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MODELING THE INTERNATIONAL COMPETITIVENESS OF BOTSWANA'S COAL

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ABSTRACT

Modeling the International Competitiveness of Botswana's Coal

Khaulani Fichani

Botswana has vast proven deposits of steam coal, which for a long time it has wanted to develop but without much success. The main objectives of this study are: 1) to analyze the time schedule of coal exports likely to be forthcoming from Botswana and the land routes for these exports 2) to determine the competitiveness of Botswana's coal in the world steam coal markets and 3) to make recommendations on the appropriate policy for the exploitation of this coal. To accomplish these objectives, we construct a model of the seaborne steam coal trade consisting of exporters and importers with a substantial share in this trade. We econometrically estimate the long run marginal cost functions for net exporters and employ these to construct a spatial and dynamic model of the world steam coal trade with elastic supply and inelastic demand. This model is applied to simulate Botswana's competitiveness in this trade over the period 1995 to 2010 from a 1990 base year with a decision criterion that minimizes the sum of discounted capital costs of mine development, variable supply costs, rail and maritime transportation costs. Finally, we employ the model to forecast the likely optimal size of mine, timing of production capacity and choice of export port for Botswana's coal for the years 2005 and 2010. The base year for the forecast is 2000. The simulation results indicate that Botswana's coal would have been competitive in the steam coal markets of Western Europe and Asia. The forecast results indicate that Botswana's coal would also be competitive in these markets in the future. These results are least sensitive to changes in rail transportation and variable supply costs but are sensitive to capital costs for mine development.

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CHAPTER 1

INTRODUCTION

1.1 Background

Botswana has vast deposits of coal; it has wanted for a long time to exploit them but without much success. For a long time the country was considered a potential exporter of coal due to its abundant reserves, some of which are strippable (WOCOL 1980, Abbey and Kolstad 1983 and Raschke 1986). In a 1984 report by the US Bureau of Mines, it was estimated that Botswana would by the end of the decade be in a position to export 5 million to 10 million metric tons of steam coal to Western Europe. Factors that may have weighed heavily against the success of efforts to exploit these coal deposits take a variety of forms, such as: the lack of a domestic market for coal, the great distance from sea ports (at the time the only option was railway line to the port of Walvis Bay in Namibia, a distance of about for a 1600 km), political instability in the region which for a long time limited the available options for regional spatial developments in the goods transport sector, and also existing barriers to entry into the coal export business due to the concentrated nature of this industry in South Africa, where the coal export facilities were and still are privately owned by coal exporters. Other factors that may explain the lack of exploitation of Botswana's coal may have a lot to do with the characteristics of the world steam coal trade, such as, the conduct of this trade through long-term contracts and also the concerns by importers over security of supply issues.

The development of coal in Botswana has, therefore, been very meager and directly linked to the domestic demand for electricity. The country's only colliery is located on the Morupule coalfield, which has proven reserves of some 8.0 billion metric tons coalfield (see Table 1.3). It has a capacity of some one million metric tons per year, with most of this coal used for power generation by the Botswana Power Corporation’s mine-mouth power plant with a rated capacity of 132 MW.

In a 1980 report of the World Coal Study (WOCOL), Botswana is shown to hold close to two-thirds of the coal resources in the African continent at some 100 billion metric tons of coal equivalent, ahead of South Africa at 57.6 billion (see Table 1.1). The quality of these resources is good and compares very favorably with steam coal from other coal producing countries, which have a developed steam coal export industry (see Tables 1.2 and 1.3). In spite of this endowment, it is South Africa that has both a thriving domestic and export coal industry from mines located on the Witbank region of one of its provinces, Mpumalanga. There is also a mine located near the town of Ellisras in the Northern Province, a distance of not much more than a hundred kilometers from the Botswana border, the Grootgeluk colliery, that produces coal for both the domestic and export markets. This colliery is close to the Mmamabula coal deposits, which occur on a coalfield that straddles the Botswana and South Africa border and is known as the Waterberg on the South African side (see Figure 1.1). This coalfield is estimated to hold over one third of South Africa’s coal reserves. The quality of this coal makes it suitable for other uses such as in the production of synthetic fuels (para 2, “Future developments”, n.d.).

Table 1.1 Hard Coal Resources of Africa (Million mtce)

Country	Coal Resources
Botswana, Republic of	100,000
Morocco	200
Mozambique	400
South Africa, Republic of	57,566
Swaziland	5,000
Democratic Rep. of Congo (DRC)	808
Zambia	228
Zimbabwe	7,130
Others	1,560
Total	172,892

Source: Greene, R.P. and Gallagher, J.M. (Ed), Future Coal Prospects: Country and Regional Assessments, Report of the World Coal Study (WOCOL), 1980, Nimrod Press, Boston, p561.

Table 1.2 Gross Heat Content for Selected Steam Countries (MJ/kg)

Country	Gross Heat Content	Sulfur Content (%)
Botswana	24.20 – 27.73	0.8 – 1.16
South Africa	16.8 – 31.9	0.23 – 1.84
Indonesia	26.2 – 33.5	0.3 – 1.0
Australia	23.0 – 33.0	0.3 – 0.8
Poland	23.88 – 24.02	1.0 – 2.0
U.S.A.	27.54 - 34.92	0.41 – 4.29

Source: International Coal, 1999-2000, National Coal Association, Washington, D.C., p I-3.

Table 1.3 Characteristics of Coals on Botswana's Major Coalfields

Coalfield	**Reserves (000s m. tons)**	**Thickness (Meters)**	**Depth (Meters)**	**% Yield[a]**	**GCV (MJ / kg)**	**% Sulfur (Washed)**
Morupule	7 910 000	6.5-9.5	40-300	46.9	27.9	0.66
Mmamabula Central Block	442 943					
: Upper	70 923	2.07	2.5-32.5	30	28.24	0.42
: Middle	212 769	5.39	12.5-42.5	46	27.76	0.41
: Lower	159 251	2.83	30.0-60.0	80	27.35	0.44
Mmamabula South Block	2 440 000	2.07– 5.39	82.5 - 160	n.a.	n.a.	n.a.
Rest of Mmamabula	2 292 057	Similar to Central Block	Similar to South Block	n.a.	n.a.	n.a.
Letlhakeng	3 530 000					
: E2b	325 800	1.45-3.16	60-200	74.0	28.66	0.41
: G1	679 274	2.9 - 7.4	80 -220	52.3	28.25	0.36
Rest of Letlhakeng	2 524 926	n.a.	n.a.	n.a.	n.a.	n.a.
Dutlwe	2 000 000	1.5-4.0	<300	50.0	26.88	0.60
S.W. Moijabana	1 300 000	same as Morupule	same as Morupule	n.a.	n.a.	n.a.
Total	19 915 000					

Source: Clark, G.C., Lock, N. P. and Smith, R. S., The Coal Resources of Botswana, n.d., Department of Geological Survey, Lobatse, Botswana.
Note: (a) – The yield % is from coal washability tests at an S.G. of 1.5

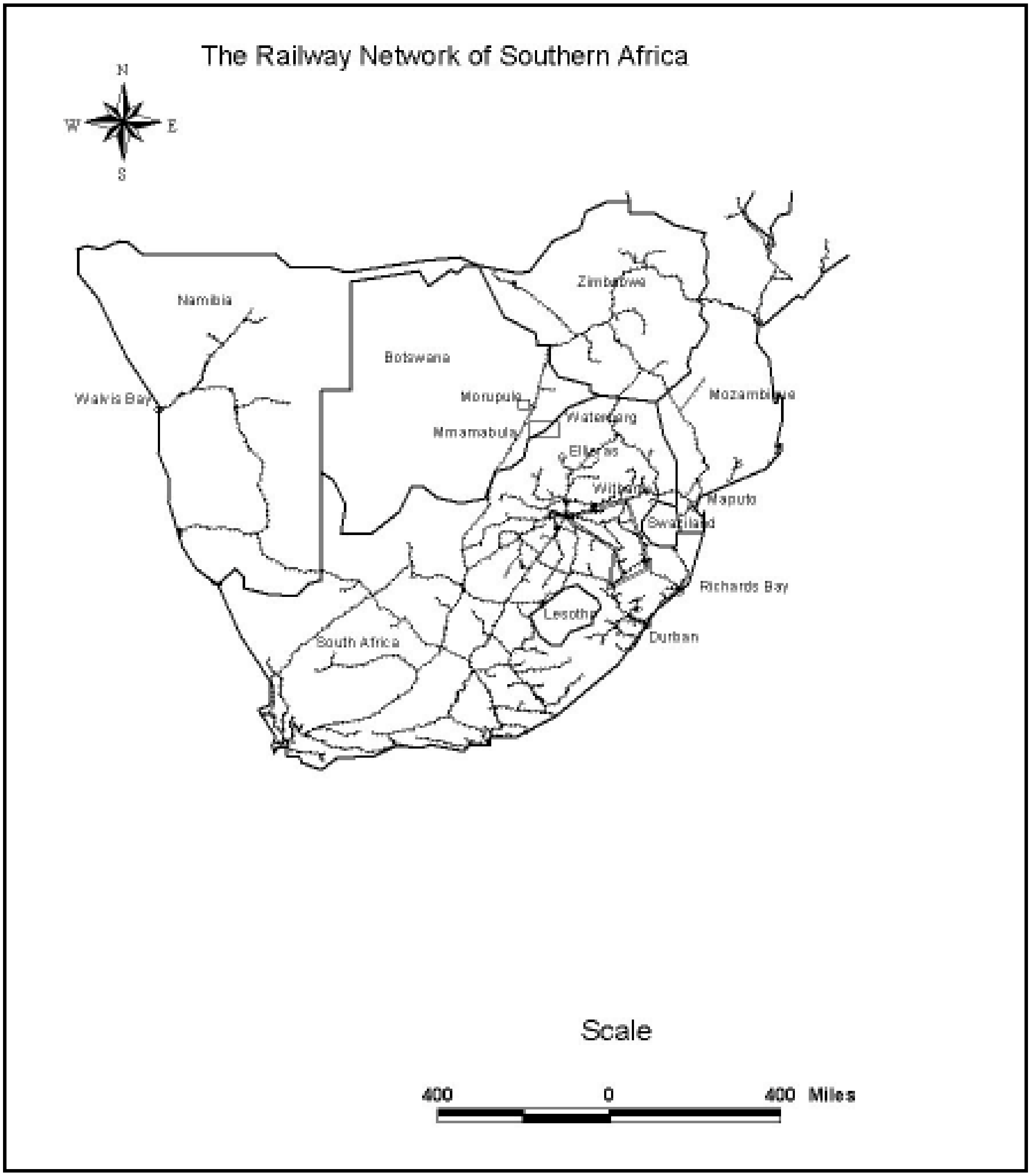

Figure 1.1 The Coal Deposits of Interest and Their Approximate Location Relative to the Railway Network of Southern Africa

Source: Compiled by author from GIS database files retrieved on April 19th, 2002 from: http://www.maproom.psu.edu/dcw/

Note: Coal deposits location is not geo-referenced and is therefore only illustrative.

In the year 2001, South Africa was ranked fifth in world bituminous coal production after Australia, India, the United States and China but was the second largest coal exporter after Australia[1]. During the same year, South Africa produced 224.2 million metric tons of coal, out of which a total of 218.68 million metric tons was saleable coal valued at R25.814 billion (about US $2.87 billion at an average exchange of about R9.00 to US$1.00 for 2001). Export coal, at 66.7 million metric tons, was just under one third of total sales tons but contributed R16.27 billion (about US $1.81 billion) to total sales, representing about 63% of total revenue, thus highlighting the role of exports to the South African coal industry[2]. Most of South Africa's steam coal exports are destined for markets in Western Europe. The continued growth in steam coal exports reflects the country's cost competitiveness as a supplier of steam coal to international markets. There have been recent reports that the South African government, out of concern for its diminishing coal reserves, has embarked on a study to take inventory of its reserves. This concern was highlighted by a recent report by the government that the country's coal reserves were sufficient for another forty years at current extraction rates. It is therefore likely that the export coal capacity will peak at some 85 million metric tons, which is the estimated export handling capacity of the Richards Bay coal terminal after the current phase of expansion[3]. This would present an opportunity for Botswana to build up capacity so that it could, in addition to

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[1] Table 5.3 World Coal Production, 1992 – 2001 (Million short tons). Retrieved March 10th, 2003, from the Energy Information Administration world wide web: http://www.eia.doe.gov/pub/international/ieapdf/t05_03.pdf

[2] South African Mining Industry Statistical Tables, 2001. Retrieved on February 28th, 2002, from the Chamber of Mines of South Africa world wide web: http://www.bullion.org.za/bulza/publications/Stats2001/StatsTables.pdf

[3] Bain, J., "About 20% of the Coal Will be Left Unmined", Business Day, February 20th, 2002. Retrieved on March 23rd, 2002 from: http://www.bday.co.za/bday/content/direct/1,3523,1027499-6078-0.00.html. This article reports that South Africa's proven coal reserves stand at 34.4 billion metric tons and that expansion of the RBCT will lead to some 82 million tons of rated capacity in 2004 but with a safety to reach 85 million metric tons without major capital investment. The port of Matola is expected to increase its capacity from 1 million to 6.5 million by 2005.

any market share that it would gain away from the present suppliers, take up any future supply shortfall from Southern Africa as a result of this binding constraint on South Africa's exports.

The existence of large deposits of coal in Botswana and their lack of exploitation has always been a worrisome issue for policy makers. This concern led to government sponsored pre-feasibility type investigations into options for exploiting these coal deposits. From a project completed in 1983 and designed to investigate the feasibility of an export coal mine to produce steam coal for sale in the international market, it was concluded that the single most important factor contributing to the project's unfavorable economics was the cost of rail transportation from the Kgaswe coalfield to Walvis Bay in Namibia, a distance of about 1600 kilometers. A feasibility study was conducted in 1992 for a coal-fired power station to generate electricity from Mmamabula coal for sale to South Africa. This project too was found to be uneconomic at the time, as it would have produced electricity at a price that was then higher than the rates in South Africa.

The Southern Africa region has seen substantial progress in the areas of political stability and regional cooperation on spatial development initiatives covering infrastructure projects that embrace a regional as opposed to only national government objectives in the wake of a democratically elected government in South Africa in 1994. These developments justify renewed interest by policy makers in Botswana to explore the options that can be pursued to facilitate the exploitation of the country's coal deposits. There has also been growth in cooperation among Southern African countries in the selling and buying of electricity, which has been facilitated by the formalization of the Southern Africa Power Pool (SAPP) in 1995. This has resulted in inter-connections between national grids in the region. The significance of the SAPP is that it is only the third of its kind in the world after those in Europe and the United States. This has reduced the risk of loss of load, lowered capacity and reserve requirements by national utilities, reduced fuel costs, and raised the efficiency of utilization of the regions hydropower (O’Leary, Charpentier and Minogue, June 1998). The region’s projected investment in power generation to meet demand for electricity over a period till 2025 shows that even under modest load projections, the scale of investment in new capacity would be very substantial (Dingley, 2000).

Following on the wave of deregulations of the electricity industry, a maneuver devised first in the United Kingdom and then adopted in other European countries and recently in the United States, South Africa has also joined the growing list of countries with a deregulated electricity generating market (see Green and Newbury, 1992). This projected growth in electricity demand is likely to be met from coal fired power plants, whose location within the region may also depend on the ability of national governments to provide financing as project partners, thus placing Botswana, which is a capital surplus country, in a very favorable position to develop its coal reserves for power generation to meet the projected regional demand in electricity.

There has long been curiosity on the relationship between electricity consumption and economic growth arising out of the dual role of electricity as both an infrastructure good as well as input that raises firm productivities and living standards. Murry and Nan (1994) conducted causality tests on a cross-section of countries and concluded that for those countries with fast expanding electrification programs, there is a two-way causality between electrification and economic growth. Burney (1995) conducts a similar study but using the random coefficient method and concludes that socio-economic factors such as literacy, urbanization, industrialization are key determinants of the demand for electricity and therefore need to be included in any estimation of electricity consumption. The region is therefore projected to expand its residential electricity demand resulting from projects such as those of the accelerated housing delivery in South Africa, where some two million households were added to the grid in the first half of the 1990's and a further four million are estimated to be added in the next decade or so. In Botswana, the rural electrification project has improved access in rural areas. Some 72 villages have been connected to the national grid and it is foreseen that in the period from 2002 onwards, 14 villages would be connected every year (Budget Speech, 2002). All of these projects are likely to increase the regional consumption of coal, thus raising the need for capacity expansion or new mine development for the regional market. A clear policy to take advantage of economies of scale in mine production could result in the entry of Botswana into the world steam coal trade.

The foregoing possibilities only confirm the soundness of past studies that identify the potential for the exploitation of Botswana's coal deposits as: 1) to develop these for the international steam coal markets, and 2) to invest in power plants to meet projected demand growth in both the domestic and regional electricity markets. In this study only the international competitiveness of Botswana coal, paying much emphasis to the likely time phasing of production capacity and the land routes to seaports will be modeled.

1.2 Statement of Problem

The Botswana government has sponsored two major studies, one in 1983 for an export coal mine and the other in 1992 for an export power station. In the intervening period and also since 1992, there have been smaller investigations aimed at determining the local demand potential for coal. Pre-feasibility type studies are costly and the usefulness of their results is not long lived. This means that the policy maker in Botswana has to make ad-hoc decisions to study whether conditions have sufficiently improved to justify the detailed feasibility type studies on ways to exploit the country's coal deposits. For instance, in 2002, the government once again indicated its intention to re-investigate the potential for exploiting the country's coal deposits.

One way to avoid this ad-hoc decision making would be to develop a simple and user friendly spatial and dynamic optimization model of the world steam coal trade upon which policy makers would rely to gain some insight about whether economic factors favored the development of Botswana's coal deposits for the export markets. This would provide a means to determine the likely competitiveness of a possible export coal mine to exploit Botswana's coal. Such a model would also provide information on the likely role of government policy regarding provision of support infrastructure for an export coal mine development. For these reasons there is justification for developing a steam coal model that policy makers can rely on for decision making on energy development and infrastructure issues related to coal.

The improved regional stability and increased cooperation in spatial development projects presents an opportunity for policy makers in Botswana to investigate options for alternative export ports to facilitate the development of the country's coal deposits. There is need to objectively determine the factors that impede the development of an export coal industry instead of attributing this failure to distance from seaports. A 1993 study by the US Bureau of Mines comparing the costs of selected coal mines in Australia, Canada, Colombia, South Africa and the United States found that South African coal mines had the second lowest delivered steam coal costs for markets in Europe and the U.S. Gulf Coast region after Columbia[4]. Mines from

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[4] _ " A Cost Comparison of Selected Coal Mines from Australia, Canada, Colombia, South Africa, and the United States", United States Department of the Interior, U.S. Bureau of Mines, August 1993.
Case VI: European Electric Utility Delivered Costs are: Columbia -$28.85, RSA – $32.36-42.20,
Australia - $32.64 –54.33 and USA - $44.91-51.21
Case VII: Japanese Electric Utility Delivered Costs are:
RSA- $28.01-37.85, Australia - $28.92-35.20 and USA - $46.04-67.52

Australia and the United States were ranked in third and fourth positions respectively. In the Japanese steam coal market, South Africa had the lowest delivered costs followed by Australia and then the United States. In a 1996 study by Ames Minerals Research as cited in Coal Age (1996), South Africa and Indonesia were found to have the lowest f.o.b. cash costs at US $22.80 per metric ton of steam coal exported. The study further observed that the growing cost disadvantage that Australia suffered would most likely rule out any new mine development in the steam or semi-coking coal category for the next 5 to 10 years. The cost advantage enjoyed by South Africa is further helped by its depreciating currency against the U.S. Dollar.

