Minimum Total Annualized Cost for a Heat Exchange Network using the IDEAS Framework

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A classic problem that has occupied the area of process engineering for over four decades is the synthesis of heat exchanger networks (HEN). Several approaches have been employed to address this problem. They can be generally categorized into sequential synthesis[1-4] or simultaneous synthesis methods[5-9] and are often based on evolutionary or optimization principles. Neither of these method categories are able to guarantee global optimality; the former because they are based on ad-hoc rules and the latter because they are based on nonlinear programming techniques that can only guarantee local optimality.

The *Infinite DimEnsionAl State-space* (IDEAS) method is a novel conceptual framework for the synthesis of general process networks. With this approach, all possible process networks are considered and the resulting mathematical formulation gives rise to infinite dimensional optimization problems with feasible regions defined by linear constraints thus guaranteeing global optimality of the obtained solution[10].

In this work we discuss the application of the *MultiFamily IDEAS* based computer software developed at UCLA to a problem first proposed by Lee, Masso and Rudd[1]: 4sp1. This is a classical case study for HEN synthesis and one of the milestone tests for HEN synthesis methods. The data for this particular problem are summarized in Table 1, since they are often misquoted in the literature.

Table 1. 4sp1 Design Problem Data[1]

Stream No.	Flow Rate [lb/h]	Input Temp. [°F]	Output Temp. [°F]	Heat Capacity [BTU/lb/°F]
1 (C1)	20,643	140	320	0.70
2 (H1)	27,278	320	200	0.60
3 (C2)	23,060	240	500	0.50
4 (H2)	25,000	480	280	0.80

Saturated steam pressure	962.5	psia
Cooling water temperature	100	°F
Maximum water output temperature	180	°F
ΔT_{min} ; Heat Transfer Coefficient		
Heat exchanger, ΔT_{min} ; U_{HE}	20 ; 150	°F ; $BTU/h/ft^2/°F$
Water cooler, ΔT_{min} ; U_C	20 ; 150	°F ; $BTU/h/ft^2/°F$
Steam heater, ΔT_{min} ; U_H	25 ; 200	°F ; $BTU/h/ft^2/°F$
Equipment downtime	260	h/y
Heat exchanger cost parameters α,b	350, 0.6	
Cooling water cost, C_w	$5x10^{-5}$	$/lb
Steam cost, C_s	$1x10^{-3}$	$/lb
Annualizing factor, φ	0.1	1/y
Heat exchanger cost function, E	$E [\$] = \alpha A^b$, $A \equiv [ft^2]$	
Total Annualized Cost[a]	TAC [$/y]= φ E + CU + HU	

[a] CU ≡ Cold Utility cost, HU ≡ Hot Utility cost

The Rudd and co-worker approach to solution of the HEN synthesis problem[1] consisted of a sequential algorithm that considered all cold stream/ hot stream matches that met thermodynamic/design constraints. For each such feasible match either one or both of the streams involved were exhausted and the match's contribution to the overall cost was evaluated. When a stream could not be matched, it was sent to the corresponding utility. After all the matches were completed, an algorithm was followed abiding to established heuristic guidelines in order to generate the feasible network with the minimal cost. Since the maximum number of possible process networks that could be generated using this methodology for this particular problem was 4200, the authors employed a brand and bound methodology to simplify the computational burden. Using a constraint of ΔTmin = 20 °F, and the total annualized cost function defined in Table 1., the optimal network identified had a TAC of $13,481. This network is presented in **Error! Reference source not found.**.

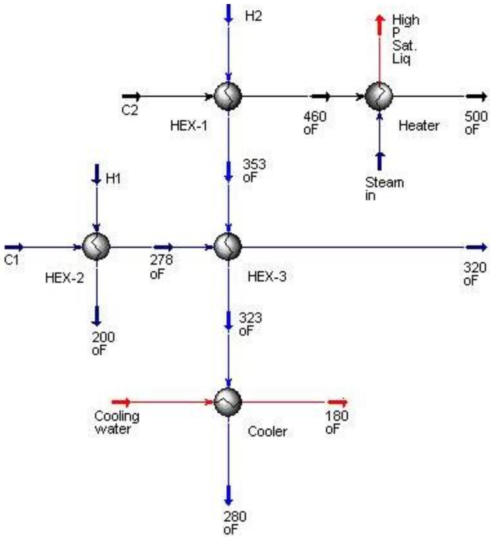

Figure 1. Network for 4sp1 Problem[1] simulated in UniSim Design.

The capital cost of a heat exchanger can be expressed not only using the cost function employed by Lee, Masso, and Rudd, but can also be expressed by a function with linear dependence on the heat exchanger's area and an incremental cost corresponding to an infinitesimally small heat exchanger area. . Figure 2 illustrates how both these cost functions may be realistic representations of a heat exchanger's capital cost.

