Financial Risk Management in the Planning of Energy Recovery in the Total Site†

Miguel J. Bagajewicz* and Andrés F. Barbaro

University of Oklahoma, 100 E. Boyd T-335, Norman, Oklahoma 73019

A two-stage stochastic formulation to plan the implementation of heat integration in the total site over a long-term horizon is presented. Uncertainty in the price of heating utility and the operational level of the plants is considered. Financial risk is introduced and its management is discussed and incorporated into the model. Finally, a multiperiod model for the detailed heat-exchanger location planning is presented.

Introduction

Heat integration across plants can be at times very profitable. The designs can be implemented either directly using process streams or indirectly using an intermediate fluid such as steam or dowtherms. Morton and Linnhoff[1] used the overlap of grand composite curves to show the maximum possible heat recovery between two plants using steam as an intermediate fluid. Ahmad and Hui[2] also used the concept of overlapping grand composite curves to study direct and indirect heat integration and proposed a systematic approach for heat recovery schemes for interprocess integration. The concept of "Total Site" was introduced by Dhole and Linnhoff[3] to describe a set of processes serviced by and linked through a central utility system. Rodera and Bagajewicz[4] discussed the energy integration between a crude unit and an FCC unit. Finally, a linear programming model to target maximum energy savings for heat integration across plants was presented by Rodera and Bagajewicz[5] who introduced the concepts of "assisting" and "effective" heat. They showed that heat transfer among plants may occur in three regions: above pinches, between pinches, and below pinches, as shown in Figure 1. Indeed, Rodera and Bagajewicz[5] proved that heat transfer between pinches leads to energy savings, reducing the total site heating and cooling utilities. The amount of heat transferred in this zone is referred to as "effective heat" (Q_E). In addition, they showed that no net savings could be obtained by transferring heat in the regions above or below pinches. However, heat transfer from Plant 1 to Plant 2 in either of these regions (Q_A, Q_B) can facilitate the transfer of heat in the region between pinches, increasing the energy savings; hence, Q_A and Q_B are referred to as "assisting heat". Rodera and Bagajewicz[5] also showed that in some cases assisting heat could not be delivered to de-bottleneck one plant because the receiving plant is limiting such delivery and, hence, maximum effective heat cannot be achieved. Bagajewicz and Rodera[6,7] extended the original case for two plants to multiple plants and presented an industrial case study where the integration of four units in a petrochemical complex (Crude fractionation, FCC, Alkylation and Claus plant) is determined. They also proposed a methodology for the design of multipurpose heat-exchanger networks.[8]

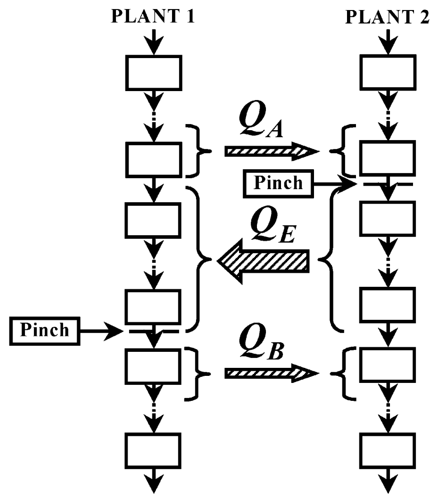


Figure 1. Directions of heat transfer for the two plants case.

In this paper, an MILP formulation to plan the implementation of energy savings in the total site over a long-term horizon is presented. To develop this model, the location of all pinches, including the "combined plant" pinch, must be considered. The goal is to determine the timing and size of capacity expansions to achieve maximum profitability. We extend a recent formulation,[9] which simultaneously targets capital and operating cost of a heat-exchanger network. The formulation corresponds to a transportation model, rather than the classical trans-shipment one.

A two-stage stochastic formulation with risk control to plan the implementation of energy savings in the total site over a long-term horizon is also presented. The goal of the model is to determine the time, size, and location of expansions in the heat-exchanger network to achieve maximum savings. In two-stage stochastic programming models, the expansion schedule is decided before the uncertainty is realized, and only some recourse actions can be taken to adjust to the actual conditions. The formulation simultaneously targets capital and operating cost of a heat-exchanger network through a mixed integer linear programming transportation model. In principle, the uncertain parameters for this model are as follows: (a) flow rate of each stream; (b) inlet temperature of each stream; (c) utility prices;

† Portions of this paper were first presented at Empromer 2001 (Santa Fe, Argentina) and Escape 12 (2002, Hague, The Netherlands).

* To whom correspondence should be addressed. E-mail: bagajewicz@ou.edu.

10.1021/ie020389u CCC: $25.00
Published on Web 09/06/2003

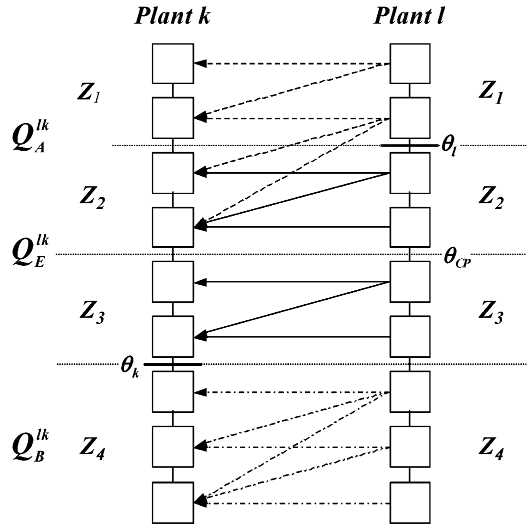


Figure 2. Heat transfer from plant l to plant k.

(d) heat-exchanger cost prices; (e) interest rates used to calculate discount factors.

A simplified model that only considers as uncertain parameters the throughput of each plant and the price of heating utility is presented here. These two parameters are the ones with a higher stochastic nature due to the normal variability in plant throughput and the volatility in the fuel prices. It is assumed that flow rate of each stream in the plant will vary accordingly with the corresponding throughput.

Economic risk associated with the uncertainty is an additional factor to be accounted for in the two-stage stochastic model. We first introduce a model without the inclusion of financial risk that has a structure similar to the stochastic programming model described by Liu and Sahinidis[10] for the capacity planning problem. Financial risk constraints are added later.

Deterministic Planning Model for Direct Heat Integration of *N* Plants

The formulation considers the direct heat integrations of N plants and takes into account the resulting utility savings and the capital cost for the heat-exchanger network to maximize the net present value (NPV) of the project. The planning horizon consists of a finite number of time periods during which utility prices, capital costs, and the available investment budget can vary. It is assumed that, at time zero, the plants are individually integrated and that the heat load and required area for process−process and utility−process matches are known.

Considering the concepts introduced by Bagajewicz and Rodera,[6,7] four different heat-transfer zones for every pair of plants are defined, as illustrated in Figure 2. In a grass root design case, this partition ensures the attainability of maximum energy savings at the end of the investment horizon according to the concepts of assisting and effective heat transfer. Figure 2 shows the cascade diagrams of two plants (k and l) for a case in which the pinch of plant l (θ_l) is higher than the pinch of plant k (θ_k) and the combined plant pinch for the total site (θ_{CP}) lies between them. In general, there will be four zones (Z_1−Z_4) for assisting and effective heat transfer across plants. Each zone is defined through a set of equations dependent on the pinch locations and is defined for two purposes: to avoid that heat be transferred across the combined plant pinch (which would increment the utility consumption) and to define the areas for assisting and effective heat transfer.