This advantage in costs is likely to apply to all mines within the Southern African region as it derives mainly from the low costs of mining. The country's low wage rates and the geology of the coal deposits contribute to these low per unit costs of coal supply and since the region as a whole also has low wage rates and, to some extent, similar geology (Clark, Lock and Smith, n.d.) this cost advantage can be extended to all existing and potential coal suppliers from Botswana's coalfields. In other words, an assumption of a single regional supply function would be justified. Even with this assumption, there is flexibility to have differing levels of profitability for the individual mines as the regional export price may be in excess of that required by the mine with the highest marginal costs. In the demand regions, the price paid to suppliers is not necessarily that which equals the marginal costs of the highest producer. Suppliers are willing to accept any price that exceeds their own marginal costs but less than that paid to the supplier with the highest marginal cost. This practice leads to infra-marginal pricing based on marginal supply costs (Kolstad, Bivins and Abbey, 1983 and Elliot-Jones, 1986).

Case IX: U.S. Gulf Coast Electric Utility Delivered Costs are: Columbia -$29.70, RSA – $33.41-40.40, Australia - $55.73-58.28 and USA - $35.04-61.30
All costs figures are in January 1989 $ /short ton saleable coal.

On the issue of distance, and hence, rail transportation costs to export ports, Iscor's Grootgeluk mine located near Ellisras in the Northern Province is only about a hundred kilometers from one of the major coalfields, Mmamabula on the Botswana side of the border and Waterberg, on the South African side, and, therefore, is at a distance from the seaport of Richards Bay that is comparable to a would be a mine located on the Mmamabula coalfield. This distance would be much reduced if a railway line were built along the same route indicated under a spatial development initiative project for the Northern Province to link it to the coal handling port of Matola, Mozambique. It is doubtful whether the short distance separating Grootgeluk and Mmamabula would lead to rail transportation costs that would be so large as to erode the cost advantage that South African coal, and therefore coal from the region, would enjoy on international steam coal markets.

The existence of barriers to entry into the South African coal export industry manifests itself in the close control that the coal exporting companies have over the privately owned coal handling and export facilities at the Richard's Bay Coal Terminal (RBCT). The coal companies controlling the RBCT allocate themselves export quotas that are proportional to their shareholding in the export facility. Botswana has built a very good reputation in its dealings with foreign investors and it is a successful mining country. The country should be able to take advantage of its existing joint venture partnerships with South African transnational corporations to lessen the barriers to entry into the international steam coal trade.

The role of distance in rail transportation costs needs to be viewed in comparison with hauling distances in other world regions such as western Canada and the Illinois Basin of the United States, which have similar, if not longer, distances to seaports. It is most likely that the rail tariff structures in the Southern Africa region, which can vary substantially across borders, acts as a serious deterrent to the regional freight business and it is this selfish rent-seeking behavior that in the past, could also have affected the profitability of a would be export coal mine from Botswana. This situation is expected to change under the provisions of the 1996 Southern African Development Community's (SADC) protocol on Transport, Communications and Meteorology.

1.3 Objectives

This study has two main objectives: 1) to analyze the time schedule of coal exports likely to be forthcoming from Botswana and the land routes for these exports from among the existing and simulated railway lines to seaports at Matola (Mozambique), Richards Bay coal terminal (Republic of South Africa) and Walvis Bay (Namibia), and 2) to provide input towards the development of an appropriate policy on the development of coal export infrastructure that would encourage investment in projects to exploit the country's coal reserves. To accomplish these objectives, it is necessary to conduct the following research:

(i) to construct a spatial and dynamic optimization model of the world steam coal trade that is capable of analyzing a number of issues;

(ii) to determine the time phasing and capacity of production that is likely from Botswana coalfields;

(iii) to identify possible land routes for exporting Botswana coal, and

(iv) to forecast the spatial and temporal distribution of the international steam coal trade, to simulate the share of Botswana coals in this trade, and to make policy recommendations regarding the provision of railway infrastructure to encourage Botswana's coal exports.

1.4 Method of Approach

The majority of spatial price equilibrium models for trade in fuel and energy minerals are static and differ only in their treatment of supply and demand. For instance, the U.S. coal model by Zimmerman (1981), the world steam coal trade model by Dutton (1982) and the US Department of Energy's international coal trade model (ICTM) of 1982, all use marginal supply functions that are derived from engineering cost data, where data availability permits, and inelastic estimates where there is paucity of such data. The demand used in these models is estimated exogenously. In the early non-linear coal trade models such as the Argonne Coal Model by Macal (1979), the supply function used differs from the cumulative cost function approach by Zimmerman and Dutton and, instead, is derived through a simple econometric model that regresses unit production costs on production. The demand is still exogenously estimated. In the regional models, the demand for coal is estimated from two step models of energy demand in which the first step is to estimate the total regional energy for residential and commercial users on the one hand and industrial users on the other and secondly, to employ a conditional logit model for the choice of fuels to meet the estimated energy demands (Baughman, Joskow and Kamat, 1979). In the non-linear regional trade models with both elastic supply and demand functions included in the model, the estimation of the supply and demand equations invokes the regional market equilibrium conditions that supply should equal to demand (see Labys and Yang, 1980).

The objective function for the spatial and dynamic optimization model for this study consists of four terms: capital expenditure costs, rail transportation costs, maritime transportation costs and variable supply costs. The constraints conditions consist of both domestic demands in the net exporting countries and import demands in the net importing countries. For a study of this type, two possible approaches to modeling the import demands exist. The first involves the estimation of steady state regional export supply and import demand functions (Lord, 1991). The two step procedure in estimating the import demand functions is as follows: first, the total import demand for a commodity is determined from the usual utility maximization between imports and a composite or numeraire good subject to a nominal level of income in the importing region. The first order conditions provide conditional demand functions for the import good and the composite good. The second step is another utility maximization to select from among the available exporters subject to an import budget constraint to satisfy the demand for imports estimated from the first step. The resulting conditional import and export demand functions are expressed as functions of real income, relative prices between the pair of countries exporting and importing and market share. The choice of functional form is the log-linear as it readily provides price elasticities for both export demand and import demand. These models use only relative prices, market share and income levels to explain trade and prove to be too restrictive, as they do not allow for the possibility of substitution (Lord 1991). This approach was not adopted for this study as its non-linear functions do not readily lend themselves to the quadratic programming that is widely applied in spatial price equilibrium models.

The second approach begins with the econometric estimation of country supply and demand functions. Some authors have invoked assumptions of inelastic supply with the result that only the demand functions are econometrically estimated using ordinary least squares (OLS) estimation. Examples include Hashimoto's (1979) world iron and steel economy (wise) model and Toweh and Newcomb's (1991) spatial equilibrium analysis of the world iron ore trade. In this study, we estimate the supply and demand functions for countries in the model using the appropriate methods after the data has been tested to avoid the main pitfalls such as simultaneity, non-stationarity and co-integration. The estimation of supply and demand functions for the countries in the model follows the approaches by Meyers, Devados and Helmar (1989) and Labson (1997), where in the latter it was applied in modeling the world steel and iron ore trade.

The spatial and dynamic optimization model developed in this study will determine the time phasing and size of production capacity for Botswana's coal. This is the model upon which forecasts and policy simulations will be based. The application in this work will add a spatial, temporal and time phasing component to the approaches used by Labson (1997) and Meyers, Devados and Helmar (1989).

A simple multi-period linear programming model of the world seaborne steam coal trade will precede this optimization model. The purpose of this linear programming model would be to determine whether rail and sea freight costs impede the development of Botswana's steam coal deposits for the export market. The interpretation of the marginal values, which are the shadow prices associated with the supply of coal or transportation costs along both existing and simulated routes, obtained from this model will provide some very useful insights about whether or not Botswana's coal would not have been competitive in the world markets in the past and their likely competitiveness in the future. This model is described together with its results in Appendix G.

1.5 Expected Results

The spatial and dynamic optimization model, which is formulated as a quadratic, temporal and spatial allocation model, is expected to provide useful information on the likely timing and size of coal development on Botswana coalfields. The expected results are for inclusion of coal from these fields in the world steam coal trade but in the event that the results show no immediate cost advantage for these coals, it is expected that within the forecast horizon, coals from Botswana would become competitive. The marginal values from this optimization would provide useful insights on the appropriate policy and level of intervention that would be necessary to encourage the development of Botswana coal for the export market. As the model is dynamic, it will find use in conducting sensitivity analyses. For instance, in the event that the base case forecast fails to include Botswana coal, then a sensitivity analysis of the forecast demand growth would indicate the likely timing of development of these coals. The advantage of this model is that it attempts to replace the adhoc policy decisions on when to revisit the issue of exploiting these huge coal deposits with a systematic approach that informs the policy maker about whether economic conditions existing at any point in time are sufficiently favorable to justify detailed investigations of projects for developing Botswana's coal deposits.

1.6 Contribution

The international steam coal trade only began advancing in the late 1970's; and when the first coal trade models emerged in the early 1980's, there was a general paucity of time series data, which precluded the estimation of the temporal characteristics of this trade. This paucity of data led to the reliance on engineering cost methods to estimate marginal supply functions and trade theory methods to estimate steady-state export and import demand functions for use in these static spatial price equilibrium models. In some models, there is reliance on expert opinion as to the levels of supply and demand to use in the forecasts, thus exposing these models to subjective judgments. The trade theoretic approaches to the estimation of import demands tend to ignore the substitution effects between fossil fuels in their use for power generation.

Our contribution in this work is that we take advantage of the appearance of data on the international steam coal trade to estimate country supply and demand functions econometrically for countries within the model. This approach leads to the computation of the import demand quantities in these countries as the residual of domestic supply and demand. We apply microeconomic theory in the specification of the derived demand for steam coal for electricity generation and, therefore, take into account substitution effects among the fossil fuels for electricity generation. While existing regional studies that have employed econometrically estimated supply functions (Yang, Hwang and Sohng, 2002, Yang and Labys, 1991 and 1980), these have tended to concentrate on the short run marginal supply functions as opposed to those for the long run. In this study, we estimate the long run marginal cost functions for the net exporting countries within the model and these are then used in the spatial and dynamic optimization model both to simulate and to forecast the temporal and spatial distribution of the seaborne steam coal trade. This approach relies on publicly available data, which should make the model easy to maintain. The model also has the advantages of quadratic programming such as endogenously determining the temporal supply quantities, capacity additions, trade flows, and supply prices.

This study represents an application of the Spatial Temporal and Price Allocation (STPA) methodology that focuses on development aspects of Botswana's steam coal deposits. This provides an alternative approach for analyzing the competitiveness of Botswana's steam coal in the international markets as opposed to project evaluation approaches. The advantage of this method over the project evaluation approaches is that, where there are increasing returns to scale such as in mining operations, this approach selects the scale of operations that minimizes supply costs since the scale of operations also impacts on project profitability.

Lastly, the modeling approach has the following advantages over the feasibility study approach: 1) it provides the Botswana government with an alternative to ad-hoc decisions relying on feasibility studies to determine the country's competitiveness as a steam coal exporter, 2) it presents an opportunity for the Botswana government to explore policy approaches to provide for railway infrastructure to seaports and 3) it provides a basis upon which the Botswana government could present a case for a regional approach towards the development of rail and port infrastructure under the Southern African Development Community's (SADC) protocol on Transport, Communications and Meteorology.

1.7 Outline of the Study

This study is divided into six chapters with the first primarily made up of the introduction. Chapter 2 provides a review of the international steam coal trade with special emphasis on 1) trends in supply and demand, 2) transportation, which is discussed separately for rail and maritime transportation costs and 3) the role of Botswana.

In chapter 3, a review of the literature on spatial price equilibrium models in the modeling of the mineral and energy trade includes: linear programming, non-linear programming the variational inequality problem and mixed integer programming. The chapter also reviews applications of these models in both international and regional trade in steam coal.

Chapter 4 presents the modeling framework, which involves both econometric and optimization techniques. The main subsections are: 1) the proposed model, 2) assumptions about the world steam coal trade, 3) the choice of countries for the model, 4) the mathematical model, 5) formulation of the empirical model, 6) the supply and demand components under which the specification and estimation of the long run marginal cost functions for the net exporters of the model are presented, 7) spatial and dynamic optimization and finally, 8) data sources for the model.

In Chapter 5, we present the empirical results. The main subsections for this chapter are as follows: 1) policy approach, 2) results of the estimation of the country supply and demand functions, 3) validation of the results for country supply and demand functions, 4) results and validation of the long run marginal cost functions and 5) simulation with the spatial and dynamic optimization model. In the last subsection, we also provide the validation of the spatial and dynamic optimization model through two approaches. The first is a comparison of the model's optimal values with the historical values for supply, exports and imports for the countries of the model. The second approach is that of an experimental design approach to test which factors have a significant impact on the changes in Botswana's exports.

Chapter 6 is concerned with the sensitivity analysis of the base case simulation scenario and also with applying the model towards forecasting Botswana's future steam coal exports. The sensitivity analysis is also applied to the base case forecast results to determine the responsiveness in Botswana's steam coal exports to changes in rail transportation costs, capital costs and changes in demand.

Finally, chapter 7 provides summary of the study, results, policy implications, conclusions and recommendations for future research. The Appendix presents results of the econometric estimations, the simple multi-period linear programming model and the GAMS code and a partial output from the base case simulation scenario. The description of the appendices follows below:

1. Appendix A – Results from the econometric estimation of country supply and demand functions;

2. Appendix B – Results from the econometric estimation of the long run marginal cost functions for net exporters in the model;
3. Appendix C – Results of the time series estimation of sea freight costs;
4. Appendix D – Sensitivity results of the long run marginal cost functions;
5. Appendix E – Graphical comparison of market shares;
6. Appendix F – The Resultant Market Shares With Botswana’s Capital Costs at 20% Above Their Base Case Forecast Levels;
7. Appendix G – A simple Multi-Period Linear Programming Model of the World Steam Coal Trade, and
8. Appendix H – The GAMS Code and Output for the Base Case Simulation Scenario of the Spatial and Dynamic Optimization Model of the World Steam Coal Trade.

CHAPTER 2

THE INTERNATIONAL STEAM COAL TRADE

2.1 Introduction

The international seaborne trade in hard coal consists of trade in two categories of coal, coking coal and steam coal. Coking coal has applications in the steel industry while steam coal is used in any one of the following three ways: generating steam for electricity generation; production of heat and steam for final end use such as in the residential and transportation sectors, and as pulverized injection coal (PCI) that is used together with coking coal in the steel industry (Coal Information 2001, p I.87). Towards the end of the 1970's, the reporting of separate trade data for the seaborne steam coal trade began (Coal Information, 1996). This chapter analyses the growth in the seaborne steam coal trade over the period beginning in 1980 and ending in 2000. This period is also relevant as it coincides with the period in which the pre-feasibility study on the viability of an export coal mine on the Kgaswe coal field, one of several major coal fields in Botswana, was carried out. The chapter goes on to look at trends in supply and demand, the role of transportation on the seaborne trade, focusing specifically on developments in the rail and maritime transportation costs and finally reviews the regional political situation in Southern Africa and how this shapes a role for Botswana in this trade.

2.2 Trends in Supply and Demand

Figure 2.1 depicts the growth trend in the seaborne steam coal trade and shows that this has increased by slightly more than 3.5 times in the period 1980 to 2000. As a percentage of the total seaborne hard coal trade, steam coal has shown consistent growth from about 46% in 1980 to about 66% in 2000. In figure 2.2, the share of the steam coal exporting countries under study is shown. The United States has always been a major producer of steam coal, second only to China, which has been left out of the model in the class of the rest of world supply. The position of the United States as a marginal producer for the international steam coal market is only sustainable due to the substantial demand for coal in the domestic market. This has placed the United States, with both its productive and transportation capacity, in a position to respond quickly to offset any supply shocks from lower cost producers. This happened in the early 1980's when there was a disruption of supply of steam coal from Poland destined for Western European markets. The graph depicts a spike in United States' steam coal exports that raised their share of this trade from about 27% in 1980 and to 42% in 1981. By the time the disruptions to coal supply from British collieries occurred in 1984-85, Australia and South Africa were in a position to compete for this increase in import demand with the United States (Coal Information, 1996, pp I.20).

In the second half of the 80's decade, new supply came on stream from countries outside of this model, such as Indonesia, Colombia and Venezuela. These new exporters began to play a significant role at the start of the 90's decade. The impact of new entrants would as expected be highest on the United States, as they are the marginal supplier. Figure 2.2 shows that in 1990, the market shares held by the United States, Australia and South Africa were 19%, 23% and 23% respectively. These countries had a combined share of 65% of this trade. By the year 2000, the United States' market share had declined substantially to about 7% while Australia and South Africa still commanded 23% and 20% respectively. In the intervening period, Australia's share reached a high of 27% while that of South Africa peaked at 25%. The three countries still commanded a market share of 50% in the year 2000 (see Fig. 2.3).

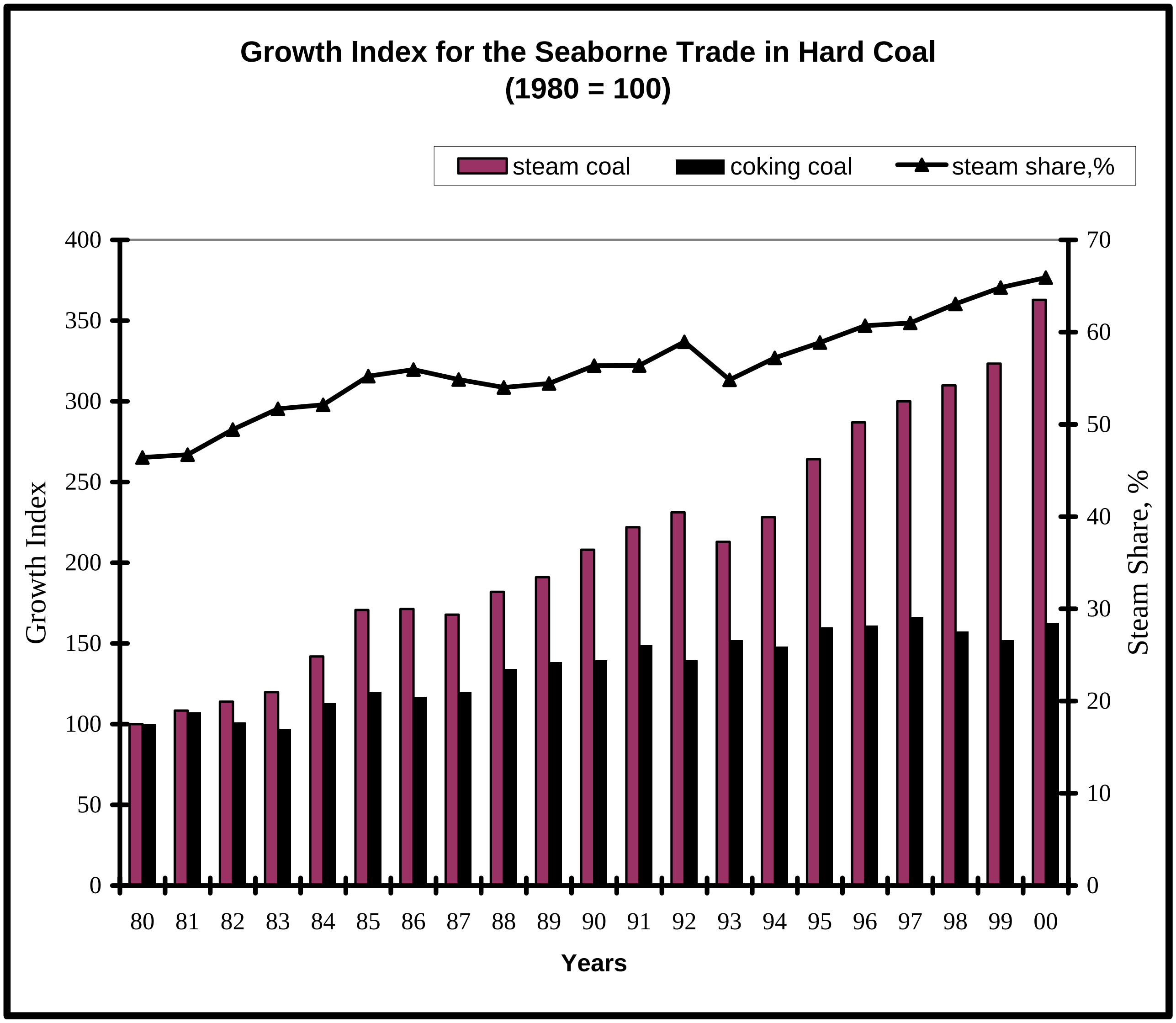

Figure 2.1 Selected Country Percent Shares in the World Seaborne Steam Coal Trade
Source: Coal Information, 2001, International Energy Agency / OECD, Paris, p I.150.

