Pollution and Cost in the Coke-Making Supply Chain in Shanxi Province, China

Applying an Integrated System Model to Siting and Transportation Trade-Offs

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Keywords

air pollution
coke making
decision support tools
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transportation cost modeling

Summary

An integrated system trade-off model has been developed to assess costs and pollution associated with transportation in the coke-making supply chain in Shanxi Province, China. A transportation-flow, cost-minimization solver is combined with models for calculating coke-making plant costs, estimating transportation costs from a geographic information system road and rail database, and aggregating coke-making capacity among plants. Model outputs of economic cost, nitrogen oxides (NO_x) emissions, and transport distributions are visualized using an Internet-based graphic user interface. Data for the model were collected on survey trips to Shanxi Province as well as from secondary references and proxies. The modularity and extensibility of the system trade-off model facilitate introduction of new data sets in order to examine various planning scenarios.

Scenarios of coke-making plant aggregation, rail infrastructure improvement, and technology transfer were evaluated using the model. Costs and pollution emissions can be reduced by enlarging coke-making plants near the rail stations and closing down other plants. Preferential minimization of transportation costs gives a lower total cost than simply minimizing plant costs. Therefore, policy makers should consider transportation costs when planning the reallocation of coke-making capacity in Shanxi Province. Increasing rail-transport capacity is less effective than aggregating plant capacity. On the other hand, transfer of low-pollution truck technology results in a large emission reduction, however, reflecting the importance of truck transportation in the Shanxi Province coke-making industry.

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Introduction

Coke production is an important output in China and especially in Shanxi Province. In 1997, the coke production in Shanxi Province was about 60 million metric tons,[1] or 40% of the total coke production in China. As China was expected to produce more than 40% of the coke in the world by 2000, Shanxi Province may soon be producing about 16% of the global total (Polenske and McMichael 2002). Coke production is responsible for more than 50% of the total consumption of coal within Shanxi Province, and about 60% of the coke produced in Shanxi is transported to other provinces and overseas (Akatsuka 2001). Even within Shanxi Province, most of the coke is produced at plants located, on average, more than 50 km from the coal suppliers and considerably further from the coke consumers.[2] Therefore, the transportation of coke is a serious issue in Shanxi Province. Shipped unwashed coal typically sells for 100 RMB/ton, where RMB is used to designate the Chinese unit of currency, the yuan, which was approximately equivalent to 12.5 U.S. cents in 2000. Using a transportation cost of approximately 0.3 RMB/ton-km calculated from data given below, we determined the transportation cost to be about 15% of the delivered cost.

In the past, Shanxi Province has been characterized by a severe lack of transportation infrastructure, especially railways (Lieberthal and Oksenberg 1988). This lack of transportation facilities led to a situation in which, even though coal mines and coke-making plants were operating below capacity, there were shortages of coal and coke in other provinces (Kuby et al. 1995). Recently, this bottleneck appears to have eased slightly (Ma 2000); however, because countries such as the United States are reducing their domestic production of coke (Polenske and McMichael 2002), demand for coal and coke from China may once again place a strain on the road and rail system in Shanxi Province.

Our interviews during four field trips in 1999–2001 to Shanxi Province have indicated that the lack of sufficient rail transport has led coke-making companies to opt to build up their own fleets of diesel trucks to transport their coke. In fact, many plant managers whom we interviewed informed us that despite the higher cost of transportation by truck, it is often favored over rail transportation, particularly by smaller coke-making plants, because of the convenience and flexibility of that transportation mode.

During our field trips to Shanxi Province, we made direct observations of high concentrations of pollutants in conditions of heavy diesel-truck traffic (Polenske 1999). We used a mobile, battery-operated monitor to measure particles smaller than 1 micron (μm), which are believed to carry polycyclic aromatic hydrocarbons (PAHs) (Qian et al. 2000). Preliminary observations indicate that the PAH concentrations of the emissions from large diesel trucks on the local roads hauling the coal and coke may often be 2 to 10 times higher than that from the coke-making plant itself, except at the stage of the coke-making process where the coke is pushed out of the oven and quenched with water to halt the thermal decomposition process. In addition, we observed that the lack of sufficient road-repair facilities in the areas outside the cities has resulted in poor road conditions, which often cause a significant loss of coal and coke directly from the truck during transportation. Thus, planning officials and plant managers must choose between low-cost, low-pollution, low-energy-intensive rail transport and higher cost but flexible, convenient truck transport.

An additional important factor has been introduced into the decision-making environment in the Shanxi coke-making industry by the local government, namely, the closing down of small coke-making plants having the least advanced technology. The industry has been characterized by small plants often operated by township and village enterprises scattered around Shanxi Province (Chen et al. 1999). These enterprises usually have relatively little investment capital, so that they can only afford to build plants with less-advanced technology. Since 1998, in response to new regulations passed at the national level, Shanxi local government officials issued a statement for establishing a "clean energy" region in Shanxi. The Environmental Protection Bureau (EPB) officials in Shanxi Province have told us that all indigenous ovens at plants were to be closed by 1998 and most modified-indigenous ovens by 1999, with an exception give until 2003–2004 for those ovens that produce fuel gas for local household use. We expect that there will be an attempt for some of the small plants to combine efforts to invest in new equipment and to expand their capacity in an effort to meet this mandate.

Depending on how the plants are spread throughout Shanxi Province, closing the small plants could either reduce or increase the problems associated with transportation. By eliminating remotely located plants and increasing production at sites located near transportation facilities, transportation costs could be reduced. Too much aggregation of production capacity, however, would actually result in increases in the transportation required for both coal and coke. In the extreme case of a single plant supplying all coke requirements for Shanxi Province, that plant would have to ship coke to consumers located all around the province and to all purchasers of coke external to Shanxi Province. Having several plants makes it possible to locate the required production capacity close to the mines from which they purchase coal and/or close to the coke consumer, thereby reducing transportation costs (Leyland et al. 2003).

We examine two types of trade-offs: (1) trade-offs between increased plant size and increased transportation costs and (2) trade-offs between transport by road and transport by rail. Both of these trade-offs will be important considerations as the Shanxi government reorganizes the coke-making industry in the province. Policy makers need to assess the effects of improving road conditions, using cleaner trucks, and adding rail and road capacity, in addition to other social and administrative conerns (Bai 2002; Rock et al. 1999). A policy-making tool that evaluates these trade-offs would be a valuable and timely asset for planning officials in Shanxi Province.

Purpose

The purpose of this article is to introduce a system trade-off model that we have developed to study different measures for increasing the energy efficiency and reducing the pollution emissions of the coke-making sector in Shanxi Province. This work is a part of the Shanxi coke-making "technology-energy-environment-health chain" project to identify the energy, environmental, and health costs along the supply chain of the coke-making industry in Shanxi Province. The trade-off model is designed so that it is easy to examine various scenarios related to constructing new coke-making plants, resizing or closing old plants, changing the transportation infrastructure, and introducing different forms of technology transfer. Planning officials can easily introduce new input data sets into a policy framework in order to examine various future scenarios of increases in coke production. We have also made the model components as reusable as possible, so that they can be applied to the study of a wide range of other industrial sectors and regions. Our method combines the advantages of a top-down approach in terms of holistic system understanding with the advantages of a bottom-up approach in terms of flexibility and extendibility. This combined approach makes it possible to extend the system trade-off model easily with new data sets, new scenario run conditions, and even new models while maintaining a clear, well-defined view of the whole system. This work is part of an ongoing effort of some of us to develop an Internet-based collaborative modeling infrastructure for solving sustainability problems (together with the references to Kraines et al. 2001; Kraines et al. 2003; Kraines and Wallace 2003).

We present results here for the economic costs and the emissions of NO_x from transport vehicles including diesel trucks, diesel trains, and electric trains used in the two transportation segments of the coke-making supply chain: transportation of coal from mines to coke-making plants and transportation of coke from plants to coke consumers. NO_x was chosen as a representative air pollutant because it is related to transportation and because we were able to obtain sufficient data to run the model. Clearly, problems of other air pollutants, such as SO_2 and suspended particulate matter, are of greater concern than NO_x for the coke-making industry in Shanxi Province; however, we have been unable to obtain these data as a result of bureaucratic problems. We are working closely with the Shanxi Environmental Protection Authority (EPB) in order to get the data sets necessary for studying other pollution emissions. The EPB officials have shown considerable interest, so that we believe there is great potential for future application of the model in Shanxi Province. Inclusion of information on the emissions of SO_2 and suspended particulate matter in our modeling analysis framework would certainly affect the findings that we have presented here. We note, however, that diesel trucks and trains generally have higher emissions of SO_2 and particulates than electric trains, and larger coke-making plants are expected to have more pollution-control equipment installed and thus fewer emissions per unit production than the smaller plants, as we alluded to in the introduction. Therefore, we expect that an analysis that accounts for emissions of these pollutants would lend further support to our conclusion that resiting and transportation improvements can significantly reduce pollution emissions throughout the coke-making supply chain at low to zero total cost.

In this article, we use the system trade-off model to assess the effectiveness of the following options for reducing the cost and NO_x emissions from transportation in the coke-making industrial sector:

- Aggregation of the coke-making capacity of the existing plants
- Adding railway capacity by track electrification, increasing capacity of existing railroads, and construction of new railroads
- Reduction of truck-pollution emissions by introducing low-pollution trucks
- Reduction of electric-train-pollution emissions by introducing new coal-fired power plant technology

The results of our analysis are intended to provide a menu of alternative government investment options for reducing pollution from the transportation segment of the coke-making industry supply chain in Shanxi Province, giving the maximum potential effect in terms of reducing NO_x emissions and the costs of making those reductions.

