Cost Minimizing Coal Logistics for Power Plants Considering Transportation Constraints

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***Abstract*—Fuel coal supply chain is a complex network in which multiple suppliers, coal products, multiple transportation methods with trans-loading option exist. Each supplier offer different prices for the coal contracts and depend on the location of the supplier, the transportation cost varies. The heat content of the coal needs to be evaluated as it is used to estimate the amount of energy that can be gained from the coal. This energy output should be able to meet the electricity demand which is expected from the power plant. In this paper, a linear model is developed to find the set of supplier, coal products, and transportation route that will minimize the purchase and transportation cost of the fuel coal for the power plants and also will meet the electricity demand. The solution methodology is applied in a case study in Midwest USA. 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.**

***Index Terms*—Coal supply chain, energy demand, linear programming, transportation optimization**

I. Introduction

Coal currently is the most important energy source in the world. In developing countries and in large countries like USA, China and India coal based electricity generation is increasing. Coal has to be extracted, processed and transported to where it is needed using a set of transportation vehicles. Since it is the most abundant and largest energy resource, it is commonly used in the electricity generation in the world. It's availability in nature, flexibility to use and its distribution around the world make coal a more reliable source. A report in [1] shows that the coal usage will increase %80 in next 20 years and it will be the major energy resource until 2030. The coal resources are distributed in a country and often far away from where the coal is consumed.

Coal shows different characteristics and has not unique and homogeneous structure that change for each coal type. The right product can be purchased for the best use of plant resources and minimizing the cost. Another issue is the emission gas outputs from coal fired power plants which have been an important problem since 1990s. Carbon emissions (Carbon dioxide, CO_2) and green gas 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 rains in nature. Coal fired power plants are accepted as a major source of air pollution [1].

The suppliers provide coal contracts for each coal type which is being sold on a merchandise exchange to power companies. A coal contract is an offer that includes the amount, type, the price, the heat content, the ash content, the sulfur content, moisture content, volatile matter and the chemical structure of the coal that will be delivered to the power company. The price for each contract is different and often times it is the mine mouth-price which does not include the transportation cost. A supplier has different coal contracts available each of which has their own price and related product descriptions [2]. A power company faces the problem of choosing the best coal contracts that will meet his demand in a cost-effective way given that he has one or multiple power plants at different locations.

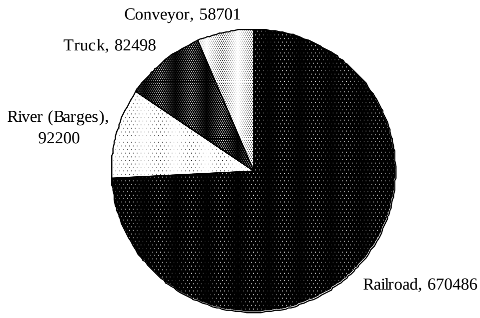

Figure 1. Coal transportation in USA in 2012 (tons)

It is best to locate the coal-fired power plant to a location where it is close to the coal mine. However, it is not usually the case as the generation point should also be in close proximity to demand point where the power is transmitted and consumed. The coal then should be transported from where the coal is blended or mined to its final destination plant. The coal is usually shipped by professional transportation companies but it is also common for power companies to have their own fleet of coal transportation. In US, the railway companies have the largest share of coal transportation as they have their own railroads and specialized transportation cars. Other methods such as transportation using coal barges on waterways or trucks on highways are also used. Fig. 1 shows the amount of coal that is transported in USA in 2012 for electricity generation [1]. The coal can be

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transported directly to the power plants using one of these methods without any disruptions. Or it can be transported to a trans-load location where it is loaded to another vehicle at this hub point for further shipment to power plant or to another trans-load location.

Notice that the final destination is the power plant but the transportation cost is expected to be different depends on the method, multi-mode transportation, the distance, and selected route mix. The transportation capacity on each route is limited and the tariff to ship coal is different. The power company should also ensure that an effective and minimum cost transportation methodology is chosen.