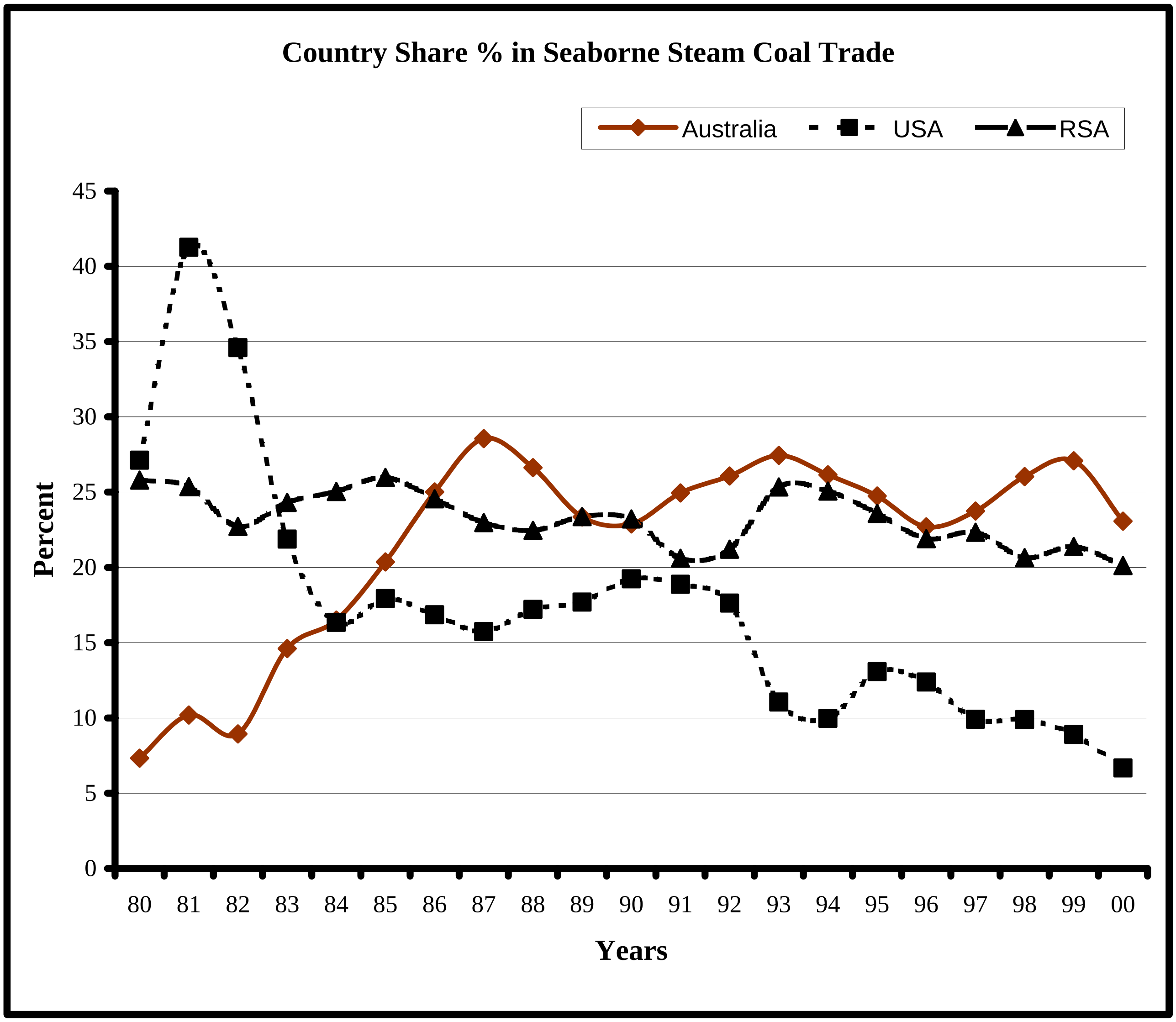

Figure 2.2 **Selected Country Percentage Share in the International Seaborne Steam Coal Trade**

Source: Coal Information, 2001, International Energy Agency / OECD, Paris, p I.150.

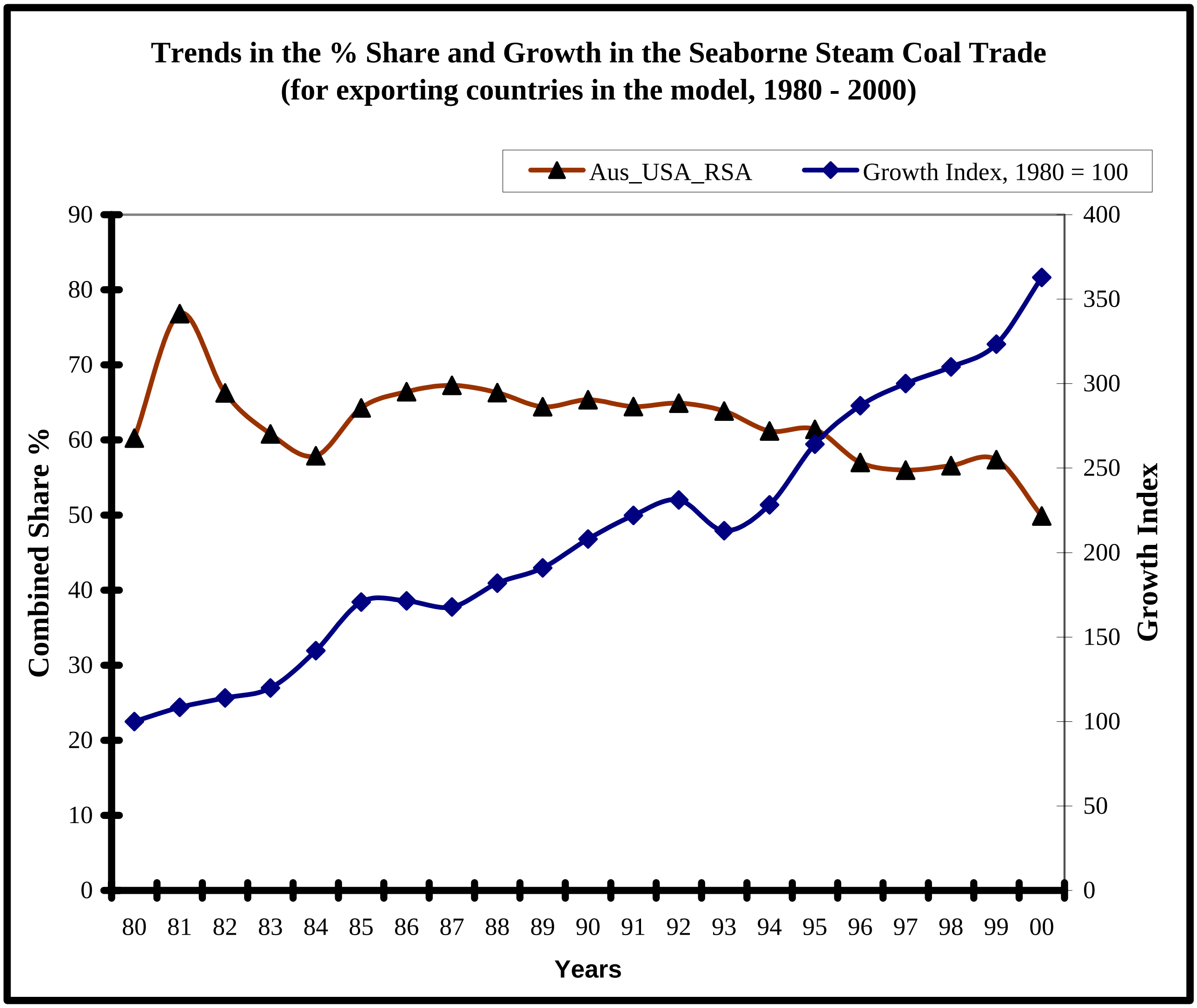

Figure 2.3 Trends in the combined percentage share of selected steam coal exporting countries in the model against the growth index in sea borne steam coal trade

Source: Coal Information, 2001, International Energy Agency / OECD, Paris, p I.150.

The major markets for seaborne steam coal are in two geographic regions, Asia and Western Europe. In this study only a few countries in each of these regions have been included as the demand countries in the model. The market in Western Europe is made up of Belgium, Germany, France, Italy, Netherlands, Spain and the United Kingdom while that of Asia includes only Japan and South Korea. The rate of growth in these markets, relative to a 1980 base year, is shown in Figure 2.4. The demand for steam coal in the Asian market grew eleven fold in the period 1980 to 2000 while in Western Europe it just about doubled over the same period. Figure 2.5 shows the trend in the individual and combined market shares for these regions. The latter has remained at about 60% in the 1990s. The individual market shares for these regions have trended in opposite directions, with the share for Western Europe declining by almost one-half between 1980 and 2000 to about 30%. The Asian market grew over the period by about three and one-half times to 35%. Long term projections for steam coal demand in these markets all show an increase in coal demand. For the period 2005 to 2010, steam coal demand Western European is projected to grow by 3.4% while in Asia it is 3.6%. For the period 2010 to 2020, the growth in demand is projected to increases to 7.3% and 19.6% for Western European and Asian markets respectively (Coal Information, 2001 p I.102).

Figures 2.7 and 2.8 show the price ratios of heavy fuel oil and natural gas to coal in their use in electricity generation for the leading steam coal importing countries in their respective market groupings, the United Kingdom and Japan, in the Western Europe and Asia market respectively. The natural gas to steam coal price ratio for the United Kingdom over the years 1995 to 2000 averaged out at 1.44. For other countries in this market, such as Germany, Netherlands and Spain for instance, the ratio of the gas price to that of steam coal averaged in the range 1.91 to 2.73. This may help justify the level of aggregation in the model at the country level instead of the regional level, as a country’s demand for steam coal will depend on the relative prices of other fuels for electricity generation. These ratios also help explain why steam coal is the fuel of choice for electricity generation in the Asian market.

The concerns on green house gas emissions from the burning of fossil fuels and their impact on global warming has led to technological initiatives to burn these fuels in much cleaner and efficient processes. The options available for complying with environmental regulations for lower green house gas emissions include burning fuel that produces less carbon dioxide per unit of heat, using more efficient generation technology and adopting more energy efficient policies in the consumption of electricity. Some progress has been made in adopting more efficient generation technology, or what is commonly referred to as advanced clean coal technologies. These consist mainly of the integrated gasification combined cycle (IGCC), the pressurized fluidized bed combustors (PFBC), the circulating fluidized bed combustors (CFBC) and the supercritical / ultra-supercritical pulverized coal (SC/USC) (see Coal Information 2001). These technologies improve efficiency for electricity generation and therefore lower the emission of both green house gases and sulfur dioxide, which are the main pollutants from the burning of fossil fuels. The trend in the ratios of the oil and gas prices to the price of coal indicates that the latter remains cost competitive while the progress in advanced clean coal technologies bodes well for the continued use of steam coal in the generation of electricity.

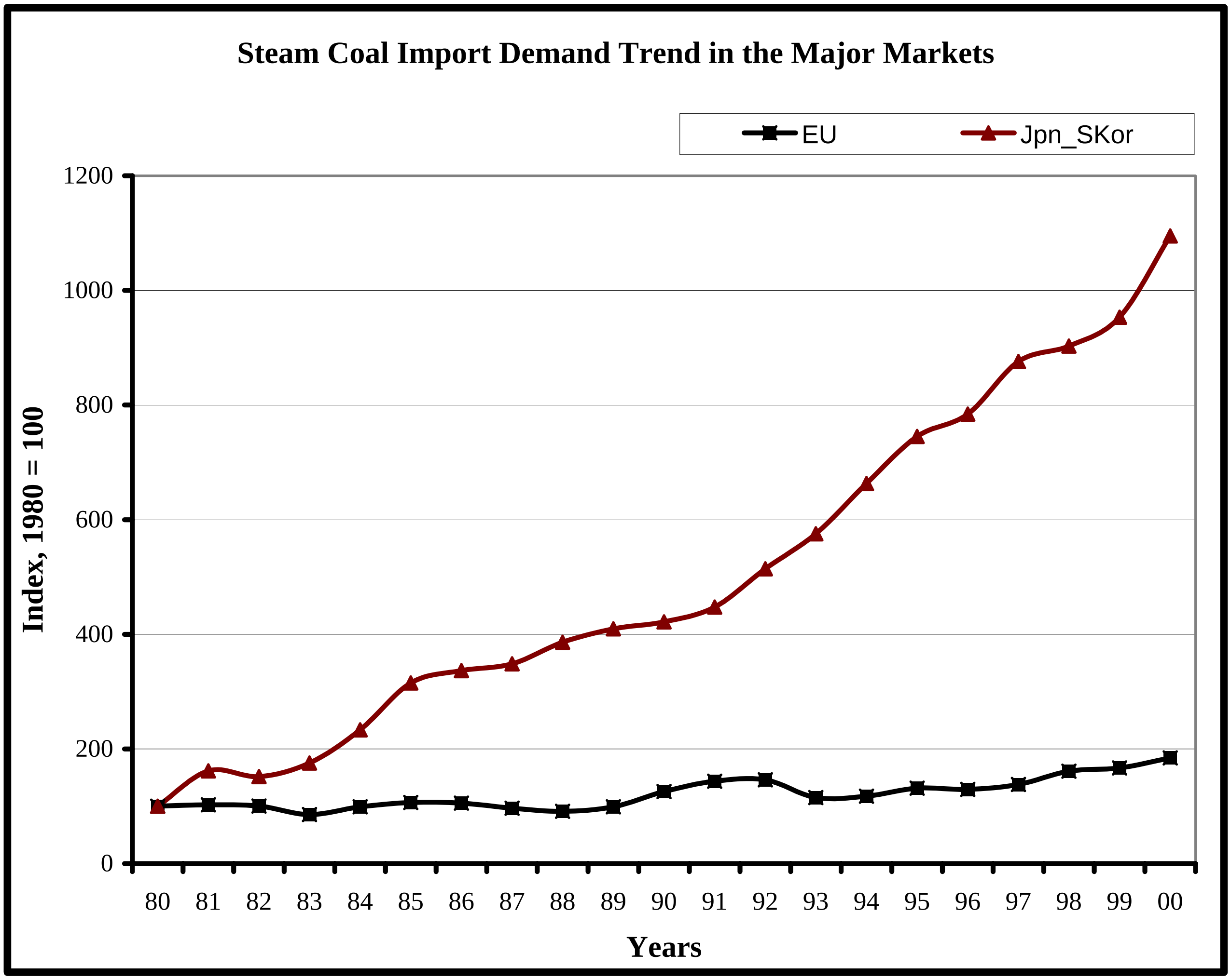

Figure 2.4 **Trends in Seaborne Steam Coal Demand for the Major Markets in the Model**

Source: Coal Information, 2001, International Energy Agency / OECD, Paris, p I.54.

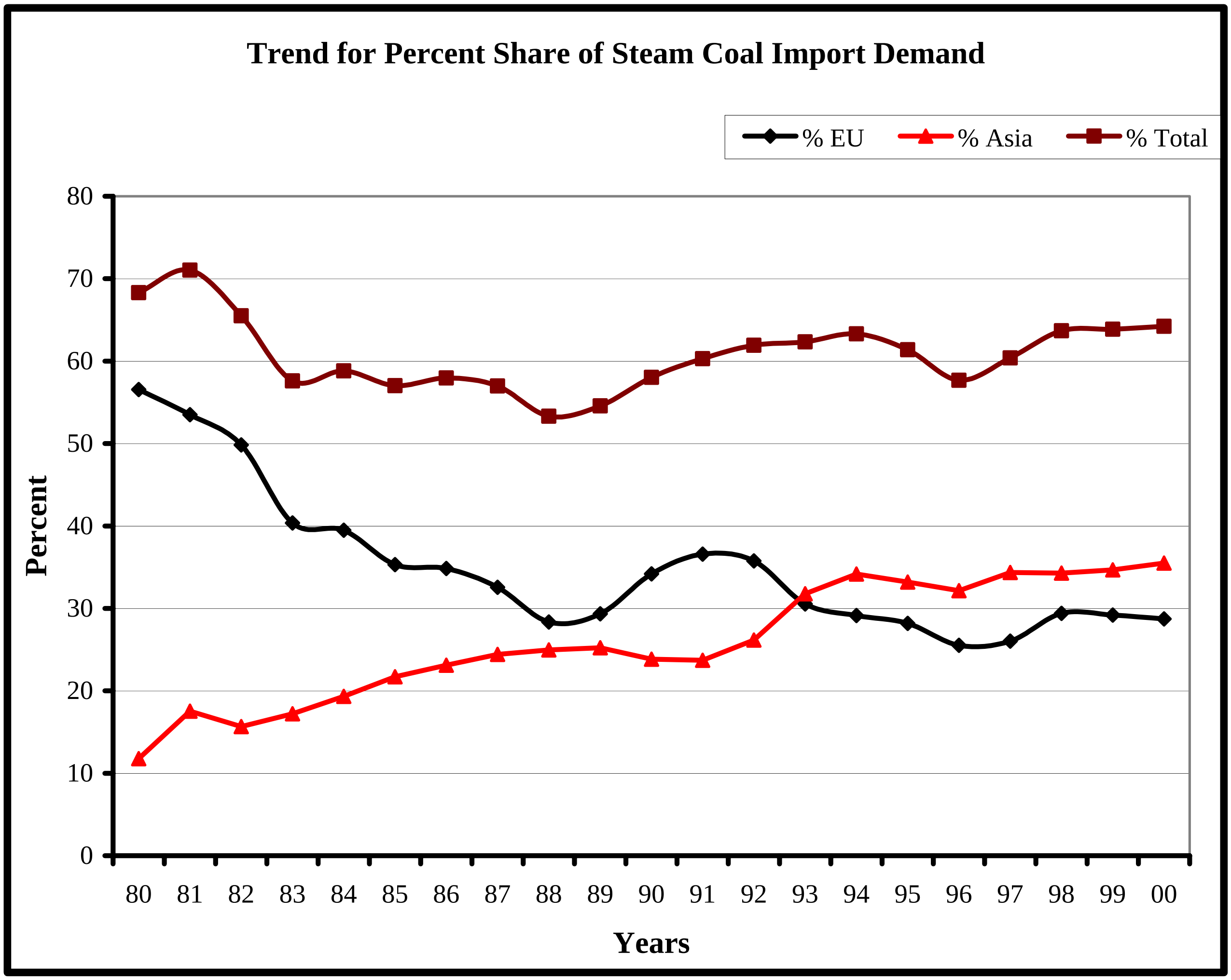

Figure 2.5 **Trends in the Percent Shares by the Major Markets for the Seaborne Steam Coal Trade**

Source: Coal Information, 2001, International Energy Agency / OECD, Paris, p I.54.

