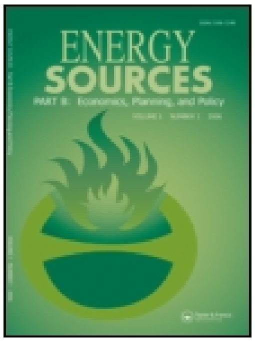

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Multi-objective Fuel Supply for Coal-fired Power Plants Under Emission, Transportation and Operational Constraints

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Coal-fired power plants need to decrease their generation cost in deregulated power markets so as to be selected, dispatched, and compete with other, cheaper, resources. On the other hand, coal prices have risen significantly, and extra costs for SO_2 and NO_x emission outputs are imposed that force power companies to lower the costs for the fuel-coal supply process. In this article, a multi-objective model for supplier, transportation, and coal order selection is developed for the coal supply of electric power plants in an environment where multiple suppliers, coal contracts, and multimode transportation routes exist. The model simultaneously optimizes multiple objectives such as minimizing purchase, transportation, sulfur dioxide, and nitrogen oxides costs and carbon dioxide and ash outputs of coal. Multi-objective linear programming and analytic hierarchy process are employed to solve the problem. The solution methodology is applied in a case study in the Midwestern United States and the alternative evaluation process is presented. It is shown that the model can be used by the power companies to find a desired solution for their coal supply and hence generate power with coal of lower cost, lower emission, and ash.

Keywords: analytic hierarchy process, coal plant, electric generation, emission outputs, fuel coal supply, multi-objective optimization, transportation optimization

1. INTRODUCTION

Coal shows different characteristics and does not have a unique and homogeneous structure that changes for each coal type. The heat content ranges from low to high which affects the energy amount gained when the coal is burned. Power producers tend to purchase coal with higher heat content to generate more electric power comparedwith the same amount of coal with a lower heat content. On the other hand, the ash content of each coal type is also different. Once the coal is burned, the ash is produced as both fly ash and bottom ash. The environmental regulations and public reactions against the produced ash force a careful handling of ash. As a result less ash is desired from the burned coal. Also, not all coal products can be burned in a power plant. The right product can be purchased for the best use of plant resources and minimization of cost.

Another issue is the emission of gas outputs from coal-fired power plants which have been an important problem since the 1990s. Carbon emissions (carbon dioxide [CO_2]) and greenhouse gas

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emissions (sulfur dioxide [SO_2] and nitrogen oxides [NO_x]) that are produced from the burning coal limits the usage of coal in electricity generation and they cause acid rain in nature. Coal-fired power plants are accepted as a major source of air pollution (EIA, 2009). If the coal resource is not carefully chosen, the cost of power would become high for power producers. On the other hand, if the power companies use coal that contains lower sulfur, nitrogen, and carbon, they will be able to save costs and lower emissions at the input level (Whyatt and Metcafle, 2004). However, the heat content of the supplied coal should also be high enough to meet the demanded power.

The power companies face the decisions of supplier, transportation, and order set selection in an environment where multiple suppliers, products, multi-mode transportation routes, multiple power plants, emission constraints and plant operational constraints exist. At this point the overall objective can be classified into six different parts. The first part is related to the supplier and coal selections and the aim is to minimize the purchase cost of order given that the coal price is different for each coal type. The second one is related to transportation and the aim is the lowest cost and reliable transportation of ordered coal resources. The third part is the minimization of ash output in the power plant. Other objectives focus on the minimization of emission outputs that are released from the power plant. The fourth and fifth objectives are minimization of the cost of SO_2 and NO_x outputs, respectively. The last objective focuses on the minimization of CO_2 outputs.

