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A Blending and Inter-Modal Transportation Model for the Coal Distribution Problem

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Abstract—The problem of how to plan coal fuel blending and distribution from overseas coal sources to domestic power plants through some possible seaports by certain types of fleet in order to meet operational and environmental requirements is a complex task. The aspects under consideration includes each coal source contract's supply, quality and price, each power plant's demand, environmental requirements and limit on maximum number of different coal sources that can supply it, installation of blending facilities, selection of fleet types, and transient seaport's capacity limit on fleet types. A coal blending and inter-model transportation model is explored to find optimal blending and distribution decisions for coal fuel from overseas contracts to domestic power plants. The objective in this study is to minimize total logistics costs, including procurement cost, shipping cost, and inland delivery cost. The developed model is one type of mix-integer zero-one programming problems. A real-world case problem is presented using the coal logistics system of a local electric utility company to demonstrate the benefit of the proposed approach. A well-known optimization package, AMPL-CPLEX, is utilized to solve this problem. Results from this study suggest that the obtained solution is better than the rule-of-thumb solution and the developed model provides a tool for management to conduct capacity expansion planning and power generation options.

Keywords—Blending and inter-modal transportation model, Integer programming, Coal fuel.

1. INTRODUCTION

The inter-modal transportation process performs the flow of materials that connects an enterprise with its suppliers and with its customers. A growing body of advances concerning several aspects of inter-modal transportation within supply chain management has appeared in the operations research literature. When inter-modal transportation costs tens of thousands of dollars a day, large cost savings can be realized by proper use of fleet. Realistic inter-modal transportation models are needed to achieve those savings.

Coal fuel is one of the most important energy resources used in electricity industry. A large and growing percentage of electricity is generated using coal fuel. Due to global economic growth and development, the demand for electricity is rapidly increasing in recent years. Most of this resource used by power plants is imported from different overseas contract coal sources in many countries.

The problem of how to plan coal fuel blending and distribution from each coal source contract overseas to each inland power plant in order to meet operational and environmental requirements is a complex task. The planning of coal shipping and blending involves many aspects. The aspects under consideration include at least supply quantity, quality and price from each contract coal source, demand and quality requirements of each power plant, transportation costs along all possible routes from contract coal sources to power plants through transient seaports, selection of fleet types, and transient seaport's capacity limit on fleet types. In addition, there are different modes of transportation. These are air, truck, rail, ship, and pipeline. Each mode has different characteristics with respect to the size of shipment, cost of shipping, and flexibility.

The basic structure of the considered blending and distribution system is a complex network, in which many points, such as coal source sites, seaports, and power plants are connected by physical links such as railways, ships, and trucks. Naturally, it suffices to assign coal fuel having a high quality to meet the operational and environmental requirements for the power plants. However, this is usually infeasible in practice, since high quality coal fuel is more expensive and has a limited supply quantity. Most often, a blending facility is installed and used to compensate between low and high-grade coal fuel in order to produce a uniform coal product.

In this study, the aim is to develop a blending and inter-modal transportation model for minimizing total logistics costs, including procurement cost, shipping cost, and inland delivery cost. A combinatorial optimization technique is proposed for dealing with the coal blending and distribution problem. This approach considers all the aforementioned features that should be accommodated in

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the decision-making process. An important and complex challenge in the study is to optimally assign integer number of vessels to the candidate links, while satisfying a number of environmental constraints and operational requirements.

The outline of the paper is as follows. In Section 2, detailed literature review is given. In Section 3, a mix-integer zero-one programming model is developed for determining an optimal shipping and blending policy. Then in Section 4, an industrial-size case problem is presented for demonstrating the validity of the proposed model. A commercial package AMPL/CPLEX 7.0 is used to solve the problem. Finally in Section 5, we conclude the paper by discussing the benefit of the developed approach in light of future trends in the industry.

2. LITERATURE REVIEW

A number of papers that have addressed land and marine transportation with a focus on the whole supply chain are reviewed in this paper. Previous surveys by Ronen (1983, 1993) indicated that optimization models for ship transportation are not widely used. His results indicated that although international seaborne shipping was the major artery of international trade, relatively little research has been done in quantitative aspects of designing and managing seaborne shipping systems. Barnhart et al. (1993) presented a network design problem that comprises of a number of plants, replenishment centers and distribution centers. Barnhart and Ratliff (1993) presented methods for determining minimum cost inter-modal routings to help shippers minimize total transportation costs. One of the transshipment applications with strategic and tactical issues was considered by Mehrez et al. (1995). They presented the modeling and solution of a real industrial ocean cargo shipping problem, the shipping of dry bulk minerals from facilities to customer sites. Sherali et al. (1999) illustrated a model and an algorithm for routing and scheduling ships in a transportation system. The model considers the different vessel sizes, products, routes, size of compartments, and demand time windows. Dempster et al. (2000) considered different transportation means and presented both deterministic and stochastic models of strategic planning for logistics operations in oil industry.

One recent investigation by Christiansen et al. (2004) suggests that the situation changes significantly in this area of study. Sambracos et al. (2004) presented a study to optimize a marine freight transport problem, in which the determination of best paths among a number of preset alternatives is addressed. Gunnarsson et al. (2004) presented a model and a solution approach that can be used as a decision support tool for strategic analysis as well as tactical planning of the supply of forest fuel. Bredstrom et al. (2004) studied the supply chain problem of a large international pulp producer located in Scandinavia. The supply chain network comprises a number of forest districts, a number of pulp mills, and the number of domestic and export costumers.