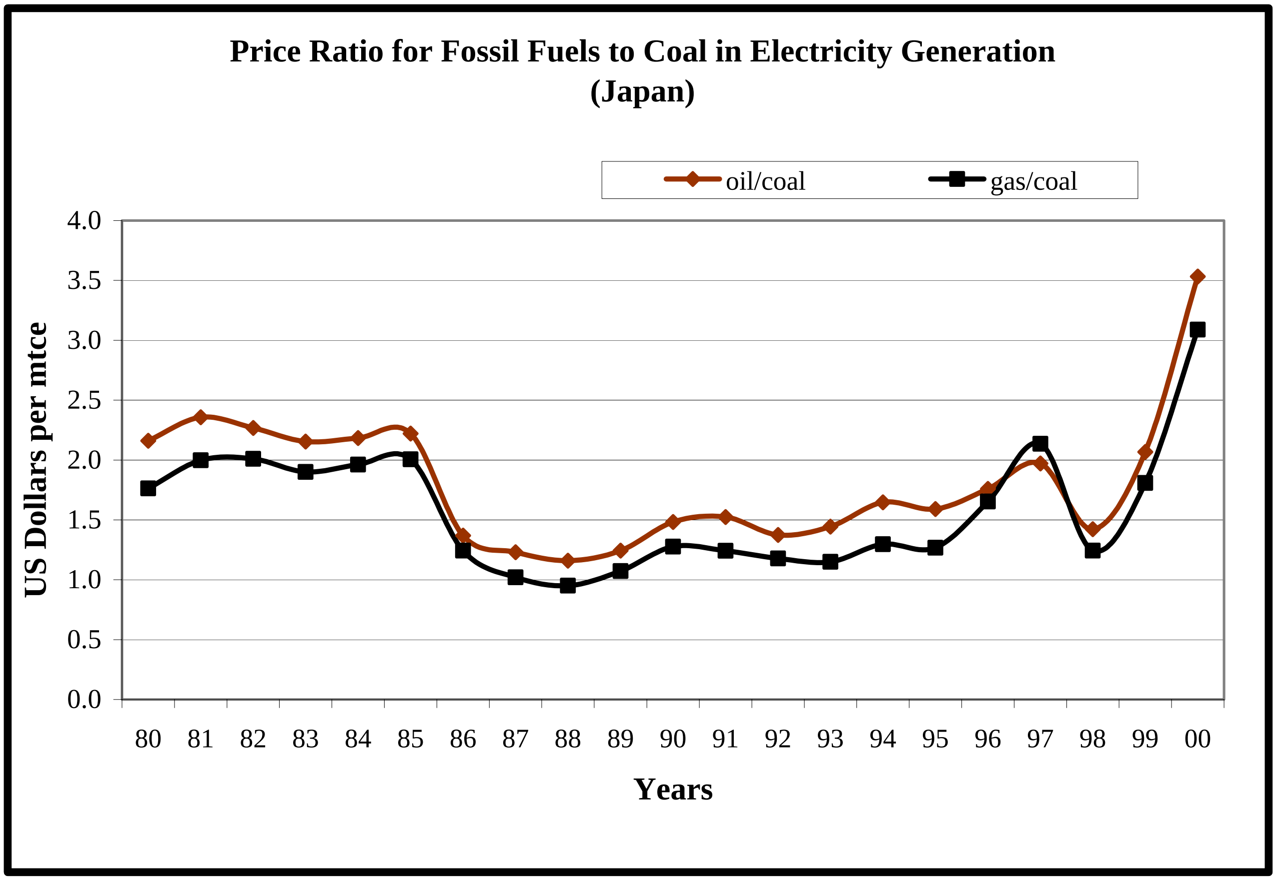

Figure 2.6 **Trends in the Japanese Price Ratios of Other Fossil Fuels to Coal**

Source: 1) Coal Information, 1990,1996 and 2001, International Energy Agency / OECD, Paris.
2) *Energy Prices and Taxes, Quarterly Statistics, Second Quarter 2001*, International Energy Agency / OECD, Paris.

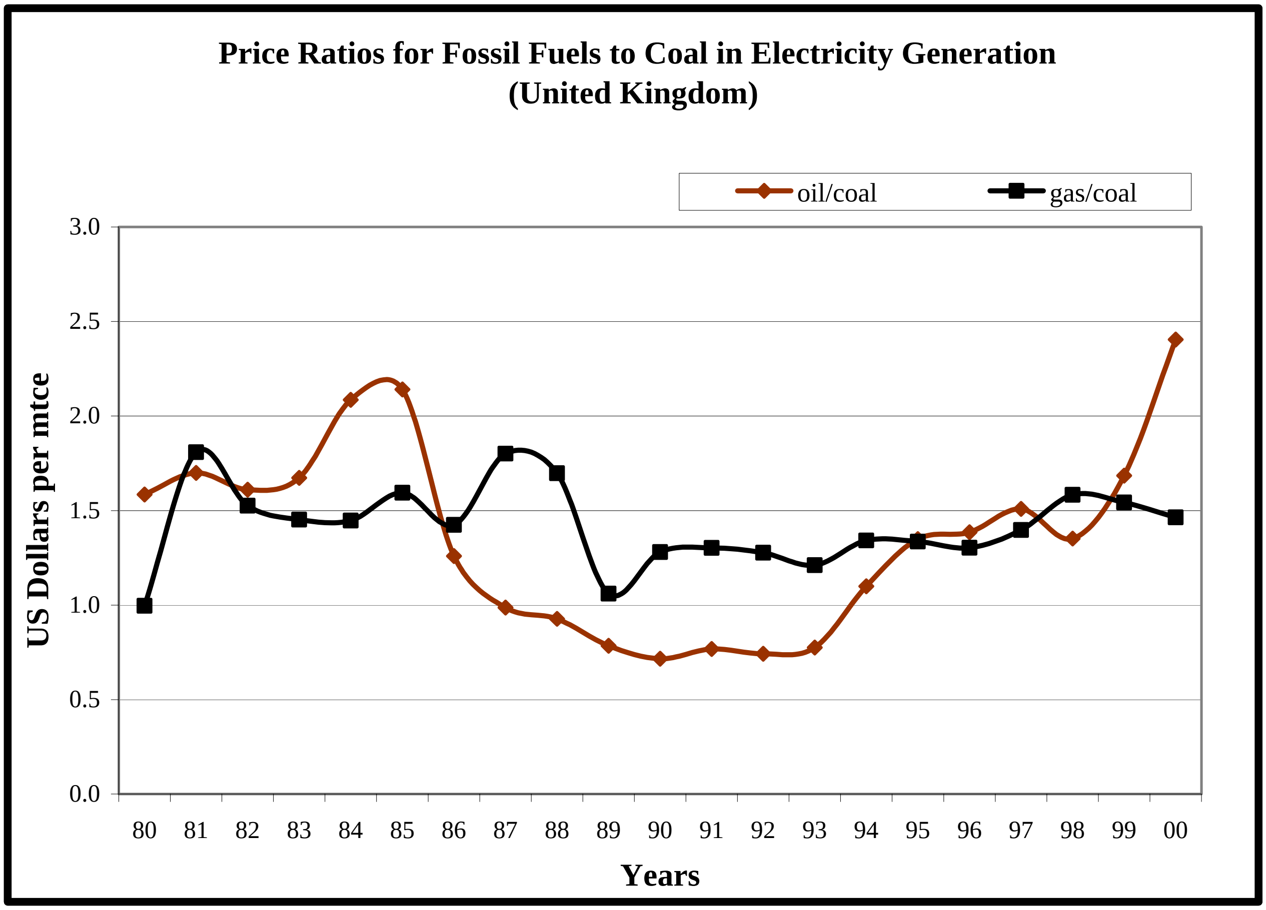

Figure 2.7 **Trends in the UK Price Ratios of Other Fossil Fuels to Coal**

Source: 1) Coal Information, 1990,1996 and 2001, International Energy Agency / OECD, Paris.
2) *Energy Prices and Taxes, Quarterly Statistics, Second Quarter 2001*, International Energy Agency / OECD, Paris.

2.3 Trends in Rail Transportation Costs

The competitiveness of rail transportation costs in the exporting countries in the model depends on the hauling distances to seaports. Among these countries, Australia has the shortest hauling distances to two of its major ports, Gladstone and Newcastle, of 280-380 km and 80-120 km respectively (Coal Information 2001, Table 5.6 p I.183). The main railway operator, Queensland rail is government owned. In South Africa, the distance from Witbank to the Richards Bay coal terminal is 625 km. Coal is also railed from ISCOR's Grootegelug mine, located about 100 km from the Mmamabula coalfield, to the seaport of Durban, some 1100 km away. The rail operator, Spoornet is government owned. In the United States, the hauling distances for mines located in Appalachia exceed those in South Africa. For instance mines located in central Appalachia, which is the region assumed for this study, face rail distances of 700 km – 1350 km to the seaport of Hampton Roads in Virginia. Some coals from Wyoming and Montana are railed to the Canadian seaport of Roberts Bank, a distance of 2250km – 2330km (Coal Information, 2001, Table 5.7, p I.185). There is competition in the provision of rail transportation services in the United States, a factor that facilitates the country's position as a marginal supplier of steam coal to the world markets.

Figure 2.6 shows that rail transportation costs have been declining over the period 1980 to 2000. In the five-year period 1995 to 2000, rail transportation costs for Australia fell by 43% from $10.29 to $ 6.05 per mtce and those for South Africa fell 43% to $7.28 from $12.83 per mtce. In the United States, rates only fell marginally by 5% to $19.16 from $20.24 per mtce in 1995. The decline in rail costs for Australia and South Africa may be explained in part by the depreciation of these countries' currencies against the U.S. Dollar.

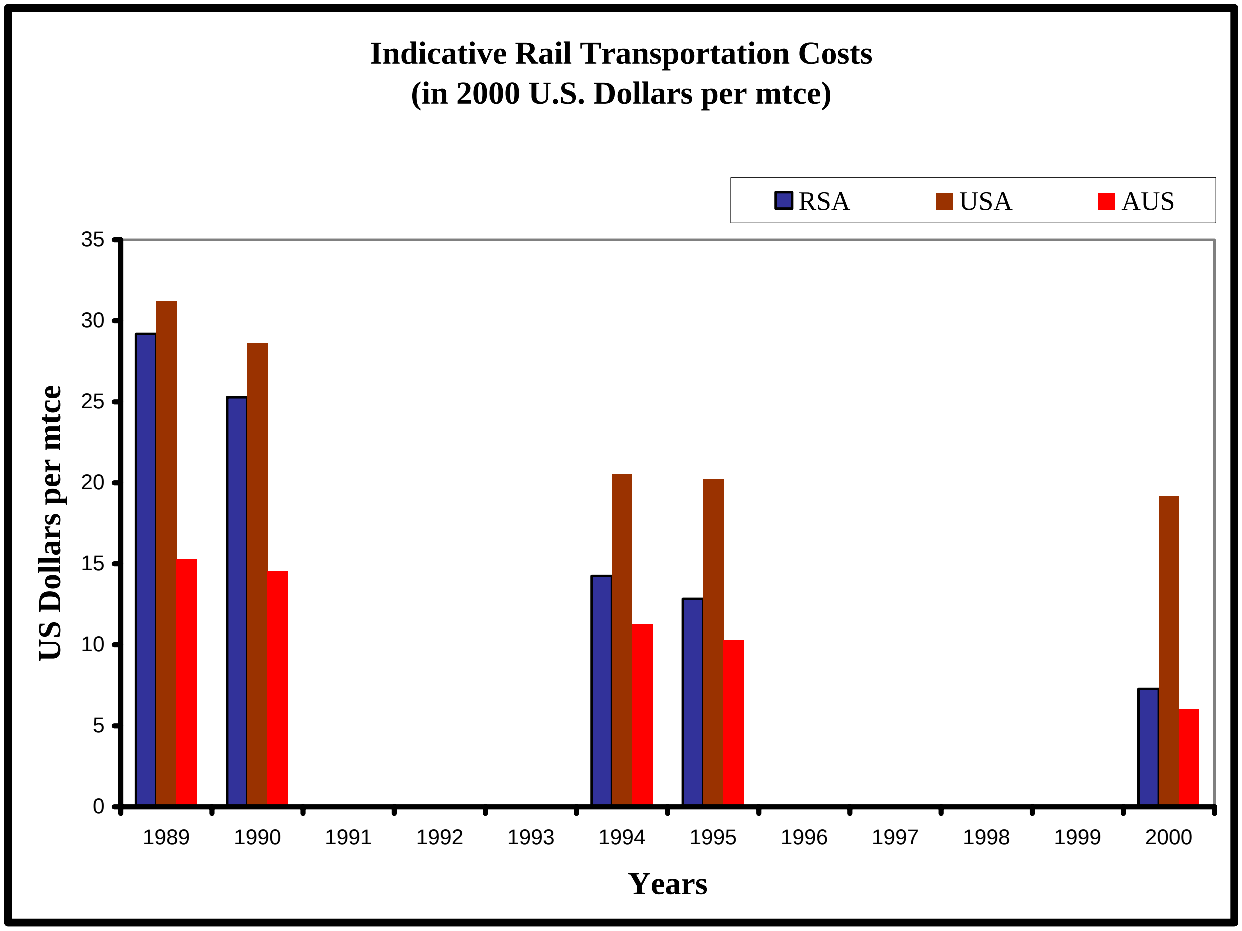

Figure 2.8 Trends in Rail Transportation Costs for Exporters in the Model

Source: 1) Coal Information, 1990, International Energy Agency / OECD, Paris, p26.
2) Coal Information, 1996, International Energy Agency / OECD, Paris, p I.148.
3) Coal Information, 2001, International Energy Agency / OECD, Paris, p I.183 and I.185

2.4 Trends in Maritime Transportation Costs

The seaborne trade in steam coal can be characterized as having two major markets, one in Western Europe and the other in Asia. If we imagine the imposition of prohibitive maritime transportation costs or if the price of coal were to decline to levels that would discourage the seaborne steam coal trade, then we would end up with truly regional markets. These would be in the Americas, Western Europe, Southern Africa and the Pacific. In the existing geographic definition of these markets, it is necessary to determine the cost competitiveness of suppliers to these markets and thus help to define which supplier would have cost advantages in which markets.

Figure 2.7 shows trends in the marginal supply costs for exporters in the model. All exporters show a consistent decline in their marginal supply costs. Figure 2.8 demonstrates that in the Asian markets, Australia faces the lowest unit maritime transportation costs followed by South Africa. The U.S., on the other hand, faces higher maritime transportation costs. In the Western European market, the U.S. has the lowest unit maritime transportation costs followed by South Africa (see Figure 2.9). The competition picture that emerges, then, is that of South Africa being the main link between these two major markets. It competes with Australia in the Asian markets and with the United States in the Western European markets. In this model, therefore, both Australia and the United States individually assume the role of marginal supplier in the Western Europe and Asian markets respectively while South Africa is a significant supplier to both markets. Maritime transportation costs have been on the decline as depicted in figures 2.8 and 2.9. The seaborne trade in major dry bulk commodities such as coal, metal concentrates and grains has seen a shift towards the use of larger sea going vessels in the size ranges exceeding 100 000 metric tons as these are more profitable to operate (Coal Information, 2001, p I.160).

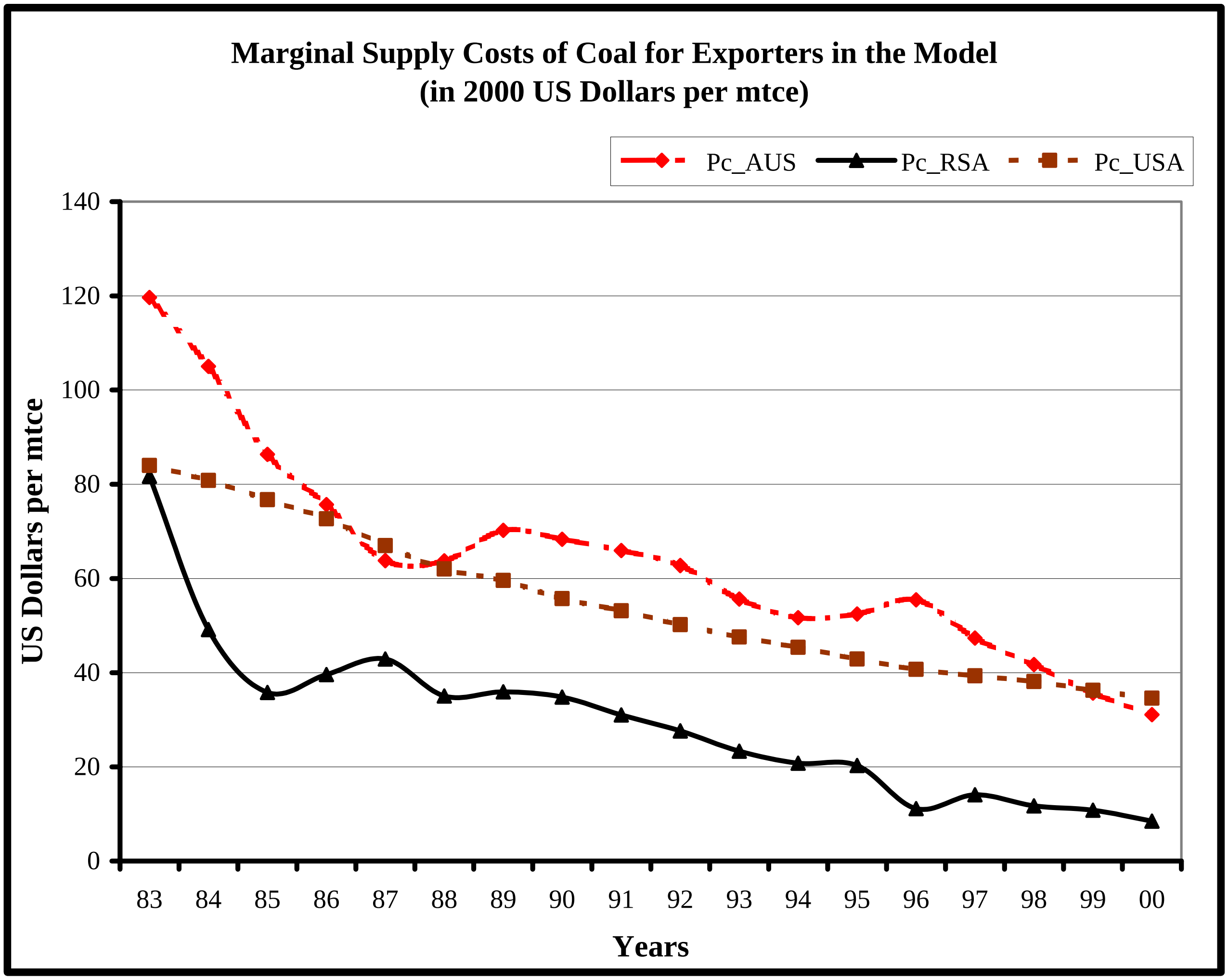

Figure 2.9 **Trends in Marginal Supply Costs for Exporters in the Model**

Source: Based on authors computation based on data from Coal Information 1990, 1996 and 2001, and Energy Prices and Taxes, Quarterly Statistics, Second Quarter 2001.
Note: Australia is f.o.b. price.

