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Managing Fuel Coal Supply Chains With Multiple Objectives and Multimode Transportation

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Abstract: Power companies require sophisticated tools to manage fuel-coal supply chains which include multiple suppliers, coal contracts, and multimode transportation routes. In this article, a multi-objective model which is integrated with multi-attribute decision-making for the selection of suppliers, transportation routes, and coal orders is developed. The model simultaneously optimizes multiple objectives such as minimizing purchase costs, transportation costs, and ash output, and it also presents a decision framework on the selection of suppliers, transportation routes, and coal products that will achieve these objectives. The network and capacity constraints of suppliers and transportation routes are included in the model. The study utilizes multi-objective linear programming and well-known decision rules such as minimax, maximin, and compromise programming, and Analytic Hierarchy Process is employed to determine preferred solutions. The methodology for the solution is illustrated via a case study and an alternative evaluation process is presented. The study demonstrates that the model can be used by power companies to find desired solutions, as it provides an opportunity for the inclusion of the preferences of decision-makers and adjustments of the weights for each objective.

Keywords: Fuel Coal supply, Supply Chain, Supplier Mix, Transportation Optimization, Analytic Hierarchy Process, Multi-Objective Optimization

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In the world, coal is the most abundant and commonly used energy resource in the generation of electricity. Since it is readily available, flexible to use, and accessible all around the world, it is one of the most reliable resources. A report issued by EIA (2009) noted that coal usage will increase by 80% in the next 20 years and that coal will be a major energy resource until 2030. Both in Europe and the USA, coal is recognized as an important alternative to oil and gas and as an essential component to energy supply, and efforts have been undertaken to make coal more cost-effective and to promote the increasing importance of coal-based power generation (EU, 2009).

However, coal as a product has different characteristics and each coal type differs. The heat content ranges from low to high, which affects the amount of energy gained when it is burned. Power producers tend to purchase coal with high heat content as it generates more electric power in comparison with the same amount of coal with lower heat content. Additionally, the ash content of each coal type differs, and when coal is burned, it produces both fly ash and bottom ash. Environmental regulations and public reactions have made it necessary to handle ash carefully, and coal which produces less ash is favored. Also, not all coal products can be burned in a power plant, and it is necessary to purchase the right coal product to most efficiently use plant resources and minimize costs.

Coal is also used by other industries, such as in steel and iron production. Around 64% of steel and iron are produced using coal-based furnaces. Additionally, coal is essential energy source for cement production, as a large amount of energy is needed to produce cements in kilns. Other industries that utilize coal include paper manufacturing, alumina production facilities, and chemical and pharmaceutical industries.

Although coal is crucial for the industrialized world, the environmental impacts should be carefully handled. The land where coal is mined becomes temporarily unavailable for other uses such as agriculture, and it makes the land susceptible to soil erosion in addition to creating noise, water pollution, and dust. Moreover, coal mines are a source of methane gas which is harmful to the environment, and the gas is released during mining. Also, coal has environmental impacts when it is burned, which is its major challenge. The oxides of sulfur (SO_2) and nitrogen (NO_x), CO_2, particulate, and trace elements such as mercury can have serious impacts on nature. It has been found that the release of greenhouse gas emissions derived from human activities is related to global warming, and increasing amounts of sulfur and nitrogen oxides lead to acid rain. For these reasons, coal-fired power plants are known to be a major source of air pollution (EIA, 2009). Current CO_2 capture and storage technologies (CCS) and green house gas emission capture technologies are not enough to control all of the outputs. According to the Kyoto protocol, which has been signed by 187 countries, each country is obligated to reduce their emissions to below 1990 levels. Additionally, community pressure against pollution is another major concern for power producers. The cap and trade program developed in the USA and the EU Emission Trading Scheme (EU ETS) are two important examples of government regulations on power markets to limit emission outputs. If a coal resource is not carefully chosen, the cost of power generation can be higher for power producers and the environmental hazards will also be higher.

Suppliers provide coal contracts for each coal type that are sold via a merchandise exchange to power companies. A coal contract includes the amount, type, price, heat content, ash content, sulfur content, and chemical structure of the coal that will be delivered to the power company. The price for each contract is different and often times the mine mouth-price does not include transportation costs. Suppliers issue different coal contracts each of which has its own price and related product descriptions. Power companies must contend with the problem of choosing the best coal contracts that will meet the demand in a cost-effective way, given that there may be multiple power plants at different locations.

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It is best to locate a coal-fired power plant near a coal mine, but this is not usually the case as a generation point should also be in close proximity to where power is consumed. Coal then must be transported from where it is blended or mined to its final destination plant, and it is usually shipped by professional transportation companies; it is also common, however, for power companies to have their own fleet for coal transportation. In the US, railway companies have the largest share of coal transportation as they have their own railroads and specialized transport cars. Other methods of transportation include coal barges on waterways and trucks on highways, and with these, coal can be transported directly to the power plants. Coal can also be transported to a trans-load location where it is loaded to another vehicle at a hub point for further shipment to power plants or to another trans-load location. While the final destination is the power plant, transportation costs differ based on the method, the distance, and selected route mix. Also, the transportation capacity of each route is limited, and the tariff to ship coal can differ. For these reasons, power companies must ensure that effective transportation methodologies are chosen at a minimum cost.

Power companies are required to make decisions about suppliers, transportation, and order mix selection in a supply chain where suppliers, products, and a diversity of transportation possibilities exist. The overall objective can be classified in three different ways. The first is related to suppliers and coal selection, and the aim is to minimize the purchase cost of orders. The second is related to transportation, and the aim is minimal costs and the reliable transportation of coal resources. The third is minimizing ash output in the power plant.

Integrated Supply Chain

The nature of the fuel coal supply operation requires an integrated end-to-end supply chain in which multiple products, transportation alternatives, supplier data and plant specific characteristics are considered. A limited amount of research exists in the literature that integrates suppliers, transportation, and order diversity for the power industry. Liang (2008) presents a fuzzy multiple-objective linear programming model for production-transportation planning problems in a supply chain. The proposed model attempts to simultaneously minimize many objectives like total production and transportation costs along with the number of rejected items, total delivery time, and labor level. The fuzzy data is in a modifiable format so that a decision-maker can develop a satisfactory solution that will improve the supplier-distributor relationship. Kim et al. (2002) develop a model for a manufacturer's supply network in which there are numerous suppliers with capacity limitations, numerous products, and uncertain demand. The model considers market demand uncertainty, costs, and product characteristics, and the main objective is to find how much of each material to order from each supplier given that supplier and manufacturing companies have a limited capacity. Ding et al. (2009) presents a multi-objective stochastic model for optimizing the production-distribution network that includes the supply chain configuration and operational decisions. The objective is to balance the cost and customer service levels by simulating all possible configurations of production-distribution networks and control strategies. Chang (2008) develops a model to select the best routes in international intermodal networks where multiple commodities and multimode transportation opportunities exist. The objectives are to minimize the total flow cost and the total travel time where a time window constraint is imposed. The problem is NP-hard and hence langrangian relaxation and a decomposition method with a heuristics method is used to solve the problem. The existing research considers supplier-transportation, supplier capacity-product and multiple products-transportation, and it develops methods to solve problems for a supply chain. However, these studies do not respond to problems when they involve multiple products, multimode transportation, order diversity, and supplier diversity with capacity constraints. Furthermore, the operational constraints in coal-fired plants impose new limitations on coal, such as energy content and non-homogeneity. This body of knowledge assumes that products are identical and do not have operational constraints.