In the case shown in Figure 2, zone Z_1 represents the temperature intervals above the higher temperature pinch (θ_l) where only assisting heat (Q_A) is transferred from plant l to plant k. Zone Z_2 in turn includes the intervals between the higher temperature pinch (θ_l) and the combined plant pinch (θ_{CP}) where plant l can provide effective heat and plant k receive both assisting and effective heat. Zone Z_3 corresponds to intervals between the combined plant pinch (θ_{CP}) and the lower temperature pinch (θ_k) where plant l can provide effective heat to plant k. Finally, zone Z_4 represents the intervals below the lower temperature pinch (θ_k) where only assisting heat (Q_B) is transferred from plant l to plant k.

Model Equations

Before the model equations are introduced, the following sets are defined:

Sets. $K = \{k|\ k$ is a chemical plant$\}$; $H = \{i|\ i$ is a hot stream$\}$; $C = \{j|\ j$ is a cold stream$\}$; $U = \{u|\ u$ is a hot utility$\}$; $W = \{w|\ w$ is a cold utility$\}$; $M = \{m|\ m$ is a temperature interval$\}$; $D_{kl}{}^z = \{(n,m)|\ (n \in k,\ m \in l)$ refers to pairs of temperature intervals in heat-transfer zone $z\}$.

The model constraints and objective are explained next.

Heat Balance for Hot Streams. For any hot stream, heat can be transferred to cooling utilities (first right-hand-side term), cold process streams in the same plant (second term), or cold process streams in another plant:

$$\Delta H^{\mathrm{H}}_{ikm} = \sum_z \sum_{\substack{n \in D^z_{kk} \\ n \ge m}} \sum_{j \in C_{kn}} q^{z,t}_{ikm,jkn} + \sum_z \sum_{\substack{n \in D^z_{kk} \\ n \ge m}} \sum_{w \in W_n} q^{z,t}_{ikm,wn} + \sum_z \sum_{\substack{l \in K \\ l \ne k}} \sum_{\substack{n \in D^z_{kl} \\ n \ge m}} \sum_{j \in C_{ln}} q^{z,t}_{ikm,jln} \quad \forall\ t;\ \forall\ k \in K;\ \forall\ m \in D^z_{kk};\ \forall\ i \in H_{km} \qquad (1)$$

Heat Balance for Cold Streams. A cold stream can receive heat from heating utilities (first right-hand-side term), hot process streams in the same plant (second term), or hot process streams in another plant:

$$\Delta H^{\mathrm{C}}_{jkn} = \sum_z \sum_{\substack{m \in D^z_{kk} \\ m \le n}} \sum_{s \in S_m} q^{z,t}_{sm,jkn} + \sum_z \sum_{\substack{m \in D^z_{kk} \\ m \le n}} \sum_{i \in H_{km}} q^{z,t}_{ikm,jkn} + \sum_z \sum_{\substack{l \in K \\ l \ne k}} \sum_{\substack{m \in D^z_{lk} \\ m \le n}} \sum_{i \in H_{lm}} q^{z,t}_{ilm,jkn} \quad \forall\ t;\ \forall\ k \in K;\ \forall\ n \in D_{kk}{}^z;\ \forall\ j \in C_{kn} \qquad (2)$$

Heat Balance for Hot Utilities. These equations enforce flow rate consistency for heating utilities by making the ratio of heat transfer/temperature equal in all temperature intervals:

$$\frac{\displaystyle\sum_z \sum_{\substack{n \in D^z_{kk} \\ n \ge m}} \sum_{j \in C_{kn}} q^{z,t}_{u(m+1),jkn}}{\Delta T_{m+1}} = \frac{\displaystyle\sum_z \sum_{\substack{n \in D^z_{kk} \\ n \ge m}} \sum_{j \in C_{kn}} q^{z,t}_{um,jkn}}{\Delta T_m} \quad \forall\ t;\ \forall\ z;\ \forall\ m \in D^z_{kk};\ \forall\ u \in (U_m \cap U_{m+1}) \qquad (3)$$

Heat Balance for Cold Utilities. These equations enforce flow rate consistency for cooling utilities by making the ratio of heat transfer/temperature equal in all temperature intervals:

$$\frac{\sum_{z}\sum_{\substack{m\in D_{kk}^z\\ m\le n}}\sum_{i\in H_{km}} q_{ikm,w(n-1)}^{z,t}}{\Delta T_{n-1}} = \frac{\sum_{z}\sum_{\substack{m\in D_{kk}^z\\ m\le n}}\sum_{i\in H_{km}} q_{ikm,wn}^{z,t}}{\Delta T_n} \quad \forall\ t;\ \forall\ z;\ \forall\ n\in D_{kk}^z;\ \forall\ w\in(W_n\cap W_{n-1}) \quad (4)$$

Savings in Heating Utilities. At every period, the energy savings are given by the difference between the initial case without interplant integration and the actual energy consumption:

$$\hat{U}_u^t = \sum_z\sum_{k\in K}\sum_{m\in D_{kk}^z}\sum_{\substack{n\in D_{kk}^z\\ n\ge m}}\sum_{j\in C_{kn}}(q_{um,jkn}^{z,0} - q_{um,jkn}^{z,t}) \quad \forall\ t;\ \forall\ u\in U \quad (5)$$

Savings in Cooling Utilities.

$$\hat{W}_w^t = \sum_z\sum_{k\in K}\sum_{m\in D_{kk}^z}\sum_{\substack{n\in D_{kk}^z\\ n\ge m}}\sum_{i\in H_{km}}(q_{ikm,wn}^{z,0} - q_{ikm,wn}^{z,t}) \quad \forall\ t;\ \forall\ w\in W \quad (6)$$

Feasibility of Original Process Matches. The original existing matches between streams are performed in exchangers that have a certain area. This set of constraints ensures that the existing area is able to accommodate the new heat loads:

$$0 \le \sum_{m\in D_{kk}^z}\sum_{\substack{n\in D_{kk}^z\\ n\ge m}}\frac{q_{ikm,jkn}^{z,t}}{(h_i+h_j)\cdot\Delta T_{mn}^{\mathrm{ML}}} \le A_{ikm,jkn}^{z,0} \quad \forall\ k\in K;\ \forall\ z;\ \forall\ i\in H_k;\ \forall\ j\in C_k \quad (7)$$

Feasibility of Original Heating Utility Matches.

$$0 \le \sum_{m\in D_{kk}^z}\sum_{\substack{n\in D_{kk}^z\\ n\ge m}}\frac{q_{um,jkn}^{z,t}}{(h_u+h_j)\cdot\Delta T_{mn}^{\mathrm{ML}}} \le A_{um,jkn}^{z,0} \quad \forall\ k\in K;\forall\ z;\ \forall\ u\in U;\ \forall\ j\in C_k \quad (8)$$

Feasibility of Original Cooling Utility Matches.

$$0 \le \sum_{m\in D_{kk}^z}\sum_{\substack{n\in D_{kk}^z\\ n\ge m}}\frac{q_{ikm,wn}^{z,t}}{(h_i+h_w)\cdot\Delta T_{mn}^{\mathrm{ML}}} \le A_{ikm,wn}^{z,0} \quad \forall\ k\in K;\ \forall\ z;\ \forall\ w\in W;\ \forall\ i\in H_k \quad (9)$$

