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Financial Pinch Analysis for Selection of Energy Conservation Projects with Uncertainties

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Expenditure for energy utilities is significant for most process plants. The identification and implementation of various energy conservation projects are essential in reducing the operating cost and greenhouse gas emissions associated with energy use. Typically, energy conservation projects need capital investments drawn from limited funding sources. Appropriate selection of these projects is important to ensure overall financial and environmental benefits. Varying energy prices, an evolving carbon emissions regulatory regime, changes in product quality, energy efficiency requirements, and unscheduled maintenance of different process equipment/units make the overall financial returns inherently uncertain. In this work, Financial Pinch Analysis is extended to incorporate uncertainties for the appropriate selection of energy conservation projects. Monte Carlo simulations are performed to account for various sources of uncertainty in financial return metrics for the energy conservation projects. A stochastic linear programming problem is formulated to identify appropriate energy conservation projects. The chance constraint programming method is applied to convert the original stochastic linear programming problem into a deterministic Pinch Analysis framework at different reliability levels. The applicability of the proposed method is illustrated through an example.

1. Introduction

Efficient use of energy is an imperative need for competitiveness and profitability enhancement in the process industries. Typically, energy conservation projects are capital intensive and funded by limiting funding sources. A proper capital budgeting strategy is required to implement these projects profitably, an important prerequisite for sustainable industrial operations especially from an economic viewpoint. An appropriate selection of projects from a pool of identified projects is the most important aspect of the above capital budgeting procedure. Typically, capital budgeting is performed assuming specified returns from these energy conservation projects. However, in most cases, the economic returns of the projects are uncertain due to varying energy prices, unscheduled maintenance needs, changes in product quality, etc. Therefore, the effect of uncertainty in project returns should be incorporated in the capital budgeting framework for long-term planning. Proper methods need to be developed for the capital budgeting of energy conservation projects with uncertain annual returns.
Pinch Analysis-based methods have demonstrated insightfulness in resource optimisation of source-sink problems using graphical techniques like Limiting Composite Curve (Agarwal and Shenoy, 2006), Material Recovery Pinch Diagram (Prakash and Shenoy, 2005), etc. Pinch Analysis-based methods extended their applicability in the capital budgeting domain by Roychaudhuri and Bandyopadhyay (2018). Bandyopadhyay (2020) developed economic Pinch Analysis for appraisal of the sustainability projects. Graphical and algebraic methods were proposed in this paper for calculating the economic indicators like Net Present Value (NPV), Annual Worth (AW), etc. Shukla and Chaturvedi (2021) developed a graphical Pinch Analysis-based methodology to reduce the capital investment and energy requirements for gas transportation in process

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industries, an important aspect for framing the environmental policy of a specific industry. Pinch Analysis-based graphical methods were also applied for cash flow management of industrial projects (Ongpeng et al., 2019). Established methods of capital budgeting consider only deterministic returns from these projects. In this paper, an algebraic procedure has been proposed to select energy conservation project(s) with uncertain returns while satisfying the financial profitability constraints of every project and the limited cash available for the implementation of various projects. Uncertain returns from the projects make the financial profitability constraints probabilistic. Chance Constrained Programming techniques are applied to convert the probabilistic constraints into a linear realisation framework (Charnes and Cooper, 1959). The details of the problem and methodology are discussed in Section 2 of the manuscript.

2. Problem statement and mathematical formulation

The proposed methodology solves a specific type of capital budgeting problem involving energy conservation projects with probabilistic returns. NPV is considered as the measure of profitability for both the projects and funds to capture the time value of money over the project lifetime. Discounted Return on Investment (DROI) is used to quantify the worthiness of the projects and funds in terms of financial returns (Roychaudhuri and Bandyopadhyay, 2018). The problem statement is schematically shown in Figure 1 and mathematically stated below.