Some research also investigates the importance of the supply chain configuration and diversity as well as its relationship with product characteristics. Govel (2010) presents a transportation model that combines shipment and route choice under multimode transportation to show the importance of in-transit visibility. He uses a simulation methodology for different levels of visibility and shows that increased in-transit visibility can improve on-time delivery performance. Butler et al. (2006) presents a methodology for the supply chain network design of a company to determine production capacities, distribution locations, and material flows. They present a case study developed for a Fortune 200 company to validate the model for finding an overall solution for given scenarios of demand growth. Harris et al. (2010) discusses the importance of supply chain strategies and their alignment with product characteristics to increase the performance of the supply chain. The research shows that the supply chain design should be consistent with the characteristics of the product. Adobor and McMullen (2007) discuss supplier diversity issues in the supply chain management of companies. They emphasize a consideration of supplier diversity, as it is a part of the reliability issue and sometimes is a requirement. A diverse range of suppliers increases the reliability of the supply chain and thus secures more opportunities for a company. Capacity problems and price negotiations can also be managed smoothly in a diverse environment. However, the problem presented in this article includes supplier, product and route diversity and they have to be considered at the same time to have a better performance.

Coal Logistics

The transportation of the fuel coal from where it is mined or blended to its final destination is an important problem. Although there are much research about the transportation and logistics of the goods, only the researches about the coal are gathered here. Miles and Sinha (1981) develop a method to optimize a regional railroad network. The main objective is the minimization of total costs in transportation when there is increased coal shipment traffic and resources are allocated among demand points. Shih (1997) proposes a mixed integer programming method for the planning of fuel-coal imports for power plants. A diversity of supply sources for power companies that have more than one plant complicates coal logistics. The main objective is the minimization of total inventory costs and holding costs, and the constraints are harbor unloading capacity, demand balance, and inventory balance. The model is developed for the central coal logistics system of a Taiwanese power company to demonstrate its validity. Sherali and Puri (1993) present a model for coal blending and cleaning silos for supplies of coal from different resources and delivery to customer locations to meet demand. They develop three different linear programming models based on problem complexity and computational burden. The main objective is the minimization of total operational cost, and a decision-making tool is developed for implementing cost-effective decisions with multiple products, ores, and demands over time. Zhao et al. (2010) develops a model for a coal loading port in China. The coal is first transported to the port via trains and then barges are used to deliver the coal to the final destinations. They develop a Markov decision model that minimizes holding costs, shortages, and transportation costs by integrating ordering and delivery decisions. The study briefly considers product and route diversities which are usually the decision variables that make the problem challenging.

Ash and Waters (1991) provide a simulation methodology for coal shipment from mines in western Canada to power stations in the east. The transportation cost for such distances becomes increasingly important as it is a major component of final coal prices. They simulate alternative routes across Canada and present the possible outcomes of each scenario for strategic route planning. McCollum (2007) presents research on existing coal distribution infrastructure and develops four scenarios lasting until 2050 to analyze coal consumption and possible problems for meeting coal demand. He discusses the research on coal distribution dates back to the 1980s and proposes that efforts should be made regarding this problem regarding reliable coal supply. He first presents coal transportation routes and maps in the US and carries out a coal demand analysis based on power consumptions to determine the possible bottlenecks and congestions on transportation routes. Tu and Guldman (2001) develop a model and a tool called the Geographic Information System to identify coal transportation routes considering coal production sites, power plants, and costs of transportation. They visualize the transportation process and validate the model in a case study developed for Ohio. Kaplan (2007) presents a comprehensive study on coal transportation to power plants and its reliability in the US. He explores major coal resources and discusses transportation reliability issues while noting the importance of coal for energy supplies. Liu (2007) proposes a model for coal blending and transportation in which an inter-model transportation network for coal import exists. The coal supply, quality, price, and demand at the power plant are included in the model, and it is a mix-integer zero-one programming problem in which the main objective is overall cost minimization. These research studies consider transportation issues and the main objective is to minimize the total cost. They do not include trans-loading and they assume an identical commodity and develop their model based on this assumption. This article uses some of the methods that are previously used and extends the research by including product and supplier diversity.

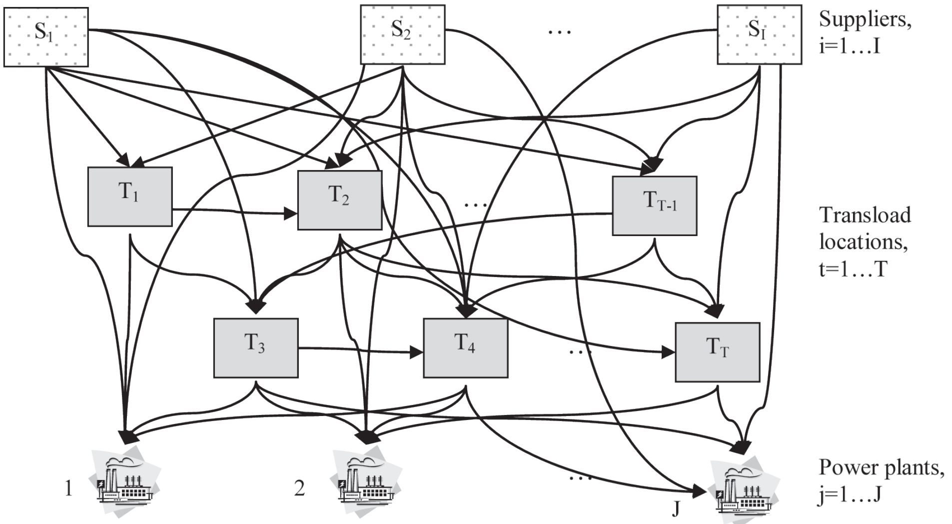
In this research, a multi-objective model that considers multimode transportation alternatives, multiple products, and multiple suppliers is developed to create a managerial tool for the efficient management of the coal supply of an electric power company with more than one plant at different locations. The tool is able to optimize the supply of fuel-coal over the network and also able to help configure the supply chain by providing alternative solutions to the decision-maker. Capacity limitations on transportation routes, supplier capacity for a particular product, and plant burn capability constraints are also considered in the model. The remainder of the article is organized as follows: Section 2 formulates the problem. The solution methodology is presented in Section 3. Section 4 provides a real case study developed for a power company in the Midwestern USA. Conclusions are given in Section 5.