Area Constraints. The required area for an interplant match between a hot and a cold stream is given by

$$\tilde{A}_{ik,jl}^{z,t} = \sum_{m\in D_{kl}^z}\sum_{\substack{n\in D_{kl}^z\\ n\ge m}}\frac{q_{ikm,jln}^{z,t}}{(h_i+h_j)\cdot\Delta T_{mn}^{\mathrm{ML}}} \quad \forall\ k,l\in K,\ k\ne l;\ \forall\ z;\forall\ i\in H_k;\ \forall\ j\in C_l \quad (10)$$

If the required area for a match is greater than the existing area, then a new heat exchanger must be added. This is expressed by the following set of equations,

$$\underline{A}_{ik,jl}\cdot Y_{ik,jl}^{z,t} \le A_{ik,jl}^{z,t} - A_{ik,jl}^{z,t-1} \le \bar{A}_{ik,jl}\cdot Y_{ik,jl}^{z,t}$$
$$A_{ik,jl}^{z,t} \ge \tilde{A}_{ik,jl}^{z,t} \quad (11)$$
$$Y_{ik,jl}^{z,t} = (0,1) \quad \forall\ k,l\in K,\ k\ne l;\ \forall\ z;\ \forall\ i\in H_k;\ \forall\ j\in C_l$$

where $\bar{A}$ and $\underline{A}$ are upper and lower bounds for the area expansion.

Investment Cost. The total investment cost for the expansions at a certain period is

$$I_c^t = \sum_z\sum_{k\in K}\sum_{\substack{l\in K\\ l\ne k}}\sum_{i\in H_k}\sum_{j\in C_l}(\alpha_{ik,jl}^t(A_{ik,jl}^{z,t} - A_{ik,jl}^{z,t-1}) + \beta_{ik,jl}^t\ Y_{ik,jl}^{z,t}) \quad \forall\ t \quad (12)$$

where α and β are the variable and fixed heat-exchanger costs. Finally, the expansion cost is limited by the investment budget available at each period:

$$I_c^t \le I_b^t \qquad \forall\ t \quad (13)$$

Objective Function. The objective is to maximize the net present value of the project,

$$\mathrm{NPV} = \sum_{t=1}^{T} d_t\left(\sum_{u\in U} c_u^t\ \hat{U}_u^t + \sum_{w\in W} c_w^t\ \hat{W}_w^t - I_c^t\right) \quad (14)$$

where d_t is the discount factor at period t.

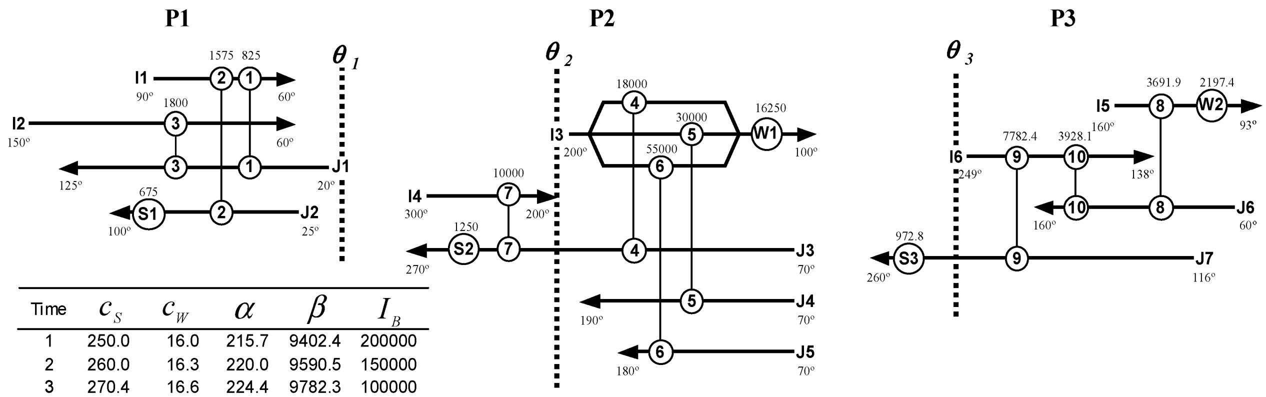
The proposed MILP formulation optimizes the heat transfer across plants to obtain maximum profitability. Consequently, the model gives, for every time period, the heat load and the estimated required area for each interplant stream match. The area estimated by the model corresponds to a “spaghetti” set of matches and may differ from the actual network area. As the number of intervals increases, the area prediction improves.

Example 1

A numerical example is presented next. Consider three plants. The original heat-exchanger network for each plant as well as the cost information is shown in Figure 3. The model results are summarized in Table 1, which shows the heat exchangers added at each time period (pinch locations θ_1, θ_2, θ_3, and θ_{cp} are 21, 4, 3, and 4, respectively). Finally, a heat-exchanger network is shown in Figure 4. The exchangers added in periods 1 and 2 are represented by squares and rhombuses, respectively.

Observing the results shown in Table 2, some immediate conclusions are evident. For example, it might be a good idea to consider a higher investment budget for the first period to avoid the need of adding exchangers for the same matches in the second period. There are two instances of this case: exchangers 12 and 16 and exchangers 14 and 18. In addition, the fact that no investment is utilized in later periods suggests that the original network is limiting the transfer of effective heat. In other words, if larger savings were sought, then some existing heat exchangers would have to be eliminated or relocated.

One important feature of the model is that solutions can be constructed, even for a low number of intervals.



Time	c_S	c_W	α	β	I_B
1	250.0	16.0	215.7	9402.4	200000
2	260.0	16.3	220.0	9590.5	150000
3	270.4	16.6	224.4	9782.3	100000
4	281.2	17.0	228.9	9977.9	50000

Figure 3. Example heat-exchanger network without integration across plants.

