Financial Planning with Risk Control of Energy Recovery in the Total Site

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Abstract
A Two-Stage Stochastic formulation to plan the implementation of energy savings 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. The concept of Financial Risk is introduced and the management of risk is discussed and incorporated to the model.

Introduction

Heat integration across plants can be at times very profitable. The designs can be implemented either directly using process streams or indirectly through the use of an intermediate fluid such as steam or dowtherms. Rodera and Bagajewicz (1999,a,b,c) presented an industrial case study where the integration of four units in a petrochemical complex (Crude fractionation, FCC, Alkylation and Claus plant) is determined. Barbaro and Bagajewicz (2001) presented a financial planning of such integration over a time horizon, specifically determining what heat exchangers should be added at each time.

In this paper, 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 presented. The goal of the model is to determine the time, size and location of expansions in the heat exchanger network in order 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 in order to adjust to the actual conditions. The formulation simultaneously targets capital and operating cost of heat exchanger network through a mixed integer linear programming transportation model. In principle, the uncertain parameters for this model are following:

- Flow rate of each stream
- Inlet temperature of each stream
- Utility prices
- Heat exchanger cost prices
- Discount rates

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 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 (1996) for the capacity planning problem. Financial risk constraints are added later.

Stochastic Programming Model without Risk Considerations

The two-stage stochastic model for the planning of energy recovery in the Total Site is presented next. This model will be referred as model ***P*** and represents an extension of a deterministic formulation for the planning of heat integration introduced by Barbaro and Bagajewicz (2001). In this model, the objective function (1) 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.

$$\boldsymbol{P} = \text{ Max } NPV = \sum_s \sum_t \sum_{h\in H} p^s c_h^{ts} \hat{S}_h^{ts} + \sum_s \sum_t \sum_{c\in C} p^s c_c^{ts} \hat{S}_c^{ts} - \sum_t I^t \tag{1}$$

subject to

$$E^L_{zijkl}\, Y^t_{zijkl} \le E^t_{zijkl} \le E^U_{zijkl}\, Y^t_{zijkl} \qquad \forall\ t; z\in Z; k,l\in K; i\in I_k;\ j\in J_l \tag{2}$$

$$E^L_{zhjkk}\, Y^t_{zhjkk} \le E^t_{zhjkk} \le E^U_{zhjkk}\, Y^t_{zhjkk} \qquad \forall\ t; z\in Z; k\in K; h\in H;\ j\in J_k \tag{3}$$

$$E^L_{zickk}\, Y^t_{zickk} \le E^t_{zickk} \le E^U_{zickk}\, Y^t_{zickk} \qquad \forall\ t; z\in Z; k\in K; i\in I_k; c\in C \tag{4}$$

$$A^t_{zijkl} = A^{t-1}_{zijkl} + E^t_{zijkl} \qquad \forall\ t; z\in Z; k,l\in K; i\in I_k;\ j\in J_l \tag{5}$$

$$A^t_{zhjkk} = A^{t-1}_{zhjkk} + E^t_{zhjkk} \qquad \forall\ t; z\in Z; k\in K; h\in H;\ j\in J_k \tag{6}$$

$$A^t_{zickk} = A^{t-1}_{zickk} + E^t_{zickk} \qquad \forall\ t; z\in Z; k\in K; i\in I_k; c\in C \tag{7}$$

$$\begin{aligned} I^t = & \sum_z \sum_k \sum_l \sum_{i\in I_k} \sum_{j\in J_l} \alpha^t_{zijkl} E^t_{zijkl} + \beta^t_{zijkl} Y^t_{zijkl} \\ & \sum_z \sum_k \sum_{h\in H_k} \sum_{j\in J_l} \alpha^t_{zhjkk} E^t_{zhjkk} + \beta^t_{zhjkl} Y^t_{zhjkk} \\ & \sum_z \sum_k \sum_{i\in I_k} \sum_{c\in C_l} \alpha^t_{zickk} E^t_{zickk} + \beta^t_{zhjkl} Y^t_{zickk} \end{aligned} \qquad \forall\ t\in T \tag{8}$$

$$I^t \le B^t \qquad \forall\ t\in T \tag{9}$$

$$\hat{S}_h^{ts} = \sum_k f_k^{ts} U^{\mathrm{o}}_{hk} - \sum_z \sum_k \sum_m \sum_{j\in J_k} \sum_{\substack{n\in M_j \\ n\in P_{zkkhjmn}}} q^{ts}_{zhjkkmn} \qquad \forall\ t\in T; s\in S; h\in H \tag{10}$$

$$\hat{S}_c^{ts} = \sum_k f_k^{ts} U^{\mathrm{o}}_{ck} - \sum_z \sum_k \sum_m \sum_{i\in I_k} \sum_{\substack{m\in M_i \\ m\in P_{zkkicmn}}} q^{ts}_{zickkmn} \qquad \forall\ t\in T; s\in S; h\in H \tag{11}$$