Several research efforts to-date have concentrated on the optimal acquisition and blending of coal fuel using linear programming and mixed-integer programming techniques. In concert with a linear programming approach, Ravindran and Hanline (1980) investigated an optimal location of coal blending plants using mixed-integer programming technique. Haynes et al. (1983) presented a coal industry distribution planning model considering the environmental issues Kao et al. (1993) applied inventory theory to determine an optimal shipping policy in which the procurement costs, the holding costs, and the shortage costs are considered in the model development. However, an inventory model by itself is insufficient for addressing all the facets of the coal shipping and blending problem. Lyu et al. (1995) developed a goal programming model for determining appropriate quantities of coal from different stockpiles for a consistent feeding of blended coal while meeting environmental and boiler performance requirements. Shih and Frey (1995) presented a coal blending optimization approach under uncertainty. Tzeng et al. (1996) formulated a fuzzy bi-criteria multi-index transportation problem for coal allocation planning. Shih (1997) proposed a mixed integer programming model for scheduling the fuel coal imports, focusing on the coal logistics subsystem that included only several power plants and harbors for unloading imported coal. The foregoing study does not consider any coal blending and environmental issues. Sherali and Puri (1993) and Sherali and Saifee (1993) provided linear programming and mixed-integer programming models for coal mining, cleaning, blending and distribution from the perspective of a coal company. Both long range strategic planning models and tactical day-to-day operational models are developed and implemented. Liu and Sherali (2000) explored an optimization based heuristic approach for solving a coal blending and shipping problem.

However, the influence of blending varies according to the source of the coal fuel with respect to the different quality attributes. Some attributes such as sulfur oxide, ash content, calorific value, volatile matter, and nitrous oxide, are additive and can be characterized using a blending facility. Some other properties such as grindability and moisture content are not additive, but for these, the individual shipment is simply prohibited if it is not compatible with certain quality range specifications. In addition, the number of contract coal sources assigned to any particular power plant should be limited in order to curtail detrimental effects on blending and boiler operations. Also, some power plants lack blending facilities. Hence, this feature must also be considered in the model.

In addition to the above considerations, the problem at hand needs to include some other features that involve the selection of fleet types and the associated transient seaports in the supply chains from overseas contract coal sources to inland power plants. The choice of transient seaports depends on the location of power plants and the shipload capacity. A combinatorial optimization technique is proposed for dealing with the coal blending and distribution problem. A complex challenge in the study is to optimally assign integer number of vessels to the candidate links, while satisfying a number of environmental constraints and operational requirements.

3. DEVELOPMENT OF BLENDING AND INTER-MODAL TRANSPORTATION MODEL

The coal blending and distribution problem may be formulated as a multi-fleet blending and inter-modal transportation model having some additional side-constraints and binary side-variables. Figure 1 displays the network diagram for the problem. In this network problem, each coal source contract overseas can be represented as a supply node, each inland power plant as a demand node, and each transient seaport as a transshipment node. The links between each node consist of two types of transport. One is the international transport and the other the domestic transport.

The decision of this problem is to find optimal shipments of each fleet type per year from all possible coal source contracts to inland power plants. During the shipping process, there are several types of fleets that are used to deliver the coal fuel. These at least include the Handy-size ship having a 20,000 tons shipload capacity, the Panamax-size ship having a 65,000 tons shipload capacity, the Cape-size ship having an 110,000 tons shipload capacity, and the like.

Almost all of the possible seaports permit only one or two types of these ships to deliver coal. The similar situations can apply to the shipment from all possible coal source contracts. There are several reasons why certain fleet types are restricted in some supply sources. First, coal source contracts are scattered in different countries. Second, the seaport in some countries can only allowed certain type of fleet due to the shipload capacity utilization threshold. Third, even in the same country, different seaport and the associated shipping line can only allowed certain type of fleet. For instance, the Handy-size ship usually allows for short distance transportation, while the Panamax-size ship is mainly to allow for the transportation through the Panama channel. So the unit shipping costs differ for using different ship types. The ships are partially owned by the company and partially chartered from the markets. For simplicity, all transportations used in this problem are assumed to be chartered from the market.

The distribution of coal fuel from each coal source contract to each power plant should primarily satisfy specified upper and lower limits of flow from the coal source, as well as the quantity demanded and the quality requirement of the power plant. If a power plant is installed with a blending facility, linear constraints are adopted for the blending of the additive coal attributes such as sulfur oxide, ash, calorific value, volatile matter, and nitrous oxide. For non-additive coal attributes such as grindability and moisture content, the shipment from a contract source to a given power plant is simply prohibited in practice if either of these quality attributes is incompatible for the corresponding pair of source and plant. Similar constraints are used to represent the coal quality requirements for power plants that do not possess a blending facility. To avoid the detrimental effects of blending on boiler operations, the number of contract coal sources assigned to any particular power plant is limited by some maximum value. Generalized packing constraints are used to deal with this situation. The objective function seeks to minimize the total logistics cost, including the free-on-board cost of coal fuels, the maritime transportation cost, and the inland delivery cost.

In order to formulate the coal blending and distribution problem, decision variables and problem parameters may be defined as follows and formulation of the model is developed accordingly.