Balat (2010) and Sensogut and Oren (2009) presented an overview oncoal in energy generation. There is a limited effort in the literature for the researche that integrates supplier, transportation, and order diversity for the power industry. Chang et al. (1981) developed a method to optimize a regional railroad network. The main objective is the minimization of total cost in transportation when there is increased coal shipment traffic and resources are allocated among demand points. Shih, 1997 proposed a mixed integer programming method for the planning of fuel-coal imports for power plants. The main objective is the minimization of total inventory cost and holding cost and the constraints are harbor unloading capacity, demand balance, and inventory balance constraints. Sherali and Puri (1993) presented a model for coal blending and cleaning silos for supply of coal from different resources and delivery to customer locations to meet the demand. The main objective is the minimization of total operational cost and a decision tool is developed for implementing cost-effective decisions under multiple products, ores, and demands over time. Ash and Waters (1991) provided a simulation methodology for the coal shipment from the mines in Western Canada to power stations in the east. McCollum (2007) presented researchon the existing coal distribution infrastructure and he develops four scenarios through 2050 to analyze the coal consumption and the possible problems on meeting the demand of coal. Tu and Guldman (2001) developed a model and a tool called the Geographic Information System to identify the coal transportation routes considering coal production sites, power plants, and costs of transportation. Kaplan (2007) presentedresearch on the coal transportation to power plants and its reliability in the United States. Liu (2007) proposed a model for coal blending and transportation where inter-model transportation for coal import exists.

In this research, a multi-objective model that considers multimode transportation alternatives, multiple coal products with different price and quality, and multiple suppliers for efficient coal supply of an electric power company with more than one plant at different locations, is developed. The capacity limitations on transportation routes, supplier capacity for a particular product, product emission specifications, emission costs and plant burn capability constraints are also considered in the model.

2. PROBLEM DEFINITION AND FORMULATION

The coal supply chain can be represented as a network in which suppliers, routes, trans-load locations and power plants are natural entities. Figure 1 gives a description of a coal supply

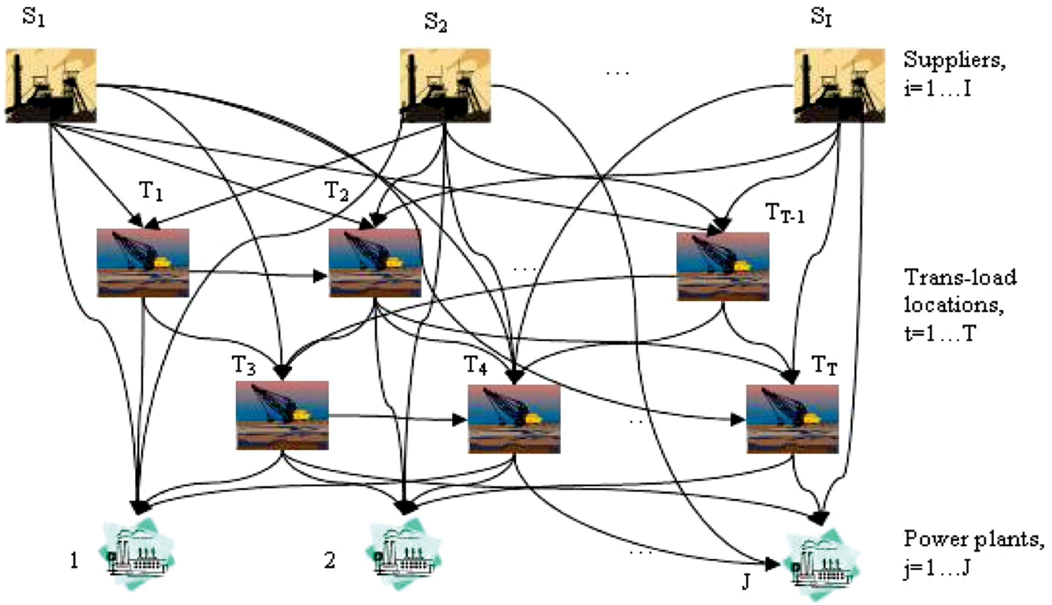

FIGURE 1 Coal transportation network. (color figure available online)

network. The coal $k \in K$ is supplied at supplier $i \in I$, and it is transported to power plant $j \in J$ directly or via trans-loading at trans-load location $t \in T$. The coal can also be shipped from a trans-load location t to another trans-load location $t' \in T$ where $t' \neq t$. The decision variable that should be determined for each power plant is $X_{i,j,k}$ total amount of coal k transported from supplier i to power plant j, where $X_{i,j,k} = X_{i,j,k} + X_{i,t,k} + X_{t,j,k} + X_{t,t',k} + X_{t',j,k}$. The decision variable includes the total coal k transported directly to plant j, the coal transported to a trans-load location t then to plant j, and the coal further transported to other trans-load locations t' then to plant j.