Fuel-Coal Supply Problems with Operational Constraints

The coal is first mined and transported to a silo where the stones and refuse are removed at the supplier's site. The next step is to crush the coal and sort it before the washing process. Then it is ready to be blended to get the desired level of physical specifications. The last step is to load the coal onto trains, barges or trucks to ship it to its next destination. The coal transportation network is heavily dominated by private railroad companies as they have their own fleet with specialized coal transportation cars and railroads for transportation. Barges on waterways are also used, especially for large power companies that have their own coal transportation fleet. The coal is transported directly to the power plant or often times it is transported to a trans-load location where it is loaded to another vehicle of a supplier or another company. The trans-load location is a hub point that is used to efficiently manage the transportation network.

The coal supply chain can be represented as a network in which suppliers, transportation routes, trans-load locations and power plants are natural entities. Exhibit 1 gives a description of a coal supply network. The coal *q*∈*Q* is supplied at supplier *i*∈*I*, and it is transported to power plant *j*∈*J* directly or via trans-loading

Exhibit 1. Coal Transportation Network



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 found for each power plant is $X_{i,j,q}$, the total amount of coal q transported from supplier i to power plant j, where

$X_{i,j,q} = X_{i,j,q} + X_{i,t,q} + X_{t,j,q} + X_{t,t`,q} + X_{t`,j,q}$. The decision variable includes the total coal q transported directly to plant j, the coal transported to a trans-load location t then transported to plant j, and the coal further transported to other trans-load locations $t`$ then transported to plant j.

The main components of the objective are cost of purchase, cost of transportation to the destination power plant, and the ash amount, which are related with supplier selection, the transportation route, and coal type, respectively. Accordingly, the main objective of the problem is the minimization of purchase and transportation cost along with the amount of ash produced. Selection of coal suppliers depends on their location and the specifications of their product, and whether they offer different price ranges for coal contracts. However, the availability of alternative transportation routes, trans-loading locations, and associated costs also force power companies to optimize the coal delivery process. The issue arising at this point is the reliability of the supplier, transportation routes, ash content, and tradeoffs between these three. Coal that has a minimum cost of purchase but is not necessarily supplied by the best supplier or the most reliable transportation route might not be the one that has the minimum cost solution. The high ash content of coal, even if this is the coal that will minimize the total cost, adds direct and indirect costs to the company and introduces hazardous materials into the environment. Accordingly, the problem is formulated as multi-objective in which the strategic preferences of a decision maker are employed. The detailed formulation of each objective is as follows:

- Purchase cost: This objective function finds purchase cost by multiplying the price of coal q with the total amount of coal q transported from supplier i whether directly to plant j or trans-load location t.

$$f_1 = \sum_{i\in I}\Big(\sum_{j\in J}\sum_{q\in Q} X_{i,j,q}P_{i,q} + \sum_{t\in T}\sum_{q\in Q} X_{i,t,q}P_{i,q}\Big) \tag{1}$$

$P_{i,q}$ is the given price of coal q at supplier i. The first part of the objective function is the cost of purchased coal that is transported directly to the plant without trans-loading. The second part calculates the purchase cost of coal q that it is transported to a trans-load location t.

- Transportation cost: The cost of transportation over the transportation network is minimized in this objective.

$$f_2 = \sum_{q\in Q}\Big(\sum_{i\in I}\sum_{j\in J} X_{i,j,q}TC_{i,j} + \sum_{i\in I}\sum_{t\in T} X_{i,t,q}TC_{i,t} + \sum_{t\in T}\sum_{t`\in T, t\neq t`} X_{t,t',q}TC_{t,t'} + \sum_{t\in T}\sum_{j\in J} X_{t,j,q}TC_{t,j}\Big) \tag{2}$$

$TC_{i,j}$, $TC_{i,t}$, $TC_{t,j}$, and $TC_{t,t`}$ represents the transportation cost of coal from supplier $i$ to plant $j$, from supplier $i$ to trans-load location $t$, from trans-load location $t$ to plant $j$ and from trans-load location $t$ to trans-load location $t`$ ($t\neq t`$), respectively.

- Ash output: This is the amount of remaining ash after coal is burned, and it includes both fly ash and bottom ash.

$$f_3 = \sum_{j\in J}\sum_{q\in Q}\Big(\sum_{i\in I} X_{i,j,q}A_q + \sum_{t\in T} X_{t,j,q}A_q\Big) \tag{3}$$

A_q is the ash content of coal q in percentage. The total ash amount is found by multiplying the total amount of product q transported to plant j, whether it is directly shipped from a supplier or from a trans-load location t, with the ash content of product q. The constraints can be classified as transportation related constraints and supply-demand related constraints. The detailed formulation for each constraint follows.

Energy demand: Electricity is a non-storable commodity that must be produced and consumed in real-time. The power plant j keeps a coal inventory that is sufficient to meet F_j (days) of power demand and orders coal that is sufficient to meet D_j (days) of power demand assuming that the plant would work at its maximum capacity. The heat content of coal q, H_q *(BTU/lb)* is released during the burning process and is converted into electric power. The total power amount that can be gained from coal q is H_q multiplied with the reserve of coal q at plant j (*ton*), which is the accumulation of the current inventory of coal q, $I_{j,q}$ (tons), and the coal inflow of coal q from suppliers and trans-load locations. As a result of the energy release process, the total BTU units of energy can be derived from coal q at power plant j to meet demand. However, the efficiency of a power plant in converting the potential energy output into electricity should be considered. The power generated from a coal-fired power plant is approximated with its heat rate R_j (*mmBTU/MWh*). Note that in order to generate M_j (*MWh*) of power for each hour, R_j x M_j (*mmBTU*) units of energy is needed. Hence, the necessary condition is that the potential power output in terms of BTUs should be higher than the required BTUs to generate M_j amount of power for $D_j + F_j$ days. After necessary unit conversions, the equation can be represented as:

$$\sum_{q\in Q}\left(\left(I_{j,q} + \sum_{i\in I} X_{i,j,q} + \sum_{t\in T} X_{t,j,q}\right)H_q\right) \geq \left(D_j + F_j\right)\left(24M_j\right)\left(R_j/500\right) \tag{4}$$

$$\text{for all } j\in J$$

Note that the units should be equal on both sides of this inequality. The left hand side has (*Ton = 2000lb*) *x* (*BTU/lb*) which is equal to *2000BTU*. The right hand side has *MWH*x *(mmBTU/MWh=10*^{6}*BTU/MWh*) which is equal to *10*^{6}*BTU*. Then the right hand side should be multiplied by 1/500 to balance the units.