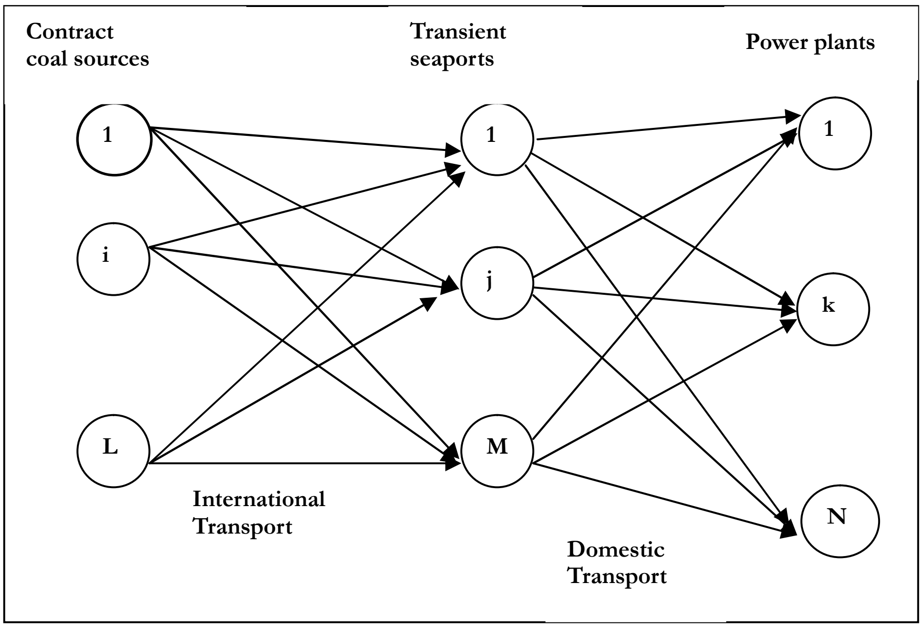

Figure 1. The coal blending and intermodal transportation network.

Decision Variables:

x^t_{ijk} = number of trips per year from contract coal source i to power plant k through transient seaport j by fleet type t;

z_{ik} = binary variable used to limit the number of contract coal sources for a particular power plant k, which takes on a value of 1 if source i supplies plant k, and 0 otherwise.

Index Set Parameters:

T = set of fleet types;

L = set of overseas contract coal sources;

L_t = subset of overseas contract coal sources that are permitted for fleet type t, $t \in T$;

M = set of transient seaports;

M_t = subset of transient seaports that are permitted for fleet type t, $t \in T$;

B = set of power plants that are installed with a blending facility;

NB = set of power plants that are not installed with a blending facility;

N = union of B and NB, representing the set of power plants.

Coefficient Parameters:

c^t_{ijk} = unit shipping cost in dollars per ton for shipment by fleet type t from contract coal source i to power plant k through transient seaport j;

cap^t = the capacity for fleet type t;

$s\min_i$ = lower limit of supply quantity in tons per year from contract coal source i;

$s\max_i$ = upper limit of supply quantity in tons per year from contract coal source i;

d_k = demand quantity in tons per year for power plant k;

s_i = percentage sulfur oxide content in coal from contract coal source i;

sl_k = minimal sulfur oxide requirement in percentage for power plant k;

su_k = maximal sulfur oxide requirement in percentage for power plant k;

h_i = calorific value in Kcal per ton for coal fuel from contract coal source i;

hl_k = minimal calorific value requirement in Kcal per ton of coal for power plant k;

hu_k = maximal calorific value permitted in Kcal per ton of coal for power plant k;

v_i = percentage volatile matter in coal from contract source i;

vl_k = percentage minimal volatile matter permitted in coal for power plant k;

vu_k = percentage maximal volatile matter permitted in coal for power plant k;

a_i = percentage ash content in coal from contract source i;

au_k = percentage maximal ash content permitted in coal for power plant k;

n_i = percentage nitrous oxide content in coal from contract source i;

nl_k = percentage minimal nitrous oxide permitted in coal for power plant k;

nu_k = percentage maximal nitrous oxide permitted in coal for power plant k;

hgi_i = grindability index of coal from contract source i;

$hgi\min_k$ = minimal grindability permitted in coal for power plant k;

$hgi\max_k$ = maximal grindability permitted in coal for power plant k;

$h2o_i$ = percentage moisture content in coal from contract source i;

$h2o\min_k$ = percentage minimal moisture content permitted in coal for power plant k;

$h2o\max_k$ = percentage maximal moisture content permitted in coal for power plant k;

$\sup_k$ = maximal number of contract coal sources that can supply power plant k.

Objective Function:

The objective function in this model is represented as a total logistics cost function to be minimized. The unit shipping cost per ton by feet type includes the procurement cost in free-on-board price, the shipping cost, and the inland delivery cost, and is required to ship coal fuel from all possible coal source contracts overseas via various seaports to domestic power plants by certain types of fleets. The total amount of shipment by fleet type and flow is the product of the capacity of fleet type and the number of shipments under that fleet type. The total logistics cost is then the product of the unit shipping cost and the total amount of shipment for the entire fleet types and flows. The developed objective function is given below.

$$\text{Minimize} \quad z = \sum_{t\in T}\sum_{i\in L}\sum_{j\in M}\sum_{k\in N} cap^t c^t_{ijk} x^t_{ijk}$$

Constraints:

The model constraints may be used to enforce several requirements. These requirements include:

(1) supply restrictions for each coal source contract,
(2) demand restrictions, sulfur oxide content restrictions, calorific value restrictions, volatile matter restrictions, ash content restrictions, nitrous oxide content restrictions, grindability index and moisture content flow restrictions for each power plant on deliveries permitted from each source to each power plant,
(3) flow restrictions due to quality requirements for power plants that do not have a blending facility,
(4) shipload capacity restrictions for each seaport,
(5) fleet type restrictions on contract sources, and
(6) maximal number of different contract coal sources that are permitted to supply each power plant.