The main objective of the problem is the minimization of purchase, transportation, SO_2 and NO_x costs ($) and minimization of ash and CO_2 outputs (ton). The detailed formulation of each objective is as follows with notations given in appendix:

$$f_1 = \sum_{i \in I} \left(\sum_{j \in J} \sum_{k \in K} X_{i,j,k} P_{i,k} + \sum_{t \in T} \sum_{k \in K} X_{i,t,k} P_{i,k} \right) \tag{1}$$

$$\begin{aligned} f_2 = \sum_{k \in K} \Bigg(& \sum_{j \in J} \sum_{i \in I} X_{i,j,k} TC_{i,j} + \sum_{k \in K} \sum_{t \in T} X_{i,t,k} TC_{i,t} + \sum_{t \in T} \sum_{t' \in T, t \neq t'} X_{t,t',k} TC_{t,t'} \\ & + \sum_{t \in T} \sum_{j \in J} X_{t,j,k} TC_{t,j} \Bigg) \end{aligned} \tag{2}$$

$$f_3 = \sum_{j \in J} \sum_{k \in K} \left(\sum_{i \in I} X_{i,j,k} A_k + \sum_{t \in T} X_{t,j,k} A_k \right) \tag{3}$$

$$f_4 = \sum_{j\in J}\sum_{k\in K}\left(\sum_{i\in I} X_{i,j,k} E_{SO_2,j} SO_{2,k}(1 - RM_{SO_2,j}) + \sum_{t\in T} X_{t,j,k} E_{SO_2,j} SO_{2,k}(1 - RM_{SO_2,j})\right) \tag{4}$$

$$f_5 = \sum_{j\in J}\sum_{k\in K}\left(\sum_{i\in I} X_{i,j,k} E_{NO_x,j} NO_{x,k}(1 - RM_{NO_x,j}) + \sum_{t\in T} X_{t,j,k} E_{NO_x,j} NO_{x,k}(1 - RM_{NO_x,j})\right) \tag{5}$$

$$f_6 = \sum_{j\in J}\sum_{k\in K}\left(\sum_{i\in I} X_{i,j,k} CO_{2,k}(1 - RM_{CO_2,j}) + \sum_{t\in T} X_{t,j,k} CO_{2,k}(1 - RM_{CO_2}, j)\right) \tag{6}$$

Equation (1) calculates the purchase cost, Eq. (2) finds transportation cost, Eq. (3) finds the ash output, Eq. (4) gives the cost of SO_2 emissions, Eq. (5) gives the cost of NO_x emissions, and Eq. (6) gives the amount of CO_2 that is released from the plant. The subject to constraints are also given:

$$SO_{2,k} = S_k\left(\frac{SO_2}{S}\right),\quad NO_{x,k} = N_k\left(\frac{NO_x}{N}\right),\quad CO_{2,k} = C_k\left(\frac{CO_2}{C}\right) \tag{7}$$

$$\sum_{k\in K}\left(\left(I_{j,k} + \sum_{i\in I} X_{i,j,k} + \sum_{t\in T} X_{t,j,k}\right) H_k\right) \geq (D_j + F_j)(24M_j)(R_j/500) \quad \text{for all } j \in J \tag{8}$$

$$\sum_{t\in T} X_{i,t,k} + \sum_{j\in J} X_{i,j,k} \leq O_{i,k} \quad \text{for all } i \in I, k \in K \tag{9}$$

$$\sum_{k\in K} X_{i,t,k} \leq U_{i,t} \quad \text{for all } i \in I, t \in T \tag{10}$$

$$\sum_{k\in K} X_{t,j,k} \leq U_{t,j} \quad \text{for all } j \in J, t \in T \tag{11}$$

$$\sum_{k\in K} X_{t,t',k} \leq U_{t,t'} \quad \text{for all } t, t' \in T, t \neq t' \tag{12}$$

$$\sum_{k\in K} X_{i,j,k} \leq U_{i,j} \quad \text{for all } i \in I, j \in J \tag{13}$$

$$\sum_{t\in T} X_{i,t,k} - \sum_{t\in T, t\neq t'} X_{t,t',k} - \sum_{t\in T} X_{t,j,k} = 0 \quad \text{for all } i \in I, k \in K, j \in J \tag{14}$$

$$X_{i,j,k}, X_{i,t,k}, X_{t,t',k}, X_{t,j,k} \geq 0 \quad \text{for all } i \in I, k \in K, j \in J, t, t' \in T, t \neq t' \tag{15}$$