The incremental cost function is defined as follows:

$$c + \hat{c}A = Inc \tag{1}$$

where Inc is the incremental cost function, c is the incremental cost, $\hat{c}$ is the area cost coefficient and A is the heat exchanger area. The obtained values for c and $\hat{c}$ are 2,632.2 and 25.965 respectively.

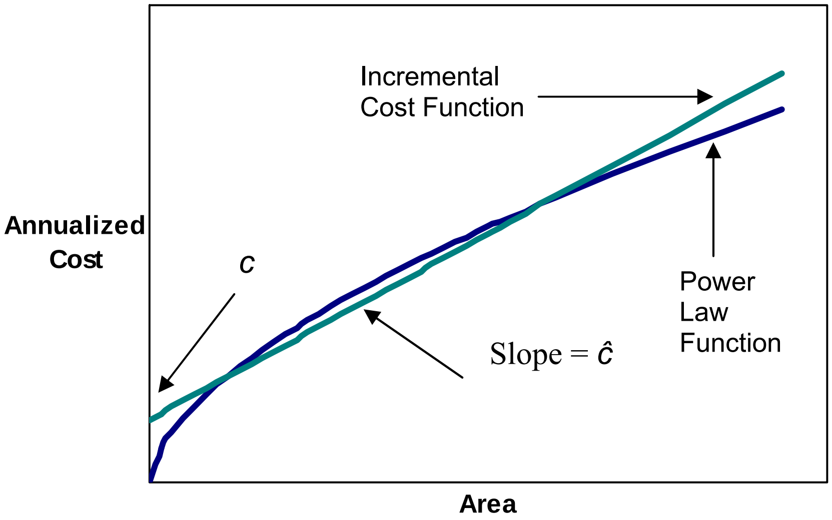

Figure 2. Incremental and power law capital cost functions for a heat exchanger

Using the above incremental cost function, a ΔT_{min} = 20°F and the Lee, Masso, and Rudd synthesis method gives rise to exactly the same optimal HEN and an optimum objective function value that is also equal to $13,481. The 4sp1 problem has been solved by numerous previous investigators. Bagajewicz et al.[11] using the power law cost function, a ΔT_{min} = 0°F and the state-space approach identified a network whose TAC cost (using the original Lee, Masso, and Rudd data) is $10,457 and ΔT_{min} = 1.3°F. The 4sp1 problem has also been approached before by Wilson[12] using the IDEAS framework, the power law objective function, and a ΔT_{min} = 0°F. The identified optimal network has a TAC cost (using the original Lee, Masso, and Rudd data) of $10,453 and a ΔT_{min} = 1.3°F. For this approach the optimization was performed in the ΔT_{min} space as well and yield a network with a cost of $10,453 and a ΔT_{min} = 1.3°F. The same network structure optimized with the incremental cost objective function results in a cost of $10,828 and a ΔT_{min} = 2.3°F. The two networks from references 11 and 12 are presented in Figure 3b, 3a respectively.