A set N number of sources (funds) is considered. Each funding source i (i = 1, 2, …, N) has a maximum limit of cash flow C_{Fi}, rate of interest x_i, and tenure of n_i^F. A set of M demands (energy conservation projects) are given. The projects are mutually independent. Each project j(j = 1, 2, …, M) has a fixed initial investment of C_{pj}, a life of n_{pj}, and a probabilistic annual return having an expected value of R_{pj} . There may be unutilised funds from the funding sources which cannot be used to implement the given set of projects due to profitability constraints. In this problem, the scope of rejecting one or more projects (either totally or partially) is exercised to satisfy the constraint of profitability of each project. If a project is not funded then the opportunity of realising any monetary benefits due to energy conservation on implementing the specific project is lost. This is referred to as the opportunity cost of the projects or the “do-nothing” funding option. The do-nothing funding option refers to the maintenance of the “status quo” of the process (Roychaudhuri and Bandyopadhyay, 2018). The objective of this problem is to minimise the cash flow of the “do-nothing” funding option, subject to the financial constraints of profitability and limited availability of funds.

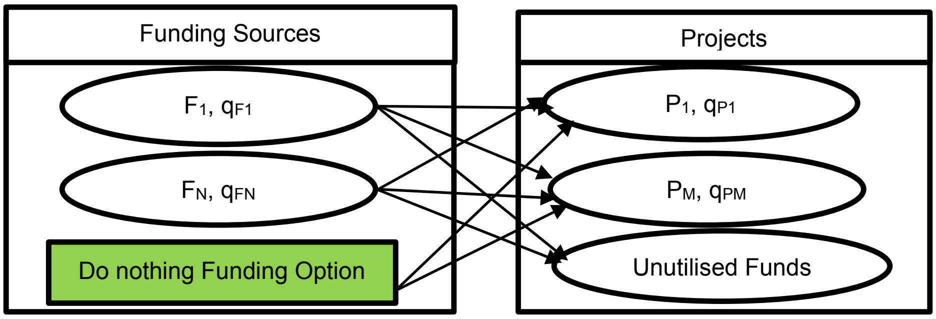

Figure 1: Source-Sink model of allocation of funds

2.1 Mathematical formulation

Positive NPV is considered as the profitability measure of the energy conservation projects. To assess the profitability of the projects the NPV of both the projects and the funds need to be calculated. The detailed mathematical formulation of the problem and pertinent equations are discussed in this section. The annualised flow of funds, AR_{Fi} is given by

$$AR_{Fi} = C_{Fi} \times CRF_{Fi} \tag{1}$$

where C_{Fi} is the maximum available limit of cash flow from funding source i. The capital recovery factor (CRF_{Fi}) is given by

$$CRF_{Fi} = \frac{x_i \times (1 + x_i)^{n_i^F}}{((1 + x_i)^{n_i^F} - 1)} \tag{2}$$

where x_i is the rate of interest and n_i^F is the tenure of the funding source i. For NPV calculation, the annualised returns of the projects and funds are to be discounted at a common discount rate decided by the pertinent industry. This discount rate is known as the Minimum Acceptable Rate of Return (MARR). The value of the discount factor for cash flow discounting at $MARR$, the discounted capital recovery factor for funds ($DCRF_{Fi}$) is given by

$$DCRF_{Fi} = \frac{(1 + MARR)^{n_i^F} - 1}{MARR \times (1 + MARR)^{n_i^F}} \tag{3}$$

The calculation of the discounted capital recovery factor for projects, $DCRF_{Pj}$ is performed in the same way as that of funds, considering the lifetime of the projects n^{Pj}.
Now by definition, the $(NPV)_{Fi}$ of the i^{th} fund is given by

$$(NPV)_{Fi} = \frac{AR_{Fi}}{DCRF_{Fi}} - C_{Fi} \tag{4}$$

Similarly, the $(NPV)_{Pj}$ of the j^{th} project is given by

$$(NPV)_{Pj} = \frac{R_{Pj}}{DCRF_{Pj}} - C_{Pj} \tag{5}$$

where R_{pj} is the probabilistic annual return of the project j, $DCRF_{Pj}$ is the capital recovery factor of the project discounted at MARR and C_{Pj} is the initial investment of the j^{th} project. Note that $(NPV)_{pj}$ is probabilistic as R_{Pj} is a random variable in the formulation of the problem under consideration.
In this problem, discounted return of investment (DROI) is taken as an economic performance assessment measure (Roychaudhuri and Bandyopadhyay, 2018). The value of DROI for the i^{th} fund is given by

$$(DROI)_{Fi} = \frac{(NPV)_{Fi}}{C_{Fi}} \tag{6}$$

Similarly, the DROI of the j^{th} project is given by

$$(DROI)_{Pj} = \frac{(NPV)_{Pj}}{C_{Pj}} \tag{7}$$

Note that as $(NPV)_{Pj}$ is probabilistic within a given range, the $(DROI)_{Pj}$ is also probabilistic following a certain probability distribution with a mean and standard deviation.