Supply equations: The amount of coal that is processed and blended at each supplier i is limited and usually determined by market conditions. The total amount of coal q transported to trans-load locations and power plants from supplier i is limited to its capacity. Note that $X_{i,t,q}$ is the amount of coal q that is transported to a trans-load location from supplier i, and it can be further transported to another trans-load location or to a power plant. On the other hand, $X_{i,j,q}$ is the amount of coal q that is directly transported to power plant j. Since both quantities were sent from supplier i, the total should sum of the amount of coal q that is provided by supplier i, which has a limited capacity is

$$\sum_{t\in T} X_{i,t,q} + \sum_{j\in J} X_{i,j,q} \leq O_{i,q} \qquad \text{for all } i\in I, q\in Q \tag{5}$$

Plant based constraints: Not all coal types can be burned in a coal fired power plant. Technological infrastructure, environmental constraints, and regulations require plants to burn pre-defined coal types. Additionally, the grindability index (size) of coal q, gi_q , should be in an interval of minimum grindability permitted in plant j, $gi_{j,min}$, and maximum grindability permitted in plant j, $gi_{j,max}$. Similarly the percentage of moisture content in coal q , mc_q, should be in an interval of $mc_{j,min}$ and $mc_{j,max}$ which are the minimum and maximum percentage of moisture allowed at plant j. To lower the SO_2 outputs from coal it is desirable to keep the sulfur content in coal q, S_q, within the limit of maximum and minimum sulfur percentage permitted at plant j, which are $S_{j,min}$ and $S_{j,\ max}$ respectively. The equations can be gathered in a single representing formula as given below:

$$X_{i,j,q} = \begin{cases} 0 & \text{if coal } q \text{ cannot be burned at plant } j \\ & \text{and / or if } gi_q \notin [gi_{j,\min}, gi_{j,\max}] \\ & \text{and / or if } mc_q \notin [mc_{j,\min}, mc_{j,\max}] \\ & \text{and / or if } S_q \notin \left[S_{j,\min}, S_{j,\max}\right] \\ X_{i,j,q} & \text{Otherwise} \end{cases}$$

$$\text{for all } q \in Q, i \in I \tag{6}$$

$$X_{t,j,q} = \begin{cases} 0 & \text{if coal } q \text{ cannot be burned at plant } j \\ & \text{and / or if } gi_q \notin [gi_{j,\min}, gi_{j,\max}] \\ & \text{and / or if } mc_q \notin [mc_{j,\min}, mc_{j,\max}] \\ & \text{and / or if } S_q \notin \left[S_{j,\min}, S_{j,\max}\right] \\ X_{t,j,q} & \text{Otherwise} \end{cases}$$

$$\text{for all } q \in Q, t \in T \tag{7}$$

Transportation capacity equations: The coal transportation network has multiple transportation routes that are used if they are more economical. The total coal amount that can be transported on a route is limited to the transportation capacity of the arc in the network.

$$\sum_{q\in Q} X_{i,t,q} \le U_{i,t} \qquad \text{for all } i \in I, t \in T \tag{8}$$

$$\sum_{q\in Q} X_{t,j,q} \le U_{t,j} \qquad \text{for all } j \in J, t \in T \tag{9}$$

$$\sum_{q\in Q} X_{t,t',q} \le U_{t,t'} \qquad \text{for all } t, t` \in T, t \ne t` \tag{10}$$

$$\sum_{q\in Q} X_{i,j,q} \le U_{i,j} \qquad \text{for all } i \in I, j \in J \tag{11}$$

Total coal transportation between supplier i to trans-load location t is limited with that of arc capacity in Eq. 8. Eq. 9 gives the capacity constraint of transportation between trans-load location t and plant j, Eq. 10 gives the transportation limit between trans-load location t to another trans-load location $t`$, and Eq. 11 gives the direct transportation capacity from supplier i to plant j.

Trans-load location balance equation: Total coal transported to a trans-load location t is transported either to another trans-load location $t`$ or power plant j.

$$\sum_{t\in T} X_{i,t,q} - \sum_{t\in T, t\ne t`} X_{t,t`,q} - \sum_{t\in T} X_{t,j,q} = 0 \quad \text{for all } i \in I, q \in Q, j \in J \tag{12}$$

The non-negativity constraints are also included to ensure non-feasible solutions.

$$X_{i,j,q}, X_{i,t,q}, X_{t,t`,q}, X_{t,j,q} \ge 0 \qquad \text{for all } i \in I, q \in Q, j$$

$$\text{for all } i \in I, q \in Q, j \in J, t, t` \in T, t \ne t` \tag{13}$$

Let $X = \{X_{i,j,q}, X_{i,t,q}, X_{t,t`,q}, X_{t,j,q}\}$.

$\text{for all } i \in I, q \in Q, j \in J, t, t` \in T, t \ne t`$ be a feasible solution set for the multi-objective linear coal supply problem, and 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 ($z=1,2,3$), the general model can be defined as

$$\text{Minimize } f = [f_1(\text{x}), f_2(\text{x}), f_3(\text{x})] \qquad s.t. \quad x \in X. \tag{14}$$

Fuel-Coal Supply Chain Management with Decision-Maker Preferences

It is important for power companies to report operational expenses in their financial reports. Each cost item has to be explained in the report and they affect the financial performance of the company, which is released to shareholders. As a result, they need to be careful to separate the cost of coal and the cost of transportation. The price of coal is determined by market conditions and it can thus be explained. However, a high cost of transportation decreases the performance of the company. For this reason, these costs have to be treated with different weights and have to be separated. Environmental concerns increase the pressure on coal plants, since international and state regulations force power companies to reduce hazardous outputs. Ash is not desired and it should be safely handled, reused if possible, or disposed of permanently. Power companies try to find ways to reuse ash or give it to third parties such as construction companies and road building companies. However, the objective is to reduce the cost of ash disposal and reduce environmental hazards rather than creating revenue. The total cost of ash disposal can reach $1.8/ton with accumulation (Cheripko, 2011). This cost, however, does not reflect the hidden hazards to the environment, nature, and human health. If ash output is converted into a cost, it becomes relatively low. Hence, the real unit of tons is preferred for analysis and it needs to be evaluated as a different objective function.

Given the three important and separate objective functions, the importance (weight) of each objective over another needs to be evaluated. A multiple criteria decision making (MCDM) method can be used to evaluate objective functions and determine weights. The weight of objectives might change during the year as the cost parameters might change in deregulated markets. There are numerous alternative solutions that include different means of transportation. Not all of the transportation routes are preferable or available all the time due to the weather conditions, time restrictions, and vehicle (train, barge) restrictions. The fuel supply department has to have the opportunity to select one of the alternatives from a set of feasible alternatives according to the preferences. Each alternative includes a supplier, coal type, transportation route, transportation cost, coal purchase cost, and ash content. An MCDM must be used to compare alternatives using priorities and weights.

However, just using an MCDM to evaluate a decision is not enough. An optimization method is needed to find the best supplier, coal type, transportation route, transportation cost, coal purchase cost, and ash content. An MCDM is a multiple-criteria decision making method and thus does not identify alternatives. Rather, it evaluates alternatives according to defined priorities and weights. The alternatives are determined via a multiple objective programming method and the MCDM is used to evaluate the alternatives. Therefore, a hybrid approach that integrates the multiple objective programming and an MCDM is needed.