Constraint (1) enforces the supply quantity from each coal source contract should be within the range of maximum and minimum amount of annual purchase contract. Otherwise, the purchase might be infeasible.

$$\left.\begin{aligned}\sum_{t\in T}\sum_{j\in M_t}\sum_{k\in N} cap^t x^t_{ijk} \geq s\min_i \\ \sum_{t\in T}\sum_{j\in M_t}\sum_{k\in N} cap^t x^t_{ijk} \leq s\min_i\end{aligned}\right\} \quad \forall i \in L \tag{1}$$

Constraint (2) enforces that the annual demand of each power plant should be satisfied.

$$\sum_{t\in T}\sum_{i\in L_t}\sum_{j\in M_t} cap^t x^t_{ijk} \geq d_k \quad \forall k \in N \tag{2}$$

Constraint (3) asks that the annual amount of sulfur oxide content emitted from each power plant with blending facility should be restricted within the range of upper limit and lower limit under the environmental regulations.

$$\left.\begin{aligned}\sum_{t\in T}\sum_{i\in L_t}\sum_{j\in M_t} s_i cap^t x^t_{ijk} - sl_k \sum_{t\in T}\sum_{i\in L_t}\sum_{j\in M_t} cap^t x^t_{ijk} \geq 0 \\ \sum_{t\in T}\sum_{i\in L_t}\sum_{j\in M_t} s_i cap^t x^t_{ijk} - su_k \sum_{t\in T}\sum_{i\in L_t}\sum_{j\in M_t} cap^t x^t_{ijk} \leq 0\end{aligned}\right\} \forall k \in B \tag{3}$$

Constraint (4) ensures that the annual amount of calorific value emitted from each power plant with blending facility should be restricted within the range of upper limit and lower limit under the environmental regulations.

$$\left.\begin{aligned}\sum_{t\in T}\sum_{i\in L_t}\sum_{j\in M_t} h_i cap^t x^t_{ijk} - hl_k \sum_{t\in T}\sum_{i\in L_t}\sum_{j\in M_t} cap^t x^t_{ijk} \geq 0 \\ \sum_{t\in T}\sum_{i\in L_t}\sum_{j\in M_t} h_i cap^t x^t_{ijk} - hu_k \sum_{t\in T}\sum_{i\in L_t}\sum_{j\in M_t} cap^t x^t_{ijk} \leq 0\end{aligned}\right\} \forall k \in B \tag{4}$$

Constraint (5) ensures that the annual amount of volatile matter emitted from each power plant with blending facility should be restricted within the range of upper limit and lower limit under the environmental regulations.

$$\left.\begin{aligned}\sum_{t\in T}\sum_{i\in L_t}\sum_{j\in M_t} v_i cap^t x^t_{ijk} - vl_k \sum_{t\in T}\sum_{i\in L_t}\sum_{j\in M_t} cap^t x^t_{ijk} \geq 0 \\ \sum_{t\in T}\sum_{i\in L_t}\sum_{j\in M_t} v_i cap^t x^t_{ijk} - vu_k \sum_{t\in T}\sum_{i\in L_t}\sum_{j\in M_t} cap^t x^t_{ijk} \leq 0\end{aligned}\right\} \forall k \in B \tag{5}$$

Constraint (6) ensures that the annual amount of ash content emitted from each power plant with blending facility should be restricted below the upper limit under the environmental regulations.

$$\sum_{t\in T}\sum_{i\in L_t}\sum_{j\in M_t} a_i cap^t x^t_{ijk} - au_k \sum_{t\in T}\sum_{i\in L_t}\sum_{j\in M_t} cap^t x^t_{ijk} \leq 0 \quad \forall k \in B \tag{6}$$

Constraint (7) ensures that the annual amount of nitrous oxide content emitted from each power plant with blending facility should be restricted within the range of upper limit and lower limit under the environmental regulations.

$$\left.\begin{aligned}\sum_{t\in T}\sum_{i\in L_t}\sum_{j\in M_t} n_i cap^t x^t_{ijk} - nl_k \sum_{t\in T}\sum_{i\in L_t}\sum_{j\in M_t} cap^t x^t_{ijk} \geq 0 \\ \sum_{t\in T}\sum_{i\in L_t}\sum_{j\in M_t} n_i cap^t x^t_{ijk} - nu_k \sum_{t\in T}\sum_{i\in L_t}\sum_{j\in M_t} cap^t x^t_{ijk} \leq 0\end{aligned}\right\} \forall k \in B \tag{7}$$

Constraint (8) ensures that the amount of grindability index and moisture content from all source contracts should be restricted within the range of upper limit and lower limit under the operational consideration for all power plants. Constraint (8) is one type of generalized packing constraints, in which some arithmetic and logical operators are used. These arithmetic and logical operators are useful and efficient when running the AMPL package (Fourer et al. (2003)).

$$\begin{aligned}&\sum_{t\in T} x^t_{ijk} = 0 \text{ if } hgi_i \notin [hgi\min_k, hgi\max_k] \\ &\qquad \text{or if } h2o_i \notin [h2o\min_k, h2o\max_k] \\ &\qquad \forall j \in M, i \in L, k \in N\end{aligned} \tag{8}$$

For those power plants without blending facility, constraint (9) enforces that the amount of sulfur oxide content, calorific value, percentage volatile matter, percentage ash content, and percentage nitrous oxide content from each source contract should be restricted within the range of upper limit and lower limit under the environmental regulations. Notice that constraint (8) and (9) are one type of generalized packing constraints, in which some arithmetic and logical operators are used. These arithmetic and logical operators can be found in the AMPL/CPLEX package (see Fourer et al. (2003)), and are useful and efficient when running the AMPL/CPLEX package. In this case, an external mechanism is not necessary to be pre-defined. In other words, constraint (8) and (9) is well defined in the formulation and can be recognized and solved when applying the AMPL/CPLEX package. Hence, when applying AMPL/CPLEX, we do not need to use an exact formulation to define constraint (8) and (9).

$$\begin{aligned}&\sum_{t\in T} x^t_{ijk} = 0 \text{ if } s_i \notin [sl_k, su_k], \text{or if } h_i \notin [hl_k, hu_k], \\ &\qquad \text{or if } v_i \notin [vl_k, vu_k], \text{or if } a_i > au_k, \\ &\qquad \text{or if } n_i \notin [nl_k, nu_k] \\ &\qquad \forall j \in M, i \in L, k \in NB\end{aligned} \tag{9}$$