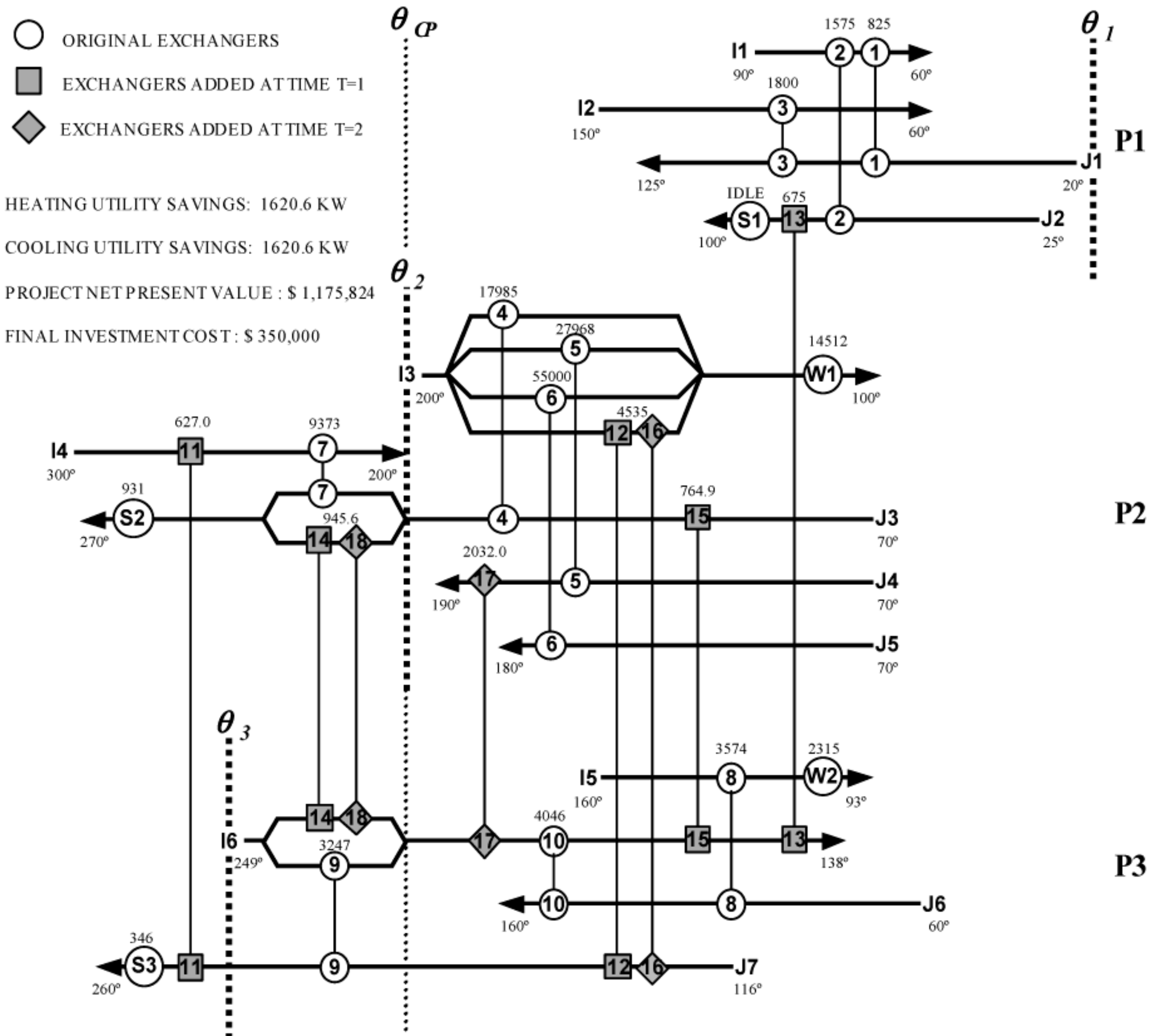


Figure 4. Heat-exchanger network for the heat loads distribution given by the model.

In addition, once obtained, the solution does not seem to change structurally for a larger number of intervals, only the new areas being adjusted. Some of the difficulties rely on the structure of the spaghetti solution, which sometimes does not correspond truly to the number of exchangers counted. Future work will include a better assessment of the area prediction so that the limiting process of increasing the number of intervals can be improved and the difference between the spaghetti and the actual network is minimized. Despite the present shortcomings, many of them related to the academic quest of true optimums, we feel that the model can be used in industrial practice because the solutions it finds can be implemented without further analysis.

Stochastic Programming Model

A two-stage stochastic model for the planning of energy recovery in the total site is presented next. This model for planning of heat integration represents an

Table 1. Intervals Membership to Each Heat-Transfer Zone

Zone 1				Zone 2			
$l\downarrow/k\rightarrow$	1	2	3	$l\downarrow/k\rightarrow$	1	2	3
1	1…21	1…4	1…4	1			
2	1…4	1…4	1…3	2			
3	1…1	1…1	1…1	3	4…4	4…4	

Zone 3				Zone 4			
$l\downarrow/k\rightarrow$	1	2	3	$l\downarrow/k\rightarrow$	1	2	3
1				1			
2	5…21			2		5…21	5…21
3	5…21			3		4…21	4…21

Table 2. Heat Loads Distribution and Estimated Area Given by the Model

time	HE #	heat load (kW)	required area (m^2)	supplier plant	transfer zone	hot stream	receiver plant	cold stream
T1	1	627.0	101.44	K2	Z1	I4	K3	J7
	2	566.0	282.98	K2	Z4	I3	K3	J7
	3	675.0	25.1	K3	Z3	I6	K1	J2
	4	2028.7	190.59	K3	Z2	I6	K2	J3
	5	764.9	109.15	K3	Z4	I6	K2	J3
T2	6	379.6	189.82	K2	Z4	I3	K3	J7
	7	2506.6	235.48	K2	Z1	I4	K3	J7
	8	2032.0	125.73	K3	Z2	I6	K2	J3

extension of the above deterministic formulation and will be referred to as model SP. The objective function of this new model maximizes the expected net present value (NPV) over two stages of the capacity expansion project. The expected net present value is composed of the cost savings due to the reduction of heating and cooling utilities needs and the investment cost. The investment cost is represented by a term that is proportional to the capacity expansion and a fixed charge term that accounts for economies of scale.

In contrast to the deterministic formulation, this model considers a single heat-transfer zone given that the position of each plant pinch will vary for the different scenarios due to changes in streams' temperatures and/or flow rates. The model is presented below.

Model SP

$$\text{Max NPV} = \sum_s \sum_t \sum_{u\in U} p^s c_u^{ts}\, \hat{U}_u^{ts} + \sum_s \sum_t \sum_{w\in W} p^s c_w^{ts}\, \hat{W}_w^{ts} - \sum_t I^t \quad (15)$$

subject to

$$E^{\rm L}_{ijkl} Y^t_{ijkl} \le E^t_{ijkl} \le E^{\rm U}_{ijkl} Y^t_{ijkl} \qquad \forall\ t;\ k,l \in K;\ i \in I_k;\ j \in J_l \quad (16)$$

$$E^{\rm L}_{ujkk} Y^t_{ujkk} \le E^t_{ujkk} \le E^{\rm U}_{ujkk} Y^t_{ujkk} \qquad \forall\ t;\ k \in K;\ u \in U;\ j \in J_k \quad (17)$$

$$E^{\rm L}_{iwkk} Y^t_{iwkk} \le E^t_{iwkk} \le E^{\rm U}_{iwkk} Y^t_{iwkk} \qquad \forall\ t;\ k \in K;\ i \in I_k;\ w \in W \quad (18)$$

$$A^t_{ijkl} = A^{t-1}_{ijkl} + E^t_{ijkl} \qquad \forall\ t;\ k,l \in K;\ i \in I_k;\ j \in J_l \quad (19)$$

$$A^t_{ujkk} = A^{t-1}_{ujkk} + E^t_{ujkk} \qquad \forall\ t;\ k \in K;\ u \in U;\ j \in J_k \quad (20)$$

$$A^t_{iwkk} = A^{t-1}_{iwkk} + E^t_{iwkk} \qquad \forall\ t;\ k \in K;\ i \in I_k;\ w \in W \quad (21)$$

$$I^t = \sum_k \sum_l \sum_{i\in I_k} \sum_{j\in J_l} \alpha^t_{ijkl} E^t_{ijkl} + \beta^t_{ijkl} Y^t_{ijkl}$$
$$\sum_k \sum_{h\in H_k} \sum_{j\in J_l} \alpha^t_{ujkk} E^t_{hjkk} + \beta^t_{ujkl} Y^t_{ujkk} \quad (22)$$
$$\sum_k \sum_{i\in I_k} \sum_{w\in C_l} \alpha^t_{iwkk} E^t_{iwkk} + \beta^t_{wjkl} Y^t_{iwkk} \qquad \forall\ t \in T$$

$$I^t \le B^t \qquad \forall\ t \in T \quad (23)$$

$$\hat{U}_u^{ts} = \sum_k f_k^{ts}\, U^{\rm o}_{uk} - \sum_k \sum_m \sum_{j\in J_k} \sum_{\substack{n\in M_j\\ n\in P_{zkkhjmn}}} q^{ts}_{ujkkmn} \qquad \forall\ t \in T;\ s \in S;\ u \in U \quad (24)$$