The power companies face a decision of supplier, transportation, and order set selection in an environment where multiple suppliers, products, multi-mode transportation routes, multiple power plants, and plant operational constraints exist. There is a limited effort in the literature for researches that integrate supplier, transportation, and order diversity for power industry. In [3], a method is developed 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. Author proposes a mixed integer programming method for the planning of fuel-coal imports for power plants in [4]. The diversity of supply sources for power companies that has more than one plant makes the coal logistics problem difficult. 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. The model is developed for the central coal logistics system of Taiwan power company to show its validity. In [5], authors present a model for coal blending and cleaning silos for supply of coal from different resources and delivery to customer locations to meet the demand. They develop three different linear programming models depend on the problem complexity and computational burden. 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. A model is developed for a coal loading port in China in [6]. The coal is first transported to the port via trains and then the river vessels are used to deliver the coal to the four subsidiaries. They develop a markov decision model that minimizes holding cost, shortage, and transportation cost by integrating ordering and delivery decisions. The problem slightly considers the product and route diversities which are usually the decision variables that makes the problem challenging.

Authors provide a simulation methodology in [7] for the coal shipment from the mines in the west Canada to power stations in the east. The transportation cost for such distances become more important as it will be the major part at the final coal price. They simulate the alternative routes across Canada and present the possible outcomes of each scenario for strategic route planning. A research on the existing coal distribution infrastructure is presented in [8]. Author develops four scenarios until 2050 to analyze the coal consumption and the possible problems on meeting the demand of coal. He mentions that the researches on coal distribution date back to 80's and efforts should be spend on this important problem for a reliable coal supply. He first presents the coal transportation routes and maps in US and then does a coal demand analysis based on the power consumptions to determine the possible bottlenecks and congestions on the transportation routes. Authors develop a model and a tool called Geographic Information System in [9] to identify the coal transportation routes considering coal production sites, power plants, and costs of transportation. They visualize the transportation and validate the model in a case study developed for Ohio. In [10], a wide research is presented on the coal transportation to power plants and its reliability in US. The paper explores the major coal resources and discusses the transportation reliability issues while he expresses the importance of coal for the energy supply. A model is proposed for coal blending and transportation where inter-model transportation network for coal import exists in [11]. The coal supply, quality, price, demand at the power plant are included to the model. The model is a mix-integer zero-one programming problem in which the main objective is the overall cost minimization.

In this research, a model that considers multimode transportation alternatives, multiple products, 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, and plant burn capability constraints are also considered in the model. The remainder of the paper is organized as follows: Section II gives problem definition and formulation. Section III provides a real case study developed for a power company in Midwest USA. Conclusions are given section IV.

II. THE PROBLEM FORMULATION

The coal supply chain can be represented as a network in which suppliers, routes, trans-load locations and power plants are natural entities. Fig. 2 gives a description of a coal supply 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

$$Xi,j,k = Xi,j,k + Xi,t,k + Xt,j,k + Xt,t`,k + Xt`,j,k$$

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.

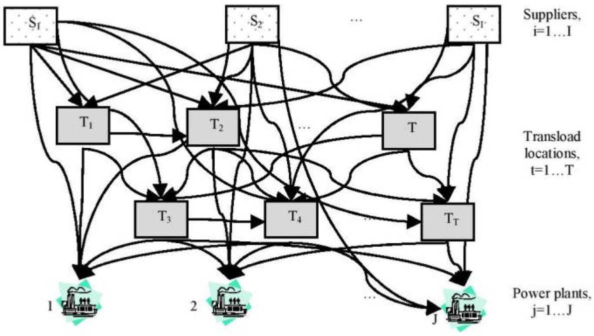

Figure 2. Coal transportation network

The main objective of the problem is the minimization of purchase and transportation cost. The detailed formulation of each objective is as follows:

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

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

$P_{i,k}$ is the given price of coal k at supplier i. $TC_{i,j}$, $TC_{i,t}$, $TC_{t,j}$, and $TC_{t,t`}$ represent 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. Eq. 1 calculates the purchase cost, and eq. 2 gives the transportation cost. A power company aims to minimize the total cost which is purchase and transportation cost which is represented as:

$$Min\ \ f = f_1 + f_2 \tag{3}$$

There are also constraints that need to be included to the model. The company has to meet the energy demand and requires enough coal for the energy demand. It can be represented as below:

$$\sum_{k\in K}\left(\left(I_{j,k} + \sum_{i\in I} X_{i,j,k} + \sum_{t\in T} X_{t,j,k}\right)H_k\right) \geq \left(D_j + F_j\right)\left(24M_j\right)\left(R_j / 500\right) \quad \forall\, j\in J \tag{4}$$