The trade-offs among objectives and the strategic preferences of decision-makers should be included in the solution methodology. A proposed solution methodology applied in Meza et al. (2007) solves the multi-period multi-objective power generation expansion problem. The authors use a two-phased solution procedure in which they employ an Analytic Hierarchy Process (AHP), an MCDM, to sort the alternative solutions and minimize the multi-objective problem with four objectives. The feasible alternatives are presented and the decision-maker is provided with some flexibility to choose among the alternatives. Another approach is employed by Tekiner et al. (2010) for the power generation expansion problem. A representative approach is adapted from Meza et al. (2007) and is used to solve the multi-objective coal supply problem to employ the preferences of the decision-maker. The article presents the results of the power generation expansion problem and analyzes the possible tradeoffs among alternatives. The solution provides an obvious investment decision. However, the solution of the problem that is modeled in this article requires product, transportation, trans-loading, and supplier information. An integrated solution that includes procurement and strategy is founded. The solution procedure is similar but the domain of the problem structure is completely different. A description of the methodology used for this study is presented next.

Limit 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. Note that the lower and upper bounds for objective *z* are

$$\min(f_z(x) : x \in X = \{X_{i,j,q}, X_{i,t,q}, X_{t,t`,q}, X_{t,j,q}\} \\ for\ all\ i \in I, q \in Q, j \in J, t,t` \in T, t \neq t`) \qquad (15)$$

$$\max(f_z(x) : x \in X = \{X_{i,j,q}, X_{i,t,q}, X_{t,t`,q}, X_{t,j,q}\} \\ for\ all\ i \in I, q \in Q, j \in J, t,t` \in T, t \neq t`) \qquad (16)$$

The lower and upper bounds for each objective will provide a feasible search space for the decision-maker when strategic decision preferences come into play.

Find solution alternatives based on 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. The minimax in decision theory follows the strategy of minimization of loss and maximization of gains. Given that ID_z is the ideal solution and AID_z is the anti-ideal solution associated with the objective function *z*, the minimax can be defined as follows:

$$Min\left[\max\left\{\frac{AID_z - f_z(x)}{AID_z - ID_z}\right\}, z = 1,2,3\right] \qquad (17)$$

On the other hand, maximin is the maximization of minimum outcomes and similarly can be formulated as follows:

$$Max\left[\min\left\{\frac{f_z(x) - ID_z}{AID_z - ID_z}\right\}, z = 1,2,3\right] \qquad (18)$$

Compromise programming aims to find the solution such that its distance to an ideal solution is minimized. It can be formulated as below:

$$Min\sum_{z=1}^{3}\frac{AID_z - f_z(x)}{AID_z - ID_z}, \qquad x \in X \qquad (19)$$

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 combined single objective functions can be solved in such a way that:

$$x^v = \min_v\left(\sum_{z=1}^{3} w_z^v f_z(x) : x^v \in X, v \in N, \ \sum_{z=1}^{3} w_z^v = 1\right) \qquad (20)$$

Notice that with a larger value of *N*, a wider feasible space is scanned for each objective function and more solution alternatives are found.

Use K-means clustering: Because the problems are solved over coal supply constraints, not all of the weight sets in the *N* random weights are expected to contribute to the same difference in the solutions. *N* solutions actually include *K* (*K*<*N*) statistically different solutions which a *K*-means clustering algorithm would differentiate with meaningful combinations. By using the *K*-means clustering algorithm on the solutions, *K* different and representative solution sets can be obtained from the *N* random solutions.

Construct the AHP hierarchy: The relationships between *K*+3 alternatives and 3 objectives are modeled in the AHP hierarchy in this step. Exhibit 2 shows the AHP relationship.

The AHP method is a popular MCDM for problems where evaluation criteria, and preferences over the criteria should be considered. It was first developed by Saaty (1980) and later became popular for the solution of decision-making problems. In this method, the problem is structured in a hierarchical manner and preferences (inputs) are represented using scales. The main components of a typical hierarchy include the main goal that needs to be achieved, the evaluation criterion below, and the main goal and the alternatives along with their relationships at the bottom. The hierarchy takes on a more detailed form from a general view. The next step is to define the priorities among the elements of the hierarchy using pair-wise comparisons of the elements. The decision-maker indicates the preferences in this step. A scaling scheme is needed to define the judgments about the priorities. The hierarchy then is evaluated using priorities. The priorities are similar to probabilities, and they are the measurement of the relative strengths of alternatives with respect to each criterion. Once the comparison matrix is created, the principal right eigenvector provides the priorities of each alternative with respect to the criterion. Once the priority calculation of each alternative with respect to each criterion is completed, each criterion has to be compared using a pairwise comparison matrix. The priority of each criterion is sometimes called the weight of each alternative and is an important step in the AHP. Then the weight of each criterion and priorities of alternatives are synthesized to obtain an overall score for each alternative with respect to all of the criteria. Note that the judgments of the decision-maker and the evaluation results for the alternatives are included in these scores. Lastly, the scores are rank ordered for the selection of the best alternative and the one with the highest score is selected.

The application of AHP as a multi-criteria decision making tool is common in the literature (Saaty, 2008). It is utilized in business decisions, public policy decisions, and personal decisions due to the fact that the preferences and a decision are included in this process. Subramanian and Ramanathan (2012) present a review of AHP applications used in operations management through an analysis of 291 peer reviewed journal papers published between 1990-2009. Ho (2008) also presents a literature review for the research that integrates AHP with other methods such as quality function deployment, meta-heuristics, and Swot analysis. It is also common to use AHP in decision making for electric power systems and energy operations. Xu et al. (2011), proposes a Grey relational analysis (GRA) and AHP-based method to evaluate the performance of coal-fired power plants in China. The problem is multi-objective and the preferences of a decision-maker can easily be adopted in the hierarchy of the AHP. Chatzimouratidis and Pilavachi (2009) use AHP to evaluate power plants from the perspectives of technology, economics, and sustainability.

Pair-wise comparison: As an important step in the AHP, the alternatives should be evaluated for each criterion based on either quantitative measures or pair-wise comparisons of each alternative with respect to each criterion. Notice that the pair-wise comparisons are 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, a common scaling scheme used in literature is proposed by Saaty as presented in Exhibit 3. The concept of scaling is essential and very important in AHP. The scale is used as a relative evaluation tool in the construction of pair-wise comparisons of each criterion over another. If both criteria are equally important, then it is represented as 1 in this scale. As the degree of preference of one criterion over another increases, relative importance levels are considered. The level of importance or preference can be expressed as moderate, strong, very strong, and extreme. Each level is assigned a number that will be used in the calculations. Note that if one attribute is strongly more important than another attribute and it is rated at 5, then weak attribute is less important than strong attribute and is valued at 1/5.