We intend these investment options to be combined with investments to reduce the emissions from the coke-making process itself. In our analysis, we have assumed that this investment is already made in the switch to the cleaner "non-recovery" coke-making technology described later. We do not analyze here the trade-off in terms of pollution reduction between investments in cleaner technology and investment in improved siting and transportation. For such an analysis, in addition to the particulate and SO_2 emission data described earlier, information on investment costs and pollution emissions of clean coke-making technologies are necessary. With this information, model components that calculate the pollution emissions of the coke-making plants as well as the emissions of SO_2 and particulates from transportation could be constructed, and the general approach we illustrate in this article could be used to analyze the trade-offs between plant technology investment options and improved siting and transportation options.

The System Trade-Off Model

We have constructed a system trade-off model based on a geographic information system (GIS) database of the transportation network and the locations and capacities of coal mines, coke-making plants, and coke consumers in Shanxi Province. The structure of the trade-off model is shown in figure 1.

System Trade-Off Model Overview

The model consists of three main components. The plant-costing model uses a simple linear formulation to calculate costs of plant investment and operation as a function of plant production capacity. The GIS link-converter module uses distance and transportation link data from the GIS database to calculate the cost and NO_x emissions associated with transporting 1 ton of coal or coke across each link. The transport-flow, cost-minimization program is based on the software program Netflow (Kennington and Helgason 1980). Netflow is a software implementation of an algorithm for finding the minimum-cost solution for transporting a certain amount of material from an input node to an output node across a network of intermediate nodes and links. In the Netflow algorithm, each link is characterized by both a fixed cost for transport of a unit of material and a limit for the amount of material that can be transported

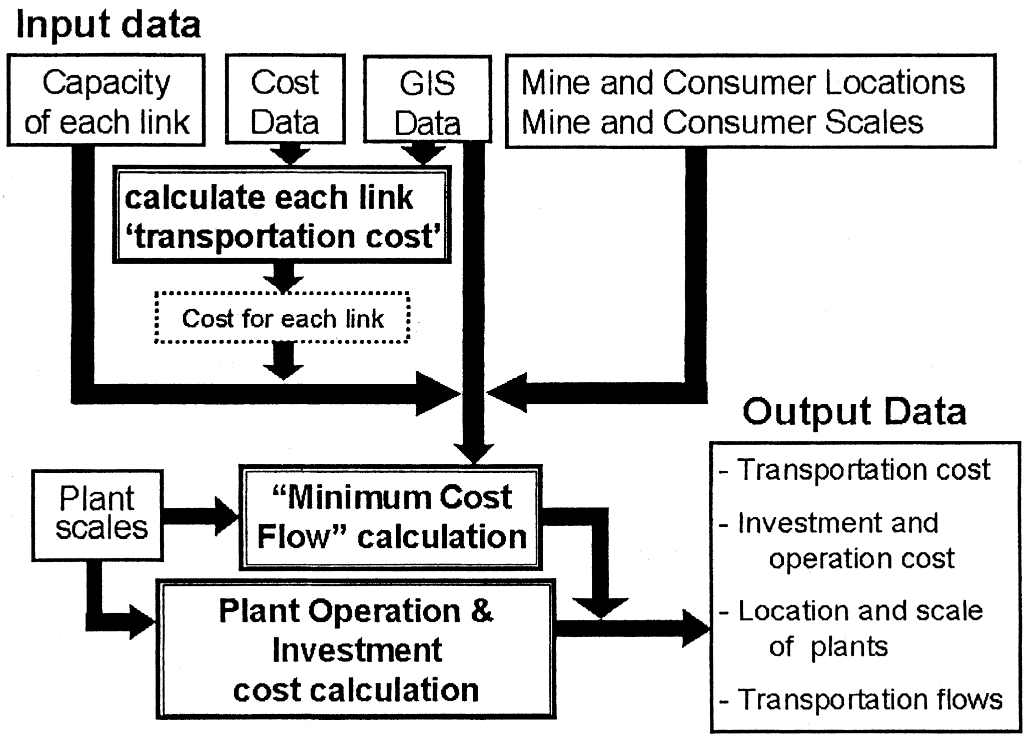

Figure 1 Structure of the system trade-off model. Data sets that are input into the model and calculated as outputs by the model are shown by the single-lined boxes. Model components are shown with the double-lined boxes. The dotted box shows an intermediate output file that is passed from one model to another. The model developed here gives outputs either in terms of economic cost or pollutant emissions.

across that link (figure 2). These properties of the links function as constraints in the optimization.

We modified the original software to calculate the optimum route for the necessary transport of coal and coke, given the selected locations of coke-making plants, the transportation network links expressed in cost or pollution emissions, and the coke requirements of the consumers. In addition, we developed an intuitive graphic-user interface (GUI) to manipulate the locations of coke-making plants and visualize the model-generated routes for coal and coke transportation.

Plant-Costing Model

The plant-costing model used here is based on results of case studies of coke-making technologies by Chen (2000).[3] We use the cost coefficients given for a "nonrecovery" coke-making plant. Nonrecovery coke-making technology is one of the simplest coke-making technologies because no attempt is made to collect or otherwise use the tar, chemicals, and coke gas produced during the thermal decomposition of coal. In this technology, these "by-products" are simply combusted, resulting in the near elimination of pollution and toxic-gas emissions. Nonrecovery coke-making with heat recovery is one of the only options that is considered to be both cost-effective and able to meet the strict U.S. environmental pollution standards (Polenske and McMichael 2002).

Because our model attempts to "trade off" the cost advantages of building larger plants against the possible added transportation costs, we are interested in modeling the "economies of scale" of coke-making technologies, that is, the effects of increases in scale on decreasing the cost of producing 1 ton of coke. Chen does not give economies of scale for the coke-making technologies in his report (Chen 2000). We have in-

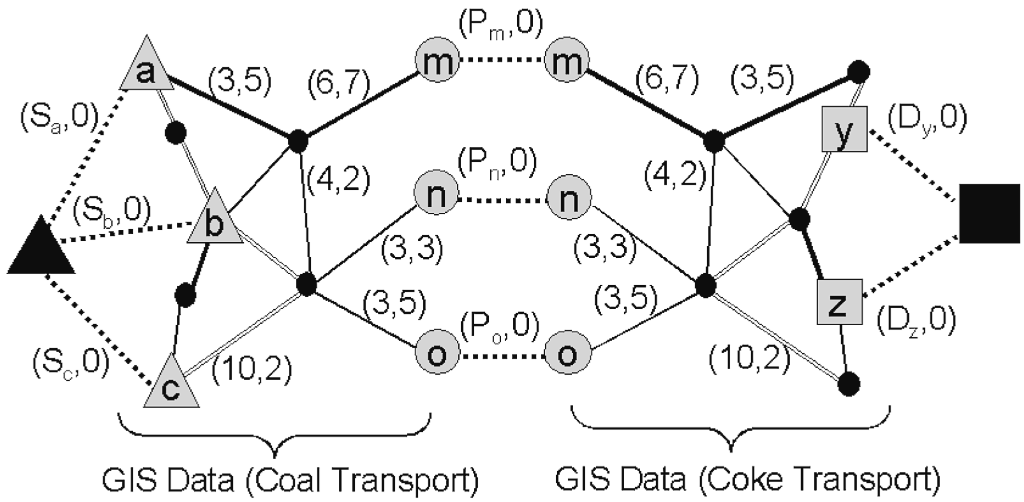

Figure 2 Application of the Netflow minimum cost flow problem to the transport problem in the Shanxi coke-making industry. The overall minimum cost flow problem is determined by the single supply node (black triangle) and the single demand node (black square) connected by a network composed of nodes and links. Gray triangles represent the coal mines in Shanxi Province, gray circles the coke-making plants, and gray squares the coke consumers. The dotted links from the supply node to the coal mines give the distribution of coal supply, S_i, for the different coal mines. The dotted links from the consumers to the demand node give the distribution of coke demand, D_k, for the different consumers. The dotted lines between the coke-making plants give the capacity of each plant, P_j. The black dots represent nodes in the GIS data, and the solid lines represent the road and rail links from GIS. The identical GIS based network is used both on the left, connecting the coal mines and the coke-making plants, and on the right, connecting the coke-making plants and the consumers. Each road and rail link has a set of two numbers shown as (capacity, cost). Note that the same sets are given for the capacity links (dotted lines) with the cost value being zero.

cluded scale effects according to the following considerations.

In many chemical plants, a single large reactor is used for the main process. Therefore, larger plants are cheaper to build per production unit because production is typically a function of reactor volume, whereas cost is more a function of reactor surface area. Coke, however, is usually produced in batteries containing a constant number of uniform-sized ovens. Therefore, increasing plant size by the addition of coke-making capacity in the form of an additional battery would not be expected to make the coke production cheaper. Even a single-battery plant, however, must have a certain amount of support infrastructure. We have taken this cost to be a constant irrespective of plant size. This constant cost is particularly important when considering pollution-control equipment. Equation (1) summarizes the form of our plant cost equations.

$$
\begin{aligned}
&\text{cost of plant with capacity C}\\
&= (\text{cost of base plant})\\
&\times (\text{\% of cost that is capacity dependent})\\
&\times (\text{capacity C})/(\text{base plant capacity}) \qquad (1)\\
&+ (\text{cost of base plant})\\
&\times (\text{\% of cost that is capacity independent})
\end{aligned}
$$

Here, "cost" includes all costs to the coke-making plant for annual production of coke incurred at the plant, including the annualized investment cost but not the transportation costs. "Base plant" refers to the 300,000 ton/yr capacity plant given by Chen (2000).

