y\ (i)$ ≤ 1.

In Eq(5), the inlet temperature $Tin\ (i)$ is supposed to lie within the defined range, $\bar{T}in(i)$ is the nominal value of parameter considered and $\hat{T}in(i)$ is the known variation amplitude from the nominal. The scaled parameter is defined in Eq(6), it measures the ratio of the difference between actual parameter and the nominal value to the measure of uncertainty.

Further, defining
J = set of coefficients $Tin\ (i)$ which is subject to uncertainty
Γ = budget of uncertainty or number of coefficients that deviate from their nominal values whose values may lie anywhere as $0 \leq \Gamma \leq |J|$.
For the specific cases
If $\Gamma = 0$, none of the parameter $Tin\ (i)$ vary from their nominal value which makes the problem deterministic and the solution has no protection against uncertainty,
If $0 < \Gamma < |J|$, decision-makers have the option to choose the value of uncertainty against the degree of conservatism of the solution, and,
$\Gamma = |J|$, infers that solution has no protection from uncertainty as all the elements of J deviate up to the extreme values. $|J|$ = total number of streams of set whose inlet temperatures varies and are subject to uncertainty.
When the budget of uncertainty Γ is incorporated into the nominal model for uncertainty in inlet temperature Eq (3), the modified formulation is as follows:

$$\sum_{i=1}^{Ns} f(ij) * Tin(i) + HU(j) - CU(j) + z * \Gamma + \sum_{i}^{Ns} q(i,j) = F(j) * Tout(j) \tag{7}$$

$$z + q(ij) \geq \hat{T}in(i) * f(ij) \tag{8}$$

$$z, q(i,j) \geq 0 \tag{9}$$

where z and $q(i,j)$ are additional variables introduced by the duality theorem for constraints Eqs(7) – (9) of the robust problem and $\hat{T}in(i)$ are the degree of uncertainty in the inlet temperature of streams.

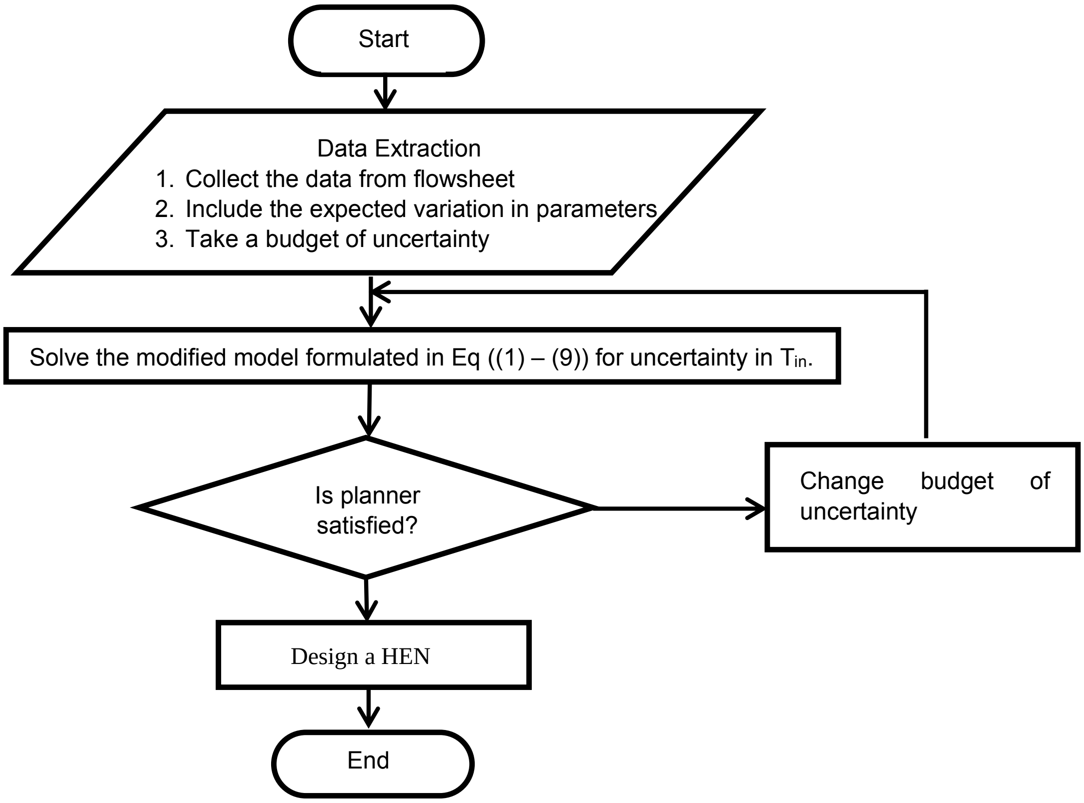

Figure 1: Flowchart for HEN design with parametric uncertainty

3. Illustrative example

The stream data of Table 1 are used to demonstrate the effect of uncertainty on HEN. There are two hot streams (H1 and H2) and two cold streams (C1 and C2) are used for the formation of HEN. The data needed for the pinch analysis includes inlet temperature Tin with some degree of uncertainty; demand temperature Tout; heat capacity flow rate F and the minimum temperature driving force ΔT_{min} taken as 20 K.