Equation (7) gives SO_2, NO_x, and CO_2 outputs of coal k, respectively. For example, SO_2 output is calculated by multiplying the sulfur content of coal k, $S_k(\%)$, with the SO_2/S atomic mass ratio. Equation (8) ensures that the potential power output in terms of BTUs is higher than required BTUs to generate power that is sufficient for $D_j + F_j$ days. Equation (9) ensures that the total amount of coal k transported to the trans-load locations and plants from supplier i is limited to its capacity. Equations (10)–(13) give capacity constraint of transportation between each

i and t, between each t and j, between each trans-load location t and t' and between each i and j respectively. Equation (14) shows that total coal transported to a trans-load location t is transported either to another trans-load location t' or a power plant j. Equation (15) ensures that nonnegative solutions are obtained. There are two other constraints that ensure that only coal with certain a physical or chemical structure are supplied by giving upper and lower bounds on grindability index, moisture content, and volatile matter for each coal k. If coal is out of the acceptable limits, it is not accepted for purchase. Additionally, two other constraints limit the total sulfur and nitrogen percentages in coal, respectively, including the coal inventory at the plant and supplied coal to the plant.

Let X $\{X_{i,j,k}, X_{i,t,k}, X_{t,t',k}, X_{t,j,k}\}$ for all $i \in I, k \in K, j \in J, t, t' \in T, t \neq t'$ be a feasible solution set for the multi-objective linear coal supply problem, the objective of the problem is to determine the optimum suppliers, coal products, and transportation routes that will satisfy the decision maker's expectations. Given that $f_z(x)$ is the z objective function ($z = 1, 2, \ldots, 6$), the general model can be defined as

$$\text{Minimize } f = [f_1(x), f_2(x), \ldots, f_6(x)] \quad \text{subject to } x \in X \tag{16}$$

3. SOLUTION METHODOLOGY

A solution method that considers trade-offs among objectives and preference of the decision maker should be employed. Meza et al. (2007) proposed a solution methodology to solve the multi-period multi-objective power generation expansion problem. They use a two-phased solution procedure in which the Analytic Hierarchy Process (AHP) is employed to sort the alternative solutions and minimize the multi-objective problem with four objectives. Another approach was employed by Tekiner et al. (2010) for the power generation expansion problem. To solve the multi-objective coal supply problem, such works were found useful and a representative approach is adapted and used. The flow of the methodology is now presented.

1. Set limits on each objective: The problem is optimized for each objective separately and an upper (ideal) and lower bound (anti-ideal) solution is found for each objective. Notice that ideal and anti-ideal for objective z can be formulated as:

$$\min(f_z(x) : x \in X = \{X_{i,j,k}, X_{i,t,k}, X_{t,t',k}, X_{t,j,k}\} \quad \text{for all } i \in I, k \in K, j \in J, t, t' \in T, t \neq t') \tag{17}$$

$$\max(f_z(x) : x \in X = \{X_{i,j,k}, X_{i,t,k}, X_{t,t',k}, X_{t,j,k}\} \quad \text{for all } i \in I, k \in K, j \in J, t, t' \in T, t \neq t') \tag{18}$$

2. Find solution alternatives based on the decision rules: Minimax, maximin and compromise programming decision methods are used to find alternative solutions for each method. Three alternatives, A_1, A_2, and A_3, respectively, are used as alternative solutions for the decision process.
3. Generate random weights for each objective: Let w_z be the weight of objective function z. N random samples for each weight can be generated to represent the importance of each objective and N sets of problems with a combined single objective function can be solved in such a way that:

$$x^v = \min_v \left(\sum_{z=1}^{6} w_z^v f_z(x) : x^v \in X, v \in N, \sum_{z=1}^{6} w_z^v = 1 \right) \tag{19}$$