$$f_k^{ts} \Delta H_{zikm} = \sum_{c\in C_n} \sum_{n\in P_{zkkicmn}} q^{ts}_{zickkmn} + \sum_{\substack{j\in J_k \\ j\in J_n}} \sum_{n\in P_{zkkijmn}} q^{ts}_{zijkkmn} + \sum_{l\ne k} \sum_{\substack{j\in J_k \\ j\in J_n}} \sum_{n\in P_{zklijmn}} q^{ts}_{zijklmn} \qquad \forall\ t\in T; s\in S; z\in Z; k\in K; i\in I_k; i\in I_m \tag{12}$$

$$f_k^{ts} \Delta H_{zjln} = \sum_{h\in H_m} \sum_{m\in P_{zllicmn}} q^{ts}_{zhjllmn} + \sum_{\substack{i\in I_l \\ i\in I_m}} \sum_{m\in P_{zllijmn}} q^{ts}_{zijkkmn} + \sum_{k\ne l} \sum_{\substack{i\in I_k \\ i\in I_m}} \sum_{m\in P_{zklijmn}} q^{ts}_{zijklmn} \qquad \forall\ t\in T; s\in S; z\in Z; l\in K; j\in J_l;\ j\in J_n \tag{13}$$

$$A^t_{zijkl} \ge \sum_{m\in M_i} \sum_{\substack{n\in M_j \\ n\in P_{zklijmn}}} \frac{h_i h_j}{(h_i + h_j)} \frac{q^{ts}_{zijklmn}}{LMDT_{mn}} \qquad \forall\ t\in T; s\in S; z\in Z; k,l\in K; i\in I_k;\ j\in J_l \tag{14}$$

$$A^t_{zhjkk} \ge \sum_{m\in M_h} \sum_{\substack{n\in M_j \\ n\in P_{zkkhjmn}}} \frac{h_h h_j}{(h_h + h_j)} \frac{q^{ts}_{zhjkkmn}}{LMDT_{mn}} \qquad \forall\ t\in T; s\in S; z\in Z; k\in K; h\in H;\ j\in J_k \tag{15}$$

$$A^t_{zickk} \ge \sum_{m\in M_i} \sum_{\substack{n\in M_c \\ n\in P_{zkkicmn}}} \frac{h_i h_c}{(h_i + h_c)} \frac{q^{ts}_{zickkmn}}{LMDT_{mn}} \qquad \forall\ t\in T; s\in S; z\in Z; k\in K; i\in I_k; c\in J \tag{16}$$

$$q^{ts}_{zijklmn}, q^{ts}_{zhjkkmn}, q^{ts}_{zickkmn} \ge 0 \qquad Y^t_{zijkl}, Y^t_{zhjkk}, Y^t_{zickk} = (0,1) \tag{17}$$

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. The second stage decisions 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 in the capacity expansion and the total capacity available are represented by equations (2) to (4). These constraints force expansions to be zero whenever the corresponding binary decision variable is zero. In turn, equations (5) to (7) define the total installed area for the correspondent match at every time period. Equations (8) and (9) define the investment cost and limit it to the available budget. Equations (10) and (11) express the savings in heating and cooling utilities, respectively. Equations (12) and (13) represent the energy balances for each stream and temperature interval. Finally, inequalities (14) to (16) assure 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 to 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:

$$Risk(\Omega) = P(NPV \le \Omega) \tag{18}$$

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 $P(NPV^s \le \Omega)$. 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 with the lower bound in the net present value (profit expectation level) and the net present value for the realization of the individual scenarios by:

$$z^s = \begin{cases} 1 & NPV^s < \Omega \\ 0 & NPV^s \ge \Omega \end{cases} \qquad \forall s \in S \tag{19}$$

Therefore, the following relation express the financial risk in terms of the probabilities of each scenario.

$$Risk(\Omega) = \sum_{s=1}^{NS} p_s z_s \qquad \forall s \in S \tag{20}$$

This equation can be used to impose an upper bound in the amount of risk allowed for a given profit expectation. The constraints that define the management of risk are detailed next. These constraints, together with (19) are then included in the previous model. Thus, the new model considering risk management is composed by all equations in model ***P*** plus constraints (22). This model will be referred as model ***PR***.

$$\begin{aligned} &\sum_{s=1}^{NS} p^s z^s \le \Gamma(\Omega) \\ &NPV^s \le \Omega + U^s(1 - z^s) \qquad \forall s \in S \\ &NPV^s \ge \Omega - U^s z^s \end{aligned} \tag{21}$$

Here U^s is an upper bound that forces z^s to take the proper values. In this way, model ***PR*** 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 1. 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. The following section provides more insights on the management of the risk curve.