The electricity is a non-storable commodity that should be generated and consumed real-time. The power plant j keeps 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 k, H_k*(BTU/lb)* is released during the burning process and converted to electric power. The total power amount that can be gained from coal k is H_k multiplied with the reserve of coal k at plant j (*ton*), which is the accumulation of current inventory of coal k, $I_{j,k}$ (tons), and coal inflow of coal k from suppliers and trans-load locations. As a result of the energy release process, totally BTU units of energy can be gained from the coal k at power plant j to meet the demand. However, efficiency of power plant to convert 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_jx M_j (*mmBTU*) units of energy is needed. Hence, the necessary condition is the potential power output in terms of BTUs should be higher than 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 in Eq. (4).:

$$\sum_{t\in T} X_{i,t,k} + \sum_{j\in J} X_{i,j,k} \leq O_{i,k} \qquad \forall\, i\in I, k\in K \tag{5}$$

$$\sum_{k\in K} X_{i,t,k} \leq U_{i,t} \qquad \forall\, i\in I, t\in T \tag{6}$$

$$\sum_{k\in K} X_{t,j,k} \leq U_{t,j} \qquad \forall\, j\in J, t\in T \tag{7}$$

$$\sum_{k\in K} X_{t,t',k} \leq U_{t,t'} \qquad \forall\, t,t`\in T, t\neq t` \tag{8}$$

$$\sum_{k\in K} X_{i,j,k} \leq U_{i,j} \qquad \forall\, i\in I, j\in J \tag{9}$$

$$X_{i,j,k}, X_{t,j,k} = \begin{cases} 0 & if\ coal\ k\ cannot\ be\ burned\ at\ plant\ j \\ & and/or\ if\ gi_k \notin [gi_{j,\min}, gi_{j,\max}] \\ & and/or\ if\ mc_k \notin [mc_{j,\min}, mc_{j,\max}] \\ & and/or\ if\ vm_k \notin [vm_{j,\min}, vm_{j,\max}] \\ & and/or\ if\ S_k \notin [S_{j,\min}, S_{j,\max}] \\ X_{i,j,k}, X_{t,j,k} & Otherwise \end{cases} \qquad \forall\, k\in K, i\in I \tag{10}$$

$$\sum_{t\in T} X_{i,t,k} - \sum_{t\in T, t\neq t`} X_{t,t`,k} - \sum_{t\in T} X_{t,j,k} = 0 \qquad \forall\, i\in I, k\in K, j\in J \tag{11}$$

$$X_{i,j,k}, X_{i,t,k}, X_{t,t`,k}, X_{t,j,k} \geq 0 \quad \forall\, i\in I, k\in K, j\in J, t,t`\in T, t\neq t` \tag{12}$$

Eq. 5 ensures that the total amount of coal k transported to the trans-load locations and plants from supplier i is limited to its capacity, $O_{i,k}$. Eq. 6 through 9 give capacity constraints of transportation between each i and t, between each t and j, between each transload location t and $t`$ and between each i and j respectively where capacity is $U_{i,t}$. Eq. 10 ensures that only coal with certain physical or chemical structure are supplied by giving upper and lower bound on grindability index (gi_k), moisture content (mc_k), volatile matter (vm_k) and sulfur content (S_k)for each coal k. If coal is out of the acceptable limits, it is not accepted for a purchase. Eq. 11 shows that total coal transported to a trans-load location t is transported either to another trans-load location $t`$ or a power plant $j$. Eq. 12 ensures that nonnegative solutions are obtained. 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 linear coal supply problem, the objective of the problem is to determine the optimum suppliers, coal products, and transportation routes that will satisfy the minimum cost.

III. CASE STUDY

The proposed methodology is illustrated for a case study in Midwest USA. The electric power industry in the region is dominated with coal-fired generation. 4 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 (Plant 1, 2 and 3) are considered. The power company has 3 coal-fired power plants located in Indiana, Ohio, and Kentucky, USA. Table I provides the coal contracts and their specifications.