The actual equations used, where the constant values are derived from data provided in Chen (2000), are given in equations (2) and (3). We do not have sufficient data to establish empirically the fraction of the total cost of a plant that is independent of plant size. For the modeling exercise here, we assume that the capacity-independent cost is 10% of the total cost for the 300,000 ton/yr capacity plant that Chen gives.

$$\text{investment cost [million RMB/yr]} = (1.35 \text{ million RMB/yr})\,(90\%\ \text{ps/bps} + 10\%) \qquad (2)$$

$$\text{operating cost [million RMB/yr]} = (3.0 \text{ million RMB/yr})\,(90\%\ \text{ps/bps} + 10\%) + (0.161 \text{ million RMB/kton})^{*}\,(\text{coke production [kton/yr]}) \qquad (3)$$

Here, ps is the scale of the plant for which cost is being calculated and bps is the base plant scale of 300,000 ton/yr. The scales that we consider here are the real production scales, not the "name-plate" capacities; that is, they include the "capacity factors" that give the ratio of the operation capacity to the name-plate capacity. Investment cost for the 300,000 ton/yr coke-making plant given by Chen with an assumed plant lifetime of 10 yr is 1.35 million RMB/yr (Chen 2000). We further divide operating costs into production-independent costs (worker's wages, maintenance, other costs) of 3.0 million RMB/yr and production-dependent costs (coal, electricity, water) of 0.161 million RMB/kton of coke production. The production-dependent costs do not include transportation costs; we model transportation costs separately, using the transport-flow, cost-minimization program described below.

In order to minimize the influence of economies of scale in the individual coke-making batteries, we assume that plants are built in units of 75,000 tons of coke-making capacity per year, the size of a single battery given by Chen (2000). Therefore, the smallest coke-making plant would be a single battery of coke ovens having a production capacity of 75,000 ton/yr, and the next largest plant would add another battery of coke ovens for a total production capacity of 150,000 ton/yr. We assume a maximum plant size of ten batteries, that is, 750,000 ton/yr, which was roughly the size of the largest coke-making plants in Shanxi Province in 2000.[4]

The GIS Link-Converter Module

The GIS link-converter module calculates the cost and NO_x emissions to transport 1 ton of cargo a distance of 1 km across each transportation link in the Shanxi Province GIS database. We use the following equations to convert distance and type of each link to costs and NO_x emissions:

$$\text{truck transport cost [RMB/ton]} = C_f * E_{ff} * d_i(1 + \alpha) + 2(C_p * d_i/v + I_n * d_i) \qquad (4)$$

$$\text{train transport cost [RMB/ton]} = C_t * d_i \qquad (5)$$

$$\text{diesel-train and -truck transport } NO_x \text{ [grams of } NO_x\text{/ton]} = N_{oe} * E_{fc} * E_{ff} * H_d * d_i \qquad (6)$$

$$\text{electric-train transport } NO_x \text{ [grams } NO_x\text{/ton]} = N_{op} * E_{ei} * d_i/P_f \qquad (7)$$

The coefficient definitions, values, and sources are given in tables 1, 2, and 3. The variable d_i is the distance across each road link for equations (4) and (6) and each rail link for equations (5), (6), and (7), v is the truck velocity, and α is the empty truck mass divided by the total mass of the loaded truck.

Like the other submodels, the GIS link-converter module is clearly separated from the rest of the system trade-off model. This "modularization" of the link-converter model formulation allows easy modification of the equations used to calculate costs and emissions as well as easy updating of the values of the coefficients. For example, equation (8) shows how the equation for calculating truck transport cost may be modified to account for added costs related to increased fuel usage to move cargo across links having inclining slopes.

$$\text{truck transport cost [RMB/ton]} = C_f * E_{ff} * d_i \times \{(1 + \alpha)\,\eta \cos\theta + (1 - \alpha)\sin\theta\}/\eta + 2\,(C_p * d_i/v + I_n * d_i) \qquad (8)$$

Here, θ is the slope inclination and η is a friction coefficient (between 0 and 1) that converts the total weight of the vehicle into a cost when combined with C_f and E_{ff}. Equation (8) is equivalent to equation (4) with the addition of the term in

Table 1 Transportation-cost coefficients for diesel trucks

Item	*Coefficient Value*	*Unit*	*Reference*
Unit capacity	10	Ton	Akatsuka 2001
Weight factor (α)	0.5	–	Akatsuka 2001
Operator wages (C_p)	0.75	RMB per ton-hour	Akatsuka 2001
Fuel efficiency (E_{ff})	0.025–0.055*	Liters per ton-kilometer	Akatsuka 2001
Fuel cost (C_f)	2.7	RMB per liter	Akatsuka 2001
Vehicle cost	200,000	RMB	Akatsuka 2001
Vehicle lifetime	10	Year	Akatsuka 2001
Investment cost (I_n)	0.05	RMB per ton-kilometer	SPSO 1999b
Loading cost	0.5	RMB per ton	Akatsuka 2001

*The fuel efficiency is calculated as a function of truck speed and road conditions.

Table 2 Transportation-cost coefficients for diesel and electric trains

	Coefficient Value			
Item	*Diesel*	*Electric*	*Unit*	*Reference*
Unit capacity	2,300	3,000	Ton	SPSO 1999a
Fuel efficiency (E_{ff})	0.005	0.0113	Liters per ton-kilometer*	SPSO 1999a
Contracted cost (C_t)	0.11	0.11	RMB per ton-kilometer	Akatsuka 2001

*Units are kilowatt hours per ton-kilometer for electric trains.

Table 3 Transportation NO_x emission coefficients for diesel trucks, diesel trains, and electric trains

Item	*Value*	*Unit*	*Reference*
NO_x emission per unit engine power (N_{oe})*	8.0	Grams per kilowatt-hour	Faiz et al. 1996
Engine power per heat value of diesel (E_{fc})	0.15	–	Global Network 2001
Heat value of diesel fuel (H_d)	9.2	Million calories per liter	TMJ 1999
NO_x emission of power plants (N_{op})	0.976	Grams per million calories	Bernstein et al. 1999
Power efficiency of electric trains (E_{ei})	0.0113	Kilowatt-hours per ton-kilometer	SPSO 1999a
Power efficiency of power plants (P_f)	0.30	–	Sadakata 2000

*This value corresponds to the Euro 1 standard for heavy-duty vehicles and was scheduled to be adopted by China for all vehicles in the country as of 1 April 2000 (Walsh 2000). We chose to use this value because of uncertainties in the measured values available.

curly brackets, which contains the sines and cosines and reflects the change in fuel required for traveling up and down the slopes. The effect of variations of slope inclination on relative cost is shown in figure 3.

The Transport-Flow, Cost-Minimization Program

The transport-flow, cost-minimization program is an application of the software program Netflow (Kennington and Helgason 1980). Netflow solves the cost-minimization problem of transporting a given quantity of material from a single supply node to a single demand node across a network of links and nodes. Each link has an associated cost and capacity. The program minimizes the total cost of transport across the network, subject to the capacities of each link.

We apply Netflow to the transportation-flow, cost-minimization problem as follows. First, we construct two identical networks expressing the

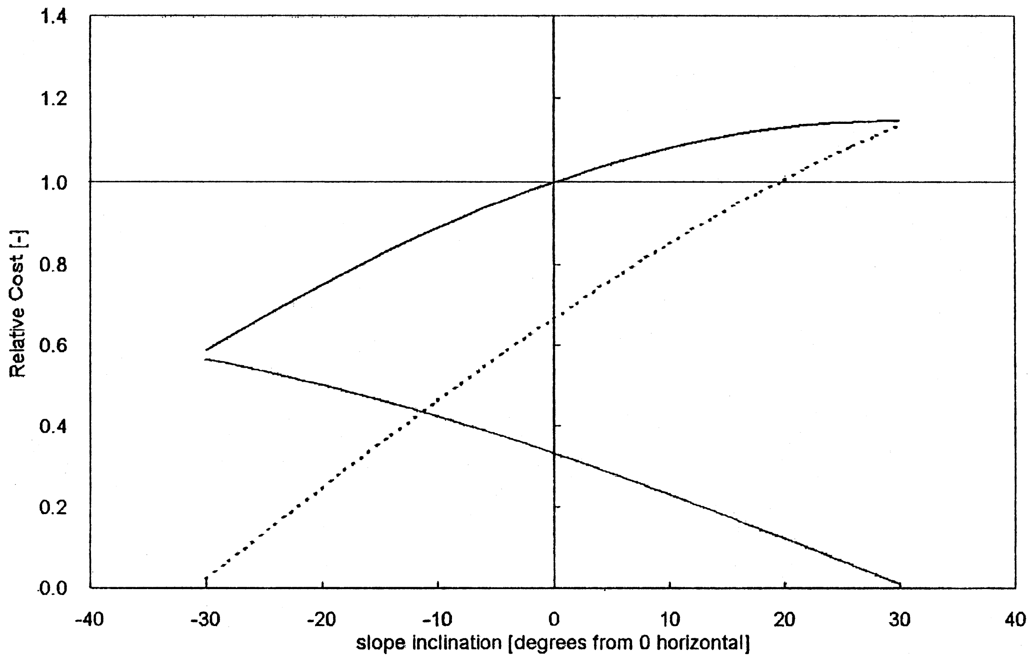

Figure 3 Relative cost of round-trip transportation with consideration of change in elevation as a function of the average slope inclination relative to the horizontal (0°) for the delivery trip (full truck trip) as described by equation (8). Dotted line: contribution from delivery trip; gray line: contribution from return trip; black line: total round-trip relative cost.

entire transportation infrastructure in Shanxi Province, using the cost-converted GIS-link data as described by Akatsuka (2001). We then connect the two networks at each of the coke-making plant nodes with a link whose capacity is the production capacity of the plant. We set the link cost to zero for the transportation problem because we consider production costs separately using the plant-costing model described earlier. By creating links between the supply node and the nodes for each of the coal mines supplying coal for coke making, we can connect the network to the single supply node in the Netflow program. We set these links with a capacity equal to the coal mine production capacity and cost equal to zero. We connect the network in the same way to the single consumption node by creating links to each of the coke consumers with capacities equal to the coke requirements of each consumer and cost equal to zero. The network links between the coke consumers and the final consumption node have to carry full capacity because all coke demand must be filled; however, some links representing the production capacities of the mines and plants carry flows that are less than their capacities because plant and mine capacities, as a rule, exceed this total demand. The resulting network is shown in figure 2.