2.2 Cash flow balance and profitability equations

Let, c_{ij} be the flow of cash from the i^{th} fund (source) to the j^{th} project (demand), and c_{ui} denotes the unutilised portion of fund i. The cash flow balance equation for the funding source i with maximum available cash flow, C_{Fi} given by

$$C_{Fi} = \sum_{j=1}^{M} c_{ij} + c_{ui} \qquad \forall\, j = 1, 2, 3, \dots, M \tag{8}$$

The cash flow balance for initial investment, C_{Pj} of the project j with an unfunded portion of projects denoted by c_{DNj} is given by

$$C_{Pj} = \sum_{i=1}^{N} c_{ij} + c_{DNj} \qquad \forall\, i = 1, 2, 3, \dots, N \tag{9}$$

In this problem, a positive value of NPV indicates that the project is profitable. Since the value of NPV is uncertain, a certain reliability level $\propto$ is assumed, at which the value of NPV will become positive i.e. the project j is profitable. Mathematically it is expressed as a probabilistic inequality shown in Eq(10).

$$Prob[C_{Pj} \times DROI_{Pj} \geq \sum_{i=1}^{i=n} (c_{ij} \times DROI_{Fi}) + (c_{DNj} \times DROI_{Pj})] \geq \propto \tag{10}$$

For individual projects to be profitable, the NPV of the projects must be greater than the summation of the NPV of the projects and the do-nothing portion of the projects. The primary objective of the problem is the minimisation of the opportunity cost, c_{DNj}, of the projects. The objective function of the optimisation problem is thus given by Eq(11).

$$\text{Minimise} \sum_{j=1}^{M} c_{DNj} \tag{11}$$

The constraints of the flow of funds and quality load (NPV) are given by Eq(8-10). Chance Constrained programming is applied for converting this inequality Eq(10) into its deterministic equivalent as discussed in the following subsection to formulate the problem within the framework of Pinch Analysis.

2.3 Mathematical Analysis - Chance Constrained programming and Monte Carlo simulation

In this problem, the annual return obtained from every project is assumed to follow a normal probability distribution. Monte Carlo simulation is performed to find a set of values of NPV_{Pj} of project j taking into consideration the uncertainty in the annual return of the project. The Monte Carlo simulation is carried out for n iterations until the difference of the Standard Deviation of the set values of NPV_{Pj} obtained at the (n-1) and n algorithmic iterations algorithmically converge to zero. By performing Monte Carlo simulations with n iterations, a set containing n values of NPV_{Pj} is obtained whose mean is found to be exactly equal to the value of the NPV_{Pj} calculated without considering any uncertainty in the return. The results of the value of mean (μ_{Pj}^{NPV}) and Standard Deviation (σ_{Pj}^{NPV}) obtained after carrying out Monte Carlo simulations with n iterations are verified. The values of the mean and standard deviation of the n values of NPV_{Pj} obtained as an output of the Monte Carlo simulation runs are used in the Chance Constrained programming approach to estimate the effective NPV_{Pj} denoted by NPV_{Pj}^{E} (Charnes and Cooper, 1959). By calculating the NPV_{Pj}^{E}, the predicted $(DROI)_{Pj}$ can be obtained by using Eq(7). The predicted $(DROI)_{Pj}$ value is deterministic and hence Eq(11) can be converted to its deterministic equivalent. By using Chance Constrained programming, the value of NPV_{Pj}^{E} considering uncertainty is calculated as shown in Eq(12).

$$NPV_{Pj}^{E} = \mu_{Pj}^{NPV} - z_{\propto}\sigma_{Pj}^{NPV} \tag{12}$$

where $z_{\propto}$ is the inverse cumulative probability distribution function of a standard normal distribution.
It should be pointed out that the above Eqs(8-11) do not encompass any non-linear terms. Eq(10) is converted into a deterministic realisation form by applying a standard Chance Constrained programming technique using Eq(12). The aforementioned problem is integrated into the conventional structure of a linear programming optimisation problem. Therefore, the minimum resource requirement for satisfying all the constraints can be obtained by using standard methods of Pinch Analysis. Minimum Opportunity Cost Targeting Algorithm as proposed by Roychaudhuri and Bandyopadhyay (2018) is used to find out the optimum resource requirement satisfying all the constraints. The proposed methodology is illustrated in the next section with an example.