3.1 Deterministic case with no uncertainty.

The maximum energy recovery (MER) design of HEN has been calculated for the deterministic case where no uncertainty in the inlet temperature of streams has been taken into account.

Table 1: Hot and Cold stream data set for a HEN (ΔT_{min} *(K)* = 20)

Stream	$\bar{T}in \pm \hat{T}in(i)$ (K)	T_{out}(K)	F=mC_p (kW/K)	Q (kW)
H1	720±20	320	45	18,000
H2	520±20	220	40	12,000
C1	300±20	900	43	25,800
C2	200±20	550	20	7,000

Minimum HU and CU are calculated to be 9,200 kW and 6,400 kW and the Hot Pinch and the Cold Pinch are at 520 K and 500 K. The schematic Grid Diagram developed based on the principles of Linnhoff and Flower (1978) of the HEN for the deterministic value is depicted in Figure 2. Here hot streams are shown in red and cold streams are in blue.

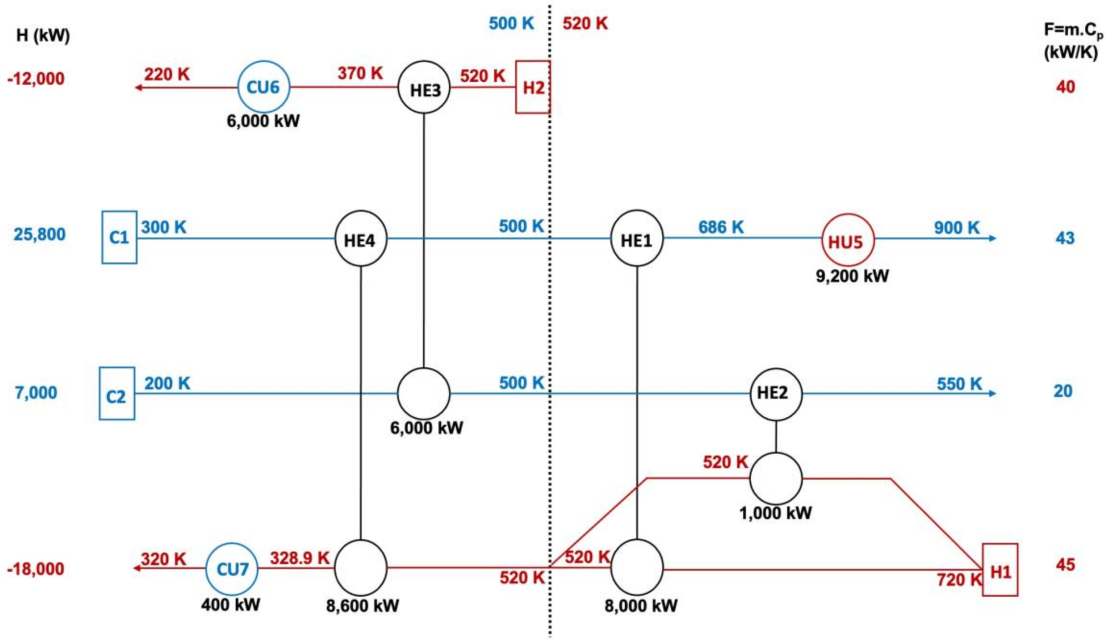

Figure 2: Grid Diagram of HEN for the deterministic value with no uncertainty

3.2 Uncertainty in the inlet temperature T_{in}.

The degree of uncertainty of the inlet temperatures of each of hot and cold utilities has been considered uniformly by ± 20 K and mentioned in Table 1. The same has also been fed to the GAMS program based on the Eqs(7) – (9) and run the program for the budget of uncertainty Γ from 0 to 4 at an interval of 0.1.

Table 2: Effect of budget parameter Γ on total utility

Budget	0	0.5	1	1.5	2	2.5	3	3.5
Hot Utility (HU)	9,200	9,962	10,245	10,365	10,460	10,460	10,460	10,460
Cold Utility (CU)	6,400	6,830	7,260	7,480	7,700	7,900	8,100	8,100
Total Utility	15,600	16,792	17,505	17,845	18,160	18,360	18,560	18,560

At the point, when Γ = 0, the result of the robust formulation changes and takes the value equivalent to the nominal model described from Eq(1) to Eq(4) and at Γ = 3.0 or more there is further no change in the objective function points to the worst-case value of the budget (Figure 3).