Exhibit 2. AHP Hierarchy for Supplier, Product, and Route Selection

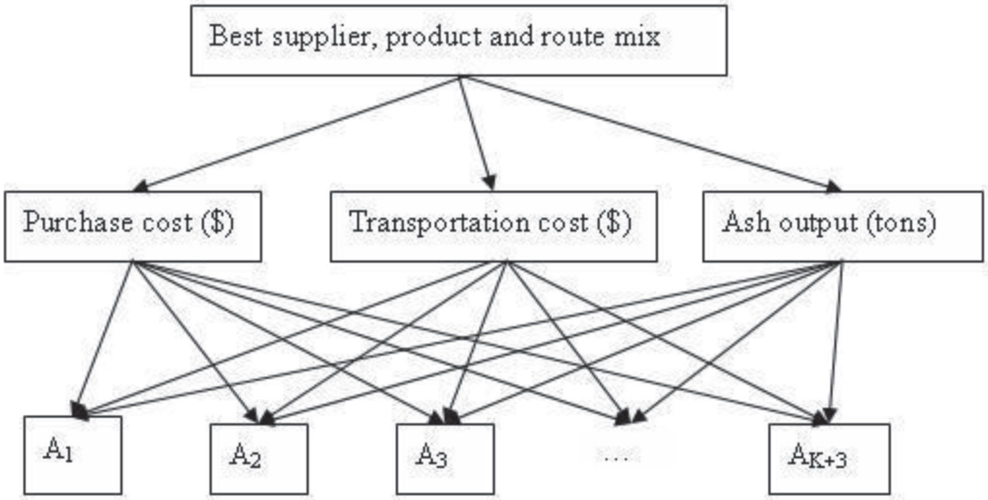


Exhibit 3. Definition of Scale Values That Are Used in AHP

Intensity of Importance Function	Definition
1	Equally important/preferred
3	Moderately more important/preferred
5	Strongly more important/preferred
7	Very strongly more important/preferred
9	Extremely more important/preferred
2,4,6,8	Between scale values

Once the matrix that includes the comparison scales of each alternative with respect to another is constructed, the matrix is normalized and the average for each alternative is found for the particular objective. On the other hand, the objectives are also evaluated among the others to give the decision-maker an opportunity to determine the importance level of each objective. The normalization of this matrix provides the weight of each objective in the AHP when making a decision concerning alternatives.

Identify the best alternative: The objective matrix and alternative matrix values provide the average score of each alternative in the AHP process. The scores are ranked and the alternative with the highest score is identified as the preferred solution.

A Case Study for the Midwestern USA

The proposed methodology is illustrated for a case study for the midwestern USA. The electric power supply in the region is dominated by coal-fired generation. Four suppliers (S_1, S_2, S_3, S_4), nine alternative contracts (q_1, q_2,… q_9), four trans-load locations (T_1, T_2, T_3, T_4), and three power plants (plant 1, 2 and 3) are taken into consideration. The power company has three coal-fired power plants located in Indiana, Ohio, and Kentucky. Exhibit 4 provides the coal contract specifications.

The fuel supply department contacted suppliers and was offered different coal contracts. The supplier price and daily capacity for each product are provided in Exhibit 5.

The power company also has plant specifications and burn abilities, as shown in Exhibit 6, for its coal fired power plants. Note that not all plants are able to burn the available coal products provided from suppliers. If a plant cannot burn a particular supplier's coal, this is indicated with a 0. These indicator variables represent true and false conditions.

Exhibit 7 gives the coal specific plant constraints, which include grindability index (GI), moisture content (MC), and permitted maximum (S_{max}) and minimum (S_{min}) sulfur rates at the plants.

Each power plant has a current inventory that is a mix of available products. Exhibit 8 shows the current inventory level at each power plant. As a policy, power companies would like to keep a safety stock that is sufficient to provide three days of energy. On the other hand, in addition to current inventory and safety stock levels, companies seek to maintain fuel that is sufficient to meet two days of power demand.

Exhibit 4. Coal Contracts and Specifications

Product	Contract	Heat Content (BTU)	S (%)	GI	MC(%)	Ash (%)
q_1	CAPP	12500	0.90	41	10	13.50
q_2	CSX Compliance	12500	0.80	43	7	12.00
q_3	CSX	12500	1.00	43	7	12.00
q_4	NS Compliance	12500	0.75	44	7	12.50
q_5	NS Rail	12500	1.00	44	7	12.90
q_6	NYMEX Big Sandy	12000	1.00	41	10	13.00
q_7	PRB 8800	8800	0.80	51	27	5.50
q_8	PRB 8400	8400	0.80	51	30	5.50
q_9	Pittsburgh Seam	13000	3.00	55	8	8.00

Exhibit 5. Supplier Price and Capacity for Each Coal Product

Supplier	Price & Capacity	Coal Products								
		q_1	q_2	q_3	q_4	q_5	q_6	q_7	q_8	q_9
S_1	Price ($/ton)	63.5	57.1	67.5	65.5	64.8	28.1	15.0	14.9	41.0
	Capacity (ton)	8640	13440	25920	0	0	0	0	0	11520
S_2	Price ($/ton)	62.4	56.2	66.4	63.2	63.1	26.8	15.2	15.1	42.1
	Capacity (ton)	13440	11520	0	17280	0	0	0	0	13440
S_3	Price ($/ton)	63.8	56.8	68.0	64.6	64.2	25.5	14.5	14.0	40.8
	Capacity (ton)	0	0	19200	10560	13440	18240	11520	17280	0
S_4	Price ($/ton)	64.1	54.8	65.2	66.7	66.3	27.1	15.8	15.8	42.9
	Capacity (ton)	0	0	10560	11520	9600	12480	13440	11520	0

Exhibit 6. Power Plant Specifications and Burn Abilities

Plant	Demand (MWh)	Heat Rate (mmBTU/MWh)	q_1	q_2	q_3	q_4	q_5	q_6	q_7	q_8	q_9
Plant 1	2862	9.2	1	0	1	0	1	0	1	1	0
Plant 2	1185	9.8	0	1	0	1	0	1	0	0	1
Plant 3	820	10.2	1	0	0	1	0	0	1	1	0

In addition to coal offers, the company has to decide about transportation routes. It is possible to deliver the coal directly from the supplier to the power plant; however, the transportation cost is usually higher. Coal is shipped via train-cars on railways, barges on waterways, trucks, or by using a multimode that utilizes a trans-load location. For the multimode alternative, there are four trans-load locations where the coal can be transferred to another form of transportation for further shipment. The transportation costs and capacities between each point are given in Exhibit 9 and Exhibit 10, respectively. Note that the trans-loading cost is included in transportation costs.

The transportation and coal specification data has been gathered from EIA (2010) and verified in NYMEX (2010). The data for the coal fired power plants has also been gathered from the same sources; however, they have been slightly modified for confidentiality reasons in the market. The illustrated case is coded in GAMS (General Algebraic Modeling System), a high level modeling and optimization tool. The solutions were obtained using a CPLEX 12.1 solver for the minimax, maximin, and compromise programming, and in total, the 2,000 single objective cases each have randomly generated weights. The ideal and anti-ideal solutions for each objective are also found using the same solver. The computations were performed on a computer with an Intel Core 2 duo 2 Ghz CPU with 4 GB RAM in 650 seconds. Two-thousand different solutions were clustered into four representative solutions using a *K*-means clustering algorithm and in total seven alternative solutions, including those of minimax, maximin, and compromise programming, were obtained. Exhibit 11 provides the alternative solutions. It should be noted that the representative alternatives of the 2,000 generated cases bring diversity to the decision environment as they provide different alternative solutions for suppliers, transportation routes, and coal products.