$$\hat{W}_w^{ts} = \sum_k f_k^{ts} U^{\rm o}_{wk} - \sum_k \sum_m \sum_{i\in I_k} \sum_{\substack{m\in M_i\\ m\in P_{zkkicmn}}} q^{ts}_{iwkkmn} \qquad \forall\ t \in T;\ s \in S;\ w \in W \quad (25)$$

$$f_k^{ts} \Delta H_{ikm} = \sum_{w\in W_n} \sum_{n\in P_{zkkicmn}} q^{ts}_{iwkkmn} + \sum_{\substack{j\in J_k\\ j\in J_n}} \sum_{n\in P_{zkkijmn}} q^{ts}_{ijkkmn} + \sum_{l\ne k} \sum_{\substack{j\in J_k\\ j\in J_n}} \sum_{n\in P_{zklijmn}} q^{ts}_{ijklmn}$$
$$\forall\ t \in T;\ s \in S;\ k \in K;\ m \in M;\ i \in I_k;\ i \in I_m \quad (26)$$

$$f_k^{ts} \Delta H_{zjln} = \sum_{u\in U_m} \sum_{m\in P_{zllicmn}} q^{ts}_{ujllmn} + \sum_{\substack{i\in I_l\\ i\in I_m}} \sum_{m\in P_{zllijmn}} q^{ts}_{ijkkmn} + \sum_{k\ne l} \sum_{\substack{i\in I_k\\ i\in I_m}} \sum_{m\in P_{zklijmn}} q^{ts}_{ijklmn}$$
$$\forall\ t \in T;\ s \in S;\ z \in Z;\ l \in K;\ n \in M;\ j \in J_l;\ j \in J_n \quad (27)$$

$$A^t_{ijkl} \ge \sum_{m\in M_i} \sum_{\substack{n\in M_j\\ n\in P_{zklijmn}}} \frac{h_i h_j}{(h_i + h_j)} \frac{q^{ts}_{ijklmn}}{\text{LMDT}_{mn}} \qquad \forall\ t \in T;\ s \in S;\ k,l \in K;\ i \in I_k;\ j \in J_l \quad (28)$$

$$A^t_{ujkk} \ge \sum_{m\in M_h} \sum_{\substack{n\in M_j\\ n\in P_{zkkhjmn}}} \frac{h_u h_j}{(h_u + h_j)} \frac{q^{ts}_{ujkkmn}}{\text{LMDT}_{mn}} \qquad \forall\ t \in T;\ s \in S;\ k \in K;\ h \in H;\ j \in J_k \quad (29)$$

$$A^t_{iwkk} \ge \sum_{m\in M_i} \sum_{\substack{n\in M_c\\ n\in P_{zkkicmn}}} \frac{h_i h_w}{(h_i + h_w)} \frac{q^{ts}_{iwkkmn}}{\text{LMDT}_{mn}} \qquad \forall\ t \in T;\ s \in S;\ k \in K;\ i \in I_k;\ c \in C \quad (30)$$

$$q^{ts}_{ijklmn}, q^{ts}_{ujkkmn}, q^{ts}_{iwkkmn} \ge 0 \quad Y^t_{ijkl}, Y^t_{ujkk}, Y^t_{iwkk} = (0,1) \quad (31)$$

The first-stage decisions consist of a set of binary variables (Y) and continuous variables (E). The binary decisions represent the selection of a capacity expansion in the heat-exchanger network, which occurs when new heat-exchange area is added to the network. The continuous decision variables are in turn the size of the area addition. In turn, the second-stage decisions are the heat flows between streams at each instance of uncertainty.

In this model, uncertainty is described by finitely many, mutually exclusive scenarios s that are independent of the first-stage decisions.

Constraints guaranteeing lower and upper bounds for the capacity expansion and the total capacity available are represented by eqs 16–18. These constraints force expansions to be zero whenever the corresponding binary decision variable is zero. In turn, eqs 19–21 define the total installed area for the corresponding match at every time period. Equations 22 and 23 define the investment cost and limit it to the available budget. Equations 24 and 25 express the savings in heating and cooling utilities, respectively. Equations 26 and 27 represent the energy balances for each stream and temperature interval. Finally, inequalities 28–30 ensure that the required area for the heat transfer does not exceed the installed area.

This model maximizes the expected net present value of the project, yet it does not provide any insight on the risk associated with the investment. Thus, a framework for the evaluation of the financial risk needs to be developed.

Definition and Incorporation of Financial Risk

The concept of financial risk is related to the probability of not attaining the expected profit level from the invested capital. In this sense, the risk associated with a given expectation level Ω is defined as follows:

$$\mathrm{Risk}(\Omega) = P(\mathrm{NPV} < \Omega) \tag{32}$$

This definition of risk is not novel and has been used previously to assess (but not manage) risk, one of the most notorious examples being the petroleum exploration and production field.[11] Risk has also been associated with "robustness" through the variance Mulvey et al.,[12] to downside risk by Eppen et al.,[13] to the upper partial mean by Ahmed and Sahinidis, and to regret function measures by Ierapetritou and Pistikopoulos.[14] Symmetric measures such as variance penalize also good scenarios, so they are to be avoided. Barbaro[15] has proven that downside risk is related to risk, as defined above, and used it as an alternative measure. The upper partial mean is inappropriate as it does not render optimal second-stage values and regret functions are just one instance of the sampling average algorithm used to solve risk-constrained problems.

The way to evaluate and manage the financial risk proposed in this work is to use the risk associated with each scenario, which is defined by the probability $P(\mathrm{NPV}^s \leq \Omega)$. To account for this probability, a new binary variable is defined for each scenario that will determine if a factor of risk is present or not (one or zero value, respectively). This variable is related to the lower bound in the net present value (profit expectation level) and the net present value for the realization of the individual scenarios by[16,15]

$$z^s = \begin{cases} 1 & \mathrm{NPV}^s < \Omega \\ 0 & \mathrm{NPV}^s \geq \Omega \end{cases} \quad \forall\, s \in S \tag{33}$$

Therefore, the following relation expresses the financial risk in terms of the probabilities of each scenario:

$$\mathrm{Risk}(\Omega) = \sum_{s=1}^{\mathrm{NS}} p_s z_s \quad \forall\, s \in S \tag{34}$$

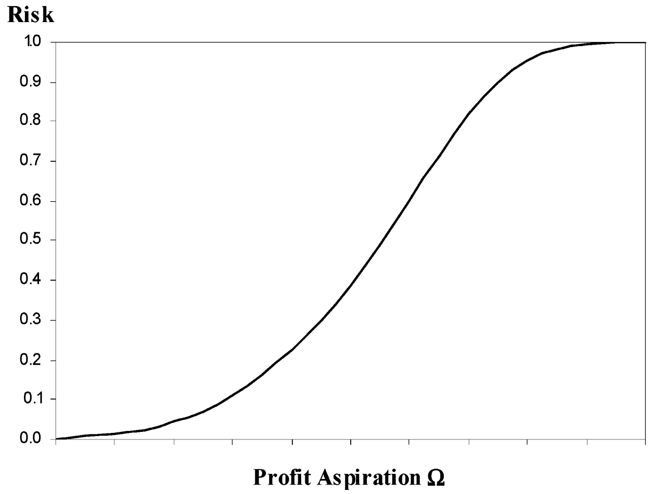


Figure 5. Cumulative risk curve.