TABLE I. COAL CONTRACTS AND SPECIFICATIONS

Product	Contract	Heat content (BTU)	S (%)	GI	MC (%)	VM (%)
P1	CAPP	12500	0.9	41	10	31
P2	CSX Compliance	12500	0.8	43	7	30
P3	CSX	12500	1	43	7	30.5
P4	NS Compliance	12500	0.75	44	7	30
P5	NS Rail	12500	1	44	7	30
P6	NYMEX Big Sandy	12000	1	41	10	30
P7	PRB 8800	8800	0.8	51	27	27
P8	PRB 8400	8400	0.8	51	30	30
P9	Pittsburgh Seam	13000	3	55	8	37.6

The fuel supply department has contacted with suppliers and was offered the following coal contracts. The coal specifications, the supplier price, and daily capacity for each product are provided in Table II.

TABLE II. SUPPLIER PRICE AND CAPACITY FOR EACH COAL PRODUCT

Supplier	Price & capacity	Coal products								
		P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9
S_1	Price ($/ton)	63.54	57.1	67.5	65.5	64.8	28.12	15	14.9	41
	Capacity (ton)	8640	13440	25920	0	0	0	0	0	11520
S_2	Price ($/ton)	62.4	56.2	66.4	63.2	63.1	26.81	15.2	15.1	42.1
	Capacity (ton)	13440	11520	0	17280	0	0	0	0	13440
S_3	Price ($/ton)	63.8	56.8	68	64.6	64.2	25.52	14.5	14	40.8
	Capacity (ton)	0	0	19200	10560	13440	18240	11520	17280	0
S_4	Price ($/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

The power company has the data given in Table III for its coal fired power plants. Notice that not all plants are able to burn the available coal products provided from the suppliers and they are represented with 0. Table IV gives the coal specific plant constraints which include grindability index, moisture content, volatile matter, and maximum allowable sulfur content.

TABLE III. POWER PLANT SPECIFICATIONS AND BURN ABILITIES

Plant	Demand (MWh)	Heat Rate (mmBTU/MWh)	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_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

TABLE IV. PLANT CONSTRAINTS FOR COAL PRODUCTS AND EMISSIONS

Plant	GI	MC (%)	VM (%)	S_{max} (%)
Plant 1	[40-60]	[5-35]	[25-33]	1.2
Plant 2	[39-58]	[6-33]	[26-39]	1.9
Plant 3	[39-57]	[5.5-32]	[25-35]	3.8

Each power plant has a current inventory that is a mix of available products. Table V shows the current inventory level at each power plant. As a policy, power company would like to keep a safety stock that is sufficient to provide 3 days demand of energy. On the other hand, in addition to current inventory and safety stock level, company wants to provide fuel that is sufficient to meet 2 days of power demand.

TABLE V. CURRENT COAL INVENTORY OF EACH POWER PLANT (TONS)

Plant	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_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

It is possible to deliver the coal directly from supplier to power plant, however, the transportation cost is usually higher. 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 that the coal can be transferred to another transportation vehicle for further shipment. The transportation cost and capacities between each point are given in Table VI and Table VII respectively. Note that the trans-loading cost is included to the transportation costs. The transportation and coal specification data is gathered from [1] and [2].

TABLE VI. 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	24.6
S_2	8.25	4.5	9.2	12.35	24.48	20.45	19.4
S_3	7.32	8.85	11.45	12.25	23.43	18.26	23.16
S_4	4.6	4.2	10.25	10.1	19.45	17.26	18.06
T_1	0	6.97	1.62	1.49	13.72	12.21	14.49
T_2	8.42	0	1.03	2.67	15.06	12.47	13.58
T_3	4.29	2.7	0	2.74	7.13	4.65	5.77
T_4	7.3	8.17	2.37	0	5.4	5.87	6.74

TABLE VII. 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 data for the coal fired power plants is also gathered from the same sources however, they are slightly modified for the 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 CPLEX 12.1. The computations were performed on a computer with Intel Core 2 duo 2 Ghz CPU with 4 GB RAM in 650 seconds. Table VIII summarizes the decision variables which are combined to summarize the results for each plant. Total cost is $3,798,700 of which

\$1,335,000 is shipping cost and \$2,463,273 is purchase cost.