Each objective function value for the alternatives lies between its ideal (lower bound) and anti-ideal (upper bound) solution. As the weight of each alternative (the importance level) changes, the solution differs, giving more weight to minimize that particular objective.

Exhibit 7. Plant Constraints for Coal Products and Emissions

Plant	GI	MC (%)	S_{min} (%)	S_{max} (%)
Plant 1	[40-60]	[5-35]	0	1.2
Plant 2	[39-58]	[6-33]	0	1.9
Plant 3	[39-57]	[5.5-32]	0	3.8

Exhibit 8. Current Coal Inventory of Each Power Plant (tons)

Plant	q_1	q_2	q_3	q_4	q_5	q_6	q_7	q_8	q_9
Plant 1	29432	0	2000	0	0	0	37440	29823	0
Plant 2	0	4000	0	2450	0	34839	0	0	450
Plant 3	8000	0	0	15100	0	0	0	13376	0

Exhibit 9. Cost of Coal Transportation Between Two Locations ($/ton)

	Destination						
Location	T_1	T_2	T_3	T_4	Plant 1	Plant 2	Plant 3
S_1	6.95	9.65	15.68	13.47	21.75	23.52	24.60
S_2	8.25	4.50	9.20	12.35	24.48	20.45	19.40
S_3	7.32	8.85	11.45	12.25	23.43	18.26	23.16
S_4	4.60	4.20	10.25	10.10	19.45	17.26	18.06
T_1	0.00	8.46	7.99	6.11	13.72	12.21	14.49
T_2	10.92	0.00	4.53	10.17	15.06	12.47	13.58
T_3	6.79	4.19	0.00	3.24	7.13	4.65	5.77
T_4	7.79	9.66	2.86	0.00	5.40	5.87	6.74

Exhibit 10. Coal Transportation Capacities to Destinations (ton)

	Destination						
Location	T_1	T_2	T_3	T_4	Plant 1	Plant 2	Plant 3
S_1	7392	17040	19344	24576	19440	24720	17856
S_2	11616	25680	18720	22128	27696	23280	16560
S_3	10512	11232	13008	11424	26736	18240	11424
S_4	9744	9696	9168	12096	26736	18768	9840
T_1	0	30000	25392	33216	21984	25056	26016
T_2	20784	0	20832	23712	29040	28608	30048
T_3	21936	21264	0	20640	17040	25776	26688
T_4	29424	34704	35856	0	29424	34704	35856

The next step is to apply the AHP method to choose the best alternative mix of suppliers, transportation routes, and coal products. The pair-wise comparisons of alternatives with respect to each objective and comparisons of objective functions are performed by the fuel supply department. Exhibit 12 shows the comparison for the objectives. The results show that the transportation cost is slightly preferred over purchase cost and ash output. Purchase cost is also slightly preferred over ash output.

The score of each alternative solution for each objective is also found based on the decisions of the fuel supply department. The calculated scores for each alternative when considering the objective weights are given in Equation 21 in ranked order.

$$A_5(0.35) > A_6(0.27) > A_7(0.25) > A_3(0.21) > A_4(0.18) > A_2(0.10) > A_1(0.02) \quad (21)$$

The values in the parenthesis are the calculated priority values of each alternative based on the judgments of the solution. Notice that when the judgments are made, the decision-maker evaluates the suppliers, transportation routes, and coal products and makes a judgment concerning the alternative. The evaluation includes all the experience, supplier credit, its reliability, and past information about the transportation routes. Based on the preferences, A_5 is the best alternative and A_1 is the least preferred alternative. A_6 and A_7 are close solutions and the preferable alternatives after A_5. This study now presents the solution for A_5 in Exhibit 13. 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

Exhibit 11. Alternative Coal-Supply Decisions

	Objective Weights			Transportation	Purchase	Ash
Alternative	w_1	w_2	w_3	Cost ($)	Cost ($)	Output (ton)
A_1	minimax			7,452,900	13,233,000	29497
A_2	maximin			926,720	13,233,000	29497
A_3	compromise programming			1,353,900	2,742,500	6588
A_4	0.1532	0.4116	0.4352	1,374,000	2,447,800	7697
A_5	0.2174	0.1963	0.5866	1,335,000	2,463,700	7697
A_6	0.5762	0.2093	0.2147	1,312,900	2,514,800	7498
A_7	0.4128	0.1719	0.4156	1,331,500	2,467,500	7697
Ideal				926,720	2,445,700	6502
Anti-ideal				7,452,900	13,233,000	29497

Exhibit 12. AHP Preferences for Objectives

Objective	Transportation Cost ($)	Purchase Cost ($)	Ash Output (ton)
Transportation cost ($)	1	3	3
Purchase cost ($)	1/3	1	2
Ash output (ton)	1/3	1/2	1

Exhibit 13. 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)	Transportation Cost /Final Price
S_4	-	-	1	q_7	3472	21.75	58%
S_4	-	-	1	q_8	11520	19.45	55%
S_3	T_3	-	1	q_7	7056	18.58	56%
S_1	T_1	T_3	1	q_1	5616	22.07	26%
S_3	T_2	T_3	1	q_7	4368	20.51	58%
S_2	T_2	T_4	1	q_1	13440	20.07	24%
S_1	T_1	T_4	1	q_1	632	18.46	22%
S_4	T_1	T_4	1	q_7	9372	16.11	50%
S_4	T_4	-	1	q_7	595	15.50	49%
S_3	T_2	T_4	1	q_7	96	24.42	63%
S_3	T_1	T_4	1	q_8	5288	18.83	57%
S_4	T_1	T_3	2	q_6	372	17.24	39%
S_4	T_2	T_3	2	q_6	9696	13.38	33%
S_3	T_3	-	2	q_6	5952	16.10	39%
S_3	T_1	T_3	3	q_8	5224	21.08	60%
S_3	T_2	T_3	3	q_8	6768	19.15	57%

trans-load location, and the fourth column is the destination power plant. The dashes imply no trans-loading. Notice that usage of more than two trans-load locations is also possible, but no solution was found for such a case.

Based on the results shown, the demand of plant 1 is supplied from four suppliers in different amounts. S_1 and S_2 supply q_1, S_3 supplies $K_{7,}$ and S_4 supplies q_7 and q_8. A mixed strategy for transportation seems optimum for plant 1 as all the transportation is made via different routes.

The coal demand of plant 2 is provided by S_3 and S_4 with coal type q_6. Trans-load locations T_1, T_2, and T_3 are used for transportation of coal. All of the coal demand for plant 3 is provided from S_3 with coal type q_8. Two different transportation routes using T_1, T_2, and T_3 are preferred. The total transportation cost and its ratio on final cost are also provided. Notice that when the purchase price is low, the ratio of transportation on total cost becomes higher.