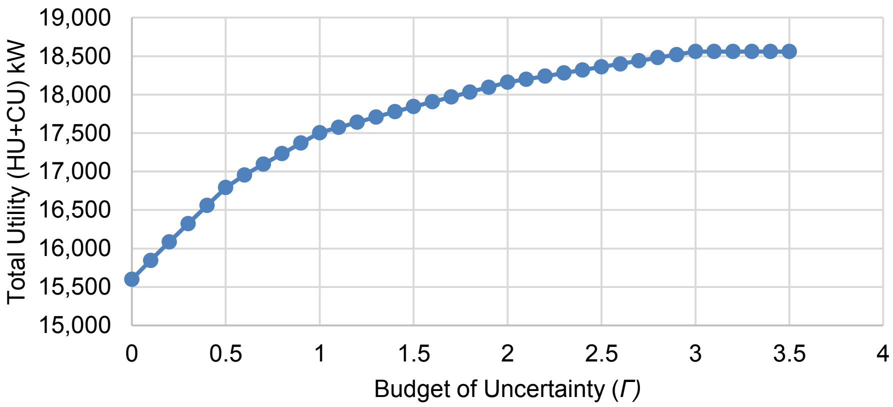

Figure 3: Graphical representation of varying budget parameters on total utility consumption due to uncertainty in inlet temp. of streams

It is interesting to note that the value of hot utility starts from 9,200 kW when HEN is at the deterministic form and keeps on increasing up to the value of 10,460 kW, till the budget attains the value, Γ = 2.0 and becomes constant thereafter (Figure 4). In contrast, the cold utility is 6,400 kW, where there is no protection against uncertainty and keeps on rising till budget Γ reaches up to 3.0 and becomes uniform afterwards. It should also be noted that the proposed model aims to estimate utility requirement handling uncertainty in inlet temperature. However, the HEN (Figure 2) is not rigid, and it could change based on uncertainty realization in parameters. It can be further modified using the methodology presented by Linnhoff and Flower (1978). Also, the methodology presented by Verheyen and Zhang (2006) could be used to design flexible HEN for multi-period operations.

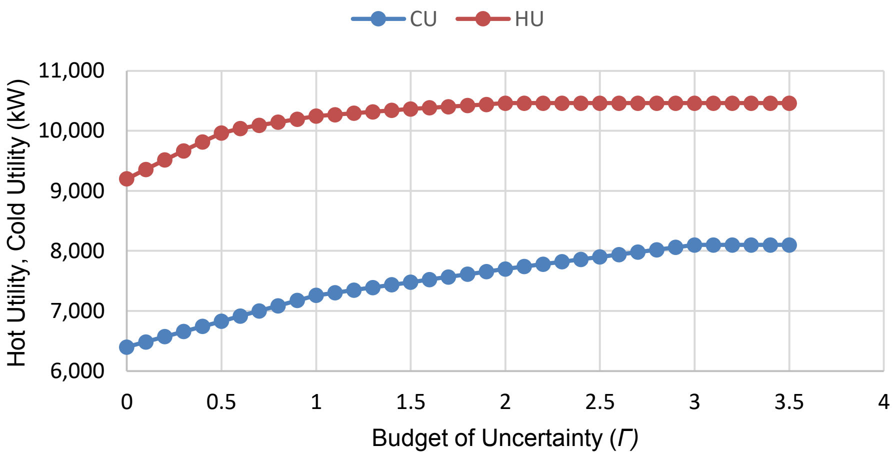

Figure 4: Graphical representation of varying budget parameters on hot and cold utilities

4. Conclusions

Compared to conservative methodologies where calculations of minimum utilities (15,600 kW) requirement in MER design of HEN, fixed and exact values for inlet temperature of streams are being taken into account, this methodology offers a means where parametric uncertainties like fluctuation in the source temperature *Tin* may be incorporated for calculating the minimum utility targets. In this particular illustrative example, variation in the budget of uncertainty $\Gamma = [0,3]$ gives changed minimum utilities requirement 15,600 kW - 18,560 kW. This paper addresses the problem of parametric uncertainty in HEN by a robust optimization approach. The budget of uncertainty is set by the decision-maker, consequently controlling the extent of variation in the parameters whose bounds of uncertainty are known. The optimum value of utilities can accordingly be calculated. Further, the attractive feature of robust optimization is that it is linear programming and can be readily solved; it is also able to tolerate parametric uncertainty under the model of data uncertainty without much affecting the objective function. In chemical process plants where uncertainties are unavoidable features, the robust optimization methodology applied here can further be extended to other processes.

Nomenclature

HU – hot utility, kW
Tin – inlet temperature of streams, K
$\hat{T}in(i)$ – deviation in inlet temperature, K
J – set of coefficients Tin (i)
$\bar{T}in$ – Nominal Value of inlet temp, K
HE – Heat Exchanger
CU – cold utility, kW
$Tout$ – outlet temperature of streams, K
ΔTmin – heat recovery approach temperature, K
Γ – budget of uncertainty
$y(i)$ – scaled deviation of $Tin(i)$

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