To avoid the detrimental effects of blending on boiler operations, the number of coal source contracts assigned to any particular power plant is limited by some maximum value. For this reason, constraint (10) and (11) are used to limit the maximal number of different coal source contracts overseas that are permitted to supply each power plant due to operational requirements.

$$\sum_{t \in T} \sum_{j \in M_t} cap^t x_{ijk}^t - \min\{s\max_i, \max\{s\min_i, d_k\}\} z_{ik} \le 0$$

$$\forall i \in L \quad k \in N \tag{10}$$

$$\sum_{i \in L} z_{ik} \le \sup_k \quad \forall k \in N \tag{11}$$

Constraint (12) asks non-negativity restrictions for integer decision variables.

$$x_{ijk}^t \ge 0, \text{ integer } \forall i \in L, \ \forall j \in M, \ \forall k \in N, \ \forall t \in T \tag{12}$$

Constraint (13) ensures logical restrictions on binary variables.

$$z_{ik} = 0,1 \ \forall \ i \in L, k \in N \tag{13}$$

In the developed model, constraint (1) and (2) constitute a set of network flow constraints that represent the supply and demand restrictions in the problem. The remaining constraints can be regarded as side-constraints that also involve additional discrete side-variables. Also, the shipload capacity restrictions for each seaport are implicitly enforced in the objective function and some other constraints. The developed coal blending and inter-modal network model is one type of mix-integer zero-one programming problems. The complete formulation of this model is displayed in Appendix A.

There are several commercial optimization packages that can be used to solve this problem. In this study, we utilize well-known optimization package software, AMPL/CPLEX 7.0, to obtain solutions. There are some reasons to use this package. First, the features for applying arithmetic, logical and set operators to develop some conditional constraints can be provided in the Appendix A, "AMPL Reference Manual" (Fourer et al. (2003)). Second, the formulation with these features can be recognized and is solvable directly by the AMPL/CPLEX. Finally, these features give much more flexibility for users to cope with some complex integer programming problems.

4. CASE STUDY

Each year, a local electric utility company purchases a large amount of coal fuel from coal source contracts overseas through various transient seaports for its coal-fired power plants. During the procurement process, this company needs to plan coal fuel blending and distribution from overseas coal sources to domestic power plants through some possible seaports by certain types of fleet in order to meet operational and environmental requirements. The coal blending and inter-modal transportation problem can be shown in Figure 2.

The coal fuel planning department in this company is responsible for the planning of the blending and distribution schedule. The entire coal fuel procurement planning is conducted in several procedures. First, the manager has to determine the total amount of coal fuel that should be purchased from each coal source contract for each power plant in the planning horizon. Then, the manager needs to determine the type of fleet and the number of shipments needed for the purchase amount. Finally, the shipment is scheduled so that each power plant's demand will be fulfilled.

The quality requirements for coal fuel used in each power plant are shown in Table 1. Seven types of ingredients, including sulfur oxide, ash, calorific value, volatile matter, grindability index, moisture content, and nitrous oxide, are used to specify the quality requirements for the coal fuel used in each power plant due to environmental and operational requirements. The maximum number of different coal source contracts that can supply each particular power plant is also shown in Table 1. For purposes of blending of coal fuels with different quality in order to obtain a mix having a specified constitution, this company has installed a blending facility in some of its power plants. In Table 1, plants 4, 5, 6, 7, 9, 10, 11, and 12 are the power plant with a blending facility and plants 1, 2, 3, and 8 without a blending facility.

The quality characteristics of coal fuel supplied from each coal source contract are shown in Table 2. In Table 2, the fleet type allowed for each coal source contract is also provided, in which fleet type 1 represents the Handy-size ship having a 20,000 tons shipload capacity, fleet type 2 the Panamax-size ship having a 65,000 tons shipload capacity, and fleet type 3 the Cape-size ship having an 110,000 tons shipload capacity.

The total cost structure is displayed in Table 3 and Table 4. In Table 3, the shipping costs including the procurement cost and the marine transportation cost from each contract coal source to each seaport are given. The inland delivery costs from each seaport to each power plant are specified in Table 4. The supply (in thousand tons per year) for each coal source contract overseas and the fleet type allowed for each seaport are also presented in Table 3. The demand quantities (in thousand tons per year) at each of the power plants are given in Table 4. Using these data as input, the case problem involves 13 coal source contracts, 4 seaports, and 12 power plants, leading to a model formulation with 1872 integer variables, 312 binary variables, and 2,566 technological constraints.

A well-known optimization package, AMPL/CPLEX 7.0, was utilized to solve his problem. It took 72 CPU seconds or 97,440 simplex iterations and 15,251 branch- and-bound nodes to obtain the solution using this software. The obtained solution is displayed in Table 5. The obtained solution includes the distribution quantities from each coal source contract to each power plant and the fleet type. The resulting quality of coal fuel shipped to each power plant satisfies all the environmental and boiler requirements. The total cost for the given solution is US$1,256,290, which is much lower than the rule-of-thumb solution obtained by the company manager.

Table 5 also displays the dual prices associated with each of the supply and demand constraints for the continuous linear programming relaxation. Those dual prices can be used in a post-optimality analysis to derive insights into capacity planning and coal fuel acquisition issues. The dual price associated with each demand constraint (2) represents the marginal cost induced when the company needs more coal fuel to generate electricity for that power plant. From Table 5, we can see that power plant 8 has the least marginal cost and should be examined first in concert with other related considerations when the company wants to increase capacity to generate more electricity.