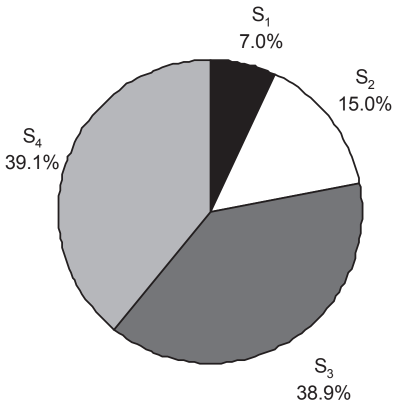
The cost and coal output distribution for each power plant are expected to be different. Exhibit 14 shows the objective decompositions for each power plant. Plant 1 has the highest demand point, which is incurred by the transportation and purchase cost along with the ash output. It is worth noting that plant 2 burns more coal than plant 3, but the transportation costs are relatively close.

Exhibit 14. Objectives Achieved by Each Power Plant

Objective	Plant 1	Plant 2	Plant 3
Transportation cost ($)	956,569	195,667	182,764
Purchase cost ($)	1,871,074	424,738	167,888
Coal output (ton)	4955	2083	660

The amount of coal supplied from each supplier is different. Exhibit 15 shows the percentage of total coal supplied by each supplier. Ignoring the coal types, a large amount of coal is supplied by S_3 and S_4; whereas, a small amount of coal is supplied by S_1. Also, the decision-maker can apply a coal-type analysis for each supplier to make further comparisons.

Exhibit 15. Comparisons of Supplier by Total Coal Supplied



It is also useful to do a comparison for the procured coal types. Exhibit 16 shows the percentages of each coal type transported to the plants. It is shown that q_2, q_3, q_4, and q_5 are not preferred coal types at this time. On the other hand, the range of preferences for four coal types is relatively close, with q_8 being the most preferred and q_1 being a lesser preferred coal.

The results show that the coal price is more important in product selection than its heat content, as q_8 and q_7 have lower prices and lower heat and ash contents; whereas, q_6 has a moderate price and a higher heat and ash content. On the other hand, q_1 has a higher price, heat, and ash content, and it is less preferred while the other coal products are not preferred. The amount of coal transported via each trans-load location should also be evaluated. Exhibit 17 shows the usage of trans-load locations, indicating that most of the coal is trans-loaded at T_3, followed by T_2, $T_{3,}$, and T_1.

Exhibit 16. Supplied Coal Types by Percentage

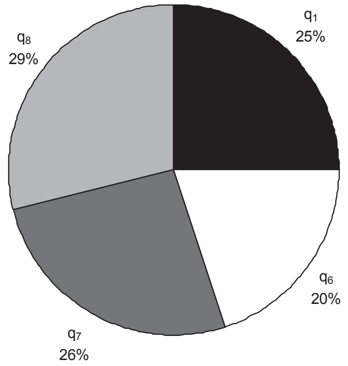
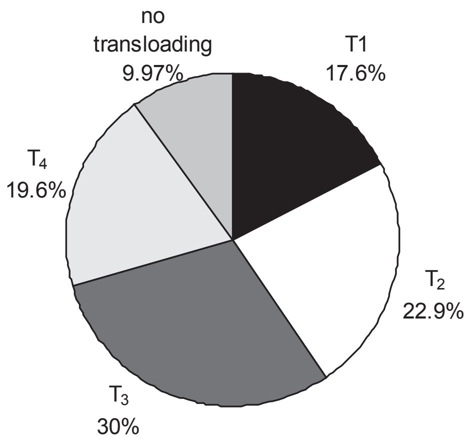
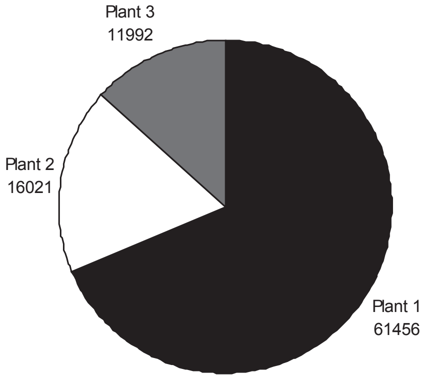


Exhibit 17. Usage of Trans-Load Locations



The coal demanded at each power plant is also presented in Exhibit 18. Notice that the heat rate of the power plant, the current inventory level and the heat content of coal affect the transported amount. Plant 1 has the highest demand, as expected, and plant 3 has the lowest demand for coal.

Exhibit 18. The Total Coal Transported to Plants



Managerial Implications and Future Research

In this article, a tool to manage the multi-objective fuel-coal supply process is developed for the selection of the best supplier, transportation alternative, and coal orders given multiple suppliers, contracts, and multimode transportation routes. The solution methodology is applied to determine alternative plans of minimax, maximin, compromise programming, and random weighted representative (clustered) solutions. AHP is employed to include decision-maker's preferences, and a preferred solution is selected based on the judgments. The solution method is applied to a case study for a power company located in the midwestern USA. The results provide a mix of suppliers, transportation routes, and coal products for the power company to meet its needs. For the presented case, it is possible to do a benefit/cost analysis based on the results and this is considered for future extensions of the research. The ratio of the transportation cost in terms of the final price is presented for comparison purposes. The sources that increase the ratio of transportation cost can be investigated with the aim of decreasing that cost. It is also worth mentioning that the purchase price dominates over other determining criteria based on the selected products. The reason for this is that the range of transportation costs is narrow; whereas, the price range for coal is broader.

The output analyses of the presented results are required to help the fuel supply department with future decisions. The methodology can be implemented in integrated fashion, using a graphical user interface (GUI). The GUI can be developed with a spreadsheet using visual basic applications or another available programming method. The flow chart of a tool developed in Microsoft Excel is provided in the Appendix. The data for suppliers, coal types, plants, transportation routes, coal inventory, and energy demand are gathered from a source – usually a spreadsheet or a database. It is possible to integrate the spreadsheet and GAMS software. The multi-objective model is run on GAMS, and the results are exported to a source, whereupon a *K*-means clustering method is applied using statistical software. The alternatives are evaluated using AHP and alternatives are ranked based on the weights and priorities. The best solution is then reported, which is selected based on the preferences of the decision-maker. It is easy to integrate the data sources of the company and feed the data to GUI for an updated solution. Once the GUI is designed, it can be run each and a solution is selected based on the results. The next step, then, is to order the coal from the suppliers and plan the transportation routes.

Although the model was validated for a particular case study, the proposed methodology is applicable to manage any supply chain as it includes network constraints, demand constraints, and product characteristics. The model is especially suitable for commodities such as oil, liquefied natural gas, wheat, corn, wood, and metallic materials, with some required modifications due to the nature of the material. A more general model for commodities can be developed as a future study in which the lot-sizing problem can be included in the model. If the model is applied for agricultural commodities, the source of the product will be more diversified and hence a more complex transportation network would be expected. It is also common to transport commodities internationally. In particular, energy commodities are supplied from countries where they are available. The model can also be extended for international supply chains. A contribution of this multi-attribute decision making with an optimization model is to create a more flexible, but reliable, decision-making process. It allows the decision-maker to select a preferred solution from among the feasible alternatives. The model can directly be used by power companies for their fuel supply decisions, as the results are promising and the computational time is relatively low as to be integrated into daily planning (research was to illustrate the value of combining) processes.

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Appendix 1. The Flow Chart for the Example GUI Developed in Microsoft Excel