We connect roads and railways in a similar fashion with links that represent train stations. Using the cost for loading and unloading shown in table 1, we calculate costs for each link. We set the capacities of these train station links to be unlimited, but we could alternatively set a capacity to reflect, for example, the handling capacity of the train station.

In order to produce 1 ton of coke in Shanxi Province, 1.3 tons of coal is thermally decomposed. Furthermore, as the coal used in the coke ovens must be washed to reduce ash and sulfur content, 1.8 tons of unwashed coal is required to produce 1 ton of coke (Akatsuka 2001; Polenske and McMichael 2002). Interviews with coke-making plant managers in Shanxi Province and our surveys of coke-making plants both indicate that coal is usually washed at the coke-making plant, rather than at the coal mine. Therefore, in our model formulation, we multiply the transportation costs and NO_x emissions given per ton-kilometer for the coal-transportation segment by 1.8 in order to express the entire flow network in terms of tons of coke production.

The program Netflow solves the network given as described above and returns a vector of costs for each link in the network. We can use that vector together with the link-type information to plot the routes on the plant-siting interface, or we can sum the vector costs to obtain the total cost of transport as well as the subtotals for each transport mode and each transported material.

The Plant-Siting Interface

We implement the plant-siting interface in Java (Sun JDK1.3) as a GUI. This interface helps users to set up scenarios involving different choices of plant sites, plant scales, and coke-making technology types; to evaluate those scenarios using the system model; and to visualize the model-generated transport routes for coal and coke (figure 4). A user loads the interface with an image map of Shanxi Province and a data set of locations for the three types of entities: coal mines, coke-making plants, and coke consumers. The user can change production scales for the coke-making plants by clicking on the circles showing the plant locations (figure 4). Also, the user can send the route-data output from the transport-flow, cost-minimization program to be visualized on the interface. The interface plots route data on the map with vectors having thicknesses corresponding to the flow volume on that route and colors corresponding to the type of flow: coal transported by truck, coal transported by rail, coke transported by truck, and coke transported by rail.

Input and Output Data Sets

This section summarizes the primary input and output data sets used in the system trade-off model.

Input Data

The following data sets are the primary inputs used by the system trade-off model.

- The locations and production rates of coal mines that produce coal for coking plants in Shanxi Province given as fixed boundary conditions (SCAC 1994)
- The locations and consumption rates of coke consumers in Shanxi Province given as fixed boundary conditions (SCAC 1994) (we treat coke consumption outside of Shanxi Province as consumer nodes located at the points where coke is transported out of Shanxi Province; because we do not explicitly model the coke consumption, expressing coke consumption outside of Shanxi Province as consumer nodes is exactly equivalent to having coke consumers located at the exit points of Shanxi Province)
- A GIS database of the transportation network in Shanxi Province, with five types of roads and four types of railways, expressed as a link-node graph
- Transportation-capacity limits for each rail link in the GIS database obtained as described by Akatsuka (2001)
- Information on transportation costs and NO_x emissions for different transportation modes used in Shanxi Province derived from direct interviews with coke-making plant officials in Shanxi Province, secondary sources such as the 1999 statistical yearbook for Shanxi Province (SPSO 1999a), and estimates from indirect sources as described above

Spatial input data used in the model are shown in figure 5. Cost and emission data are summarized in tables 1, 2, and 3.

Output Data

The following data sets and information are generated by the system trade-off model.

- The quantities of coal (tons per year) transported across each link on the GIS map by each transportation mode between the coal

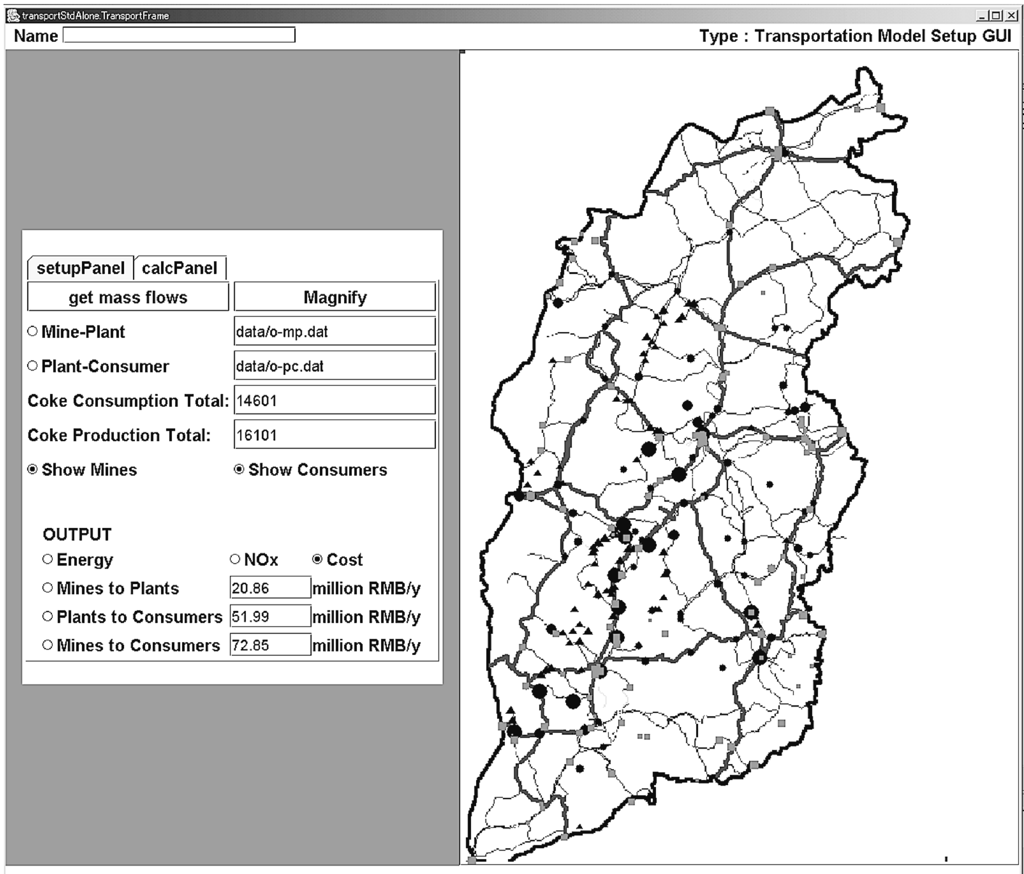

Figure 4 The plant-siting graphic-user interface (GUI). The calculation panel on the left contains the buttons and text fields available to the user for interacting with the interface to the system trade-off model. The hidden "setupPanel" has controls for allowing the user to setup the map and data sets for a particular problem. The display panel on the right shows the coal mines in black triangles, the coke-making plants in black circles, and the coke consumers in gray squares plotted on the user-loaded map. The transportation routes of coal and coke given by the model are shown with black and gray vectors.

mines and coke-making plants, visually expressed as a map of directed flows on the plant-siting interface

- The quantities of coke (tons per year) transported across each link on the GIS map by each transportation mode between the coke-making plants and final consumers/export points, visually expressed as a map of directed flows on the plant-siting interface
- The optimized total cost or total NO_x emission from the transportation sector of the coke-making industry in Shanxi Province, given the designated plant locations and sizes
- The corresponding investment and operating costs for the coke-making plants in Shanxi Province

Model-Run Conditions

Although it is possible to run the system trade-off model to minimize NO_x emissions, we have elected to conduct all of the model scenarios as "cost minimizations." We argue that even with heightened awareness of environmental is-

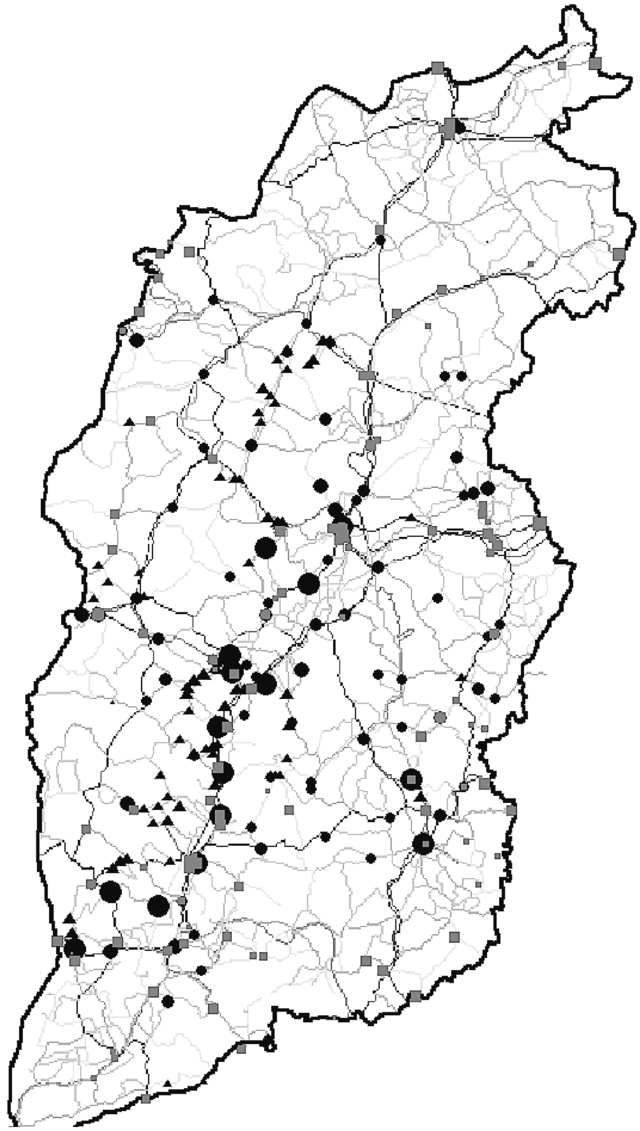

Figure 5 The GIS data set and location data used in the model. Different-shaded lines show different types of roads and rails. The coal mines are shown with black triangles, the coke-making plants with black circles, and the coke consumers with gray squares. Location data sets are taken from the 1990 Shanxi Energy Atlas (SCAC 1994). Road and rail data sets are supplied by the Australian Centre of the Asian Spatial Information and Analysis Network, Griffith University.

sues, the main factor governing the choices made by decision makers in the coke-making industry is economic cost. We investigate the following eight scenarios in which, unless otherwise specified, we use plant sites and capacities from 1990 (SCAC 1994) together with the unit-cost and NO_x emissions coefficients shown in tables 1, 2, and 3.