This equation can be used to impose an upper bound in the amount of risk allowed for a given profit expectation. These constraints have also been presented by Gupta and Maranas,[17] but not used.. The constraints that define the management of risk are detailed next. Thus, a new model considering risk management composed by all equations in model **SP** plus constraints (35) can be defined. This model is referred to as model **SP–FR**.

$$\sum_{s=1}^{\mathrm{NS}} p^s z^s \leq \Gamma(\Omega)$$

$$\mathrm{NPV}^s \leq \Omega + U^s(1 - z^s) \tag{35}$$

$$\mathrm{NPV}^s \geq \Omega - U^s z^s \quad \forall\, s \in S$$

Here, U^s is an upper bound that forces z^s to take the proper values. In this way, model **SP–FR** will render solutions that maximize the expected net present value and also have the desired level of financial risk.

Clearly, the financial risk is a function of the profit expectation. The behavior of the financial risk can be assessed using the cumulative risk curve, as shown in Figure 5.

For a given design, the cumulative risk curve shows the level of incurred financial risk at each profit. As one would expect, the risk of not meeting very low expectation levels will be null whereas very high profit expectations will have full risk. When only a finite number of scenarios are considered, the cumulative risk curve is a discontinuous step-shaped function. However, when the number of scenarios increases, the curve approaches the continuous behavior.

Management of Financial Risk

Handling the shape and position of the curve are the main interests of the decision maker. A risk-averse investor may want to have low risk for some conservative profit aspiration level, while a risk-taker decision maker would prefer to see lower risk at a higher profit aspiration level, even if the risk at lower profit values increases. Figure 6 illustrates a hypothetical example with these two types of risk curves.

Clearly, the intention of the model **SP–FR** is to identify designs that maximize the expected profit and

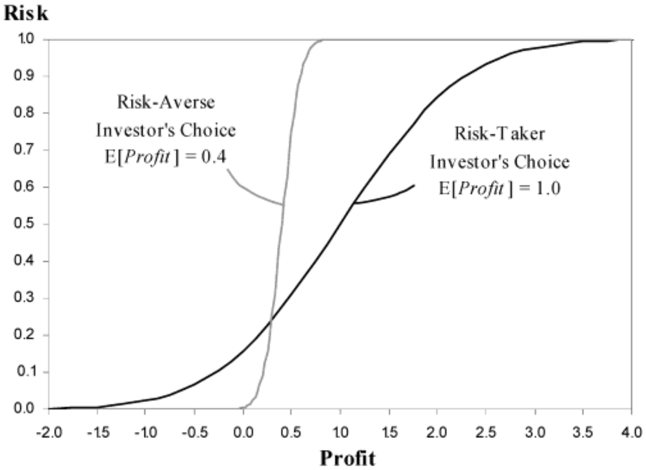


Figure 6. Different kinds of risk preferences.

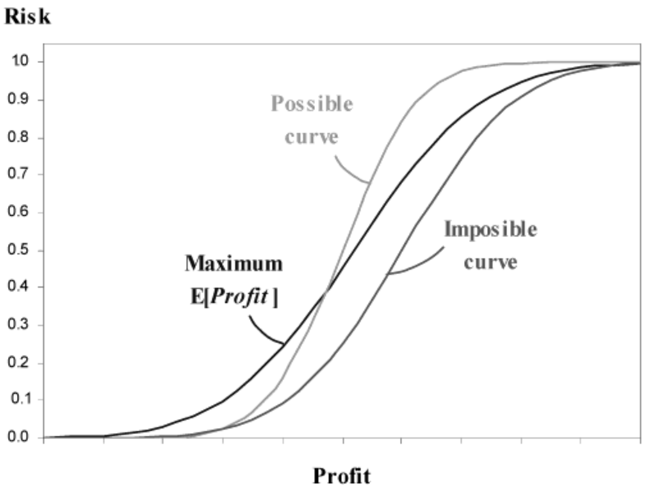


Figure 7. Possible risk curves.

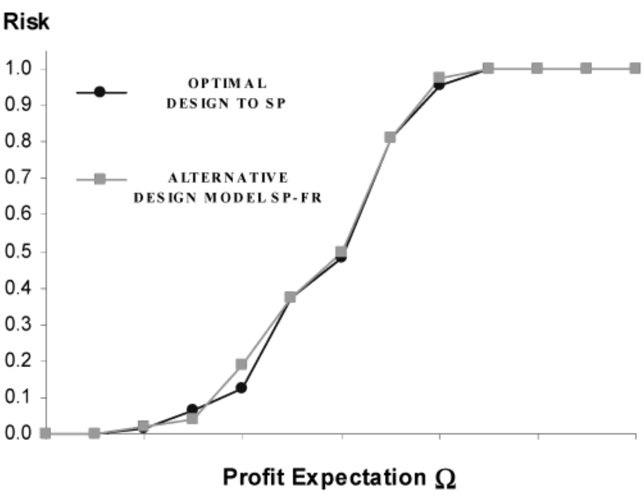


Figure 8. Risk curves.

also have the lowest financial risk possible. However, there are certain theoretical limitations for the risk associated with a given design. These limitations are expressed in the following theorem.

Theorem: The cumulative risk curve associated with any feasible design to model **SP−FR** cannot lie entirely below the risk curve associated with the optimal design to model **SP**.

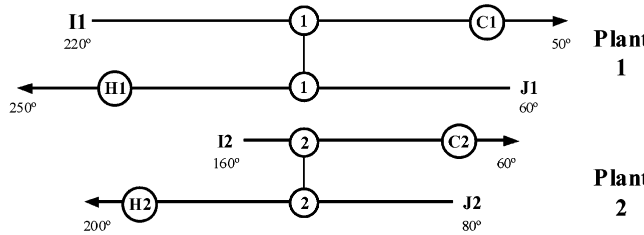


Figure 9. Original HEN.

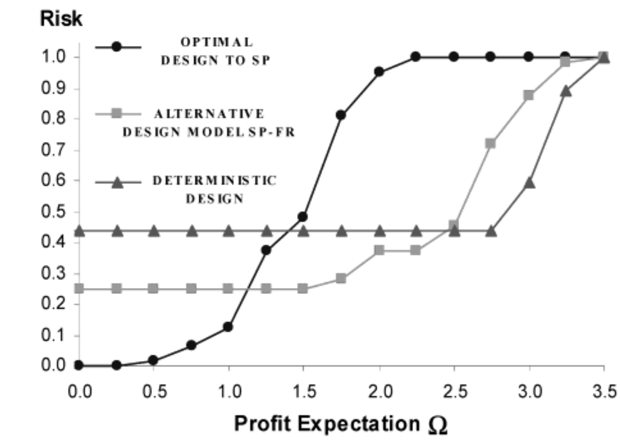


Figure 10. Risk curves for example case.