Management of Financial Risk

Clearly, the intention of the model ***PR*** is to identify designs that maximize the expected profit and 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. The proof to this theorem is omitted because of space limitations.

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

This theorem states that the risk curve associated with the optimum design to model ***P*** sets a 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 2.

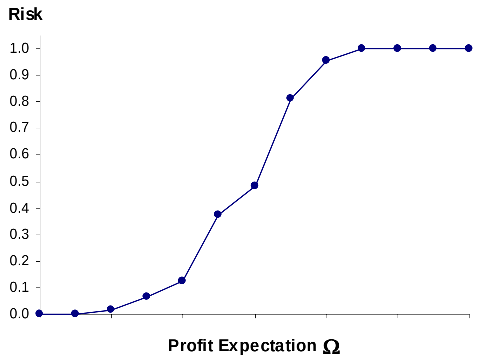

Figure 1. Cumulative Risk Curve

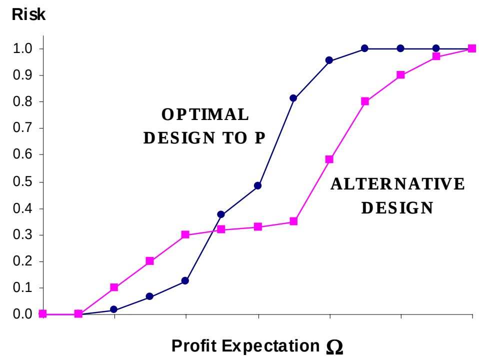

Figure 2. Risk Curve Management

As mentioned before, the intention is to manage the risk curve in order to get 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. Solving the model ***PR*** 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 correspondent to the optimal design to problem ***P***, as depicted in Figure 3.

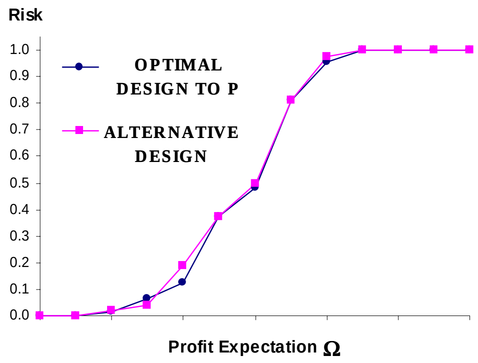

Figure 3. Risk Curves for Full Capacity Designs

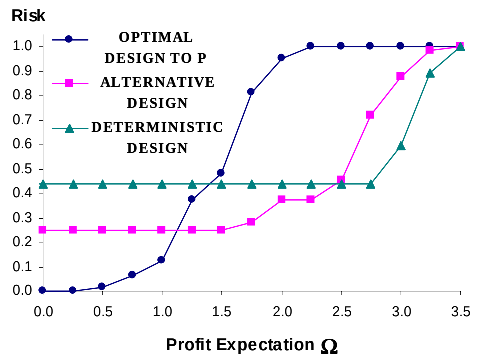

Figure 4. Risk Curves for Example Case

Therefore, we may conclude that in order to reduce the risk, especially at high expectation levels, we need to allow designs that may not be capable of operate 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 ***PR*** to account for the cost of operating at lower capacity. The new objective function and constraints to be included in model ***PR*** are described below. This modified model is referred as ***PRC***.

$$\text{Max } NPV = \sum_s \sum_t \sum_{h \in H} p^s c_h^{ts} \hat{S}_h^{ts} + \sum_s \sum_t \sum_{c \in C} p^s c_c^{ts} \hat{S}_c^{ts} - \sum_t I^t - \sum_t \sum_k f_k^{ts} (1 - \Phi_k^{ts}) \gamma_k^{ts} \qquad (1')$$

$$\hat{S}_h^{ts} = \sum_k \Phi_k^{ts} f_k^{ts} U_{hk}^{o} - \sum_z \sum_k \sum_m \sum_{j \in J_k} \sum_{\substack{n \in M_j \\ n \in P_{zkkhjmn}}} q_{zhjkkmn}^{ts} \qquad \forall t \in T; s \in S; h \in H \qquad (10')$$

$$\hat{S}_c^{ts} = \sum_k \Phi_k^{ts} f_k^{ts} U_{ck}^{o} - \sum_z \sum_k \sum_m \sum_{i \in I_k} \sum_{\substack{m \in M_i \\ m \in P_{zkkicmn}}} q_{zickkmn}^{ts} \qquad \forall t \in T; s \in S; h \in H \qquad (11')$$