- *Cost-efficient transportation base scenario (base scenario)*. This scenario gives the transportation costs and pollution emissions that would be expected if the most cost-efficient transportation pattern for the 1990 distribution of coke-making plants were to be used. Using this scenario as the base case allows us to exclude the social and political factors that affect actual transportation use and to focus on the effects of changes in plant siting, sizing, and transportation technology on pollution and cost.
- *Transport-cost-minimization scenario*. First, we set the capacity of each plant in the

base scenario to the maximum coke-making capacity of 750,000 ton/yr. Next, we solve the transport-flow, cost-minimization program as described previously. By setting plant production so that each plant is able to produce any amount of coke up to the maximum possible, consumers are more likely to be able to buy from a nearby plant, which minimizes the transportation costs. Thus, this calculation gives the lowest possible transportation cost given our maximum plant size constraint. Then, we resize each plant to have a production capacity just exceeding the production rates required by the transport-flow, cost-minimization program. Plants at which no production capacity is required are not built. We calculate plant costs using the plant-costing model and add them to the transport cost to give the total cost. Therefore, this scenario gives the minimum possible transportation cost together with the minimum plant cost for the transportation cost needed to supply the total coke demand given the locations and capacities of coal mines, the possible locations for coke-making plants, and the maximum coke-making plant size. Our survey results have indicated that all coke-making workers live close to the plants regardless of the location of the plant. Therefore, we have not included any analysis of worker commute effects on transportation.

- *Plant-cost-minimization scenario.* In this scenario, we first set the plants to maximum capacity and solve the transport-flow, cost-minimization program as in the transport-cost-minimization scenario. We also calculate the number of maximum-capacity (750,000 ton/yr) plants required to meet the total coke demand in Shanxi Province. We then assign one of these maximum-sized plants to the site having the largest production rate calculated by the transport-flow, cost-minimization program. We continue to assign maximum-sized plants to the sites with the largest calculated production rates until we have assigned the total required number of plants. We assign the last plant a production capacity just large enough to meet the total demand. Thus, in contrast to the transport-cost-minimization scenario, for this scenario we have the smallest possible number of the largest possible coke-making plants to supply the coke requirements for Shanxi Province. We then run the transport-flow, cost-minimization program again with these siting conditions and calculate the plant costs by the plant-costing model. This scenario gives the minimum plant cost required to supply the total coke demand together with a reasonable estimate for the minimum total cost.
- *Rail-electrification scenario.* We change the type of all nonelectrified railways to "electrified." This scenario shows the effect of rail electrification on the NO_x emissions and transportation cost.
- *Rail-unlimited-capacity scenario.* We set all rail links in the Netflow network to have unlimited capacity. This scenario gives the maximum effect that may be expected by increasing the capacity of existing railways in Shanxi Province.
- *Rail-construction scenario.* We change all railways of the type "under construction" given in the GIS database to "single electrified" and "double electrified," as described by Akatsuka (2001). This scenario gives the effect of additional railroad availability on transportation costs and NO_x emissions.
- *Truck-technology-transfer scenario.* We substitute coefficient values in table 3 for truck transportation with the values for 10 ton diesel trucks that produce low NO_x emissions, are manufactured by Hino Motor Company, and are available in China today. This scenario gives the pollution reduction resulting from the lower pollution emissions from the newer diesel trucks.
- *Power-generation-technology-transfer scenario.* We substitute coefficient values for electric power generation in table 3 with values corresponding to the NO_x emissions and power-generation efficiency of the coal-fired power plant technology available in Japan today. This scenario shows the effect on pollution emissions from the use of elec-

tric trains resulting from reduced emissions from power plants.

These scenario conditions are summarized in table 4.

Results

We have found three principal effects on costs and NO_x emissions. (1) Aggregation of plant coke-making capacity produces about a 25% transportation cost decrease and a more than 30% reduction in NO_x emissions with little or no increase in total cost, even when the cost of building the plant is included. (2) The addition of rail capacity and electrification of railroads do not seem to have major impacts on NO_x emission reductions. (3) A switch to low-pollution diesel-truck technology appears to be an effective approach to reducing NO_x emissions.

Base, Transport-Cost-Minimization, and Plant-Cost-Minimization Scenarios

With the first three scenarios, we are essentially examining the effect of optimizing the locations of coke-producing capacity on cost and NO_x emissions. Total costs for the transportation of coal and coke show a decrease of about 25% for the two plant-aggregation scenarios, reflecting the large beneficial effect of moving coke-making capacity to plants that have lower transportation costs (figure 6). NO_x emissions associated with transportation for the different scenarios show an even greater decrease of more than 30% (figure 7). The larger reduction in NO_x emissions is a result of a modal shift from truck transport to train transport, and it reflects the relative values of the data sets we have established for the model runs, where NO_x emissions from trains are 10 to 20 times less than those from trucks, but the cost is only 2 to 4 times less (tables 1, 2, and 3). Of the two plant-aggregation scenarios, the transport-cost-minimization scenario (i.e., aggregation of coke-making capacity to minimize transportation costs first) lowers costs and NO_x emissions about 10% and 20% more, respectively, than the plant-cost-minimization scenario. This difference reflects the higher transportation cost resulting from aggregation of the transportation-cost-optimized distribution of coke-making plants to the smallest number of plants allowed by the maximum plant size that we have set.

Clearly, the current distribution of coke-making plant locations that we used in the base scenario is far from optimal from a transportation perspective. In fact, even when the costs of constructing new plants are added, the two minimization scenarios give lower total costs (figure 6). We assume that all of the coke-making plants added use the nonrecovery technology given by Chen (2000), as described earlier.

Even when plant costs are included, the transport-cost-minimization scenario gives slightly lower total economic costs than the plant-cost-minimization scenario (figure 6). Therefore, under the conditions of our scenarios, aggregation of coke-making plants to the smallest number possible given the maximum size for a single plant, that is, the plant-cost-minimization scenario, does not give the lowest total-cost solution. As the difference is small, however, a slight change in our formulation of the economies of scale associated with building larger plants could cause this result to be reversed. For example, given the same distribution of plant sizes for the two scenarios, changing the capacity-independent cost fraction in equations (2) and (3) from 10% to 15% would increase the relative costs for plants smaller than the standard plant size of 300,000 ton/yr and decrease the relative costs for larger plants enough to give the plant-cost-minimization scenario the lowest total economic cost.

Under the two plant-aggregation scenarios, the total quantity of transport for coal and coke, given in ton-kilometers and obtained by multiplying the distance traveled by the mass of coal or coke transported, also shows a significant decrease, although it is not as large as the decrease in cost and NO_x emissions (figure 8). As the total decrease in ton-kilometers of transport is approximately 20%, we can explain about 80% of the total cost reduction (25%) and about 60% of the total NO_x emission reduction (30%) that result from plant aggregation as described above by the reduction of the overall distance over which the

Table 4 Scenario explanations

Scenario	*Item changed*
1. Base	None
2. Transport cost minimization	Plant sites set to minimize transport cost
3. Plant cost minimization	Plant sites set to minimize plant cost
4. Rail electrification	All rail types to "electrified"
5. Rail unlimited capacity	All rail capacities to unlimited
6. Rail construction	All rails of type "under construction" to "electrified"
7. Truck technology transfer	NO_x emission per unit engine power for trucks
8. Power generation technology transfer	Power generation efficiency and NO_x emissions

Note: Unless otherwise indicated, all scenarios use plant sites and capacities from 1990 (SCAC 1994) and unit cost and NO_x emissions coefficients shown in tables 1, 2, and 3.

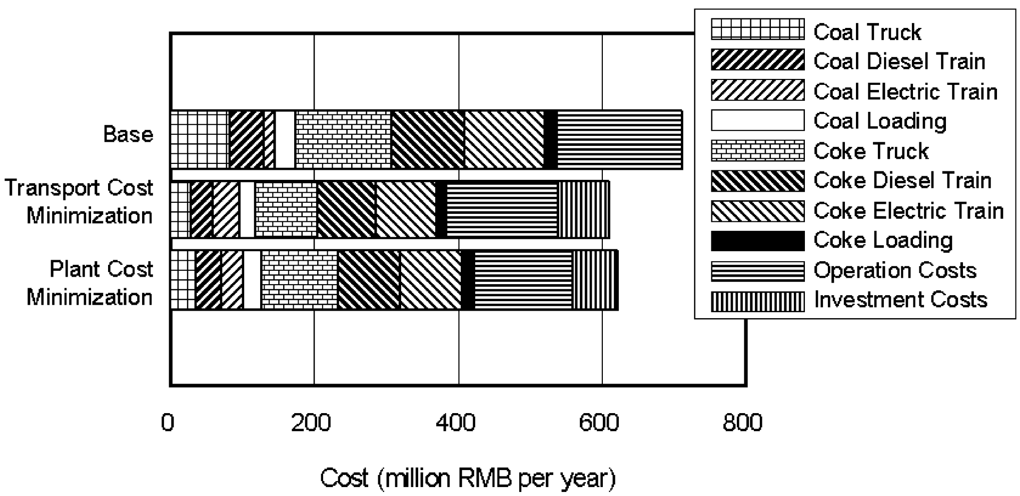

Figure 6 Cost results of the plant-aggregation scenarios. Results are shown for the base scenario, the transport-cost-minimization scenario, and the plant-cost-minimization scenario. Costs are given in million RMB per year (one RMB was approximately equal to 12.5 U.S. cents in 2000). Costs are shown for the various modes of transportation of coal and coke, the loading (and unloading) of trucks and trains at the railroad stations, the costs for operating the coke-making plants, and the investment costs for constructing the coke-making plants.

coal and coke must be transported, which results from the relocation of plants closer to the mines and consumers.

