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Multi Objective Lifecycle Budget Allocation for Fusion Power Plant Installation

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Abstract

Successful installation of a fusion power plant demands a critical assessment of capital costs and operating costs. Reduction strategies for such costs are desirable in order to achieve an economically competitive position. The paper develops a multiobjective goal programming model and initially, the objective function is defined. The model seeks to minimize the deviation variables of the objective function, subject to the goal values of budgetary expenditure allocated to capital costs and operating costs of fusion power plant installation. The sum of deviations is minimized so that actual expenditure on capital costs (direct/indirect construction costs) and operating costs (fuel, waste management, maintenance, manpower) meets the projected expenditure. Using the simplex method, the standard minimization problem is solved. An illustrative example is presented that determines the optimal allocation of expenditure on capital costs and operating costs for fusion power plant installation. Results from the numerical example presented indicate that certain goals on capital costs (direct/indirect construction costs) and operating costs (fuel, waste management, maintenance, manpower) can be fully or partially achieved. This, however, depends upon the priority levels and targets set for budgeted expenditure; in line with the categories of fusion power plant installation costs. The solution approach enables satisfactory allocation of expenditure based on the priority levels or goals set for energy production. The multiobjective goal programming approach can be effective where relevant categories of costs can be prioritized if necessary. It ensures cost-effectiveness in installing fusion power plants.

Keywords: Allocation, Budget, Fusion, Installation, Lifecycle.

1 | Introduction

The creation of a sustainable, cost-effective energy source is of paramount importance in several nations worldwide. Although fusion energy can be one of the most cost-competitive sources of power, fusion power plants have not lived up to their potential. The investment profile has generally been unattractive for private investors and venture capital firms. It is because such firms typically seek returns within 3 to 5 years; which

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is comparatively a short time for fusion energy returns. When considering the prospect of installing a fusion power plant, it is important to assess the capital (direct/indirect construction) costs as well as the operating (fuel, maintenance, waste management) costs. Despite the high capital costs usually incurred, reductions of such costs must be devised in order to achieve an economically competitive level. However, initial estimates of costs for fusion energy in power plants are somehow uncertain, and it may be difficult for early large fusion designs to be cost-effective. Although fuel costs are generally low, other operations costs are significant in order to sustain fusion plant installations. Unfortunately, small fusion power plants have higher cost barriers due to the diseconomies of their scale. However, they could offer a faster route to market fusion power as a source of fuel/energy stores for the manufacturing industries and the transportation sector. Therefore, the installation of fusion power plants needs coordinated financial management to realize the benefits of the investment potential. Development of fusion power requires a transition from research and development to commercial deployment, and the clearest best-funded route to fusion appears to be magnetic confinement. Therefore, the construction and installation of fusion power plants can be planned in program terms, as the commitment to constructing many plants will be made necessary for it to become a commercially viable venture.

The paper is organized as follows: a brief introduction is presented in section 1. Section 2 highlights the related literature on financing fusion power plant installations. In section 3, the paper gives a description of the problem and the associated model formulation. In section 4, the optimization process is given, and an illustrative example is presented in section 5, showing the possible application of the proposed model. Lastly, conclusions and future research follow in section 6.

2 | Related Literature

Shroder [1] highlighted the criteria for good performance of fusion as a technology with no CO2 emission during normal operations and low external costs. It reflected the advantageous environment and safety characteristics to become a viable option to win considerable market shares in future electricity markets. However, the economic performance in terms of investment cost and cost of electricity has been noted in numerous studies. In a related development, Hender et al. [2] examined the economics of magnetic fusion power generation, where comparisons were made with other generation sources. The magnetic fusion costs were benchmarked by comparison with those of ITER since considerable effort was invested in establishing the validity of the ITER costs. The overall conclusion was that the likely economic performance of fusion, combined with its safety and environmental concerns, made it a prime candidate for 21st-century electricity generation.

Hamacher et al. [3] examined the possible role of fusion as a future energy source. These considerations were linked with physical issues and social-economic aspects. The factors affecting the design of a future fusion power plant, its safety and environmental features and possible costs of fusion power contributed significantly to the external cost value. The essential costs of fusion were in the same range as the external costs of photovoltaic and wind energy. In a related study, Hamacher et al. [4] elaborated on the external costs of fusion with external methodology. The external costs were in the range of a few mEuro/kwh, although this depended on the plant model. The external costs were not dominated by the impacts due to radioactive emissions and releases. Holland and Berry [5] also presented the current status of fusion research and described the steps ahead that can lead to power generation. The advances made in fusion research and economic factors affecting the design of a fusion power plant, environmental features as well as the possible costs of fusion power plants were discussed. Although fusion power plants do not run continuously for a whole year, the cost of fusion electricity can be driven by its capital cost and by how many hours the plant can run each year, according to the report by the andlinger centre for Energy [6].