4. Use K-means clustering: N solutions actually include K $(K < N)$ statistically different solutions in which a K-means clustering algorithm would differentiate the meaningful combinations. Using the K-means clustering algorithm on the solutions, K different and representative solution sets can be obtained from the N random solutions.
5. Construct the AHP hierarchy: The relationships between $K + 3$ alternatives and 6 objectives are modeled in the AHP at this step.
6. Pair-wise comparison: The alternatives should be evaluated for each criteria based on either quantitative measures or pair-wise comparisons of each alternative with respect to each criteria. Notice that the pair-wise comparisons expected to include the decision maker's preferences and should be scaled based on the values that provide consistency. Although different scaling schemes can be used for the analysis, the common scaling scheme used in literature is proposed by Saaty (1980).
7. Identify the best alternative: The objective matrix and alternative matrix values provide the average score of each alternative. The scores are ranked and the alternative with the highest score is identified as the preferred solution.

4. A CASE STUDY FOR THE MIDWESTERN UNITED STATES

The proposed methodology is illustrated for a case study in the Midwestern United States. The electric power industry in the region is dominated with coal-fired generation. Four suppliers (S_1, S_2, S_3, S_4), 9 alternative contracts ($P_1, P_2, \ldots, P_9$), 4 trans-load locations (T_1, T_2, T_3, T_4) and 3 power plants (Plants 1, 2, and 3) are considered. The power company has 3 coal-fired power plants located in Indiana, Ohio, and Kentucky. Table 1 provides the coal contracts and their specifications. The fuel supply department has contracted with suppliers and was offered price and capacity for each coal contract.

Each power plant has a current inventory that is a mix of available products. As a policy, power companies would like to keep a safety stock that is sufficient to provide 3 days power demand and order fuel that is sufficient to meet 2 days of power demand. The coal is shipped via train cars on railways, barges on waterways, trucks, or using multimode transportation that is using a trans-load location. For the multimode alternative, there are 4 trans-load locations where the coal can be transferred to another transportation vehicle for further

TABLE 1
Coal Contracts and Specifications

Product	*Contract*	*Heat Content, BTU*	*S, %*	*N, %*	*C, %*	*GI*	*MC, %*	*VM, %*	*Ash Content, %*
P_1	CAPP	12,500	0.9	1.1	71.13	41	10	31	13.5
P_2	CSX Compliance	12,500	0.8	1.2	70.4	43	7	30	12
P_3	CSX	12,500	1	1.18	71.31	43	7	30.5	12
P_4	NS Compliance	12,500	0.75	0.8	72.18	44	7	30	12.5
P_5	NS Rail	12,500	1	0.86	71.92	44	7	30	12.9
P_6	NYMEX Big Sandy	12,000	1	1.09	69.07	41	10	30	13
P_7	PRB 8800	8,800	0.8	0.73	49.92	51	27	27	5.5
P_8	PRB 8400	8,400	0.8	0.55	48.68	51	30	30	5.5
P_9	Pittsburgh Seam	13,000	3	1.5	74.65	55	8	37.6	8

shipment. The transportation cost and capacities between each point are known by the fuel department.[1]

The transportation and coal specification data is gathered from the US Energy Information Administration (EIA, 2009) and the US Environmental Protection Agency (EPA, 2009), and verified by the New York Mechandise Exchange (NYMEX, 2010). The illustrated case is coded in the General Algebraic Modeling System (GAMS), a high level modeling and optimization tool. The solutions were obtained using a CPLEX 12.1 solver for the minimax, maximin, and compromise programming. In total 2,000 single objective cases with randomly generated weights were obtained. The ideal and anti-ideal solutions for each objective are also found using the same solver. The computations were performed on a computer with Intel Core 2 duo 2 Ghz CPU with 4 GB RAM (Dell, Round Rock, TX) in 650 seconds. Two thousand different solutions were clustered to three representative solutions using K-means clustering algorithm. Hence five alternative solutions, including those of minimax, maximin, and compromise programming, were obtained. Minimax and maximin solutions presented as a single alternative as they overlapped at this time. Table 2 provides the alternative solutions.