We recall that 1.8 tons of coal must be transported from the coal mine to the coke-making plant for each ton of coke produced, so more ton-kilometers of transport are required for a given distance of coal transportation than of coke transportation. The results in figure 8 show that the reduction in ton-kilometers of transport is greater for coke transportation than for coal transportation in both of the minimization scenarios, however. Therefore, the reduction in ton-kilometers of transportation must be controlled by the distribution of coal mines and coke consumers in the province. A large number of small coal mines are scattered around the province, but there are only a small number of coke consumption locations dominated by the export site (figure 5). More importantly, there is a surplus of coal production, whereas all of the coke consumption requirements must be filled. Therefore, it pays more to choose sites for coke-making plants that are close to coke consumers and

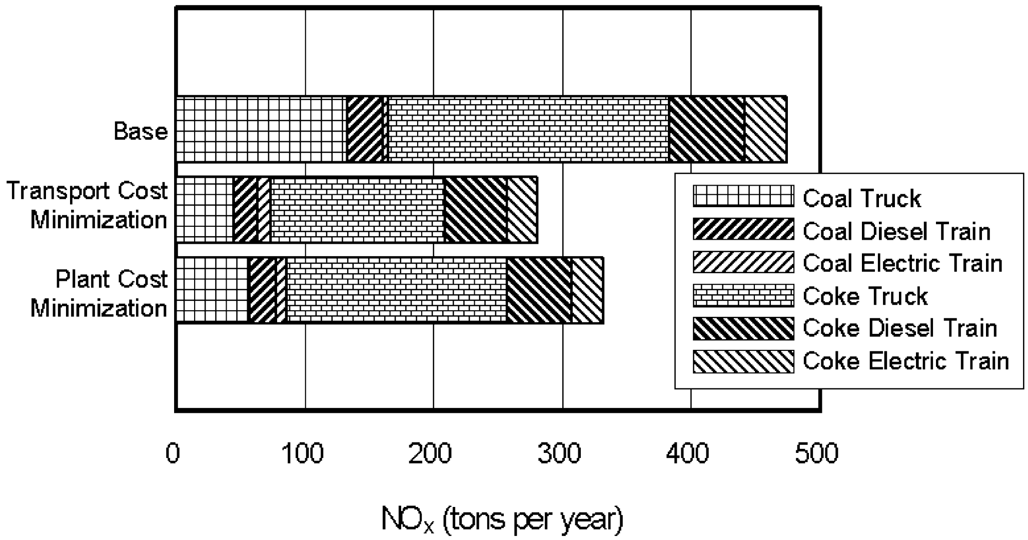

Figure 7 NO_x results of the plant-aggregation scenarios. Results are shown for the base scenario, the transport-cost-minimization scenario, and the plant-cost-minimization scenario. Results are given in tons of NO_x per year. Emissions are shown for the various modes of transportation of coal and coke.

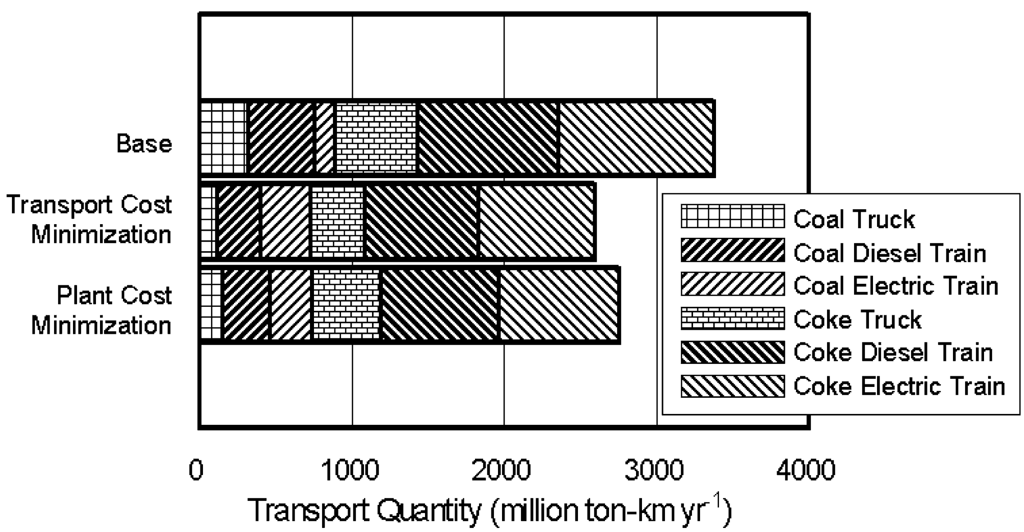

Figure 8 Transport quantity results of the plant-aggregation scenarios. Results are shown for the base scenario, the transport-cost-minimization scenario, and the plant-cost-minimization scenario. Results are given in million ton-kilometers of transportation per year and shown for the various modes of transportation of coal and coke.

therefore preferably reduce the coke transportation cost. The graphical output given by the GUI of the plant-siting interface clearly shows the change in coal and coke transportation patterns from the base scenario to the transport-cost-minimization scenario (figure 9).

The distribution of ton-kilometers of transport among the different modes of transportation

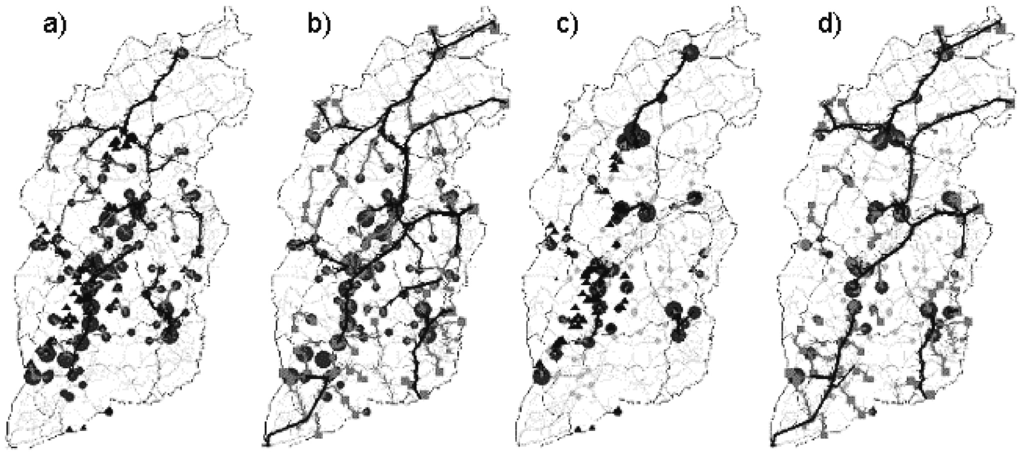

Figure 9 Difference of routes between the base scenario and the transport-cost-minimization scenario: (a) transport of coal from the coal mines to the coke-making plants under the base scenario; (b) transport of coke from the coke-making plants to the coke consumers under the base scenario; (c) transport of coal from the coal mines to the coke-making plants under the transport-cost-minimization scenario; (d) transport of coke from the coke-making plants to the coke consumers under the transport-cost-minimization scenario. Black lines show transport by railroad, and gray lines show transport by road.

shows the extent to which mode shifting contributes to the reductions in cost and NO_x emissions (figure 10). The major mode shifts occur in the transportation of coal from coal mines to coke-making plants, with a significant shift from road and diesel-train transport to electric-train transport. This shift reflects the cheaper cost of electric-train transportation. Thus, although the cost and emissions reductions from the decrease in ton-kilometers of transport occur mainly in the transportation segment of the coke-making supply chain from plant to consumer, the reductions due to mode shifting occur mainly in the mine-to-plant transportation segment.

Rail Electrification, Capacity-Increase, and Construction Scenarios

The three scenarios that examine effects of changing the rail infrastructure in Shanxi Province have different effects on the system trade-off model. Electrification of all of the railroads in Shanxi Province under the rail-electrification scenario (scenario 4) only changes the conditions of the transport-flow, cost-minimization program by the slightly larger transport capacity of electric trains versus diesel trains (table 2). Therefore, the changes in transportation costs for that scenario compared to the base scenario are small. The investment cost for electrification of the tracks has to be balanced by the reduction in NO_x emissions due to the substitution of diesel trains by electric trains. The increase of rail capacity in the rail-unlimited-capacity scenario (scenario 5) allows a greater modal shift from truck transportation to train transportation. This modal shift could result in significant decreases of both transportation costs and NO_x emissions, with the shift from trucks to trains occurring as long as the cost resulting from the extra distance of travel required by using rail transport does not exceed the reduction in cost to transport by train.

Finally, for the rail-construction scenario (scenario 6), we assume that the railroads under construction in Shanxi Province, shown in figure 5, are completed as planned, and we add those new railroads to the GIS-based node-link network. In reality, the effectiveness of this scenario to reduce costs and NO_x emissions depends on how well the added railroads link the transport routes that currently have insufficient rail capacity.