Dalton [7] also noted how the capital costs for the development of a new generation of nuclear fusion reactors were high at around £100/MWh. However, a substantial program of the standard build can bring such cost to a viable target of £60-£70 MWh. According to Turchi et al. [8], the upfront capital costs of a fusion power plant, as with many other power plant approaches, were likely to hinge heavily upon the scale of the plant and the balance of plant components. However, it is important to know how construction cost estimates for new nuclear plants are very uncertain, as Bruce [9] notes. Such costs have increased significantly in recent years. Questions also arise about whether fusion energy can be cost-competitive and commercially viable, as Lindley et al. [10] argue. The authors claim that for fusion to be competitive beyond 2040, costs will likely need to be at or below $80-100/MWh at 2020 price. It will be hard to achieve for early fusion designs, both small or large, due to low power availability from the pulsed operation, frequent replacement of vessel components, and low-efficiency power cycles. In a related development, Cardozo et al. [11] presented a deployment model that described the fastest deployment achievable with the constraint that the industrial capacity needed to be built up must be continuous.

The cost was dominated by the capital investment, which allowed for a simple comparison of different energy technologies. Although cost development was very challenging, the analysis pointed towards an emphasis on simpler and cheaper reactor designs. On the side of economic performance, Shutaro and Shogeki [12] quantitatively analyzed the economic performance of steady-state power plants on deregulated electricity markets through a constructed market model. Results indicated that the economic performance of fusion power plants had higher sensitivity to the frequency of unplanned outages. Abdullah also studied financing fusion energy, Alhamdan et al. [13] through a megastructure in which a large number of projects were securitized into a single holding company funded through various debt and equity tranches. The model expanded the pool of available capital, created tranches with different risk-return tradeoffs and provided a diversified fusion index, which was used as a long hedge against fossil fuels. Simulations of a fusion mega fund demonstrated Positive Returns on Equity (ROE) and low default rates for capital-raised debt. An investment and operating cost study by Entler et al. [14] brought the ex-ante economic analysis of the fusion power plant model in terms of the cost of electricity. The levelized cost of electricity of fusion power plants was found to be a competitive venture compared to the actual renewable resources. Several economic factors impede fusion energy deployment as Cardozo [15] argues.The author considered the speed at which fusion energy could be deployed, where several economic factors were identified that impede this speed. The energy market was considered at the time fusion could make its entry. The competition was also analyzed, taking into consideration the unique contribution fusion could make.

3 | Model Development

3.1 | Problem Description

In this study, the optimization of a set of objectives is involved in the decision-making process for budget allocation toward fusion power plant installation. Considering the lifecycle stages of design, construction and installation, instead of optimizing the objectives directly, achievement of the assigned target values called aspiration levels of expenditure is considered. Using the goal programming method, the unwanted deviations (under and/or over) from the aspired levels are minimized in the goal achievement function (objective function) to reach a satisfactory solution in a crisp decision environment. We consider the budget allocation problem for fusion power plant installation with the goals of allocating capital (direct/indirect construction) costs and operating (fuel, maintenance, waste management) costs incurred. Since it is possible to express the objectives of the problem in the form of linear constraints, the resulting set of constraints will hardly have a single and clearly optimum solution. The goal programming model must, therefore, find a solution that comes as close as possible to satisfying the goals of budgetary expenditure, taking into account the relative priorities of direct and indirect costs for installing the fusion power plant under consideration. Given that goal programming is a special case of linear programming, the simplex method can be used to solve the corresponding goal programming problem in order to satisfy budgetary priorities toward fusion power plant installation. The key notation used for developing the model is presented in *Table 1*.

Table 1. Key notation for lifecycle budget allocation of fusion power plant.