Notice that each objective function value for the alternatives lies between its ideal and anti-ideal solution as expected. As the weight of each alternative (the importance) changes, the solution differs, giving more weight to minimize that particular objective. The next step is to apply the AHP method to choose the best alternative for the set of suppliers, transportation routes, and coal products that will bring the objectives into decision maker preferences. The pair-wise comparisons of alternatives with respect to each objective and comparisons of objective functions are performed by the fuel supply department. The score of each alternative solution for each objective is also found based on the fuel supply team decisions. The calculated score for each alternative when considering the objective weights are given in ranked order.

$$A_4(0.34) > A_5(0.26) > A_3(0.23) > A_1(0.13) > A_2(0.03) \tag{20}$$

The values in the parentheses are the calculated priority values of each alternative based on the judgments on the solution. Based on the preferences A_4 is the preferred alternative plan and A_2 (compromise programming) is the least preferred alternative. A_5 and A_3 are close solutions and the preferable alternatives followed after A_4. Now we present the solution for A_4 in Table 3. Note that the decision variables are combined to summarize the results for each plant.

The transportation route is represented in such a way that the first column is the beginning point (supplier), the second column is the first trans-load location, the third column is the second trans-load location, and the fourth column is the destination power plant. Notice that usage of more than two trans-load locations is also possible but no solution is found for such a case. Based on the results shown, each power plant purchases coal from different suppliers, in different amounts and with different products and mixed strategies are used for transportation. The total transportation cost on the total route ($/ton) and its ratio to sum of coal price and transportation cost are also provided. Notice that when the purchase price is low the ratio of transportation on total cost becomes higher.

The cost and coal output distribution for each power plant are expected to be different. Table 4 shows the objective decompositions for each power plant. Plant 1 is the highest demand point which is incurred by the high transportation and purchase cost along with the ash output. The coal outputs are affected with the capture efficiency, the emission allowance cost, and selected coal product.

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[1] For those who are interested in details, an extended version of the paper that includes the details of data and solution procedure is available at: https://docs.google.com/viewer?a=v&pid=explorer&chrome=true&srcid=0B64KvEJz9AkrZGE3NjUyODMtYTM3OS00ZjZlLTk4MWMtZGU2M2RlMTlhOTVk&hl=en&authkey=CPPA8KcF

TABLE 2
Alternative Solutions for Coal Supply

Objectives & Weights		Alternatives						
		A_1	*A_2*	*A_3*	*A_4*	*A_5*	*Ideal*	*Anti-ideal*
	w_1			0.0977	0.1689	0.1537		
	w_2			0.1485	0.2322	0.1657		
Objective weights	w_3	minimax & maximin	compromise programming	0.2379	0.1143	0.1118		
	w_4			0.1732	0.2206	0.1471		
	w_5			0.1532	0.1061	0.2454		
	w_6			0.1894	0.158	0.176		
Transportation cost ($)		1,666,300	6,779,900	1,335,084	1,335,010	1,335,109	1,335,000	6,779,900
Purchase cost ($)		4,477,900	11,847,000	2,463,762	2,463,871	2,463,798	2,463,700	11,847,000
Ash output (ton)		8,912	26,800	7,701	7,793	7,734	7,698	26,800
SO_2 cost ($)		193,170	849,030	110,712	110,756	110,696	110,690	849,030
NO_x cost ($)		167,970	749,340	159,341	159,364	159,347	159,340	793,400
CO_2 output (ton)		147,690	449,810	147,703	147,708	147,782	147,690	449,810