Table 3. Problem Data

Plant Throughput

K1	K2	probability
0.90	0.90	0.25
1.00	1.00	0.50
1.10	1.10	0.25

Utility Costs \$/(kW yr)

	T1	T2	probability
H1	88.88	106.65	0.25
	106.65	142.20	0.50
	88.88	106.65	0.25
C1	6.83	6.97	

Exchanger Costs \$/(kW yr)

	T1	T2
α	64.96	66.24
β	7545.76	7693.71

Original HE Area and Load

	m^2	kW
1	1462.6 m^2	10000
2	3357.6	9000
H1	2109.5	13750
H2	1386.9	15000
C1	1585.2	7000
C2	1339.2	6000

Discount Factor for NPV

T1	T2
1.00	0.952

Profit and Risk Expectation

W	\$200,000
$\Gamma(\Omega)$	0.40

The proof of this theorem is given by Barbaro and Bagajewicz.[15] This theorem states that the risk curve associated with the optimum design to model **SP** sets a

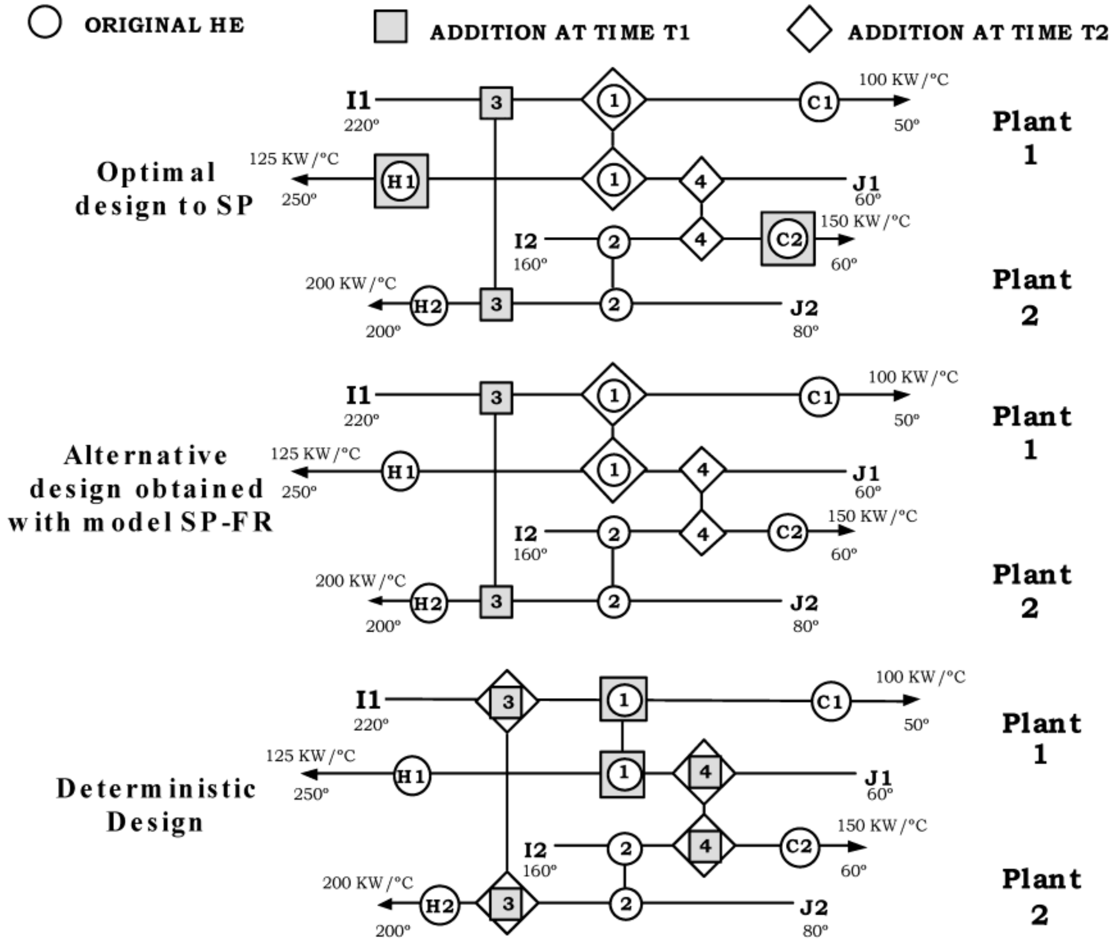


Figure 11. Designs for example case.

Table 4. Heat Loads Distribution and Estimated Area Given by the Model

period	hot stream.plant	cold stream.plant	area, m^2
	Model **SP** Solution		
T1	I3.K1	J1.K1	2441.2
T1	I1.K1	J2.K2	614.5
T1	I2.K2	J3.K2	1614.6
T2	I1.K1	J1.K1	2369.9
T2	I2.K2	J1.K1	399.7
	Model **SP-FR** Solution		
T1	I3.K1	J1.K1	2460.3
T1	I1.K1	J2.K2	601.5
T1	I2.K2	J3.K2	1608.5
T2	I1.K1	J1.K1	2395.8
T2	I2.K2	J1.K1	373.8

theoretical limit. It is possible to find designs that have lower risk for some range of profit expectation but inevitably they will have a higher risk at other expectation levels. This behavior is shown in Figure 7.

As mentioned before, the intention is to manage the risk curve to obtain a design that has a high expectation of net present value and a risk that meets the criterion for investment. This criterion is usually determined by the risk premium of other investment possibilities for the available capital budget.

Example 2

Solving the model **SP−FR** for several test cases, it was observed that designs that operate at full capacity in every scenario would have a risk curve almost identical to the one corresponding to the optimal design to problem **SP**, as depicted in Figure 8. To illustrate this behavior, a small example was chosen. The problem data are given in Table 3 and Figure 9, and the resulting designs are shown in Table 4.

Modified Model Heat Integration Model

To reduce the risk, especially at high expectation levels, we need to allow designs that may not be capable of operating at full capacity for every instance of uncertain parameters. The effect of operating at a lower capacity for some unfavorable scenarios is that designs with lower capital investment may become available; hence, the associated risk can be reduced at higher profit expectations. However, there is a cost penalty for not operating at full capacity, which is associated with the profit not perceived by the lower production. In commodity plants, for instance, this penalty is given by the difference in the cost of the product produced at the plant and the price of buying it from another market supplier. Thus, a simple penalty term can be added to the model **SP−FR** to account for the cost of operating at lower capacity. The new objective function and constraints to be included in model **SP−FR** are described below. This modified model is referred to as **SP−FR−C**.

$$\text{Max NPV} = \sum_s \sum_t \sum_{u \in U} p^s c_u^{ts} \hat{U}_u^{ts} + \sum_s \sum_t \sum_{c \in C} p^s c_w^{ts} \hat{W}_w^{ts} - \sum_s \sum_t \sum_k f_k^{ts} \gamma_k^{ts} (1 - \Phi_k^{ts}) - \sum_t I^t \quad (15')$$

$$\hat{U}_u^{ts} = \sum_k \Phi_k^{ts} f_k^{ts} U_{uk}^{o} - \sum_k \sum_m \sum_{j \in J_k} \sum_{\substack{n \in M_j \\ n \in P_{zkkhjmn}}} q_{ujkkmn}^{ts} \quad \forall\ t \in T;\ s \in S;\ u \in U \quad (24')$$

$$\hat{W}_w^{ts} = \sum_k \Phi_k^{ts} f_k^{ts} U_{wk}^{o} - \sum_k \sum_m \sum_{i \in I_k} \sum_{\substack{m \in M_i \\ m \in P_{zkkicmn}}} q_{iwkkmn}^{ts} \quad \forall\ t \in T;\ s \in S;\ w \in W \quad (25')$$

$$\Phi_k^{ts} f_k^{ts} \Delta H_{ikm} = \sum_{w \in W_n} \sum_{n \in P_{zkkicmn}} q_{iwkkmn}^{ts} + \sum_{\substack{j \in J_k \\ j \in J_n}} \sum_{n \in P_{zkkijmn}} q_{ijkkmn}^{ts} + \sum_{l \neq k} \sum_{\substack{j \in J_k \\ j \in J_n}} \sum_{n \in P_{zklijmn}} q_{ijklmn}^{ts} \quad \forall\ t \in T;\ s \in S\ ;\ k \in K;\ i \in I_k;\ i \in I_m \quad (26')$$

$$\Phi_k^{ts} f_k^{ts} \Delta H_{jln} = \sum_{u \in U_m} \sum_{m \in P_{zllicmn}} q_{ujllmn}^{ts} + \sum_{\substack{i \in I_l \\ i \in I_m}} \sum_{m \in P_{zllijmn}} q_{ijkkmn}^{ts} + \sum_{k \neq l} \sum_{\substack{i \in I_k \\ i \in I_m}} \sum_{m \in P_{zklijmn}} q_{ijklmn}^{ts} \quad \forall\ t \in T;\ s \in S;\ l \in K;\ j \in J_l;\ j \in J_n \quad (27')$$

Example 3

Figure 10 shows the risk curves corresponding to to three different designs for example 2 presented in the previous section. The original heat-exchanger network as well as the final designs are shown in Figure 11.