TABLE VIII. 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
S4	-	-	1	P7	4067	19.45	55.18%
S4	-	-	1	P8	10924	19.45	55.18%
S1	T1	T4	1	P1	6248	13.84	17.89%
S2	T2	T4	1	P1	13440	12.57	16.77%
S3	T1	T4	1	P8	5288	16.11	53.50%
S3	T2	T3	1	P7	10503	17.01	53.98%
S3	T3	-	1	P7	1016	18.58	56.17%
S4	T1	T4	1	P7	3852	11.49	42.10%
S4	T1	T3	1	P7	5616	13.35	45.80%
S3	T1	T3	2	P6	5223	13.59	34.75%
S3	T2	T3	2	P6	728	14.53	36.28%
S4	T2	T3	2	P6	9696	9.88	26.72%
S3	T3	-	3	P8	11991	17.22	55.16%

The transportation route is represented in such a way that the first column is the beginning point (supplier), second column is the first trans-load location, third column is the second trans-load location and 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 case. Based on the results shown, the demand of the plant 1 is supplied from 4 suppliers in different amounts. S_1 and S_2 supply P_1, S_3 supplies P_7 and P_8, and S_4 supplies P_7 and P_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 types P_6. Trans-load locations T_1, T_2 and T_3 are used for transportation of coal. All coal demand of plant 3 is provided from S_3 with coal type P_8. 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. Plant 1 has the highest demand point that is the much transportation and purchase cost along with the ash output incurred. It is worth noting that plant 2 burns more coal than plant 3 but the transportation costs are relatively close.

The amount of coal supplied from each supplier varies. Fig. 3 shows the percentage of total coal supplied by each supplier. Ignoring the coal types, much 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 based analysis for each supplier to make further comparisons.

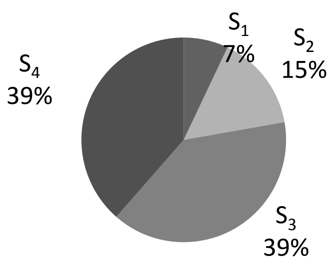

Figure 3. Comparisons of supplier by total coal supplied

It is also useful to do a comparison for the procured coal types. Fig. 4 shows the percentages of each coal type transported to the plants. It is shown that P_2, P_3, P_4, and P_5 are not preferred coal types at this time. P_8 is the most preferred and P_6 is being the less preferred coal. Results show that the coal price is more important on product selection than its heat content as P_8 and P_7 have lower prices and lower heat content whereas P_6 has moderate price and higher heat content. P_1 on the other hand has higher price, and heat content and it is less preferred while other coal products are not preferred.

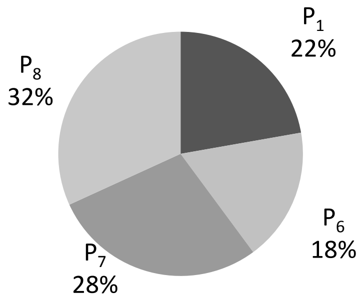

Figure 4. Supplied coal types by percentage

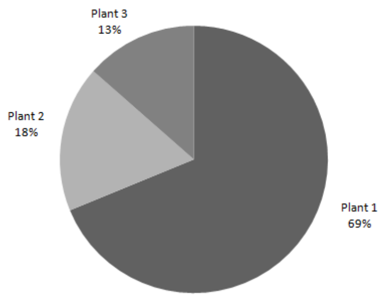

Figure 5. The total coal transported to plants

The coal demanded at each power plant is also presented in Fig. 5. Notice that heat rate of power plant, the current inventory level and 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.

IV. CONCLUSION

In this paper, a linear integrated model for supplier, transportation, and coal orders is developed under multiple suppliers, contracts, and multimode transportation routes in fuel supply chain. The solution method is applied to a case study for a power company located in Midwest USA. The results provide the mix of suppliers, transportation routes, and coal products for the power company to meet its demand.

The output analyses on the presented results are required to help fuel supply department in terms of management of this engineering process for their future decisions. Ratio of the transportation cost on the final price is presented for the comparison purposes. The causes that increase the ratio of transportation cost can be investigated to decrease the cost. It is also worth mentioning that the purchase price dominates other determining criteria based on the selected products. The reason for that is the transportation cost ranges between close ranges in lower and upper bounds whereas the price range on coal is wider. The model can directly be used by power companies for their fuel supply decisions as results are promising and computational time is relatively low for such daily processes.

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