TABLE 3
Suppliers, Transportation, and Coal Amounts for Power Plants

Supplier	*First Trans-load Location*	*Second Trans-load Location*	*Plant*	*Coal Type*	*Amount, ton*	*Transportation Cost, $/ton*	*Ratio of Transportation Cost*
S_4	—	—	1	P_7	13,440	19.45	55.18%
S_4	—	—	1	P_8	1,552	19.45	55.18%
S_3	T_3	—	1	P_7	5,649	18.58	56.17%
S_1	T_1	T_3	1	P_1	6,248	15.7	19.81%
S_2	T_2	T_3	1	P_1	5,143	12.66	16.87%
S_2	T_2	T_4	1	P_1	8,297	12.57	16.77%
S_3	T_1	T_4	1	P_7	10,512	14.21	49.49%
S_3	T_4	—	1	P_7	41	15.5	51.67%
S_3	T_2	T_4	1	P_7	967	16.92	53.85%
S_4	T_4	—	1	P_8	556	15.5	49.52%
S_3	T_2	T_4	1	P_8	4,272	16.92	54.72%
S_4	T_1	T_4	1	P_8	4,779	11.49	42.10%
S_3	T_2	T_3	2	P_6	5,993	14.53	36.28%
S_4	T_2	T_3	2	P_6	9,696	9.88	26.72%
S_4	T_1	T_3	2	P_6	332	10.87	28.63%
S_4	T_1	T_3	3	P_8	4,633	11.99	43.15%
S_3	T_3	—	3	P_8	7,359	17.22	55.16%

TABLE 4
Objectives Achieved by Each Power Plant

Objective	*Plant 1*	*Plant 2*	*Plant 3*
Transportation cost ($)	966,274	186,524	182,312
Purchase cost ($)	1,864,676	423,797	175,325
Ash output (ton)	4,967	2,095	672
SO_2 cost ($)	69,953	25,620	15,123
NO_x cost ($)	84,268	58,315	16,765
CO_2 output (ton)	103,026	29,551	15,132

5. CONCLUSION

The supply of fuel-coal that will minimize the cost and emission outputs is an effective plan to apply. In this article, a multi-objective integrated model for supplier, transportation, and coal orders is developed under multiple suppliers, contracts, and a multimode transportation routes environment. AHP is employed to include decision maker's preferences and a solution is determined based on the judgments. The solution method is applied to a case study for a power company located in Midwestern USA.

The output analyses on the presented results are required to help fuel supply departments for their future decisions. The objective of minimizing the emission costs for SO_2 and NO_x was included so that the power generation cost would be lower. The environmental effects would also be decreased due to the fact that emission releases and ash outputs are decreased. The model can be used by power companies for their fuel supply decisions as results are promising and computational time is relatively low for a daily process.

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NOMENCLATURE

j	index for power plants, $j = 1 \ldots J$
t	index for trans-load locations, $t = 1 \ldots T$
i	index for coal suppliers, $i = 1 \ldots I$
k	index for coal types, $k = 1 \ldots K$
$X_{i,j,k}, X_{i,t,k}, X_{t,j,k}, X_{t,t',k}$	amount of coal k transported between two locations (ton)
$P_{i,k}$	price of coal k at supplier i (\$/ton)
$TC_{i,j}, TC_{i,t}, TC_{t,j}, TC_{t,t'}$	transportation cost between two locations
A_k	ash content of coal k (%)
$E_{SO2,j}$	SO_2 emission price at plant j (\$/ton)
$SO_{2,k}$	emission output of coal k (SO_2-ton/coal-ton)
$RM_{SO2,j}$	efficiency rate of plant j for capturing SO_2 outputs (%)
S_k	S content of coal k (%)
$E_{NOx,j}$	NO_x emission price at plant j (\$/ton)
$NO_{x,k}$	emission output of coal k (NO_x-ton/coal-ton)
$RM_{NOx,j}$	efficiency rate of plant j for capturing NO_x outputs (%)
N_k	N content of coal k (%)
$CO_{2,k}$	CO_2 gas output of coal k (CO_2-ton/coal-ton)
$RM_{CO2,j}$	efficiency rate of plant j for capturing CO_2
C_k	carbon content of coal k (%)

F_j	number of days that coal inventory can meet demand for
D_j	number of days that ordered coal can meet demand for
H_k	heat content of coal k (BTU/lb)
$I_{j,k}$	current inventory of coal k at plant j (ton)
R_j	heat rate of plant j (mmBTU/MWh)
M_j	amount of power at plant j (MWh)
$O_{i,k}$	capacity of supplier i for coal k (ton/day)
$U_{i,t}, U_{t,j}, U_{t,t'}, U_{i,j}$	transportation capacity between two locations (ton/day)
SO_2/S	amount of SO_2 produced per S atom
NO_x/N	amount of NO_x produced per N atom
CO_2/C	amount of CO_2 produced per C atom