3. Illustrative example: A case study from Indian Paper and Pulp industry

The applicability of the proposed method described in Section 2 is illustrated in a case study involving the selection of energy conservation projects in the Indian Paper and Pulp industry. The attributes of the projects and funds are taken from the literature (Roychaudhuri and Bandyopadhyay, 2018) Table 1 gives the specific details of the funds whereas the ones associated with the projects are given in Table 2.

Table 1: Details of funds

Funds	Cash flow (k$)	Tenure (y)	Interest rate	DROI
F1	80	10	12 %	0
F2	80	10	20 %	0.348
F3	160	10	30 %	0.828

Table 2: Details of projects

Projects	Investment (k$)	Life (y)	Annual Savings (k$/y)	DROI
P1	24.67	10	4.78±5%	0.095
P2	210	10	43.66±5%	0.175
P3	8.33	10	1.77±5%	0.201
P4	11.67	10	3.24±5%	0.569
P5	11.67	10	5.01±5%	1.426
P6	16.67	10	17.4%±5%	4.898

From Table 1, it can be seen that all attributes of the funds are deterministic. From Table 2, it can be seen that the annual return of the projects is probabilistic. The annual return of the projects is assumed to be varying between 5 % higher or lower than the expected value. For deterministic cases (50 % reliability), P1 is rejected completely and P2 is partially rejected (about 30 %). All other projects are accepted.

3.1 Calculation of the unfunded portion of the projects for probabilistic returns

In this section, the opportunity costs available from the project(s) are calculated assuming uncertain annual returns following normal probability distribution profiles. The constraint in Eq(10) is met at 95 % reliability. The inverse of a standard normal distribution at 95 % reliability is 1.644. The DROI of projects is shown in Table 3. The opportunity cost available from the projects is calculated using the Minimum Opportunity Cost Targeting Algorithm (MOCTA) as illustrated by Roychaudhuri and Bandyopadhyay (2018) and shown in Tables 3 and 4. The graphical illustration of the project selection procedure using Pinch Analysis is provided in Figure 2.

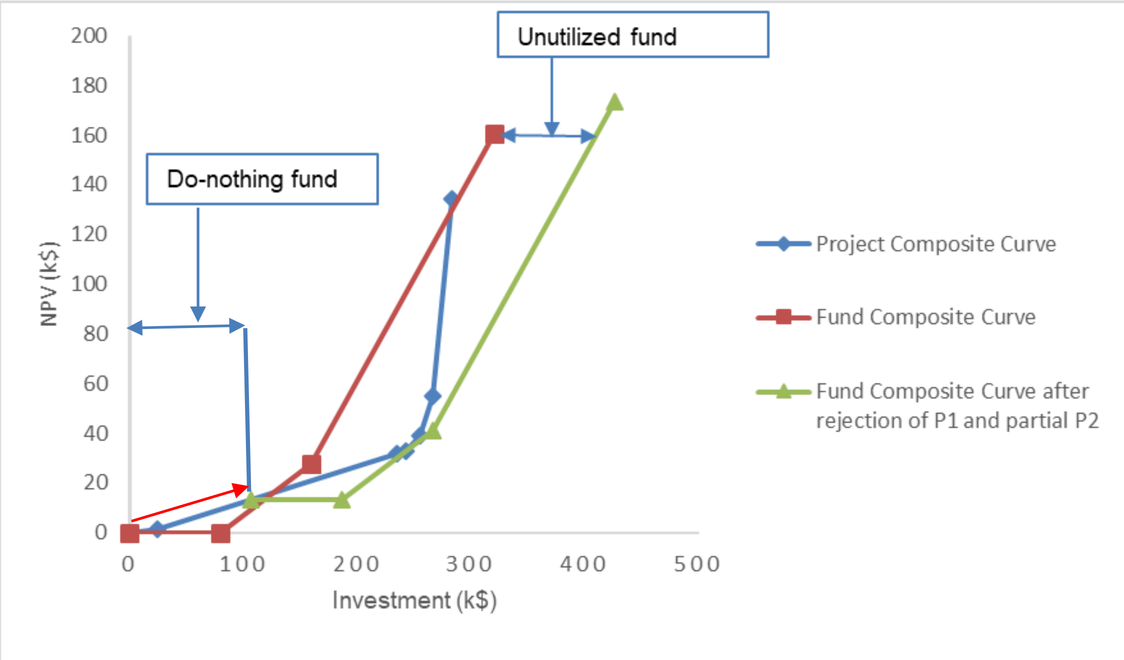

Figure 2: Graphical representation of Project and Fund Composite Curves and do-nothing funds