The cost results for the three scenarios show only minor differences, with the lowest transportation costs predicted for scenario 5 (figure 11). Greater effects occur in NO_x emission reduc-

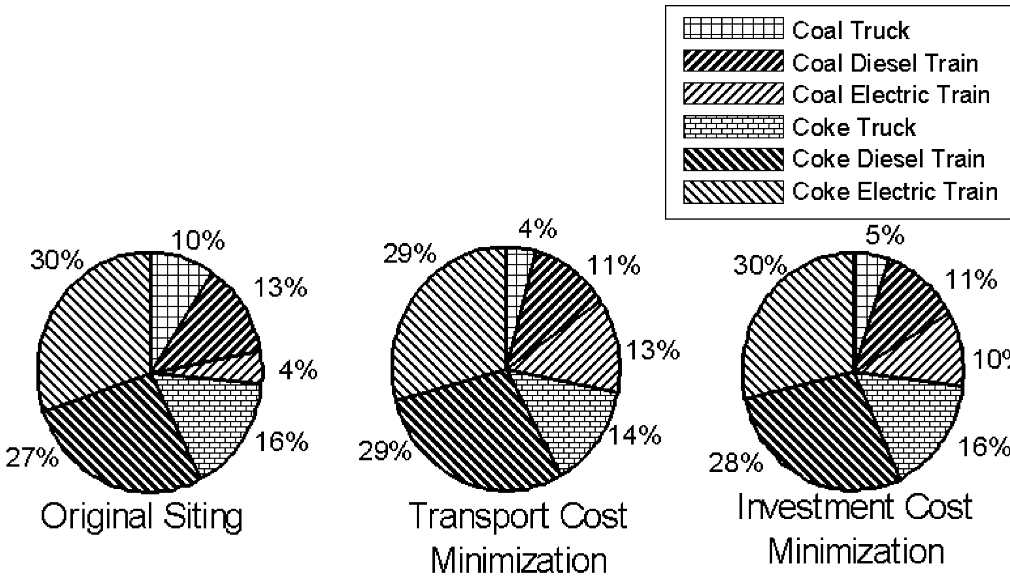

Figure 10 Distribution of transport quantities for the different modes of transportation. Results are shown for the base scenario, the transport-cost-minimization scenario, and the plant-cost-minimization scenario.

tions, and again scenario 5 shows the best performance, with approximately a 20% emission reduction (figure 12).

We can estimate the costs of electrifying all of the railroads for scenario 4 and constructing the planned railroads for scenario 6 using costs reported for the construction of similar railroads in Shanxi Province (SPSO 1999b). We are unable to estimate the costs associated with scenario 5. We assume that the coke-making industry would only be responsible for the fraction of the total railroad modifications that are actually used for transportation of coal and coke for coke making. Thus, for each rail segment, the cost to be borne by the coke-making industry is calculated as

$$\text{(total construction cost)} \times \text{(capacity for coke-making industry)/(total capacity)} \quad (9)$$

These costs could be assigned in several ways. In order to facilitate the comparison between the scenarios, we assume that costs are borne by some authority outside of the coke-making industry, perhaps the provincial government. This assumption fits with the underlying theme of our approach, which is to provide the provincial government with a "menu" of alternatives for using its limited resources to reduce pollution. Therefore, the railroad modification costs are not reflected directly in the transportation costs used for calculating the link costs in the railroad network for the transport-flow, cost-minimization program. We add the resulting railroad investment costs to the transportation costs for scenarios 4 and 6 in figure 11.

By comparing the scenario implementation costs with the respective cost and emission reductions from the base scenario, we can estimate the cost-effectiveness of scenarios 4 and 6. The resulting costs per unit NO_x reduction are 0.87 and 1.35 million RMB/ton for the rail-electrification scenario and the rail-construction scenario, respectively.

Truck and Power-Generation Substitution Scenarios

For the truck-technology-transfer scenario (scenario 7), we substitute the coefficient for the NO_x emission per unit engine output power with the value of the average NO_x emissions of 4.5 g/kWh for 10 ton diesel trucks manufactured by Hino Motor Company (JAA 2000). We calculate the cost associated with introducing the Japanese truck technology as follows. From the price of the Hino trucks on the market in China of

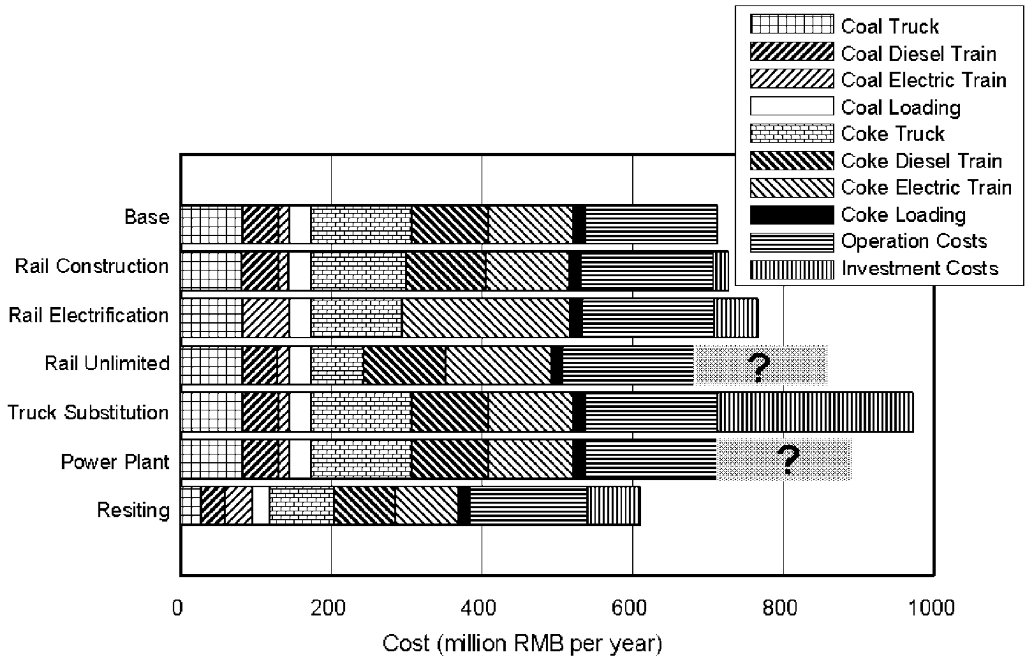

Figure 11 Cost results for the rail-construction scenario, the rail-electrification scenario, the rail-unlimited-capacity scenario, the truck-technology-transfer scenario, and the power-generation-technology-transfer scenario. Results for the base scenario and the transport-cost-minimization scenario are also shown for comparison. Costs are given in million RMB per year (one RMB was approximately equal to 12.5 U.S. cents in 2000). Costs are shown for the various modes of transportation of coal and coke, the loading (and unloading) of trucks and trains at the railroad stations, the costs for operating the coke-making plants, and the investment costs for constructing the coke-making plants. The parts of the bars with the question marks for the rail-unlimited-capacity scenario and the power-generation-technology-transfer scenario indicate that the investment cost values cannot be estimated for those scenarios.

approximately 800,000 RMB (Hino Motor Company 2000), we calculate that the investment cost is 4 times that of the Chinese trucks. We assume that the cost to upgrade the trucks is the difference between the investment costs of the Chinese and Japanese trucks. Referring to the value given in table 1 for Chinese trucks, the cost of upgrading the trucks would be 0.15 RMB/ton-km. We multiply this cost by the total transport quantity in ton-kilometers of all trucks given by the cost-minimization transport model in order to get the total cost per year required to retrofit the existing truck fleet in the Shanxi coke-making industry with the new technologies. As before, we consider that this cost is borne outside of the coke-making industry, so that the cost is not reflected directly in the transport-flow, cost-minimization program.

Although we have used an electric-power-generation efficiency of 30% for the power plants supplying electricity for the electric-powered trains in Shanxi Province, coal-fired power plant technology in Japan exists with efficiencies of 38% (EPDC 2000). In addition, plants in Japan equipped with NO_x removal technology achieve a reduction in NO_x emissions from the value of 0.976 g/Mcal used for the Chinese power plants to 0.359 g/Mcal. For the power-generation-technology-transfer scenario (scenario 8), we have used these numbers to calculate NO_x emissions associated with rail transportation by electric trains.