Notation	Description
i=1,2	Category of cost
j=1,2,3	Set of lifecycle stages
k=1,2,3	Set of budgetary goals
Z	Value of objective function
d_k^+ (j)	The overachievement of kth goal for stage j of the life cycle
d_k^- (j)	The underachievement of kth goal for stage j of the life cycle
E_T (j)	Total budgeted expenditure to sustain stage j of the lifecycle
B_j(i)	Targeted costs for sustaining stage j of the lifecycle
P_k	Pre-emptive priority of the kth goal

3.3 | Objective Function

$$\text{Minimize } Z = \sum_{k=1}^{3}\sum_{j=1}^{3}\sum_{i=1}^{2} P_k(i,j)[d_k^+(j) + d_k^-(j)]. \tag{1}$$

3.4 | Goal Constraints

$$\sum_{k=1}^{3}\sum_{j=1}^{3}\sum_{i=1}^{2} X_j\text{ (i) - } d_k^+(j) + d_k^-(j)] = \sum_{j=1}^{3}\sum_{i=1}^{2} B_j(i). \tag{1.1}$$

$$\sum_{k=1}^{3}\sum_{j=1}^{3}\sum_{i=1}^{2} X_j(i) - d_k^+(j) + d_k^-(j)] = \sum_{j=1}^{3} E_T(j). \tag{1.2}$$

$$X_j(i),\ d_k^+(j),\ d_k^-(j)],\ E_T(j),\ B_j(i) \geq 0. \tag{1.3}$$

3.5 | Multiobjective Goal Programming Model

$$\text{Minimize } Z = \sum_{k=1}^{3}\sum_{j=1}^{3}\sum_{i=1}^{2} P_k(i,j)[d_k^+(j) + d_k^-(j)], \tag{1.4}$$

S.t,

$$\sum_{k=1}^{3}\sum_{j=1}^{3}\sum_{i=1}^{2} X_j\text{ (i) - } d_k^+(j) + d_k^-(j)] = \sum_{j=1}^{3}\sum_{i=1}^{2} B_j(i), \tag{1.5}$$

$$\sum_{k=1}^{3}\sum_{i=1}^{2}\sum_{j=1}^{3} X_j(i) - d_k^+(j) + d_k^-(j)] = \sum_{j=1}^{3} E_T(j), \tag{1.6}$$

$$X_j(i),\ d_k^+(j),\ d_k^-(j)],\ E_T(j),\ B_j(i) \geq 0. \tag{1.7}$$

3.5.1 | Design phase

$$\text{Minimize } Z = \sum_{k=1}^{3}\sum_{j=1}^{3}\sum_{i=1}^{2} P_k(i,j)[d_k^+(j) + d_k^-(j)], \tag{2}$$

S.t,

$$X_1(1) + d_1^-(1) = B_1(1),\ \text{Capital costs}, \tag{2.1}$$

$$X_1(2) + d_2^-(1) = B_1(2),\ \text{Operating costs}, \tag{2.2}$$

$$X_1(1) + X_1(2) - d_3^+(1) = E_T(1),\ \text{Design Budget}, \tag{2.3}$$

$$X_1(1), X_1(2), d_1^-(1), d_2^-(1), d_3^+(1), B_1(1), B_1(2), E_T(1) \geq 0. \tag{2.4}$$

3.5.2 | Construction phase

$$\text{Minimize } Z = \sum_{k=1}^{3}\sum_{j=1}^{3}\sum_{i=1}^{2} P_k(i,j)[d_k^+(j) + d_k^-(j)], \tag{3}$$

$$X_2(1) + d_1^-(2) = B_2(1),\ \text{Capital costs}, \tag{3.1}$$

$$X_2(2) + d_2^-(2) = B_2(2),\ \text{Operating costs}, \tag{3.2}$$

$$\backslash X_2(1) + X_2(2) - d_3^+(2) = E_T(2),\ \text{Design Budget}. \tag{3.3}$$

$$X_2(1), X_2(2), d_1^-(2), d_2^-(2), d_3^-(2), B_2(1), B_2(2), E_T(2) \geq 0. \tag{3.4}$$

3.5.3 | Installation phase

Minimize $Z = \sum_{k=1}^{3} \sum_{j=1}^{3} \sum_{i=1}^{2} P_k(\text{i,j})[d_k^+(\text{j}) + d_k^-(\text{j})]$, **(4)**

$X_3(1)+d_1^-(3)= B_3(1)$, Capital costs, **(4.1)**

$X_3(2)+d_2^-(3)= B_3(2)$, Operating costs, **(4.2)**

$X_3(1)+X_3(2)- d_3^+(3)=E_T(3)$, Design Budget. **(4.3)**

$X_3(1), X_3(2), d_1^-(3), d_2^-(3), d_3^+(3), B_3(1), B_3(2), B_T(2) \geq 0$, **(4.4)**

4 | An Illustrative Example

In this section, we present an example to demonstrate the applicability of the proposed model. Consider fusion power plant X whose life cycle phases during design, construction and installation incur capital and operating costs (in million USD) as presented in *Table 2*.

Table 2. Capital and operating costs of fusion power plant X.