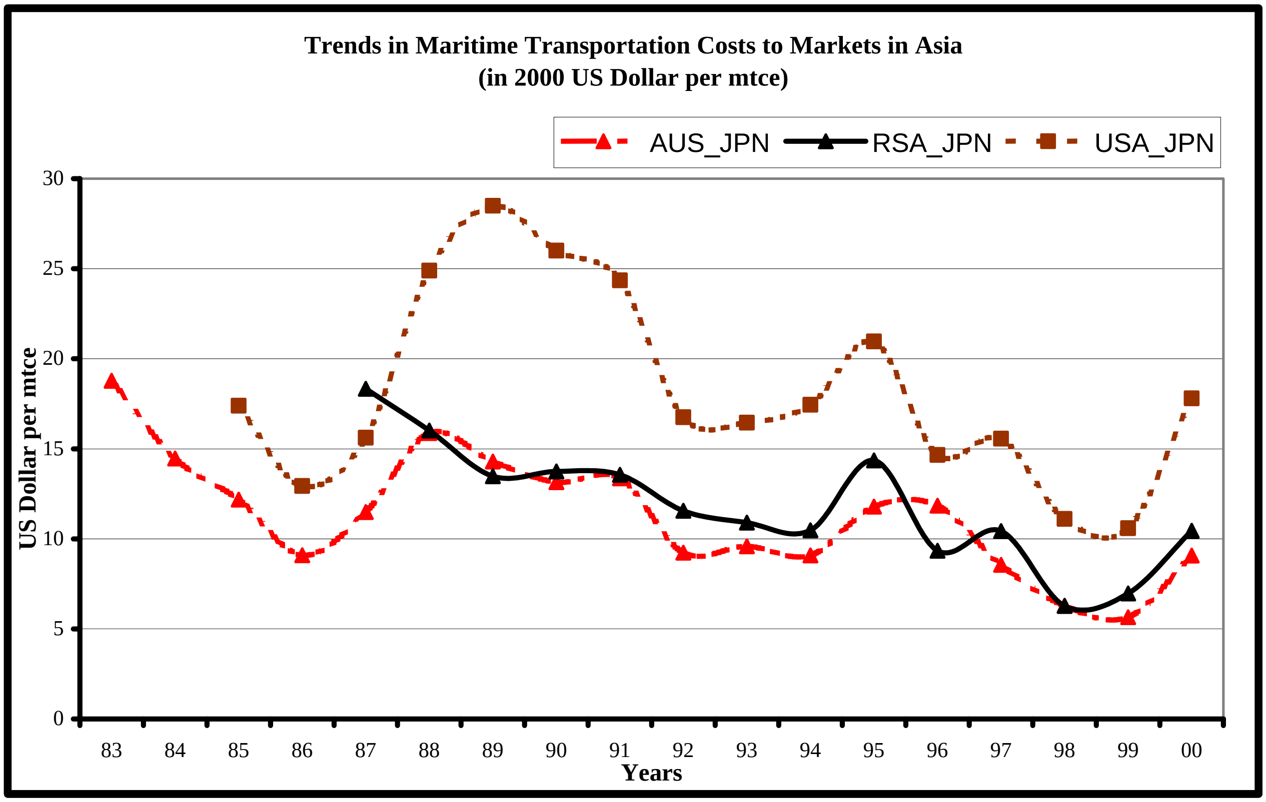

Figure 2.10 **Trends in Maritime Transportation Costs for Selected Exporters to Markets in Asia**

Source: Based on authors computation based on data from Coal Trade Freight Report, Rodriguez Sons Co. as cited in *International Coal Review Monthly*.

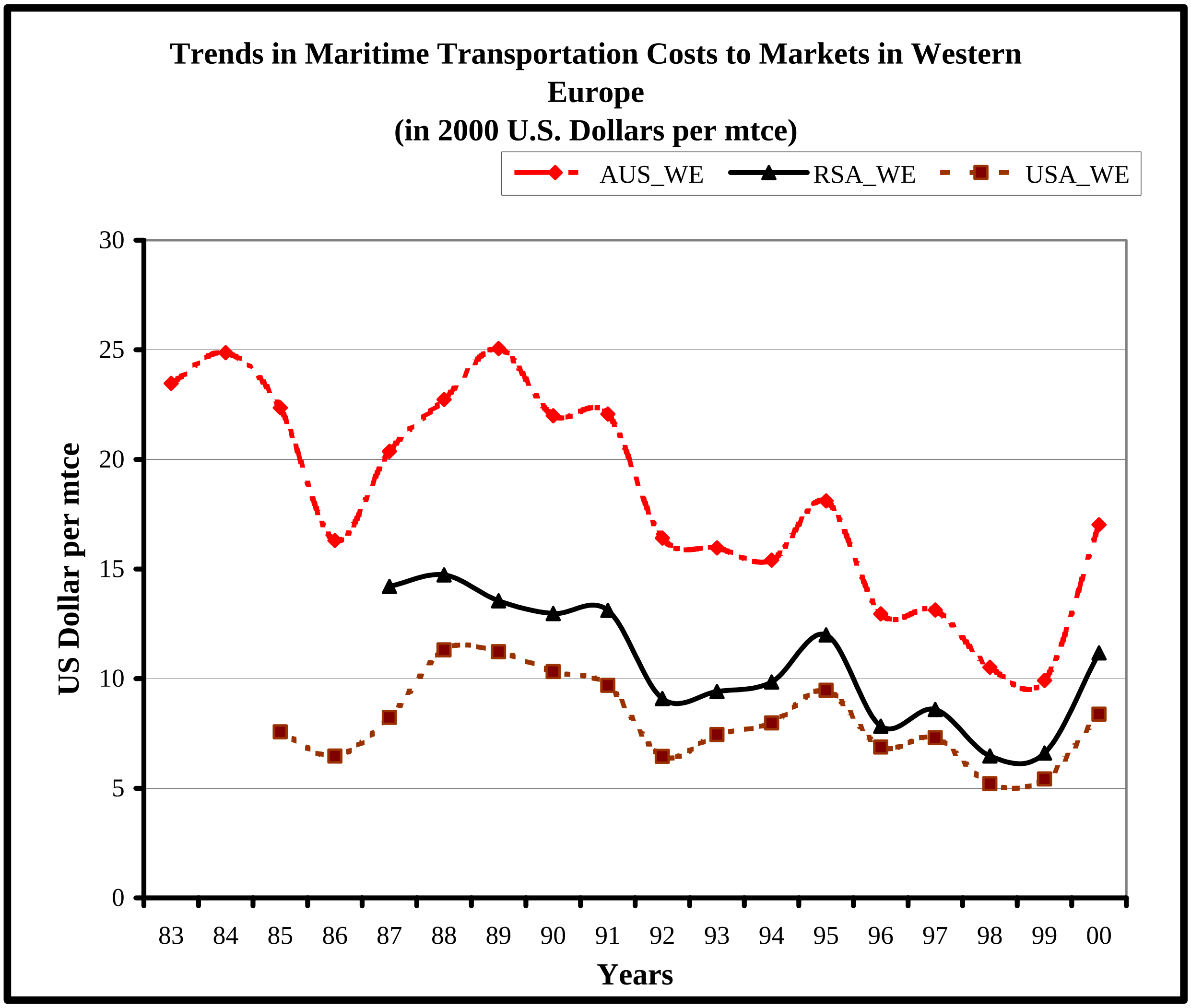

Figure 2.11 Trends in Maritime Transportation Costs for Selected Exporters to Markets in Western Europe

Source: Based on authors computation based on data from Coal Trade Freight Report, Rodriguez Sons Co. as cited in *International Coal Review Monthly.*

2.5 Role of Botswana

An analysis of steam coal exports from the United States and Australia to those markets in which these countries face high maritime transportation costs provides an indication of the annual tonnages that these countries control in their role as marginal suppliers to these markets. In the first half of the 1990s, Australia's steam coal exports to markets in Western Europe averaged some 8.776 million metric tons. These fell in the second half of the decade to 6.952 million metric tons. In the Asian markets, steam coal exports from the United States rose from an average of 3.445 million metric tons in the first half of the 1990s to 4.080 million metric tons in the second half. The total tonnage controlled by Australia and the United States in those markets in which they play the role of marginal supplier, Western Europe and Asia, respectively, provides an indication of the tonnage that could be won away by a new entrant facing an overall cost advantage in these markets over these marginal suppliers. The average tonnage controlled by these marginal suppliers in the second half of the 1990s was some 11.0 million metric tons.

The regional export coal supply in Southern Africa is concentrated in the Republic of South Africa (RSA). Most of these collieries exploit coals on the Witbank coalfield in the Mpumalanga province. There is one large-scale colliery, Grootgeluk, in the Northern province near Ellisras, and therefore also in the general vicinity of a would be mine on the Mmamabula coalfield, that produces coal for both the domestic and export markets. South Africa's steam coal is transported by rail from Witbank to the Indian Ocean sea port of Richards Bay, where a private coal handling export terminal by the same name and is operated by the coal exporting companies, provides access to the only high volume dedicated coal handling terminal in the region. Botswana's role is further discussed in the following two sub-sections that emphasize the country's geographical location relative to the world's major steam coal markets and the improved conditions for regional cooperation citing a specific framework for regional cooperation on transport infrastructure and related issues.

2.5.1 Taking Advantage of Botswana's Geographical Location

The landlocked nature of Botswana has in the past meant that rail transportation costs to seaports rendered high volume low value exports such as coal unprofitable. When one views the geographical location of Botswana in relation to the main supply and demand regions for seaborne steam coal trade, it then becomes apparent that the country is almost equi-distant between the two major world markets for seaborne steam coal, Western Europe and Asia. This presents possibilities for the country to be cost competitive in these markets. For instance, Figures 2.8 and 2.9 respectively show that in a three country or region competition, the Southern Africa region would be in competition with Australia in the Asian market and with the United States in the Western European market.

The question then is whether or not steam coal from Botswana can gain market share from the United States on the Asian markets and from Australia in the Western European market. Figure 2.7 also shows that the supply price for steam coal in Southern Africa is the lowest among the three countries selected for this study. Figure 2.6 shows that railway costs have been declining in real terms and in some regional markets, and as discussed under the section on rail transportation above, hauling distances would be comparable to those faced by Botswana's coal exports. Botswana should seek ways by which it would take advantage of its geographical location relative to the world's main steam coal markets and explore further possibilities for gaining market share away from those countries / regions farthest away from these markets.

2.5.2 Framework for Regional Cooperation on Transport Infrastructure

There have been substantial changes in the Southern Africa region and these justify a renewed interest by policy makers in Botswana to explore the options that can be pursued to move towards exploiting the country's coal deposits. Some of these changes are in the area of political stability and the increased regional cooperation that has come about with a democratically elected government in South Africa in 1994. A framework for regional cooperation in the area of transport has been devised and formalized under the regional economic body, the Southern African Development Community's (SADC) Protocol on Transport, Communications and Meteorology, that was signed by the Heads of State and government of the SADC countries in August 1996. Some of the transport specific issues that the protocol deals with are found in Articles 3.3 and 3.5, dealing with transport infrastructure and institutional framework respectively. The intention is to have cross-border corridor planning committees drawn from both the government and private sectors and who will be tasked with, among other things, the identification of regional corridors and their prioritization for integrated development (SADC, 1996). In view of these regional efforts at integration, there is justification for simulating rail transport routes across regional borders to sea ports in the region as will be done in this study. The simulation of a railway line to link Mmamabula with the port of Walvis Bay in Namibia could be viewed in the regional context as satisfying the need for faster delivery times for steam coal and other products to the European market. There would also be possibilities for shorter access routes to the ocean through links from Mmamabula to the Witbank-Maputo railway line for the high steam coal demand growth markets in the Asia Pacific countries.

There have since been regional spatial development initiatives on infrastructure projects along these defined concepts. Some examples include an agreement between the governments of

South Africa and Mozambique under the Maputo Development Corridor over the rehabilitation and management of the Ressano Garcia railway line between Witbank and the ports of Matola and Maputo[5]. The Ressano Garcia Railway Company would be majority owned by a consortium led by Spoornet of South Africa (51%), the Mozambique railway company, CFM (33%) and regional interests including Mozambique (16%)[6]. There has also been close cooperation between regional railway lines such as that between Botswana Railways and Spoornet of South Africa involving the operation of a dry port in Botswana's capital, Gaborone. Proposals that have been put forward for the development of the ports of Maputo and Matola, under the Maputo Corridor Company, would require an ownership structure that includes the governments of South Africa, Botswana, South Africa, Swaziland, Mozambique and Zimbabwe on the one hand and a private sector investor on the other. Such an export port would offer an alternative to coal mines located in Botswana and even South Africa itself as the existing export facilities at the Richard's Bay Coal Terminal are privately owned and operated by the existing consortium of South African coal exporting companies. Other developments in the regional rail transport sector show SADC governments' policy of encouragement of private sector participation in the transportation infrastructure projects.[7]

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[5] Maputo Development Corridor, Update of Key Investment Opportunities, June 1996. Retrieved on January 27th, 2002, from the South Africa Department of Transport: http://www.transport.gov.za/library/index.html

[6] Additional investments in the coal terminal at Matola would increase port capacity to more than 4.3 million tons. As with the coal link line from Witbank to the Richard's Bay Coal Terminal, the section of the Ressano Garcia line between Komatipoort and Maputo is considered for electrification. Retrieved on January 28th, 2002 from: http://www.businessday.co.za/bday/content/direct/1,3523,1004048-6078-0,00.html.

[7] The Beitbridge Bulawayo Railway Company was awarded a concession by the Zimbabwean government to rehabilitate and operate the 350 km of railway line from, Beitbridge, South Africa to Bulawayo, Zimbabwe. The project took 16 moths and cost US $85 million. The President of Zimbabwe commissioned the line on September 1, 1999. The company has been given other concessions to operate more railway lines in Zimbabwe. This project is in line with the SADC protocol as cited here as "… increasing private sector involvement in railways investment with a view to improving railway work and service standards." Retrieved on January 28th, 2002 from the New Limpopo Projects Investment: http://nlpi.main-server.co.uk/bot_projects.html

It is therefore helpful that there is some level of success with regional cooperation and it may be that this success will help sustain the political will for an integrated regional infrastructure for transportation.

2.6 Conclusion

This chapter reviewed the seaborne international steam coal trade, placing emphasis on the trends in: supply and demand, rail transportation costs, maritime transportation costs, and marginal supply costs for steam coal. We then went further to define the role for Botswana, by recognizing the geographic advantage that the country enjoys relative to the United States and Australia in the Asian and Western European steam coal markets respectively. The prospects for Botswana as a major steam coal producer also rely on regional cooperation in matters of regional infrastructure provision. Here too, we demonstrated that regional cooperation now exists as may be read from other regional cooperation initiatives such as those of the Southern African Power Pool, that between the rail authority of South Africa, Spoornet, and Mozambique, to operate the rail link from Witbank to Maputo, and more generally, those provisions of the SADC protocol on Transport, Communications and Meteorology, which recognize the need to approach infrastructure development on a regional rather than country basis.

CHAPTER 3

COAL TRADE MODELS IN RETROSPECT

3.1 Introduction

This chapter reviews the literature on spatial price equilibrium models that have been applied to model the trade in coal. The types of models reviewed are discussed under section 3.2, literature review, and under specific headings of: 1) linear programming, 2) non-linear programming, 3) the variational inequality problem and 4) mixed integer programming. Subsection 3.2.2, on non-linear programming, provides a detailed theoretical treatment of the spatial, temporal and price allocation (STPA) model of Samuelson (1952) and Takayama and Judge (1971). The variational inequality problem is presented with the aim of emphasizing the link between this type of problem with the STPA model under given conditions. In subsection 3.2.4, mixed integer programming, the approach is to define the conditions that justify the use of this model type and therefore any optimization model that is geared towards project selection as opposed to capital budgeting methods used in project evaluation. The chapter then proceeds to provide examples of the applications of these models under section 3.3 and finally, section 3.4 concludes this chapter.

3.2 Literature Review

Spatial price equilibrium models have found plenty of application in models to explain the pattern in both the regional and international trade in mineral, energy and agricultural commodities (see van den Bergh, Nijkamp and Rietveld, 1995, Labys, Takayama and Uri, 1991, Labys and Yang, 1991, for a review of mineral and energy models; and Koo and Larson (1985) for a review of agriculture models). This review covers linear programming, quadratic programming, which is a type of non-linear programming, variational inequality and mixed integer programming, which can be linear or non-linear. The complexity of these models increases from the linear to the mixed integer type models.

3.2.1 Linear Programming

The logical starting point for spatial price equilibrium models is the transport problem, which, in its primal form, is concerned with minimizing the total cost of transporting a commodity between supply and demand regions subject to physical supply and demand constraints and also to non-negativity constraints on all variables. The linear programming model has both a linear objective function and linear constraints. In such a model, the following variables are given: 1) unit transportation costs between each possible pair of supply and demand, c_{ij}, 2) available quantities in supply regions, q_i, and 3) quantity demanded in the market regions, q_j. The model determines the optimal quantities shipped between supply and demand regions, q_{ij}.

$$\text{Min } TC = \sum_{i=1}^{n} \sum_{j=1}^{m} c_{ij} q_{ij} \tag{3.0}$$

$$\text{s.t.} \quad -\sum_{j=1}^{m} q_{ij} \geq -q_i \quad \text{for all } i \text{ in } n; \tag{3.1}$$

$$\sum_{i=1}^{n} q_{ij} \geq q_j \quad \text{for all } j \text{ in } m; \tag{3.2}$$

The constraint condition in equation 3.1 is material availability constraint and it ensures that total shipments cannot exceed available supply for a given source *i*. At the destination points, total inflows should at least be greater than demand. This is expressed through constraint condition

3.2, which reads that demand in region *j* must be less than or equal to total quantities shipped from all regions in *i* or that there should be no shortage at the destination points.

The dual of the cost minimizing transportation problem is the maximization of value added between supply and demand markets. In this formulation, the given variables are: 1) prices in the supply and demand regions, 2) available quantities in supply regions and 3) quantity demanded in the market regions. In either of these formulations, the locational price equilibrium condition demands that the price differential between the supply and demand regions should be at least greater than or equal to the unit transportation cost between these regions for there to be a positive shipment between such pair of supply and demand regions. The model permits the flow of trade from the supply to the demand region for as long as demand exists. In linear programming the sum of supply from all the sources must be exactly equal to demand.

3.2.2 Nonlinear Programming

The nonlinear programming model discussed here is the quadratic programming model. The credit for defining the excess supply in a region as a linear function of the difference between the equilibrium price with trade and that under autarky is attributed to Enke (1951). At this time, it was only possible to solve spatial price equilibrium models consisting of a maximum of three regions by first determining the role of the region with the median autarky price. The resulting trade possibilities set was either for one export and two import regions or the reverse. Enke devised a solution for the n-region problem by applying an electrical analogue where each circuit represented a region while the voltage and current represented pre-trade equilibrium prices and quantities respectively. When measured across these circuits, the voltage and current then represented equilibrium price and quantities with trade.

In his 1952 paper, Samuelson applied Enke’s representation of the excess supply function to the classic Koopmans-Hitchcock transportation problem, which is a linear programming problem such as the one described above. He defined the social pay-off for a region as the area under its excess demand function, and as excess demand is simply the negative of excess supply, it could also be defined as the negative of the area under the excess supply function. He went on to define the net social pay-off as the sum of the producer surplus in the exporting region plus the consumer surplus in the importing region less the fixed per unit transportation costs between the regions and showed that the original cost minimization problem could be re-stated, equivalently, as that of maximizing net social pay-off. This required the formulation of a quadratic programming model with a nonlinear objective function and linear constraints. The objective function is shown below in the quantity formulation, wherein the inverse demand and supply functions are expressed as a function of demand and supply quantities respectively.

$$\text{Max Net Social Payoff} = \sum_{j=1}^{m}\int_{0}^{q_j} P_j(q_j)dq_j - \sum_{i=1}^{n}\int_{0}^{q_i} P_i(q_i)dq_i - \sum_{i=1}^{n}\sum_{j=1}^{m} c_{ij}q_{ij} \qquad (3.3)$$

$$\text{s.t.} \quad -\sum_{j=1}^{m} q_{ij} \geq q_i \quad \text{for all } i \text{ in } n; \qquad (3.4)$$

$$\sum_{i=1}^{n} q_{ij} \geq q_j \quad \text{for all } j \text{ in } m; \qquad (3.5)$$

Samuelson did not advance a formal solution to this maximization problem apart from that by trial and error involving different values of quantities traded that lead to a maximization of the net social pay-off (Samuelson 1952, p292).