Both of these scenarios do not alter the price or capacity characteristics of the transportation network; therefore, the distribution of transport quantities on the transportation network calcu-

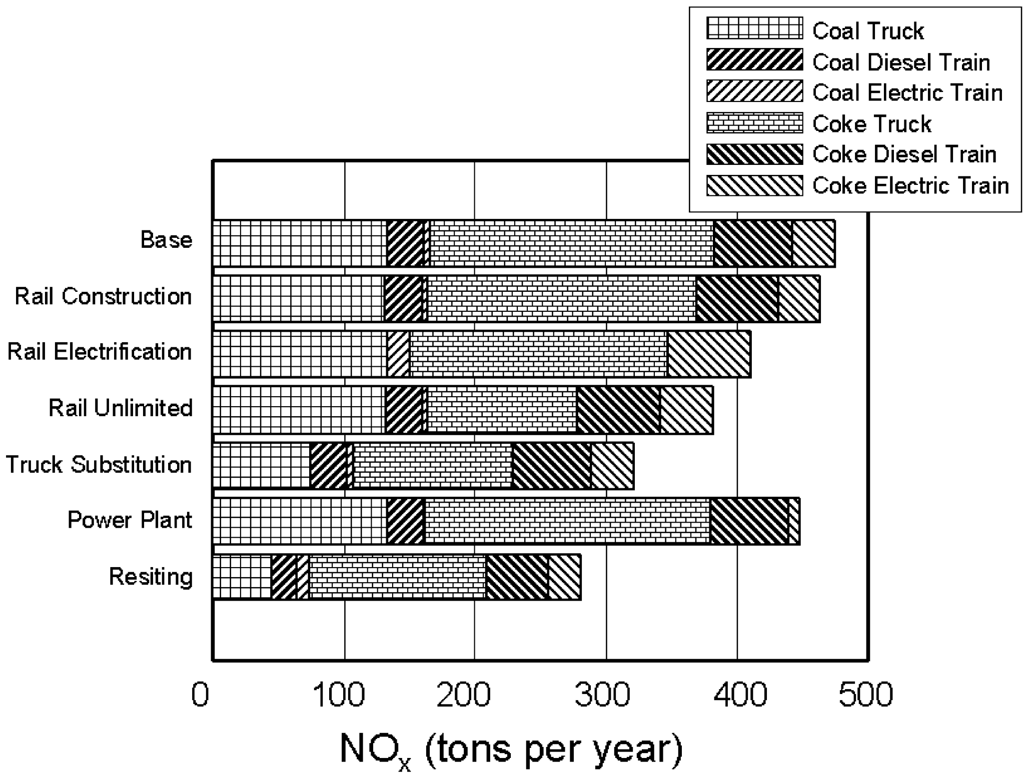

Figure 12 NO_x results for the rail-construction scenario, the rail-electrification scenario, the rail-unlimited-capacity scenario, the truck-technology-transfer scenario, and the power-generation-technology-transfer scenario. Results for the base scenario and the transport-cost-minimization scenario are also shown for comparison. Results are given in tons of NO_x per year. Emissions are shown for the various modes of transportation of coal and coke.

lated by the transport-flow, cost-minimization program is the same as the base scenario. NO_x emissions are reduced dramatically for scenario 7, with reductions almost as large as the plant-aggregation scenario results (figure 12). NO_x emission reductions are less dramatic for scenario 8 than for scenario 7, primarily because in the base scenario transport by electric train is a rather small fraction of the total transport (figure 10). The cost-effectiveness of scenario 7 is 1.69 million RMB per ton of NO_x reduction.

Discussion of Results

Although the model results here are highly dependent on the accuracy of the data that we have used for calculation of the cost and NO_x emissions by the different modes of transportation in Shanxi Province, we feel confident that we have established a solid enough set of data to draw some important qualitative conclusions. As a verification of the magnitude of the coefficient values we have used, we have cross-checked the cost per ton of coke transportation calculated by the model versus estimates from the actual costs of coal and coke based on the interviews that we carried out at the plants.

First, the scenarios optimizing the siting of coke-making plants in Shanxi Province clearly show a great potential for reducing both costs and pollutant emissions through the relocation of the plants (and also energy use; data not shown here). For this initial study of the coke-making industry, we assume an ideal market with perfect information leading to uniform prices for delivered coke (at the coke consumer) and undelivered coal (at the mine). We also assume, based on our interviews with the plant managers, that the coke-making plants bear all of the transportation costs for both coal and coke, so that they should be motivated to buy and sell to the coal suppliers and coke consumers that are closest to them. In this situation, the plant managers would benefit from any decrease in transportation costs. Therefore, in all scenarios, we assume that plant managers would act to minimize their transportation costs by purchasing coal from mines and selling coke to consumers that are as close as possible.

Unfortunately, this is often not the case: Some of the plant managers we interviewed had purchase contracts with mines located as far away as 100 km. These contracts, although possibly being appropriate from the perspective of each individual company, result in great transportation inefficiency and large excess costs and pollution. We suggest that this inefficiency could be at least partially averted by providing information for a provincewide coordination of efficient coal and coke transportation. One way that this optimization of transportation efficiency could be realized would be through some information broker that coordinates with the plant managers where each plant should get its coal and sell its coke in order to minimize the total transportation and thereby the pollution from transportation. The degree to which our model results show that costs and NO_x emissions can be reduced is an indication of the potential contribution of such an entity.

Of the two aggregation scenarios that we examined, the plant-aggregation scenario that minimizes transportation costs first showed a slightly better cost performance than the scenario that preferentially minimizes plant costs. Thus, the aggregation of coke-making capacity in Shanxi Province to the largest plant sizes possible in order to minimize plant costs may not necessarily give the best overall cost and pollution reductions. This result supports our hypothesis that consideration of the transportation segments of the coke-making industry supply chain when planning the replacement of the many small plants in Shanxi Province with a smaller number of large plants is important.

The scenarios examined that relate to the addition of rail transport capacity indicate that the cost– and NO_x emission–reduction potential is not so high. Apparently, under the conditions of our scenarios, the railway network is large enough to support the required transportation of coal and coke. If the demand for coke continues to increase without a corresponding increase in rail-transport capacity, however, we expect that these findings could change dramatically. Because the model has been developed so that it is easy to introduce new input data sets, planning officials can use the model to examine the effect of increasing coke demand on the rail transport capacity constraints.

Of all of the scenarios examined that consider technology transfers, the greatest potential appears to be in the improvement of truck technology. This result is a clear reflection of the importance of trucks both in transportation and in pollution emissions in Shanxi Province. Even greater reductions in NO_x emissions could be expected with the introduction of trucks fueled with compressed natural gas, hybrid electric vehicles, or fuel-cell-powered vehicles. Analysts could examine these scenarios using the tradeoff model that we have developed by introducing an appropriate data set for vehicle costs and emissions.

Although we have not treated social and administrative factors here, our position is that by clarifying the technological and economic factors, decision makers will be better able to identify the options that best meet the social and administrative factors that cannot be quantified in a model. Therefore, we believe that the overall approach of providing quantitative information on technological and economic factors to decision makers supports the consideration of other more qualitative factors. Researchers working with us have written articles that deal with social factors, such as training and education (Chan 2002). In addition, there are several comprehensive analyses of the social and administrative factors that affect decisions for resiting of industrial facilities in countries such as China (Bai 2002, Rock et al. 1999). We believe that a combination of these considertations of social and administrative factors with our system model framework for evaluating technological and economic factors would yield a timely information resource for planning officials in China and other East Asian countries.

Conclusions

We have presented a system trade-off model for evaluating the various trade-offs associated with plant scales and transportation in the coke-making supply chain of Shanxi Province, China. The model draws on a GIS database for the region as well as cost coefficients and the size and locations of the different types of plants on the supply chain. The model consists of several functionally independent computational components. The first is an empirical plant-costing model that estimates the investment and operation costs for different sizes of coke-making plants. The second is a GIS link-converter module that translates the distance and type of road and rail network data contained in the GIS database into the different types of costs to be evaluated, such as economic cost and pollution cost, using cost coefficients that can be set by the user of the trade-off model. Here, we have used a set of coefficients for estimating economic cost and NO_x emissions that we have established from a variety of primary and secondary data sources. The third computational component is a transport-flow, cost-minimization program that optimizes the routing of coal and coke transportation on the road and rail network using the cost-translated network-link data from the GIS link-converter module. We developed this program by adapting the Netflow software package to the problem of transportation in industrial-manufacturing supply chains. The fourth component of the trade-off model is a plant-siting GUI implemented in the platform-independent programming language, Java. This interface provides the user with a simple point-and-click-style visual interface that makes it easy for decision makers to generate different scenarios to evaluate. The interface also presents a graphic visualization of the cost-minimized routes generated by the model. In this way, the interface allows users to interact intuitively with the total system trade-off model.

We used the system trade-off model to study the trade-offs between different scenarios of aggregating the coke-making capacity of the existing plants in Shanxi Province or improving the transportation of coal and coke for the coke-making supply chain in terms of economic cost and NO_x emissions. The results presented here indicate that both economic costs and NO_x emissions from the transportation of coal and coke for the coke-making industry could be reduced by aggregating coke-making capacity to plants with low transportation costs, even when the costs of constructing the enlarged plants are included. On the other hand, using the data sets that we collected, our scenarios indicate that replacing the large number of small coke-making plants with the smallest number of cost-efficient, large-scale plants might not be the least-cost solution, even if the plants are sited ideally from the perspective of the transportation network. Choosing a larger number of plants scaled to meet the local demands for coke may result in the overall lowest-cost solution.

Scenarios examining the effects of changing the transportation infrastructure by increasing the number or capacity of railroads or by electrification of the existing railroads result in only a small reduction in NO_x emissions; however, scenarios examining the introduction of new technologies, particularly for low-emission trucks, suggest a more significant impact on pollutant emissions from the transportation segments of the coke-making-industry supply chain in Shanxi Province. Costs for transportation and operation do not vary much among these scenarios. Investment costs could only be calculated for the scenarios of rail construction, rail electrification, and low-emission trucks. Investment costs were highest for the low-emission trucks, resulting in relatively high marginal costs for NO_x emission reduction under this scenario. Of the three scenarios, marginal costs were lowest for rail electrification.

Future research efforts will be directed toward integrating models of plant costs and pollution emissions being developed by other research-project members into the modeling infrastructure presented here. Also, we will establish data sets for other key pollutants, such as particulates and SO_2 emissions. Finally, we will continue to use the trade-off model to study other options for reducing pollutant emissions from the coke-making sector in Shanxi Province as well as extending to the application of other industrial sectors and other regions.

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Notes

1. The tons used in this article are metric tons (1 metric ton equals 1,000 kg and is equivalent to 1.1 short tons).
2. These characteristics of coke-making in Shanxi Province were determined through a series of interviews of several different coke-making plant managers and environmental officials in Shanxi Province conducted by Karen Polenske and colleagues from July 5–9 2001.
3. The results given by Chen (2000), including assumptions in regard to discount rates and other investment-calculation assumptions, were verified and modified by Polenske and McMichael (2002), but reference is to Chen throughout the remainder of this article.
4. See note 2.

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