Category of Costs	Life Cycle Phase of Fusion Power Plant		
	Design (Million Usd)	Construction (Million Usd)	Installation (Million Usd)
Capital costs	225	150	125
Operating costs	75	90	55
Budgeted exp	360	350	120

A Multiobjective goal programming model was developed for optimal allocation of capital and operational costs. This was done to satisfy budgetary constraints, considering the fusion power plant life cycle phases of design, construction and installation.

4.1 | Multiobjective Goal Programming Models

4.1.1 | Design phase

Minimize $Z = \sum_{k=1}^{3} \sum_{j=1}^{3} \sum_{i=1}^{2} P_k(\text{i,j})[d_k^+(\text{j}) + d_k^-(\text{j})]$, **(5)**

S.t,

$X_1(1)+ d_1^-(1)=225$, **(5.1)**

$X_1(2)+ d_2^-(1)=75$, **(5.2)**

$X_1(1)+ X_1(2)- d_3^+(1)=360$, **(5.3)**

$X_1(1), X_1(2), d_1^-(1), d_2^-(1), d_3^+(1) \geq 0$. **(5.4)**

4.1.2 | Construction phase

Minimize $Z=\sum_{k=1}^{3} \sum_{j=1}^{3} \sum_{i=1}^{2} P_k(\text{i,j})[d_k^+(\text{j}) + d_k^-(\text{j})]$, **(6)**

S.t,

$X_2(1)+d_1^-(2)=150$, **(6.1)**

$X_2(2)+ d_2^-(2)=90$, **(6.2)**

$X_2(1)+ X_2(2)+ d_3^-(2)=350$, **(6.3)**

$X_2(1), X_2(2), d_1^-(2), d_2^-(2), d_3^-(2) \geq 0$. **(6.4)**

4.1.3 | Installation phase

Minimize $Z=\sum_{k=1}^{3}\sum_{j=1}^{3}\sum_{i=1}^{2} P_k(i,j)\ [d_k^+(j)+d_k^-(j)]$, (7)

S.t,

$X_3(1)+d_1^-(3)=125,$ (7.1)

$X_3(2)+d_2^-(3)=55,$ (7.2)

$X_3(1)+X_2(2)+d_3^-(3)=120,$ (7.3)

$X_3(1), X_3(2), d_1^-(3), d_2^-(3), d_3^-(3)\geq 0.$ (7.4)

5 | Results and Discussion

The multiobjective goal programming model for fusion power plant X was solved using MATLAB to establish budget allocation criteria for design, construction, and installation. Data input was done in MATLAB TM; and using the linprog solver, an optimal solution was obtained whose values are presented in *Table 3* and *Table 4*.

Table 3. Optimal solution from matlab-decision variables.

Design		Construction		Installation	
$X_1(1)$	$X_1(2)$	$X_2(1)$	$X_2(2)$	$X_3(1)$	$X_3(2)$
225	75	150	90	125	55

Table 4. Optimal solution from matlab-deviation variables.

Design			Construction			Installation		
$d_1^-(1)$	$d_1^-(2)$	$d_1^+(3)$	$d_2^+(1)$	$d_2^-(2)$	$d_2^+(3)$	$d_3^-(1)$	$d_3^-(2)$	$d_3^+(3)$
0	0	0	0	0	110	0	0	60

5.1 | Discussion of Results

5.1.1 | Design phase

The budgetary goals on capital costs, operating costs and total costs can be fully achieved.

$X_1(1)=225$, $X_1(2)=75$ and $X_1(1)+X_1(2)=300$, where the deviation variables $d_1^-(1)$, $d_2^-(1)$, and $d_3^+(1)$ are zero for all the budgetary constraints.

5.1.2 | Construction phase

The budgetary goals on capital costs and operational costs can be fully achieved since

$X_2(1)=150$ and $X_2(2)=90$. However, the total budgetary expenditure constraint has a deficit of $d_3^-(2)=110$ M.USD.

5.1.3 | Installation phase

The budgetary goals on capital costs, operational costs and total costs can be fully achieved.

Since $X_3(1)=275$ and $X_3(2)=125$. However, the decision variables $d_1^-(3)$, $d_2^-(3)$ and $d_3^+(3)$ are zero for all budgetary constraints.

6 | Conclusion

The multiobjective goal programming model for allocating budgetary expenditure can be effective as a cost-saving strategy for fusion power plant managers. This is vital during the design, construction and installation stages of fusion power plants. In order to sustain the budgetary goals, the relevant categories of costs can be prioritized if necessary. This can build ground for motivation and further research towards fusion power plant conceptual cost studies among energy scholars.

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