The modern formulation of the spatial price equilibrium model, as a maximization problem, is attributed to Samuelson (see Takayama and Judge, 1964, Florian and Los, 1982, Nagurney, 1987 and Labys and Yang, 1991). Takayama and Judge (1964) converted the Samuelson-Enke problem into a quadratic programming problem by making assumptions of linear regional supply and demand functions. They went further to devise a simplex algorithm for the solution of this quadratic problem and then proved the existence, uniqueness and regularity of the optimal solution for this problem. The significance of these proofs for uniqueness, existence and regularity means that the Kuhn-Tucker conditions are both necessary and sufficient conditions for the optimization problem. This problem was improved to include the temporal dimension with examples of short-term optimization problems in which inventories could be carried forward to future periods. This became known as the spatial, temporal and price allocation model or STPA (Takayama and Judge, 1971). The advantage of the quadratic model is its ability to endogenously solve for the optimum prices, supply and demand quantities and optimal trade flows between supply and demand regions.

In their 1971 book, Takayama and Judge give further theoretical treatment of the quadratic programming model and demonstrate, among other things, the equivalence of the Kuhn-Tucker conditions to those for a general space-less equilibrium under microeconomic theory. These conditions require, for instance, that: (1) the price differential between the importing and exporting regions be equal to the interregional unit transportation costs; (2) there be a unique regional price; (3) there be no excess demand in any region, and (4) a uniform per unit transportation costs along a transportation leg (Takayama and Judge, 1971, p28). The equivalence of the spatial equilibrium conditions to those for a space-less economy provides the assurance that under the assumption of perfect competition, these will also be Pareto efficient. This book lays the theoretical foundation for spatial price equilibrium models beginning with the simple and static single commodity model to inter-temporal multi-commodity models under assumptions that mix both fixed and linear demand and supply functions. In addition, it also develops theoretical treatment of different market conditions and trade policy instruments such as import tariffs, export subsidies, import and export quotas, and ad valorem tariffs. There has been some empirical application of some of these theoretical models and those from the energy and minerals sectors will be discussed under section 3.4 below.

3.2.3 Variational Inequality Problem

We begin by re-stating the mathematical formulation of the STPA model in equation 3.3 as that for a cost minimization problem and then show how this can be re-cast as a variational inequality problem. We consider a bipartite spatial price equilibrium model with the following: supply price, $p_i = p_i(s_i), i = 1, 2, \dots m$; demand price, $p_j = p_j(d_j), j = 1, 2, ...n; c_{ij}$ = fixed unit cost for transporting a quantity, q_{ij} between an origin-destination pair; p_{i} is a continuous and increasing monotonic function of s_i, while p_{j}, is a continuous and decreasing function of d_j and with non-negativity conditions on all variables. The optimization form of this problem is then given by:

$$\min f(s_i, q_{ij}, d_j) = \sum_i \int_0^{s_i} p_i(x)dx + \sum_i \sum_j c_{ij} q_{ij} - \sum_j \int_0^{d_j} p_j(y)dy \tag{3.6}$$

$$\text{s.t.} \qquad \sum_i q_{ij} \le s_i \tag{3.7}$$

$$\sum_j q_{ij} \ge d_j \tag{3.8}$$

The constraint conditions for this minimization problem are identical to those for the maximization problem and only repeated here for clarity. The Kuhn-Tucker conditions for this problem are easily derived and represent the spatial price equilibrium conditions for this problem. These conditions are:

$$pi(si) + cij = 0 \quad \text{if } q_{ij} > 0 \quad \text{and} \quad pi(si) + cij \geq 0 \quad \text{if } q_{ij} = 0 \tag{3.9}$$

$$\sum_i q_{ij} = s_i \quad \text{and} \quad \sum_j q_{ij} = d_j \tag{3.10}$$

The approach by Florian and Los (1982) took advantage of the equilibrium conditions in equation 3.10, which define both the optimal supply and demand quantities by substituting for these expressions into the objective function and then solving the resulting modified objective function subject only to non-negativity conditions on the quantity flow, q_{ij}. The authors employed the Frank-Wolfe algorithm, which is a linear approximation method for the solution of this convex programming problem. The algorithm computes the descent path and applies a minimization procedure to select the step length for the next iteration.

The equivalence of the spatial price equilibrium problem to both a variational inequality and a nonlinear complementarity problem is attributed separately to Florian and Los (1982) and Friesz, Harker and Tobin (1981) (see Florian and Los, 1982, Friesz, Harker and Tobin, 1984, Nagurney, 1987). The following general definitions of the variational inequality and nonlinear complementarity problems are taken from Friesz, Harker and Tobin (1984, p483) and Nagurney (1999, p6). A variational inequality, VI (F, K) is defined as:

$$\text{Find } x^* \in K \text{ such that } F(x^*)^T.(x-x^*) \geq 0 \text{ A x E K} \tag{3.11}$$

where $F(x) = \nabla f$ and f is continuously differentiable with K a closed convex set, while x is a column vector of supply, quantity flows and demand.

The solution to this variational inequality problem also satisfies the spatial equilibrium conditions stated in equations 3.9 and 3.11 above. In the special case where the supply, transportation cost and demand functions are separable, the objective function has a symmetric Jacobian that is also positive definite. This collapses the variational inequality problem into that of the standard STPA model shown above in equation 3.6. We can further define the variational inequality in terms of the STPA variables in equation 3.6 above as follows:

Let $x \equiv (s, q, d) \in R^{m+mn+n}$ (3.12)

and $F(x) = \nabla f(x)$, then

$F(x)^T \equiv (p_i(s_i), c_{ij}, p_j(d_j))$ maps R^{m+mn+n} into itself.

Theorem 3.2 (Nagurney, 1999, p96) states that $F(x)$ is monotone, strictly monotone or strongly monotone if and only if $p_i(s_i)$, c_{ij}, $p_j(d_j)$ are each monotone, strictly monotone or strongly monotone in s_i, q_{ij}, and d_j respectively. The existence of a unique optimal vector x is guaranteed if these strong monotonicity conditions are met. The above optimization can then be transformed into the following variational inequality problem (see Nagurney, 1999, p99):

Find (s^*, q^*, d^*) in K

such that $(p(s^*).(s-s^*)+c.(q-q^*)-p(d^*).(d-d^*) \geq 0 \quad \forall (s, q, d) \in K$ (3.13)

The spatial price equilibrium optimization problem can also be formulated as non-linear complementarity, NCP, as follows (see Friesz, Harker and Tobin (1984, p483) and Nagurney, 1999, p9).

Find $x^* \geq 0$

such that $F(x^*)^T. x^* = 0$, $F(x) \geq 0$, and where F maps R^n into R^n (3.14)

The case for a linear complementarity problem is obtained when F(x) produces an affine mapping, which is defined below:

$F(x) = Mx + b$ with $M = nxn$ and $b = nx1$ (3.15)

There have been other demonstrations of the relationship between linear, quadratic, linear complementarity, nonlinear complementarity and the variational inequality problems (see Takayama and Hashimoto 1989, Yang and Labys, 1989, Cottle, Pang and Stone, 1992 and Nagurney, 1987 and 1999). These works demonstrate that the quadratic programming problem is a subset of the linear complementarity problem, which in turn is a subset of the nonlinear complementarity and which, similarly, is a subset of the variational inequality problem. Cottle, Pang and Stone (1992) extensively cover solution algorithms for the linear and nonlinear complementarity problem. In general these algorithms rely on pivoting techniques.

There is a special relationship between the extremal formulation of the Samuelson (1952) and Takayama and Judge (1971) spatial price equilibrium model and linear complementarity programming. Where the supply, transportation and demand functions are separable, the Jacobians of supply, transportation costs and demand are symmetric and the Kuhn-Tucker conditions are equivalent to the linear complementarity conditions (Cottle, Pang and Stone, 1992, Florian and Los, 1982 and Takayama and Judge, 1971). The symmetry condition is met only in cases where there are no market interactions in supply, transportation and demand. In reality, other models such as the Stackelberg and Nash-Cournot competition may explain the market behavior regarding supply and demand while transportation costs may depend on quantity flows between other supply-demand pairs and may also take into consideration the disutility from congestion (see Nagurney and Dong, 2002, Miller, Tobin, and Friesz, 1991, Nagurney, 1987, and Florian and Los, 1982). When the symmetry condition is not met, there is no equivalent optimization of the problem in the standard form of the STPA model. Such a condition requires the use of variational inequality algorithms to solve the spatial price equilibrium model.

The algorithms for variational inequality problems are intended to convert the problem into a quadratic programming problem with separable supply, transportation cost and demand functions. Nagurney (1987 and 1999) provides descriptions for the linearization methods, namely, the Gauss-Seidel linearization and the projection methods, and the equilibriation algorithms for solution of the linearized or standard quadratic programming problem of Samuelson, Takayama and Judge. The Gauss-Seidel approach is a diagonalization method that can be used to decompose the problem by supply, demand and supply and demand pairs to arrive at the quadratic programming problem (Nagurney, 1987). The projection method also re-defines supply, transportation costs and demand functions such that interactions with other supply-demand pairs are eliminated. In both cases, the resulting problem results in symmetric and positive definite Jacobians for these components, and thus the problem lends itself to solution by quadratic programming solution algorithms such as the Frank-Wolfe algorithm. The author concludes that the combination of the Gauss-Seidel linearization with the equilibration algorithms far out-perform the Frank-Wolfe algorithm in computing time.

Other solution algorithms include the reduced gradient algorithm that improves on that of Frank-Wolfe. This algorithm was developed into the well-known MINOS solver by Murtaugh and Saunders (Friesz, Harker and Tobin, 1984). Even at its early stages, the MINOS algorithm, which was designed for the solution of large and non-linear programming problems with linear and sparse constraints, was quite impressive (Rowse, 1981 p67). Drissi-Kaitouni and Florian (1991) propose a Gauss-Seidel-Newton projection algorithm combined with some restrictions and apply it to the solution of the standard spatial price equilibrium problem. Recent work in spatial price equilibrium modeling is increasingly attempting to make realistic assumptions about the market behavior wherein the interactions that exist between supply and demand markets and the demand for transportation also take into account both costs and delivery times (Nagurney and Dong, 2002 and Liu and Boyce, 2002). Some of the latest applications of variational inequality can be found in Nagurney, Ding and Dong (2002), where the authors extend the work in Nagurney and Dong (2002) by analyzing the dynamic adjustment to quantities shipped and demand prices. The authors propose a solution algorithm that is based on the Euler discretization method of the continuous time dynamics (p92) to solve the variational inequality problem. The solution algorithms are coded in the FORTRAN programming language and as yet no commercial solution packages are available.

3.2.4 Mixed Integer Programming

The question to ask, naturally, is how to decide on whether to use conventional financial and economic decision methods that rely on single project specific profitability criteria such as net present value and discounted cash flow rate of return on the one hand or a project selection method such as mixed integer programming on the other. Kendrick and Stoutjesdijk (1978) offer as a guide that, where a project exhibits economies of scale, there exists a simultaneous relationship between price and quantity as the scale of operations affects costs and is itself affected by demand, thus linking the marginal costs to the level of demand. This further links project profitability to the scale of operations and makes conventional project evaluation inappropriate in such a case.

A detailed description of the mixed integer programming method is found in Kendrick and Stoutjesdijk (1978) where the authors present it as a tool for selecting industrial projects (project selection model) that show economies of scale and have sectoral interdependencies. Other descriptions of this same model are found in Labys (1999), Labys and Yang (1991) and Labys, Takayama and Uri (1989). The model is multi-period, multi-product, and made up of the following components: (1) the transport problem, (2) production costs, (3) a process model and (4) an investment model. The objective function is to minimize discounted total costs, now defined to include all costs, such as those of production, transportation of all inputs and outputs, annualized costs of capital, and operation and maintenance on new units of equipment, over a given planning horizon and for a desired level of the discount rate. The constraints are similar to those for spatial equilibrium models but now augmented with those for material balance at the process level, intermediate product stage, and a binary variable for whether or not an investment in additional or new capacity is made. The model also deals with both intermediate and final products with the latter sold both locally and in export markets. The various components of the model lead to its ability to determine optimal values for location of plant, size of plant, time phasing of new or additional capacity, process technology to be used, and product mix. The production process is disaggregated to the process level, which requires that input-output coefficients for all processes and over all time periods be known in advance. The data requirements for the full project selection model tends to make it difficult to apply in regions where there may be a paucity of data (Kendrick and Stoutjesdijk, 1978, p80).

3.3 Model Applications

The discussion begins with linear programming models of coal supply, transportation and demand in the United States and then progresses to models used to study the international trade in steam coal and, finally, provides examples of model applications for mixed integer programming. There has been a great interest in modeling the energy-economy interactions in the United States as is evident from models such as the Federal Energy Administration’s Project Independent Evaluation System (PIES) (see MIT Energy Laboratory Policy Study Group, 1975 and Hausmann, 1975). PIES is a large-scale model with sub-models for fuel specific supply, demand and transportation. Gabriel, Kydes and Whitman (1999) provide a brief chronological development of this large- scale model into the Intermediate Future Forecasting System (IFFS) and finally into the current National Energy Modeling System (NEMS). Instead of reviewing these large-scale energy economy models, only the development of the coal sub-model in its use to forecast U.S. supply, demand, and the distribution of the coal trade will be reviewed here. The development of models for supply, transportation and demand for coal in the United States has been dominated by projects funded by agencies of the U.S. government, most notably, the Energy Information Administration. Some of these models are: (1) the National Coal Model (EIA, 1983), (2) Coal Supply and Transportation Model (EIA, 1983), (3) Argonne Coal Market (ACM) model (Macal, 1979), (4) The International Coal Trade Model (EIA, 1982) and (5) the World Steam Coal Trade model by Kolstad, Abbey and Bivins (1982). Interested readers may consult the references provided for details on these models. There have also been independent studies on both the regional and international steam coal trade such as those by Labys and Yang (1980), Zimmerman (1981), and, Senf and Fruin (1986). A review of the application of spatial price equilibrium models in the mineral and energy sectors can be found in Labys, Takayama and Uri (1989), while the use of spatial equilibrium models in the 1990's can be found in and Labys and Yang (1991) and van den Burgh, Nijkamp and Rietveld (1995).

One of the major shortcomings in the coal supply and demand module in the PIES model was that the production mix from the U.S. supply regions was set based on professional judgment as opposed to a cost minimization criterion as would be the case in a linear programming problem. The resulting regional supply curves were step functions reflecting the regional minimum acceptable selling price (MASP) for a mine life of twenty years and a discount rate of 15% (Hausmann, 1975, p27). There was therefore need for a model that would endogenize the supply function. One such model is that by Zimmerman (1981), which is a linear programming model that minimizes the delivered cost of coal to end-users in the electric utility and non-electric user industries. The model has the usual components of production, transportation and demand. The production component determines long run marginal costs for coal supply for both underground and surface mines. These costs are derived from regressions of costs on the production rate and geological properties of the coal (coal thickness and depth of overburden) and represent the minimum price for bringing such coal reserves into production. The coal reserves are then classified according to geological characteristics and as costs are defined in terms of these, a cumulative cost curve is constructed. This approach has not found widespread use in models at the EIA where the coal supply model used is similar to that used in the National Coal Model (Wood and Mason, 1982).

The demand for coal is a derived demand arising out of that for electricity. The method of estimation is that used in the regionalized energy model (REM) by Baughman, Joskow and Kamat (Chapter 4, 1979). The approach uses a two-step procedure in which energy consumption in both the residential-commercial and industrial sectors is first estimated using a flow-adjustment model. A fuel choice demand model is then used to determine the fuel split among gas, coal and natural gas to meet this energy demand.   This latter estimation of fuel proportions is achieved through a multinomial logit model.

The transportation cost equation for this model expresses rate per ton as a linear function of hauling distance, quantity hauled, difference between the price of natural gas and the f.o.b. coal price, loading plus unloading time and a dummy variable for the eastern region. Elements of this model appear in some of the EIA models, which are described next.

The National Coal Model came out in 1983 and it is a linear programming model that connects the coal supply and the electric utility industries. The model is long term and static. The objective function minimizes the total costs, defined to include, costs of coal production, transportation, and electricity generation and distribution. The f.o.b., mine gate, price of coal is estimated from the resource allocation and mine costing (RAMC) model. This essentially assigns long run marginal cost of production over a given life of mine and for existing coal reserves that are not committed and then creates a stepwise supply function for a given case year. This stepwise function is linearized to obtain a marginal supply function for an increment in output as opposed to the cumulative quantity approach used by Zimmerman. The linearization avoids lumpy additions that exceed the typical mine size (Macal, 1979). A further economic reasoning is that the price would have to be at least greater than these long run marginal costs for these reserves to be exploited. This price is then the minimum acceptable selling price, MASP, as previously defined. The exploitation of these reserves then proceeds sequentially starting with those with the lowest cost of production.

The exogenous variables to the National Coal Model are transportation rates and coal demands. The RAMC model determines the MASP for all regions whose coals become part of the solution depending on their satisfaction of the objective function of cost minimization. The 1983 Coal Supply and Transportation Model extends this model into a nonlinear programming model. The extension is in the formulation of transport costs as a quadratic function of the coal quantity traded.

The National Coal Model and the Coal Supply and Transportation Model were used to answer “what if” questions on actions that impact on the supply and demand for coal in the United States. These actions may be: changing government regulation, changing structure of the coal industry, and technological improvements, and any other actions that affect the demand for electricity, and hence that of coal. The models database has some 40 coal types, 5 heat content levels, 8 sulfur content levels, 31 supply regions, 44 demand regions, 9 mine types with 5 and 4 sub-classes for open pit and underground mining respectively and reserve information (National Coal Model, 1982).

Some applications of nonlinear programming models in the U.S. coal industry are the Argonne Coal Market model by Macal (1979) and the quadratic model of the Appalachian steam coal trade by Labys and Yang (1980). The Argonne Coal Market model differs from those by Zimmerman and the National Coal Model in that it has a quadratic objective function. This is in the supply function, which is expressed as a linear function of production. The objective function minimizes the cost of production, transportation and emission reduction. The demand is determined exogenously from the regional electricity model, just as in the National Coal Model and that by Zimmerman. The model was used to test the impact of the 1977 Clean Air Act Amendment’s best available control technology on the interregional coal trade. At the time the target reduction levels had not yet been set, so this model evaluated the impact of several scenarios regarding these and demonstrated that in the long run, there was to be a shift in coal supply that favored sources in the west central region of the United States.

In their application of quadratic programming models for the regional trade in coal, Labys and Yang (1980) used this approach to model the Appalachian steam coal trade and concluded that the optimal trade pattern was in line with what prevailed in reality. They also found that their regional quadratic programming model could be used as policy tool to determine the optimal levels of policy intervention, for instance, taxation, and the impact of exogenous shocks such as transportation cost increases, on the likely magnitude of the welfare changes. The quadratic programming model leads readily to the determination of the components of this welfare change in terms of consumer (electric utilities) and producer (coal producers) surpluses.

At the international coal trade level, there has been application of both linear and nonlinear programming models. The International Coal Trade Model's (ICTM) spatial price equilibrating model is described in a publication by the U.S. Department of Energy (September, 1982) as a medium to long-term multi-product (more than one coal type) quadratic programming model that was used to project the likely distribution of the international trade in coal for three coal types (premium or coking coal, low sulfur steam and high sulfur steam). The model relies on sub-models that produce projections about regional supply, sea transportation and demand, and then applies the spatial price-equilibrating sub-model based on both elastic demand and supply relationships for the OECD countries and inelastic supply and demands in other markets for a projected base year to obtain a solution.

The ICTM model has 18 supply and 6 demand regions with nodes placed at exit and entry ports for the coal respectively for these regions. It therefore deals only with the sea borne spatial distribution of the international coal trade. The model could be used to answer comparative static questions on the likely magnitude and direction of trade that would result from regional policies that affect demand, factor input costs in the coal supply regions or costs for both land and sea transportation. It requires detailed supply functions from engineering cost estimates and where these are not available, fixed estimates of the likely supply are estimated outside the model. The demand component is treated a little differently from the usual econometric demand function for each region and instead, a regional condensed import demand equation is used[8]. Two models released at about the same time as the ICTM and both dealing

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[8] See Description of the International Coal Trade Model (September 1982). The import coal demand for the OECD region is given by the following equation (equation 1, p29):

with international trade in steam coal are those by Dutton (July, 1982) and Kolstad, Abbey and Bivins (January, 1983).