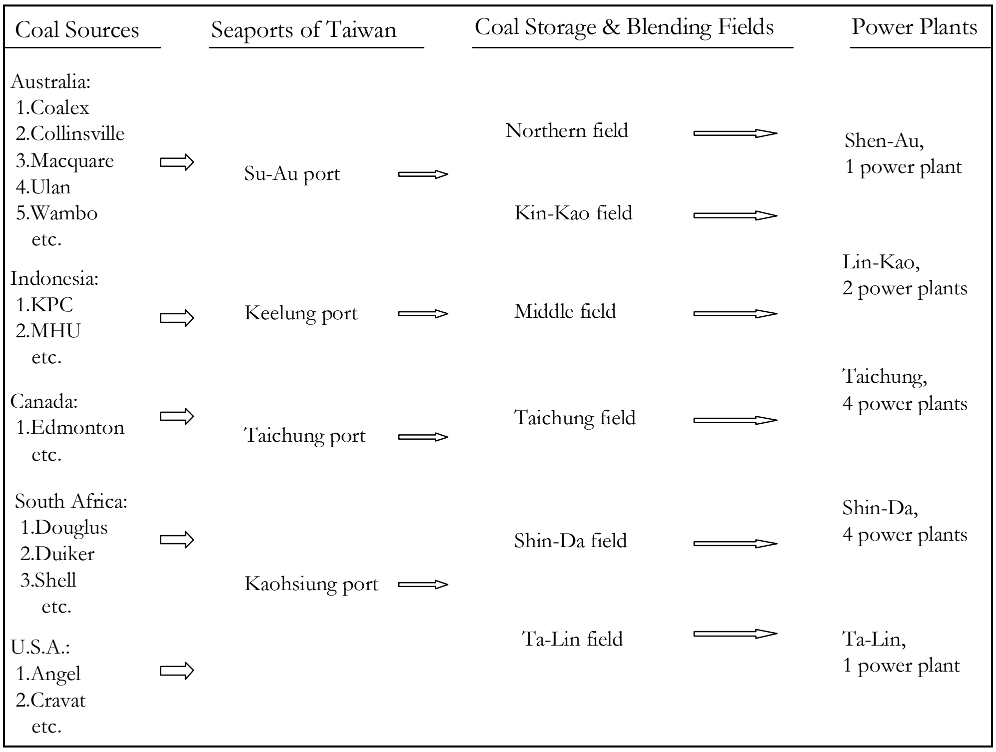

Figure 2. The coal blending and intermodal transportation problem in case study.

Table 1. Quality specifications and limits on the number of overseas source contracts for each power plant in case study

Plant	Sulfur Oxide (%)	Maximum Ash (%)	Calorific Value (Kcal/kg)	Volatile Matter (%)	Grindability Index	Moisture Content (%)	Nitrous Oxide (%)	Limit on Number of Coal Sources
1	.45 to .65	7.5	6.2 to 7	37.5 to 45	40 to 60	0 to 15	0 to 2	2
2	.8 to 1.2	16	6 to 7	30 to 34	48 to 60	0 to 15	0 to 2	2
3	.8 to 1.2	16	6 to 7	28 to 35	48 to 60	0 to 15	0 to 2	2
4	.45 to .65	14	6.5 to 7	27 to 35	45 to 60	0 to 15	0 to 2	2
5	.45 to .65	14	6.5 to 7	27 to 35	45 to 60	0 to 15	0 to 2	2
6	.45 to .65	14	6.5 to 7	27 to 35	45 to 60	0 to 15	0 to 2	2
7	.45 to .65	14	6.5 to 7	27 to 35	45 to 60	0 to 15	0 to 2	3
8	.50 to .65	16	6.4 to 7	28 to 45	45 to 60	0 to 15	0 to 2	2
9	.65 to 1.5	13.5	6.5 to 7	29 to 35	50 to 60	0 to 15	0 to 2	3
10	.65 to 1.5	13.5	6.5 to 7	29 to 35	50 to 60	0 to 15	0 to 2	4
11	.45 to .65	13.5	6.5 to 7	27 to 35	50 to 60	0 to 15	0 to 2	4
12	.45 to .65	13.5	6.5 to 7	27 to 35	50 to 60	0 to 15	0 to 2	3

Table 2. Quality specifications for coal supplied from each contract source in case study

Source	Sulfur Oxide (%)	Ash (%)	Calorific Value (Kcal/kg)	Volatile Matter (%)	Grindability Index	Moisture Content (%)	Nitrous Oxide (%)	Fleet Type Allowed
1	1.11	12.37	6.9	33.41	58	9.88	0.27	2, 3
2	0.97	15.2	6.7	33.45	54	8.85	0.23	2, 3
3	0.5	8.91	7.0	42.22	49	10.43	1.12	2
4	0.63	15.0	6.7	26.76	50	9.86	0.25	2, 3
5	0.5	14.48	6.7	32.1	55	8.53	0.33	2, 3
6	0.53	13.49	6.7	25.79	52	7.26	0.20	2, 3
7	0.70	12.04	6.7	29.49	49	8.45	0.46	2, 3
8	0.58	4.51	6.6	40.85	46	12.30	0.34	1
9	0.63	8.91	6.9	41.6	48	10.5	1.08	2
10	0.45	15.0	6.7	26.91	50	10.0	0.24	2, 3
11	0.57	14.5	6.8	30.74	50	9.96	0.1	2, 3
12	0.58	4.51	6.6	40.85	46	12.30	0.34	1
13	0.53	13.49	6.7	25.79	52	7.26	0.2	2, 3

Table 3. Unit procurement and shipping costs (in US dollars) from each source contract to each seaport, contract supply range (in thousand tons per year) for each contract source, and fleet type allowed for each seaport in case study