$$\Phi_k^{ts} f_k^{ts} \Delta H_{zikm} = \sum_{c \in C_n} \sum_{n \in P_{zkkicmn}} q_{zickkmn}^{ts} + \sum_{\substack{j \in J_k \\ j \in J_n}} \sum_{n \in P_{zkkijmn}} q_{zijkkmn}^{ts} + \sum_{l \neq k} \sum_{\substack{j \in J_k \\ j \in J_n}} \sum_{n \in P_{zklijmn}} q_{zijklmn}^{ts} \qquad \forall t \in T; s \in S; z \in Z; k \in K; i \in I_k; i \in I_m \qquad (12')$$

$$\Phi_k^{ts} f_k^{ts} \Delta H_{zjln} = \sum_{h \in H_m} \sum_{m \in P_{zllicmn}} q_{zhjllmn}^{ts} + \sum_{\substack{i \in I_l \\ i \in I_m}} \sum_{m \in P_{zllijmn}} q_{zijkkmn}^{ts} + \sum_{k \neq l} \sum_{\substack{i \in I_k \\ i \in I_m}} \sum_{m \in P_{zklijmn}} q_{zijklmn}^{ts} \qquad \forall t \in T; s \in S; z \in Z; l \in K; j \in J_l; j \in J_n \qquad (13')$$

Example

Figure 4 shows the risk curves correspondent to three different designs for a simple case. The original heat exchanger network as well as the final designs for this example are shown in Figure 5. This small example is intended to illustrate how the risk curve can be handled by using the model ***PRC*** in comparison with a design that only maximizes the expected net present value using model ***P***, 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 a low risk at high expectations. However, this design has a higher risk of not meeting low expectation levels than the optimal design to model ***P***, 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 make the design less attractive.

Plant Throughput

K1	K2	Proba.
0.90	0.90	0.25
1.00	1.00	0.50
1.10	1.10	0.25

Utility Costs $/(KW yr)

	T1	T2	Proba.
H1	88.88	106.65	0.25
	106.65	142.20	0.50
	88.88	106.65	0.25
C1	6.83	6.97	

C1	1585.2	7000
C2	1339.2	6000

Discount Factor for NPV

T1	T2
1.00	0.952

Exchanger Costs $/(KW yr)

	T1	T2
a	64.96	66.24
b	7545.76	7693.71

Profit and Risk Expectation

W	$200,000
G(W)	0.40

Original HE Area and Load

	m^2	KW
1	1462.6	10000
2	3357.6	9000
H1	2109.5	13750
H2	1386.9	15000

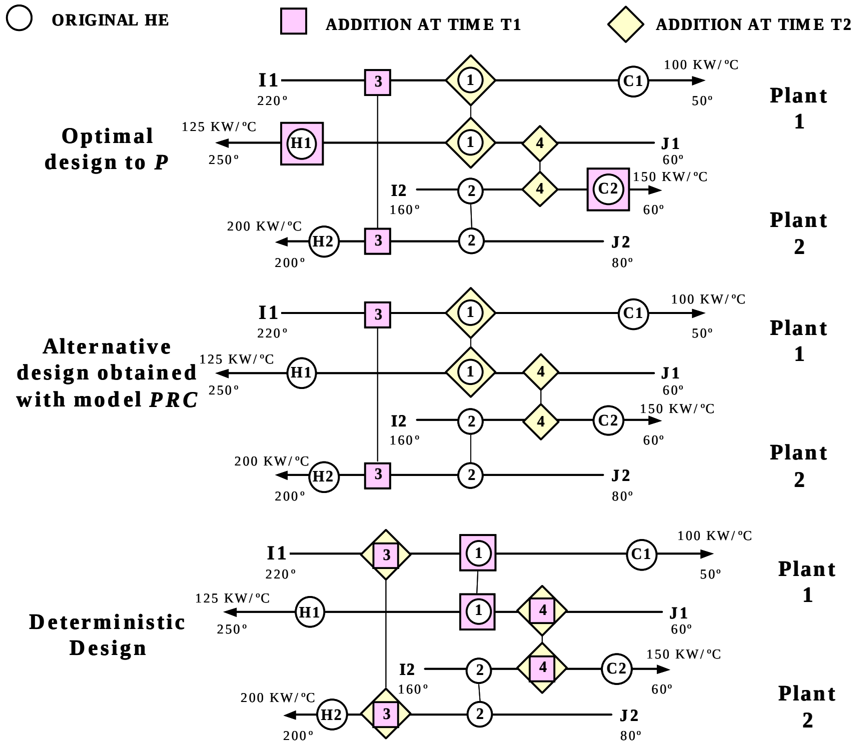

Figure 5. Designs for Example Case

Conclusions

The concept of financial risk has been incorporated to 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.

Definitions

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 exist 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

$\hat{S}$	Energy savings in utilities
U^{o}	Utility consumption if no the original heat exchanger network were operating
Y	Binary decision that decides whether a capacity expansion is produced or not
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

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