The model by Dutton, which is named an Allocation Model, maximizes net social pay-off and is as defined below (see Dutton, 1982, p 88):

$$\text{Max } W_t = -\sum_{i=1}^{n}\{S_i(X_{it-1} + \sum_{T=t-1}^{t} X_{iT})X_{it}\} - \sum_{i=1}^{n}\sum_{j=1}^{m} C_{ij}X_{ij} \qquad (3.16)$$

$$\text{s.t.} \quad \sum_{i=1}^{n} K_i X_{ijt} \geq Y_{jt}\ ; \qquad (3.17)$$

where K_i is calorific value (GJ / metric ton) of region *i* coal;

$$\sum_{j=1}^{m} X_{ijt} \leq X_{it} - Y_{it}\ ; \qquad (3.18)$$

where X_{it} and Y_{it} are supply and demand in region i for year t

$$\sum_{i=1}^{n} 2SC_i X_{ijt} \leq SE_j Y_{jt}\ ; \qquad (3.19)$$

where SC_i is sulfur content for coal from region i;

$$\sum_{i=1}^{n} (SP_j - SC_i) X_{ij} \geq 0\ ; \qquad (3.20)$$

where SP_j is upper limit for coal burned in region j.

and where also: X_{ijt} = quantity shipped from supply I to demand j in year t.

$S_i(.)$ = linearized marginal cost function from the cumulative cost curve.

$D_c^{'}(t) = D_c^{r}(t)*[P^{'}_c(t) / P^{r}_c(t)]^G$

where: $D_c^{'}(t)$ = the computed base year value of demand for coal quality, c
$P^{'}_c(t)$ = current delivered price of coal quality, c, in the base year, t and
r = the values of demand and price at the reference coal type, and
G = import elasticity of demand.

This model differs from the ICTM model in two respects. First, it is a short term model, meaning that it can be used to model the impact of increases in prices of competing fuels for generation such as oil and gas which will determine what units are deployed for generation. The second difference is that it deals only with steam coal while retaining the constraint conditions for levels of sulfur dioxide but without allowing for blending at the demand point to achieve these constraint conditions. The model differs from the standard STPA with fixed demand only in the supply function, which is derived by a linearization of the regional (country level) cumulative cost curve.

The technical relationship between coal output and the driving variables is estimated by regressions of output from three different mining methods on geological characteristics of the coal such as thickness, depth of overburden cover and technical factors, such as face length and manning levels. This cumulative cost curve is a schedule based on extraction of the cheapest resources first, which means that the graph will generally trend upward or it can be viewed as generally monotonic. The mechanics of the linearization is to graphically approximate the total cost function between two adjacent output levels corresponding to the desired time periods by a straight line. It is this approximated linear marginal cost function that is then used in the STPA model in place of the usual econometrically estimated supply function. Other assumptions of the model are in-elastic demand and constant long run marginal costs of maritime transportation. Like the other models of this type, this model is also used to conduct sensitivity analysis by varying the level of future coal demand and then observing the resulting optimal values for supply prices, quantities and trade flows (p. 87).

The allocation model has 9 supply and demand regions. Projections for the allocation of the world trade in steam coal from this model and for the period 1985-2000 show Australia supplying East Asian markets except Japan, South Africa supplying the market in Western Europe and the U.S. supplying steam coal to Canada while Japan is supplied by a combination of sources that include the United States, South Africa and Canada (Dutton, 1982, p99).

In their model of the international steam coal trade, which they named the World Coal Trade model, Kolstad, Abbey and Bivins (1982) state as their primary objective, the need to have a forecasting model for the international steam coal trade and also a tool that could be used to test U.S. government policy on a variety of issues such as the elimination of import tariffs and quotas, applying domestic subsidies to investments to deepen export ports to handle larger vessels and any other legislation that would place US coal at an advantage in this trade. The authors depart from the STPA model and instead adopt a general equilibrium model that assumes an n-country oligopoly of both consumers and producers that maximizes the objective functions of representative agents subject to feasible physical constraints. The optimality conditions for consumer, producer and tax revenue maximization conditions are repeated here as follows (see Kolstad, Abbey and Bivins, 1983 p44-46): The first order conditions for utility firms (consumers) are:

$$u_{jt} = \left\{ \sum_{k}^{K} \sum_{i}^{n} a_{ik} q_{ijkt} - d_{jt}(p_{jt}) \right\} \textit{ and } u_{jt} * p_{jt} = 0 \textit{; where } q_{ijkt} \textit{ is coal from I to j} \quad (3.21)$$

In the case of producers, their first order conditions for profit maximization are:

$$w_{ikt} = \left\{ c_{ikt}(s_{ikt}) - p_{ikt} \right\} \textit{ and } w_{ikt} * s_{ikt} = 0\textit{;} \quad (3.22)$$

where p_{ikt} supply price for coal type k

$$v_{ikt} = s_{ikt} - \sum_{j=1}^{m} q_{ijkt} \geq 0 \text{ and } v_{ikt} * p_{ikt} = 0; \quad (3.23)$$

where $c_{ikt}(s_{ikt})$ is marginal cost of supply.

The objective function for governments is the maximization of the present value of export tax revenues and is given in the equations below:

$$\mathrm{Re}\,venue_i = \sum_t (1+\rho)^{-t} \sum_k \sum_j \pi_{ijkt} * q_{ijkt} \; ; \tag{3.24}$$

where π_{ijkt} is unit tax on coal type k shipped from I to j

$$\text{F.O.C. } y_{ijkt} = \sum_{\bar{t}} (1+\rho)^{-\bar{t}} \sum_k \pi_{ij\bar{k}\bar{t}} * \frac{\partial q_{ij\bar{k}\bar{t}}}{\partial \pi_{ijkt}} \geq 0 \text{ and } y_{ijkt} * \pi_{ijkt} = 0 \tag{3.25}$$

$$\text{and where } \frac{\partial q_{ij\bar{k}\bar{t}}}{\partial \pi_{ijkt}} = \frac{1}{(1+r_{ij})\alpha_{ik}\alpha_{i\bar{k}}} \left(\frac{\partial d_{j\bar{t}}}{\partial p_{jt}} \right) \tag{3.26}$$

which for $r_{ij} = 0$ under Cournot-Nash, simplifies to:

$$y_{ijkt} = -\left\{ q_{ijkt} + d'_{jt} \frac{\pi_{ijkt}}{(\alpha_{ik})^2} \right\} \geq 0 \text{ and } y_{ijkt} * \pi_{ijkt} = 0 \tag{3.27}$$

The spatial price efficiency conditions are:

$$z_{ijkt} = \left(p_{ikt} + \tau_{ijt} + \pi_{ijkt} - \alpha_{ik} p_{jt} \right) \geq 0 \text{ and } z_{ijkt} * q_{ijkt} = 0 \tag{3.28}$$

This model is similar to the ICTM in many respects, such as supply, transportation and demand components, but differs in the market conduct assumption. For the supply component, the over-land transportation costs are added to the mine-mouth unit production costs to arrive at a price free on board port of export. It is these price and quantity figures that are fitted to obtain a marginal cost of supply curve for a region (see Kolstad, Abbey and Bivins, 1982, Table A-II, p56). On the demand side, the authors used projected price and quantity data from forecasts by the U.S. Department of Energy to fit a constant elasticity of demand function for those regions with elastic demand and relied on expert opinion for other regions where demand is fixed. The transportation cost component was estimated from cost functions that are specific to size of colliers. Unlike in the STPA model where the objective function is the maximization of net social pay-off, this model includes the following specific steps: 1) defining an objective and strategy for each agent, 2) defining a constraint set for each agent and 3) a simultaneous solution for equilibrium prices and quantities for all agents (p40). The advantage of this general equilibrium approach is that it embodies the full range of possibilities for market conduct which can be realized by the type of assumptions made about the i^{th} oligopolist's conjectural variation, which in the case of a coal producer government, is its perception of how other governments will respond to its change in coal exports. The equations used in this model are derived from the following: consumer utility maximizing conditions; profit maximizing conditions for the producers; tax revenue maximizing conditions for the governments, and price efficiency conditions between the regions. The authors use the world coal trade model to test the likely market structure for the international steam coal trade. They make the basic assumption of a Cournot-Nash competition, which means that the i^{th} country's conjectural variation is zero and further that countries take the level of exports from their competitors as fixed when deciding on their own export tax levels. The choice variable for governments is the export tax, which is chosen to maximize revenues. The market conduct assumptions are: 1) a South African monopoly with all other producers in a competitive fringe; 2) a non-cooperative duopoly among Australian and South African producers while all other countries face perfect competition conditions and 3) all producers face perfect competition. The model assumes imperfect competition among utility firms in the importing countries.

The model results are for the projected steam coal trade in 1990 and show that the cases for a South African monopoly and that for pure competition fail to include both the United States and Canada in the solution and it is only in the non-cooperative duopoly case between South

Africa and Australia that both of the North American producers enter into solution to reproduce market shares that are close to those observed in reality. The results for the pure competition case are similar to those by Dutton (1982). The authors acknowledge the model to have a weakness in that it cannot be applied to answer short to medium term policy issues just like the ICTM model and is therefore used to project long run equilibrium in the international steam coal trade. The other weakness is that it is not an econometric model and therefore fails to account for the substitution that exists between coal, oil and natural gas in their use as fuels for generating electricity (Kolstad, Abbey and Bivins, 1982, p51).

The solution of quadratic models is now readily achieved through the use of software such as GAMS, which have options for solving non-linear problems. The world coal trade model by Kolstad, Abbey and Bivins was solved using a linear complementarity programming algorithm.

In their study, Senf and Fruin (1986) use a linear programming model to determine the cost competitiveness of two Great Lakes ports, port Duluth in Minnesota and port Superior in Wisconsin, for exporting coal from Montana and Wyoming to the world steam coal markets. The authors employ a model in which the objective function is to minimize the total delivered cost of coal under two scenarios about the level of world coal demand and for three case years, 1985, 1990 and 2000. The linear programming model used has 19 coal supply regions in thirteen countries and 25 coal importing countries. There are also 65 export and 52 import ports in the model. The authors conclude that under the low demand scenario and by the case year 2000 demand projections, South Africa and Australia would account for about half the world steam coal trade while a quarter of this trade would be captured by emerging export coal countries such as China, Colombia and Canada (Senf and Fruin, 1986, p72).

The above models on the international trade in steam coal consistently show supply from South Africa as a part of the projected steam coal trade. More recent studies (USBM, 1990 and 1993, *Mining Engineering*, April 2001 p11) still place South African coal producers at a cost advantage ahead of Australia and the United States but behind Indonesia and Colombia.

Two exact applications of the project selection model of Kendrick and Stoutjesdijk can be found in Dammert (in Labys, Nadiri and Nunez del Arco, 1980) where it was used to study investments in Latin America’s copper sector in competition with the rest of the world and also in Suh (1981), who applied it to the Korean oil refining and petrochemicals industry. The model by Dammert considered all operational stages from mining and up to semi-manufacturing of copper for final use and thus has both scale economies and interdependence between product stages. The model was able to provide intuitive results that showed that mining development would occur in regions of high ore grades while the location of semi-manufacturing depended more on the costs of transportation and labor (Dammert, 1980, p82).

Suh used the model to study investment planning in the Korean oil refining and petrochemical industries. He specifically wanted to determine the time phasing of new or expansion capacity and also to explore ways of dealing with stricter environmental regulation to control pollution. This application has both the economies of scale and interdependence properties between the oil refining and petro-chemical industries. The author concludes, among other things, that because these two industries were studied together under this model, the resulting high inter-industry business reduced costs and thus the economies of scale became the most important factor ahead of transportation costs in the selection of sites for new or expansion capacity (Suh, 1981, p308).

Another model that used mixed integer programming is that by Kang (1981) in which the objective was to determine the optimal time phasing, location and size of electricity generating plants to meet Korea's demand for electricity under conditions of uncertainty of either reliability or expansion capacity. The presence of uncertainty in the reliability constraint introduced non-linearity and therefore ruled out the direct application of the linear mixed integer programming algorithm but the author was able to solve the model by a combination of a nonlinear programming code and branch-and-bound algorithm to arrive at integer solutions. The author concludes that uncertainty in either the level of reliability or expansion capacity significantly affects the investment planning decision.

There have been two recent applications of mixed integer programming modeling in the coal trade, one by Lai and Chen (1996), and the other by Suwala and Labys (1998). Lai and Chen use a mixed integer programming model to minimize the cost of imported coal for the Taiwan power company subject to environmental constraints that are met through blending of coals from the company's coal yards. The authors conclude that their model can be used to plan future coal imports by source to minimize investment costs on blending facilities.

Suwala and Labys apply mixed integer programming to model the impact of structural adjustments on the Polish coal industry. These changes arose as a result of the country's movement towards a market economy with its attendant requirement for competition and market determined product prices. The objective of the study was to evaluate policies to restructure the Polish coal industry. The study adopts a two-model approach in which the first model defines an objective function in a manner much similar to the project selection model of Kendrick and Stoutjesdijk, where discounted costs are minimized. These costs are wide ranging and include costs of imported coal, mine closure costs and environmental costs. This model identifies mines at which investments in capacity can be made and those that need to be shutdown. The second model uses the supply functions from the first model to identify the spatial distribution of the coal trade using the STPA model in which the objective function is the maximization of net social pay-off. The study uses a highly disaggregated approach with supply being at the mine level and demand at the sector level, for instance, power generation, householders and steel plants (coke ovens). The authors conclude that their model succeeds in producing results that coincide with what is expected in reality. Some of these realities include the fact that as long as local coal is more expensive than imported coal, then the share of the latter will continue to grow and that the impact of stricter environmental standards has not been a major factor in the closure of low quality coal mines.

In their U.S. Regional Ferrous Scrap Model, Giarratani, Gruver and Richmond (2002) model the spatial behavior of the US ferrous scrap industry using a static, non-linear programming model that accounts for the substitution that exists between the two grades of scrap. The model is highly disaggregated, dealing with supplies at the county level and demand at the steel mill level. The model consists of 1212 counties and 240 steel mills. The non-linearity in the model derives from the definition of a supplier's market share as a logistic function of the normalized f.o.b. price of scrap. This approach makes the supplier's market share to be endogenous to the model and to depend on the size of the county and the netted back mill prices to arrive at the f.o.b. price at the county level. The authors go further to provide a solution algorithm for their model, which basically is an iteration procedure that begins with the selection of the mill price, calculation of the total demand, suppliers' share, and total supply. The model then checks for market clearance by comparing total supply to total demand and adjusts excess demand to pick a new mill price to re-start the iteration. This model has been able to correctly simulate some of the steel mill prices and the flow of trade in US ferrous scrap.

3.7 Conclusions

This chapter reviewed the theoretical basis for spatial price equilibrium models and provided examples of their applications in the minerals and energy sectors. These models have been applied as a medium to long term tool to determine the distribution of the steam coal trade for a given base year. In many cases, demand and supply functions have been determined outside of these models. The extension of these models to incorporate mixed integer programming has resulted in these models being used to determine the optimal investment in capacity in addition to its other uses in selecting plant locations and their capacities. The purposes to which these models have been put include the analysis of government policies regarding energy and environmental policy issues, the determination of the relative competitiveness of countries in the world steam coal trade and as a tool for projecting the growth in the world steam coal trade.

CHAPTER 4

MODELING FRAMEWORK

4.1 Introduction

This chapter provides the following: a description of the proposed model of the world steam coal trade; the behavioral assumptions for firms involved in this trade; the criterion used for selecting countries to be included in the model, and the components of the model, which includes the mathematical formulation of the model and the derivation of the elements of the objective function. The modeling framework proceeds in two stages. The first stage is the estimation of the country supply, demand and long run marginal cost functions, with the latter estimated only for net exporters in the model. This modeling is done within the structure of a non-spatial econometric model of the world steam coal trade by adopting approaches by Labson (1997) and Meyers, Devados and Helmar (1989). In the second stage, the forecast domestic and import demand quantities from the first stage are exogenous to the spatial and dynamic optimization model which, due to the inclusion of capital expenditure costs, long run marginal costs, rail transportation costs and maritime transportation costs, is capable of solving for the following: capacity additions in the exporting countries of the model, supply prices, domestic supply in the net exporting countries in the model, and trade flows over time and space.

A simple multi-period transport model of the world steam coal trade precedes the spatial and dynamic optimization model. The purpose of the transport model is to determine whether coal from Botswana can be competitively delivered to markets in Western Europe and Asia when only the rail and maritime transportation costs are considered. A detailed description of this problem and its results and their interpretation are presented in Appendix G. The advantage from this approach is that a multi-period linear programming approach can easily give some insights into the likely distribution of this trade in time as a result of declining costs of rail and maritime transport. The proposed model is discussed next.

4.2 The Proposed Model

There is a need for the Botswana government to employ a modeling approach that identifies factors concerning the exploitation of the country's coal deposits and to provide useful policy insights regarding future developments of the coal industry. This model would indicate whether or not conditions that have been identified in the past as preventing the development of the country's coal deposits continue to exist or have diminished. Such a model would also assist in policy decisions with respect to the provision of railway infrastructure as any new mine development is likely to require a rail link to existing railway lines in South Africa or Namibia. The objectives of this model are as follows:

1. To apply the model to forecast the optimal size of export mine located on the Mmamabula coalfield in Botswana and the land routes for these exports for the years 2005 and 2010 from a base year of 2000;
2. To conduct sensitivity analysis on the optimal forecast values to determine their responsiveness to changes in capital costs for mine development, rail transportation costs, and changes in demand in the net importing countries of the model;
3. To validate the model by simulating the world steam coal trade over the period 1995 to 2000 beginning from a base year of 1990 and then to determine whether Botswana's coal would have been competitive in the world steam coal markets in the past, and
4. To apply an experimental design approach to determine the significance of the effects of cost factors to be minimized in the optimization model, which consist of capital costs, variable supply costs, rail transportation and maritime transportation costs on changes in Botswana's steam coal exports.

In order to build this model the following are required: a model optimization framework, capital expenditure cost equations for mine development, forecast quantities of domestic steam coal demand in the net exporting countries and import demand in the net importing countries, regressions for long run marginal cost functions in the net exporting countries, rail transportation costs and sea freight costs. The forecast maritime transportation costs along each major trading route are obtained by time series methods while those for rail transportation are projections. The regressions for capital expenditure are exogenous to this model. This leaves us with the main task of forecasting domestic and import demands for steam coal for countries of the model. It is usual in models of this type to apply a linear marginal cost function that is derived from engineering cost data but in our case the lack of this data leads us to employ a marginal cost function that is derived from an econometric model of the long run marginal cost function based on publicly available information relevant to the coal industries of countries included in the model.

4.3 Assumptions About the World Steam Coal Trade

The following main assumptions about the market behavior of the world steam coal trade are made:

1. All net exporting countries in the model start from a base year supply capacity of 2000 and can only increase supply by carrying out capital expenditure programs for capacity additions. The capacity added in this way is only available at five-year intervals beginning with the first expansion period of 2005 to 2010.
2. We assume a perfectly competitive market in which the net exporters in the model respond to increases in exogenous steam coal demand by supplying steam coal after the necessary capital expenditure on capacity has been made. This is done through a cost minimization decision criterion in which the sum of the discounted capital costs, variable supply costs, rail transportation costs and maritime transportation costs are minimized over a give time horizon.
3. Each of the net exporters in the model has a minimum acceptable selling price (MASP) that is represented by its long run marginal cost function. The MASP is transmitted through to market prices in the markets of Western Europe and Asia after unit rail and maritime transportation costs have been added, and
4. Finally, we assume an increasing cost industry to reflect the positive slope of the steam coal industry aggregate supply curve and also to accommodate the non-negativity requirement on the slope coefficient for the long run marginal cost functions for each individual producer.