This small example is intended to illustrate how the risk curve can be handled by using the model **SP−FR−C** in comparison with a design that only maximizes the expected net present value using model **SP**, and a design obtained with the deterministic model considering the mean value of the uncertain parameters. Notice that the alternative design would be a better option if one wanted to have low risk at high expectations. However, this design has a higher risk of not meeting low expectation levels compared to the optimal design to model **SP**, as the stated theorem predicts. On the other hand, the risk curve for solution of the deterministic model shows very high risk at low expectations, which makes the design less attractive.

Quite clearly, there are numerical limitations that emerge from the use of this model. In practice, one may think of using a large number of scenarios, and in such case, one would be adding one binary variable per scenario. There are, however, practical ways around this limitation: (a) One can introduce and use downside risk, which does not rely on binary variables, and (b) one can start using the sample average algorithm as used by Verweij et al.[18]

Conclusions

The concept of financial risk has been incorporated into the heat integration planning problem by using a two-stage stochastic formulation and a probabilistic definition of risk. Theoretical results and observed behaviors of the risk curves were discussed in relation to the management of risk. A new formulation that allows designs operating at lower capacity proved to be an effective tool for risk management.

Nomenclature

$K = \{k|\ k$ is a chemical plant$\}$; $(k \equiv l)$
$I = \{i|\ i$ is a hot stream$\}$
$J = \{j|\ j$ is a cold stream$\}$
$H = \{h|\ h$ is a heating utility$\}$
$C = \{c|\ c$ is a cooling utility$\}$
$M = \{m|\ m$ is a temperature interval$\}$; $(m \equiv n)$
$M_i = \{m|\ m$ is a temperature interval in which stream i exists$\}$
$I_m = \{i|\ i$ is a hot stream that exists in the temperature interval $m\}$
$Z = \{z|\ z$ is a heat-transfer zone$\}$
$P_{zklijmn} = \{(z, k, l, i, j, m, n)|\ (z, k, l, i, j, m, n)$ define a feasible direction for heat transfer$\}$
$T = \{t|\ t$ is a time period$\}$
$S = \{s|\ s$ is a scenario of uncertain parameters$\}$
A = heat-exchanger area
B^t = Investment budget at period t
c = cost
E = heat-exchanger area expansion
f = normalized plant throughput (f = 1 for nominal capacity)
I^t = investment cost at period t
p = probability
q = heat transferred
$\hat{U}$ = energy savings in hot utilities
$U°$ = utility consumption if none of the original heat-exchanger network were operating
Y = binary decision that decides whether a capacity expansion is produced or not
$\hat{W}$ = energy savings in cold utilities
α = variable cost of heat-exchange area addition
β = fixed charge cost of heat-exchange area addition
γ = penalty cost coefficient for operating at reduced capacity
Φ = normalized capacity factor (Φ = 1 for operation at the required capacity for the scenario)
ΔH = enthalpy change

Literature Cited

(1) Morton, R. J.; Linnhoff, B. Individual process improvements in the context of side-wide interactions. Inst. Chem. Eng., Annual Research Meeting, Bath, UK, 1984.

(2) Ahmad, S.; Hui, C. W. Heat recovery between areas of integrity. *Comput. Chem. Eng.* **1991**, *15*, 809.

(3) Dhole, V. R.; Linnhoff, B. Total site targets for fuel, co-generation, emissions, and cooling. *Comput. Chem. Eng.* **1992**, *17*, S101.

(4) Rodera, H.; Bagajewicz, M. J. Accomplishing profitable savings by realistically heat integrating a crude fractionation unit and an FCC unit. AIChE National Meeting, Houston, TX, 1999; Paper 45c.

(5) Rodera, H.; Bagajewicz, M. J. Targeting procedures for energy savings by heat integration across plants. *AIChE J.* **1999**, *45*, 1721.

(6) Bagajewicz, M. J.; Rodera, H. Energy savings in the total site. Heat integration across many plants. *Comput. Chem. Eng.* **2000**, *24*, 1237.

(7) Bagajewicz, M.; Rodera, H. Multiple Plant Heat Integration in the Total Site. *AIChE J.* **2002**, *48* (10), 2255.

(8) Rodera, H.; Bagajewicz, M. Multipurpose Heat Exchanger Networks for Heat Integration across Chemical Plants. *Ind. Eng. Chem. Res.* **1984**, *40* (23), 5585.

(9) Shethna, H. K.; Jezowski, J. M.; Castillo, F. J. L. A new methodology for simultaneous optimization of capital and operating cost targets in heat exchanger network design. *Appl. Therm. Eng.* **2000**, *20*, 1577.

(10) Liu, M. L.; Sahinidis, N. V. Optimization in Process Planning Under Uncertainty. *Ind. Eng. Chem. Res.* **1996**, *35*, 4154.

(11) McCray, A. W. *Petroleum Evaluations and Economic Decisions*; Prentice Hall: Englewood Cliffs, NJ, 1975.

(12) Mulvey, J. M.; Vanderbei, R. J.; Zenios, S. A. Robust optimization of large-scale systems. *Oper. Res.* **1995**, *43*, 264.

(13) Eppen, G. D.; Martin, R. K.; Schrage, L. A Scenario Approach to Capacity Planning. *Oper. Res.* **1989**, *37*, 517.

(14) Ierapetritou, M. G.; Pistikopoulos, E. N. Simultaneous incorporation of flexibility and economic risk in operational planning under uncertainty. *Comput. Chem. Eng.* **1994**, *18* (3), 163.

(15) Barbaro, A.; Bagajewicz, M. Managing Financial Risk in Planning Under Uncertainty. *AIChE J*. **2003**, in press.

(16) Barbaro A. F.; Bagajewicz, M. Financial Risk Management in Planning under Uncertainty. *Proceedings of FOCAPO 2003. (Foundations of Computer Aided Process Operations)*, Coral Springs, FL, 2003.

(17) Gupta, A.; Maranas, C. Market-Based Pollution Abatement Strategies: Risk Management using Emission Option Contracts. *Ind. Eng. Chem. Res.* **2003**, *42*, 802.

(18) Verweij, B.; Ahmed, S.; Kleywegt, A. J.; Nemhauser, G.; Shapiro, A. The Sample Average Approximation Method Applied to Stochastic Routing Problems: A Computational Study. *Comput. Appl. Optimization* **2003**, *24*, 289.

Received for review May 24, 2002
Revised manuscript received July 22, 2003
Accepted July 22, 2003

IE020389U