Source	Seaport 1	Seaport 2	Seaport 3	Seaport 4	Contract Supply Range (thousand tons per year)
1	$78.8	$68.8	$82.4	$82.4	800 to 1,000
2	$78.8	$68.8	$82.4	$82.4	1,790 to 2,210
3	$67.0	$52.0	$73.0	$73.0	300 to 500
4	$62.0	$51.0	$67.0	$67.0	720 to 880
5	$62.0	$51.0	$67.0	$67.0	690 to 910
6	$54.5	$43.5	$60.0	$60.0	912 to 1,764
7	$54.5	$43.5	$60.0	$60.0	760 to 1,703
8	$57.7	$49.2	$63.0	$63.0	900 to 1,100
9	$59.0	$48.0	$65.0	$65.0	0 to 2,000
10	$59.0	$48.0	$65.0	$65.0	0 to 2,000
11	$59.0	$48.0	$65.0	$65.0	0 to 2,000
12	$59.0	$48.0	$65.0	$65.0	0 to 2,000
13	$59.0	$48.0	$65.0	$65.0	0 to 2,000
Fleet Type Allowed	2	2	1	3	

Table 4. Unit inland delivery costs (in US dollars) from each seaport to each power plant, and the demand quantity (in thousand tons per year) for each power plant in case study

Seaport	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6	Plant 7	Plant 8	Plant 9	Plant 10	Plant 11	Plant 12
1	$15.3	$13.2	$13.2	$4.0	$4.0	$4.0	$4.0	$22.2	$25.3	$25.3	$25.3	$25.3
2	$37.5	$35.4	$35.4	$22.2	$22.2	$22.2	$22.2	$0	$3.1	$3.1	$3.1	$3.1
3	$5.1	$20.3	$20.3	$30.2	$30.2	$30.2	$30.2	$52	$55	$55	$55	$55
4	$0	$26.2	$26.2	$39.4	$39.4	$39.4	$39.4	$48.1	$62.3	$62.3	$62.3	$62.3
Demand	473	800	710	1,291	1,291	1,291	1,291	1,498	1,283	1,283	1,407	1,407

Table 5. Model flows (in thousand tons per year), fleet type and the corresponding dual prices for the case study

Source	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6	Plant 7	Plant 8	Plant 9	Plant 10	Plant 11	Plant 12	Dual Price
1									321 (2)	321 (2)	167 (2)	190 (2)	-91.7
2		800 (2)	710 (2)						218 (2)	218 (2)	118 (2)	133 (2)	0
3								300 (2)					0
4					536 (3)		344 (3)						-1.7
5						863 (3)							0
6										744 (3)	1020 (3)		-5
7				665 (3)			238 (3)						0
8	473 (1)			626 (1)									0
9								1498 (2)					0
10													0
11													0
12					755 (1)	428 (1)	709 (1)						0
13									744 (3)		102 (3)	1084 (3)	0
Dual Price	63	92	92	81	82	92	82	48	127	127	127	127	

Note: (*) represents the fleet type that serves the shipment.

Similarly, the dual prices associated with the supply constraint (1) can provide some guidelines for the acquisition of coal. For the case of positive dual prices, whence the supply constraint is active at its lower bound, the total cost can be reduced by the corresponding marginal amount per unit if the company can decrease the lower limit for the contract coal supply. For the case of negative dual prices, in which case the supply constraint is active at its upper bound, the total cost can be reduced at the corresponding marginal rate if the company can raise the upper bound for the particular contract coal supply. These interpretations hold, barring degeneracy; else, true marginal values can be determined using a parametric perturbation analysis (Bazaraa et al. (1990)). This implies that the company could potentially benefit by purchasing more coal fuel from sources 1, 4 and 6 than required by the corresponding upper and lower limits, respectively.

There are several benefits that can be obtained from the proposed approach for this coal fuel blending and inter-modal transportation problem. The first benefit is that the obtained solution can provide detailed shipment planning, including the purchase quantitative, delivery route, and fleet type. The second benefit is that the resulting total cost is much less than the rule-of-thumb solution commonly used in the company. The third and most important benefit is that the dual prices provided by the solution can derive insights into capacity planning and coal fuel acquisition issues for the manager.

Since the price and quality of coal from overseas sources vary from time to time, the company needs to frequently examine potential purchase contracts and feasible shipping plans. The automated approach proposed in this study serves as a convenient decision support system in making frequent updates to shipping and blending decisions. Also, the company needs to conduct several expansions planning studies for increasing the number of blending facilities and power plants. For this purpose, the top management of the company can benefit by using the developed model to readily evaluate the costs and benefits of various what-if scenarios.

5. CONCLUSIONS

The coal blending and distribution discussed in this paper arises in the context of the electricity industry. The aim of this problem is mainly to obtain cost effective distribution and allocation decisions. The aspects of consideration in this study include the supply, quality and price from each overseas contract, the demand, quality requirement and limit on supply sources, and presence of blending facilities at each power plant, as well as environmental and operational requirements and the transient seaport capacity utilization restrictions. A mixed-integer zero-one programming model is presented in this study to determine optimal coal distribution and blending decisions.

Real problem data obtained from a local electric utility company is used to illustrate the solution of the developed model. The model encompasses all the practical issues and constraints related to this problem, and is capable of finding implement solutions that can potentially result in considerable savings in cost. Another very useful purpose served by the model is that it provides a tool for conducting various "what-if" and feasibility analyses, by virtue of which, management can explore different capacity expansion planning and power generation options from the viewpoint of its effect on total coal distribution and blending costs.