Table 3: MOCTA for opportunity cost of P1 at 95 % reliability

Projects	DROI	C_{Fi} (k$)	Cumulative C_{Fi} (k$)	NPV (k$)	Cumulative NPV (k$)	Opportunity Cost (k$)
F1	0	-80	-80	0	0	0
P1	0.065	24.67	-55.33	-5.2	-5.2	0
P2	0.1427	210	154.67	-4.29	-9.49	-122.25
P3	0.1677	8.33	163	3.86	-5.63	-54.84
F2	0.348	-80	83	29.38	23.75	83.94
P4	0.5251	11.67	94.67	14.69	38.45	83.58
F3	0.828	-160	-65.33	28.67	67.13	87.98
P5	1.3574	11.67	-53.66	-34.58	32.54	25.18
P6	4.7439	16.67	-36.99	-181.71	-149.17	-31.88

The opportunity cost is 87.98 k$ which is greater than the available cash flow (24.67 k$) for P1 Consequently P1 is rejected.

Table 4: MOCTA for opportunity cost of P2 at 95 % reliability after rejecting P1

Projects	DROI	C_{Fi} (k$)	Cumulative C_{Fi} (k$)	NPV (k$)	Cumulative NPV (k$)	Opportunity Cost (k$)
F1	0	-80	-80	0	0	0
P2	0.1427	210	130	-6.21	-11.41	0
P3	0.1677	8.33	138.33	3.25	-8.16	-326.64
F2	0.348	-80	58.33	24.94	16.77	81.70
P4	0.5251	11.67	70	10.33	27.10	70.88
F3	0.828	-160	-90	21.20	48.30	70.49
P5	1.3574	11.67	-78.33	-47.64	0.66	0.54
P6	4.7439	16.67	-61.66	-265.26	-264.60	-57.50

From Table 3, it can be inferred that the opportunity cost of P2 is 81.70 k$. P2 is partially accepted. The opportunity cost for P2 at 95 % reliability has become 39%. It is 9 % greater than the deterministic case, shown in Figure 3.

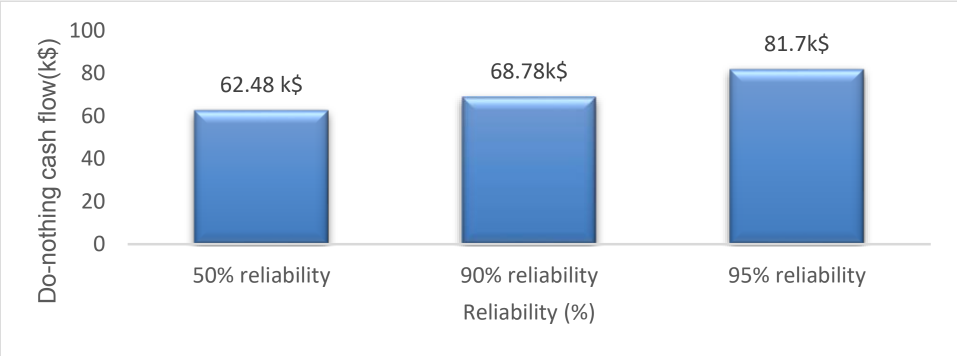

Figure 3: Do Nothing cash flow at different reliability levels

4. Conclusions

A methodology has been proposed for capital budgeting of energy conservation projects with probabilistic returns for the process industries. The returns of the projects are assumed to follow a normal probability distribution. The cash availability and the rate of interest of the funding sources are assumed to be constant. Chance Constrained programming is used to find the effective NPV and effective DROI at different reliability levels. It is observed that with the increase in reliability levels the unfunded portion of the projects increase i.e. more projects are rejected. The unfunded portion of P2 increases by 9 % with the increase of reliability from 50 % to 95 %. With the increase in reliability level, the amount of rejected projects (total or partial) increases.

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