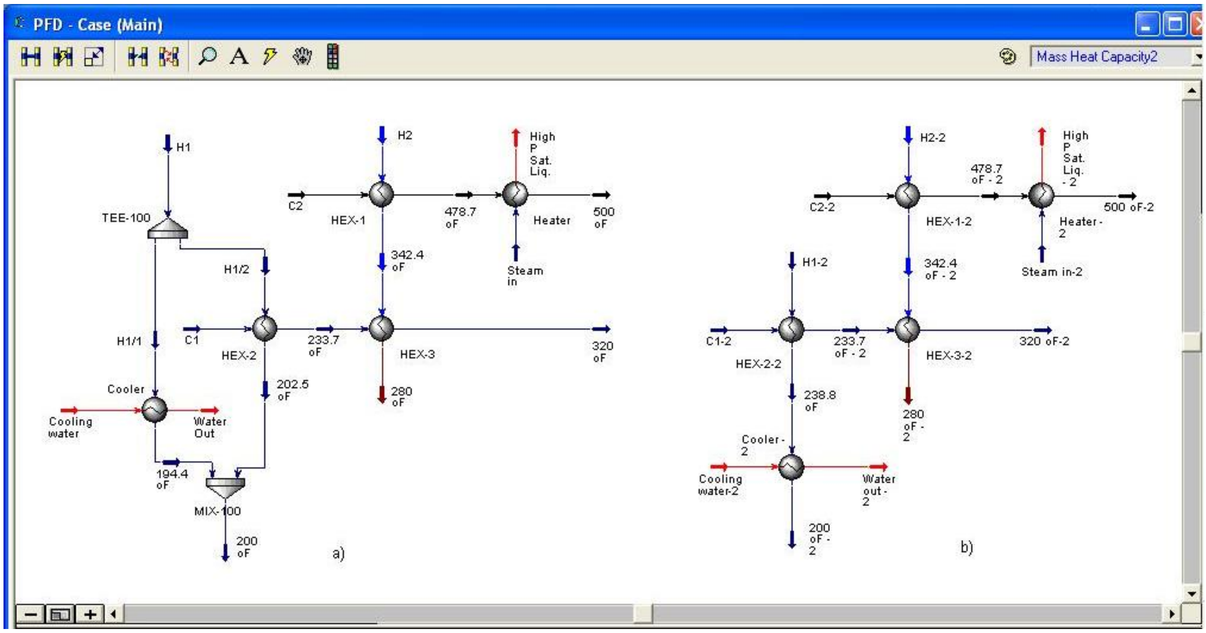

Figure 3. Optimal networks for problem 4sp1. a)IDEAS approach. b) State-space approach.

Multifamily IDEAS automatically generates HENs once the following conditions are specified: definition of fluids used, operating pressures, high and low temperature ranges, heat transfer coefficients, minimum/maximum in/out flow rates (and/or flow cost), inlet and outlet temperatures, heat exchanger cost parameters (slope and ordinate intercept) and ΔT_{min}. In addition to this, an interval discretization must be provided in order for the software to approximate the infinite generation of possible operating units. A large number of discretization points provides a better approximation but it also requires a larger amount of memory allocation and computational time.

To test MF IDEAS the original Lee, Masso, and Rudd 4sp1 data are used with the incremental cost function and ΔT_{min} = 20°F. Using a conventional PC and a coarse interval discretization (6 intervals), the network illustrated in Figure 4 was automatically synthesized by MF-IDEAS in 695.14 CPU seconds. The identified network features a TAC of $15,405 and a ΔT_{min} = 20°F and is predicted to keep improving with a more refined interval discretization.

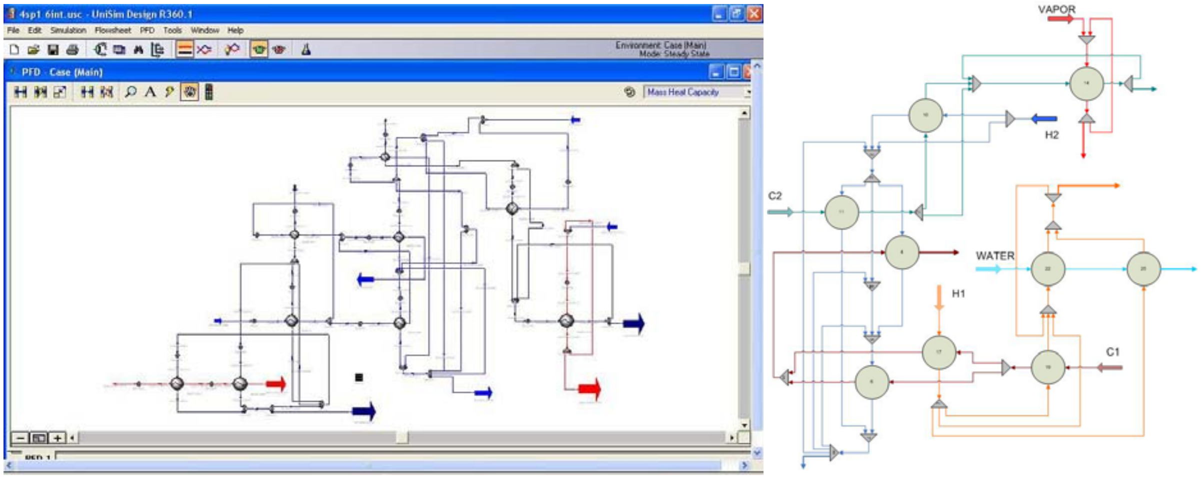

Figure 4. IDEAS-generated flowsheet for 4sp1.

Close examination of the obtained network reveals a significant number of heat exchange, splitting and mixing units. This is attributable to the coarse grid discretization, since the software will split and mix stream flowrates so as to recreate exactly the temperatures corresponding to the employed interval discretization. Increasing the number of intervals provides the software with a better ‘pool’ of matching temperatures and ultimately, as the interval size becomes small, will be able to generate the flowsheet with global optimality (3a). Further work is being developed to carry out MF-IDEAS HENS with more powerful computational resources and the implementation of parallel distribution of the operations to improve the performance and operational time of the software and hence obtain a better approximation of the optimal network.

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