Most large-scale blending units in the chemical/coal/petrochemical/bulk industry are time varying in nature. This implies that the underlying system is dynamically changing over time: heat exchangers foul, reactor catalyst decay, feedstock composition change, and so forth. Furthermore, certain parameters in the system at any given time might be stochastically determined, and these need to be incorporated appropriately into the model as discussed earlier. Structures which track these changes over time in the process, and solve either a deterministic or a stochastic (or deterministic equivalent) optimization problem to ascertain optimal operational policies, are known as real-time optimization systems. Generally, real-time systems require efficient solution methods, and variants based on the sequential fixing heuristic concept might be worth exploring in such contexts.

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APPENDIX A. THE COMPLETE OPTIMIZATION MODEL

$$\text{Minimize} \quad z = \sum_{t\in T}\sum_{i\in L}\sum_{j\in M}\sum_{k\in N} cap^t c^t_{ijk} x^t_{ijk}$$

Subject to:

$$\left.\begin{aligned} &\sum_{t\in T}\sum_{j\in M_t}\sum_{k\in N} cap^t x^t_{ijk} \ge s\min_i \\ &\sum_{t\in T}\sum_{j\in M_t}\sum_{k\in N} cap^t x^t_{ijk} \le s\min_i \end{aligned}\right\} \quad \forall i \in L \qquad \text{(A-1)}$$

$$\sum_{t\in T}\sum_{i\in L_t}\sum_{j\in M_t} cap^t x^t_{ijk} \ge d_k \quad \forall k \in N \qquad \text{(A-2)}$$

$$\left.\begin{aligned} &\sum_{t\in T}\sum_{i\in L_t}\sum_{j\in M_t} s_i cap^t x^t_{ijk} - sl_k \sum_{t\in T}\sum_{i\in L_t}\sum_{j\in M_t} cap^t x^t_{ijk} \ge 0 \\ &\sum_{t\in T}\sum_{i\in L_t}\sum_{j\in M_t} s_i cap^t x^t_{ijk} - su_k \sum_{t\in T}\sum_{i\in L_t}\sum_{j\in M_t} cap^t x^t_{ijk} \le 0 \end{aligned}\right\} \forall k \in B$$

(A-3)

$$\left.\begin{aligned} &\sum_{t\in T}\sum_{i\in L_t}\sum_{j\in M_t} h_i cap^t x^t_{ijk} - hl_k \sum_{t\in T}\sum_{i\in L_t}\sum_{j\in M_t} cap^t x^t_{ijk} \ge 0 \\ &\sum_{t\in T}\sum_{i\in L_t}\sum_{j\in M_t} h_i cap^t x^t_{ijk} - hu_k \sum_{t\in T}\sum_{i\in L_t}\sum_{j\in M_t} cap^t x^t_{ijk} \le 0 \end{aligned}\right\} \forall k \in B$$

(A-4)

$$\left.\begin{aligned} &\sum_{t\in T}\sum_{i\in L_t}\sum_{j\in M_t} v_i cap^t x^t_{ijk} - vl_k \sum_{t\in T}\sum_{i\in L_t}\sum_{j\in M_t} cap^t x^t_{ijk} \ge 0 \\ &\sum_{t\in T}\sum_{i\in L_t}\sum_{j\in M_t} v_i cap^t x^t_{ijk} - vu_k \sum_{t\in T}\sum_{i\in L_t}\sum_{j\in M_t} cap^t x^t_{ijk} \le 0 \end{aligned}\right\} \forall k \in B$$

(A-5)

$$\sum_{t\in T}\sum_{i\in L_t}\sum_{j\in M_t} a_i cap^t x^t_{ijk} - au_k \sum_{t\in T}\sum_{i\in L_t}\sum_{j\in M_t} cap^t x^t_{ijk} \le 0 \quad \forall k \in B$$

(A-6)

$$\left.\begin{aligned} &\sum_{t\in T}\sum_{i\in L_t}\sum_{j\in M_t} n_i cap^t x^t_{ijk} - nl_k \sum_{t\in T}\sum_{i\in L_t}\sum_{j\in M_t} cap^t x^t_{ijk} \ge 0 \\ &\sum_{t\in T}\sum_{i\in L_t}\sum_{j\in M_t} n_i cap^t x^t_{ijk} - nu_k \sum_{t\in T}\sum_{i\in L_t}\sum_{j\in M_t} cap^t x^t_{ijk} \le 0 \end{aligned}\right\} \forall k \in B$$

(A-7)

$$\sum_{t\in T} x^t_{ijk} = 0 \text{ if } hgi_i \notin \left[hgi\min_k, hgi\max_k\right]$$
$$\text{or if } h2o_i \notin \left[h2o\min_k, h2o\max_k\right]$$
$$\forall j \in M, i \in L, k \in N \qquad \text{(A-8)}$$

$$\sum_{t\in T} x^t_{ijk} = 0 \text{ if } s_i \notin \left[sl_k, su_k\right], \text{or if } h_i \notin \left[hl_k, hu_k\right],$$
$$\text{or if } v_i \notin \left[vl_k, vu_k\right], \text{or if } a_i > au_k,$$
$$\text{or if } n_i \notin \left[nl_k, nu_k\right]$$
$$\forall j \in M, i \in L, k \in NB \qquad \text{(A-9)}$$

$$\sum_{t\in T}\sum_{j\in M_t} cap^t x^t_{ijk} - \min\{s\max_i, \max\{s\min_i, d_k\}\} z_{ik} \le 0$$
$$\forall i \in L \quad k \in N \qquad \text{(A-10)}$$

$$\sum_{i\in L} z_{ik} \le \sup_k \quad \forall k \in N \qquad \text{(A-11)}$$

$$x^t_{ijk} \ge 0, \text{ integer } \forall i \in L, \ \forall j \in M, \ \forall k \in N, \ \forall t \in T \qquad \text{(A-12)}$$

$$z_{ik} = 0,1 \ \forall \ i \in L, k \in N \qquad \text{(A-13)}$$