4.4 The Choice of Countries for the Model

The model divides the global steam coal trade into four geographic areas, North America, Southern Africa, Western Europe and Asia-Pacific, which includes Australia (see Figure 4.1 below). The Western European region is further divided at the country level to focus on the countries that have featured consistently among the major steam coal importers in the region. These are: Belgium, Germany, France, Italy, the Netherlands, Spain and the United Kingdom. In the North American region, only the United States is included as it is generally taken to be the marginal producer of steam coal for exports due to its high mine-mouth production costs (e.g. see Abbey and Kolstad, 1983, and USBM, 1993). In the main, the countries selected represent a substantial portion of the export and import share of the seaborne steam coal trade (e.g. see Dutton, 1982, the US Department of Energy's International Coal Trade Model, 1982 and Senf and Fruin, 1986).

For a study such as this one, it would have been useful to include the emerging exporters such as Colombia, Indonesia and China but it was beyond our capacity to obtain meaningful data for these countries. The export growth potential of these countries is widely reported in mining industry journals (for instance *Coal Age*, *Mining Journal* and *Mining Annual Review*). These reports project that even though China is becoming the marginal supplier to the world steam coal trade, it does not pose a threat to Australia's ranking as the leading steam coal exporter to markets in Asia. The reason cited for this is the concern about quality and security of supply, issues that favor Australia over China. In the Asian market, Australia's steam coal exports are projected to grow further in response to growing demand in the region. China would also need to invest in infrastructure for the domestic distribution of coal to meet rising domestic demand as well as exports. The political uncertainty in Indonesia, coupled with increasing domestic demand, creates an uncertain scenario for the growth of Indonesia's exports. In the region, the continued growth in electricity demand is credited for the growth in steam coal production and exports. In South America, Colombia's exports are projected to double from their current levels of about 37 million metric tons to 70.0 million metric tons by 2010. Colombia competes against South Africa for market share in the U.S. Gulf states as well as in Western Europe. The latter is also projected to increase its exports to 80 million metric tons by 2010.

Later in this study (Table 6.4), we provide the relative competitiveness of f.o.b. prices for steam coal for the year 2000 and in U.S. Dollars per mtce. This ranking is as follows: 1) Indonesia ($24.22), South Africa ($26.84), Colombia ($28.10), Botswana ($28.89), Australia ($31.10) and the United States ($38.08). In the Western European steam coal markets, coal from South Africa enjoys a cost advantage over Colombian coal (South African Coal Report, 2002). This model rationally excludes some exporters and importers and these are dealt with as the rest of the world. The question to ask, then, is whether or not Botswana coal can compete favorably against coals from Australia, South Africa and the United States in Western Europe and Asia?

We select model mines and their locations in each of the geographic regions. For the Southern Africa region, coal exports from South Africa derive from Witbank and are exported through Richards Bay, while those from Botswana are from Mmamabula and are exported through Richards Bay (and other possible routes to seaports at Matola, in Mozambique and Walvis Bay in Namibia). For the United States, the model mine is assumed to be in Central Appalachia and exporting through the Hampton Roads port in Virginia. This assumption is valid and does not place exports from the United States at a disadvantage, as there has been consistently a premium in the range $0.50 - $2.50 per long ton of coal exported from U.S. Gulf ports destined for markets in Western Europe (*International Coal Review Monthly*). For

Australia, we make the assumption that end user prices and f.o.b. for steam are the same. In line with the maritime transportation costs data referencing, the export port is assumed to be mid-way between Gladstone and New Castle (IEA/OECD, 1984 and *International Coal Review Monthly*).

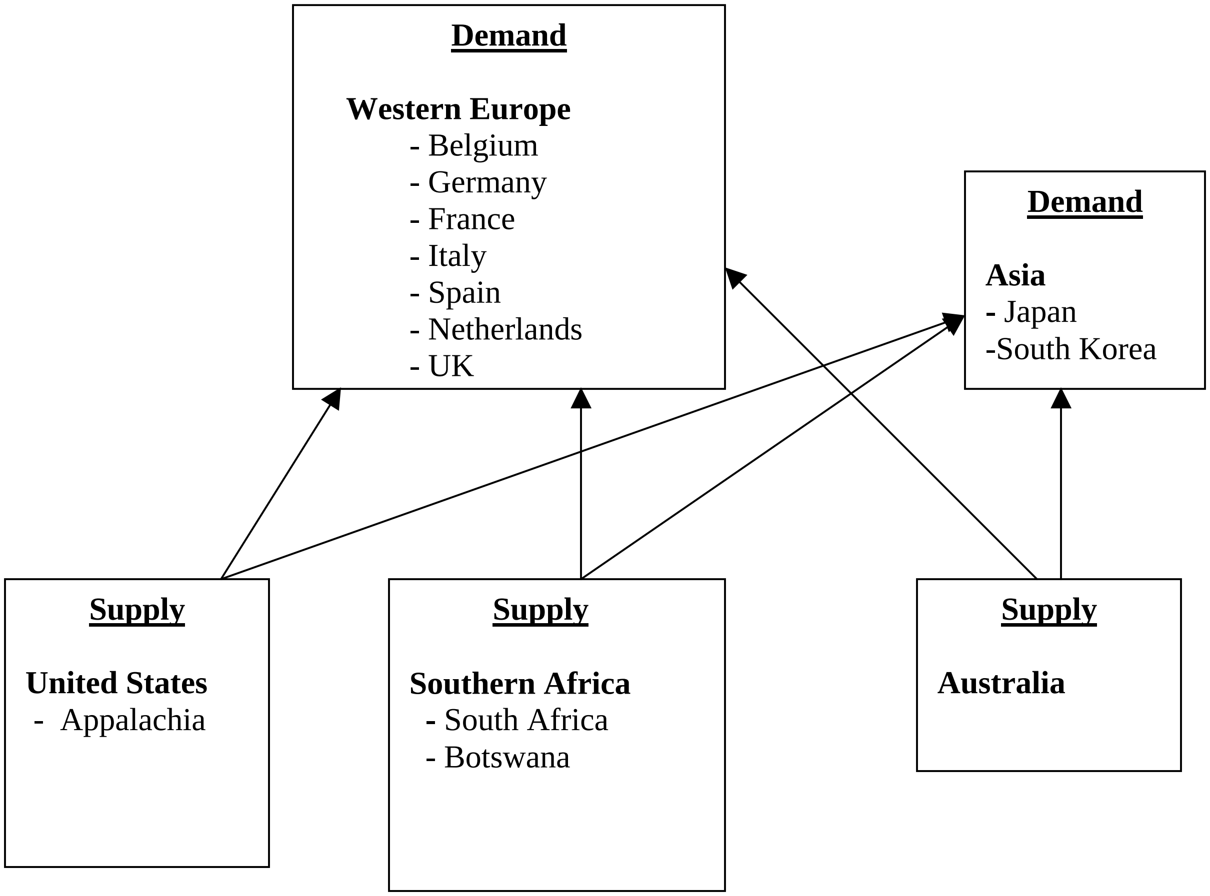

Figure 4.1 The Seaborne Steam Coal Trade Among Countries of Supply and Demand

Table 4.1 Steam Coal Supply and Demand Patterns for Countries of the Model (000's metric tons)

Country	1980	1985	1990	1995	1996	1997	1998	1999	2000
Japan									
Demand	17496	35935	45044	63829	67073	69469	69998	74315	83391
Supply	11084	12460	8152	6261	6480	4275	3665	3906	3148
Imports	6412	23475	36892	57568	60593	65194	66333	70409	80243
South Korea	**4927**	**11300**	**11500**	**26734**	**27600**	**34652**	**35607**	**37342**	**42777**
Belgium									
Demand	8994	7490	8996	7657	7541	7608	7480	6081	7004
Supply	3982	4182	2357	637	560	427	312	364	375
Imports	5012	3308	6639	7020	6981	7181	7168	5717	6629
Germany									
Demand	46092	45641	44749	40231	44845	42660	42558	39839	37890
Supply	38456	37448	31976	27172	24385	24184	21708	20027	18515
Imports	7636	8193	12773	13059	20460	18476	20850	19812	19375
France									
Demand	33510	25175	19122	14872	16371	13440	17561	15167	15940
Supply	16076	13667	9378	8056	7755	6286	5375	5130	4442
Imports	17434	11508	9744	6816	8616	7154	12186	10037	11498
Italy	**5820**	**11965**	**11797**	**11433**	**9971**	**8439**	**9436**	**10430**	**11817**
Netherlands	**3757**	**6879**	**12837**	**12234**	**11946**	**14749**	**16856**	**14532**	**17431**
Spain									
Demand	11124	20290	21861	24331	19997	24525	23477	28092	28589
Supply	11505	15184	14603	13652	13674	13804	12300	11772	11317
Imports	-381	5106	7258	10679	6323	10721	11177	16320	17272
UK									
Demand	111982	94667	98236	70856	62040	53882	53624	47544	50846
Supply	120047	91438	92797	53956	49379	47419	40589	36809	31704
Imports	-8065	3229	5439	16900	12661	6463	13035	10735	19142
Total Imports	42552	84963	114879	162443	165151	173029	192648	195334	226184
Australia									
Demand	27373	34504	43367	45865	50616	51486	53616	55267	58808
Supply	29646	61571	93564	111352	110943	116794	131827	125904	133970
Exports	2273	27067	50197	65487	60327	65308	78211	70637	75162
S. Africa									
Demand	79803	119870	119225	142985	145442	149781	147288	154017	150692
Supply	104515	162358	165492	202351	202829	216426	220806	221928	223394
Exports	24712	42488	46267	59366	57387	66645	73518	67911	72702
United States									
Demand	546581	645325	697253	743161	783995	837782	857406	858534	861484
Supply	592462	649381	760388	781448	808401	836721	868545	862342	842859
Exports [(a)]	24898	27562	35895	26541	27576	21682	22558	20443	13502
Botswana									
Demand	324	382	693	898	739	717	856	872	886
Supply	324	382	693	898	739	717	856	872	886
Exports	0	0	0	0	0	0	0	0	0
Total Exports	51883	97117	132359	151394	145290	153635	174287	158991	161366
Tot. Seaborne Trade	**95800**	**163600**	**199300**	**253000**	**274900**	**287400**	**296900**	**309800**	**347600**

Source: Compiled mainly from Coal Information 2001, International Energy Agency, Paris, p I.52
Notes: [(a)] – US exports are reported exports less reported imports.

4.5 The Mathematical Model

This model is formulated as a minimization problem in which the objective function minimizes the sum of the present value of annualized capital expenditure costs for mine capacity additions, variable supply costs, rail transportation costs, and maritime transportation costs over a given time horizon. These discounted costs are minimized subject to resource availability constraints; port capacity constraints for the Southern Africa region; conservation of flow constraints for the transshipment ports in two of the three net exporting regions of the model, that is, Southern Africa and the United States, and market demand constraints, which require supply to equal or exceed demand at the chosen world level of aggregation and for all time periods. The model applied is a variation of the STPA (Takayama and Judge, 1971) model (see Table 4.2 below for Variable Definitions). The objective function is as given in equation 4.1 below.

$$\textit{Min Total Discounted Present Value Costs (PVC)} = \sum_{t=1}^{T} \delta_t (\phi_{kt} + \phi_{ft} + \phi_{st}) \quad (4.1)$$

where
$$\phi_{kt} = \sum_{\tau=1}^{t} \sum_{i=1}^{N} \sigma(Capex_{it}(H_{it})) \quad (4.2)$$

Amortized = sum of CRF*(Capital expenditure for new capacity addition)
Capital costs

The equation for capital expenditure costs, $Capex_{it,}$ (H_{it}) is obtained from the U.S. Bureau of Mines Cost Estimating System (1995) and has the following three components, where Y_{it} is the capacity expansion in metric tons per day for a mechanized room and pillar mining operation with a production rate in the range 20 000 – 25 000 metric tons per day and operating on two production shifts using continuous miners. The variable H_{it} is converted to Y_{it}, which is in metric tons per day for computing the components of capital costs from the equations given below.

Table 4.2 Variable Definitions

Variable	Definition
Sets	
I	Set of net exporting countries, *i*, in the model (Australia, South Africa, Botswana and the United States
K	Set of export ports, *k*, for the set of I exporting countries: Australia – Gladstone, South Africa – Richards Bay, United States – Hampton Roads and Botswana – (Matola, Walvis Bay and Richards Bay)
J	Set of import ports, *j*, in Western Europe (Antwerp, Rotterdam and Amsterdam) and Asia (Yokohama)
T	Time period for expansion, *t*, is 2005 and 2010 for the forecast from a base year of 2000 and 1995, 2000, 2005 and 2010 from a base year of 1990 for the simulation;
Endogenous Variable	
q_{it}	Domestic supply of steam coal at mine in exporting country I in period T (000s mtce)
q_{ikt}	Steam coal exports from mine I to port K in time period T (000s mtce)
q_{kjt}	Steam coal shipped form export port K to import port J in time period T (000s mtce)
H_{it}	Expansion capacity at mine I in period T (000s mtce)
Exogenous Variable	
Dit	Domestic demand in exporting country I, including exports to the rest of the world markets in time period T (000s mtce)
Djt	Total steam coal import demand by market J in time period T (000s mtce)
C_{ikt}	Rail costs from mine I to port K in time period T (in 2000 US Dollar / mtce)
C_{kjt}	Sea freight costs from export port K to import port J in time period T and for vessels greater than 100K tons deadweight (in 2000 US Dollar / mtce)
Shadow Values	
λ_{Sit}	Optimal market price for steam coal in exporting country I in period T (in 2000 US Dollar /mtce)
$\lambda_{Vk,t}$	Shadow value for port capacity for Southern African ports only (in 2000 US Dollar /mtce)
$\lambda_{Tr,t}$	Optimal market price at port of exit (optimal f.o.b. price in US 2000 / mtce)
$\lambda_{D\,jt}$	Optimal market price for steam coal in importing in country J in period T (in 2000 US Dollar /mtce)

$Cost_{\mathrm{E}} = 2943{*}Y_{it}^{0.901}$ equipment capital costs (4.3)

$Cost_{L} = 405.8{*}\ Y_{it}^{0.941}$ labor capital costs (4.4)

$Cost_{S} = 390.7{*}\ Y_{it}^{0.904}$ supply capital costs (4.5)

The total capital expenditure cost is the sum of the three components. The cost estimate was updated to the base year 2000 from that of 1994 using mining cost indices for coal operations published by Western Mine Engineering Inc. (2002). The labor component of the capital expenditure is normalized relative to wages in the United States.

$$\phi_{ft} = \sum_{i=1}^{N}\sum_{k=1}^{K} c_{ikt}\, q_{ikt} + \sum_{k=1}^{K}\sum_{j=1}^{M} c_{kjt}\, q_{kjt} \tag{4.6}$$

Equation 4.6 expresses transportation costs as the sum of rail plus maritime transportation costs.

$$\phi_{st} = \int_{0}^{q_{it}} (\alpha_{it} + \beta_i q_{it})\, dq_{it} \tag{4.7}$$

where $$q_{it} = q_{i0} + \sum_{\tau=1}^{t} H_{it} \tag{4.8}$$

$$= \alpha_{it}(q_{i0} + \alpha \sum_{\tau=1}^{t} H_{it}) + 0.5\beta_i (q_{i0} + \sum_{\tau=1}^{t} H_{it})^2 \tag{4.9}$$

Equations 4.7, 4.8 and 4.9 derive the variable cost of supply function and demonstrate how the model gets its quadratic cost structure. They show that the total variable supply cost for each producer and for a given period is obtained by integrating over the linear long run marginal cost function over the limits from zero to the cumulative quantity supplied by such producer.

$$\delta_t = \sum_{\tau=1}^{\theta} (1+\rho)^{-\theta(t-1)-\tau} \tag{4.10}$$

The discount factor for period *t*, where θ is equal to the number of years per time period and ρ is the discount rate, is given by equation 4.11.

The capital recovery factor (CRF) is given by:

$$\sigma = \frac{\rho}{1-(1+\rho)^{-T}} \qquad \text{where } T \text{ is the life of project.} \tag{4.11}$$

The above objective function is minimized subject to the following constraint conditions:

Condition 1: This condition requires defining a set, *IK*, which matches producing countries to export ports to eliminate non-feasible links. The constraint says that for the set *IK*, exports should not exceed the available net supply, which is the difference between demand and base period supply plus sum of capacity additions to the present period.

$$-\sum_{k=1}^{K} q_{ikt} \geq D_{it} - q_{i0} - \sum_{\tau=1}^{t} H_{it} \quad \text{for all } i, \text{ in } IK \text{ and } t \tag{4.12}$$

Condition 2: This equality states that at the transshipment nodes, coal inflows and outflows should balance out. This applies to the Southern Africa region and the United States. The condition does not exist for Australia as the long run marginal cost function is based on export prices that already include rail transportation costs to export ports.

$$\sum_{i=1}^{N} q_{ikt} = \sum_{j=1}^{m} q_{kjt} \quad \text{for all } k \text{ and } t \tag{4.13}$$

Condition 3: This inequality requires that the sum of supplies from transshipment ports must be greater than or equal to demand in region *j*. Even though the entry ports are not the final demand points, the final distribution costs in the importing regions will be common to all coal regardless of their origins and therefore would not affect the results of the model in determining the spatial and temporal distribution of this trade.

$$\sum_{k=1}^{K} q_{kjt} \geq D_{jt} \qquad \text{for all } j \text{ and } t \tag{4.14}$$

Condition 4: This inequality is relevant for those producers that may face a binding port capacity constraint. This applies to both existing and simulated ports in Southern Africa. In the simulation scenario, the simulated port capacity is assumed to grow at rates that would mimic the growth of exports once a starting base has been selected.

$$-\sum_{i=1}^{N} q_{ikt} \geq -V_{kt} \quad \text{for all } k \text{ and } t \tag{4.15}$$

4.5.1 *The Kuhn-Tucker Conditions*

The Kuhn-Tucker conditions (K-T) for this problem are shown below:

$$L_{H_{it}} = \frac{\partial Capex_{it}(H_{it})}{\partial H_{it}} + \alpha_{it} + \beta_i(q_{i0} + H_{it}) - \lambda_{Sit} \geq 0 \tag{4.16}$$

$$L_{H_{it}} * H_{it} = 0 \tag{4.17}$$

$$L_{q_{ikt}} = c_{ikt} + \lambda_{Sit} + \lambda_{Vk,t} - \lambda_{Tr,t} \geq 0 \tag{4.18}$$

$$L_{q_{ikt}} * q_{ikt} = 0 \tag{4.19}$$

$$L_{q_{kjt}} = c_{kjt} + \lambda_{Tr,t} - \lambda_{Dj,t} \geq 0 \tag{4.20}$$

$$L_{q_{kjt}} * q_{kjt} = 0 \tag{4.21}$$

$$L_{\lambda Sit} = D_{it} - q_{i0} - \sum_{\tau=1}^{t} H_{it} + \sum_{k=1}^{K} q_{ikt} \leq 0 \tag{4.22}$$

$$L_{\lambda_{Sit}} * \lambda_{Sit} = 0 \tag{4.23}$$

$$L_{\lambda_{D_{jt}}} = D_{jt} - \sum_{k=1}^{K} q_{kjt} \leq 0 \tag{4.24}$$

$$L_{\lambda_{D_{jt}}} * \lambda_{D_{jt}} = 0 \tag{4.25}$$

$$L_{\lambda_{Tr,t}} = \sum_{i=1}^{N} q_{ikt} - \sum_{j=1}^{M} q_{kjt} = 0 \tag{4.26}$$

$$L_{\lambda_{Vk,t}} = -V_{kt} + \sum_{i=1}^{N} q_{ikt} \leq 0 \tag{4.27}$$

$$L_{\lambda_{Vk,t}} * \lambda_{Vk,t} = 0 \tag{4.28}$$

4.5.2 Economic Interpretation of the Kuhn-Tucker Conditions

The economic interpretation of K-T conditions relies on the definition of the marginal values, which in this study are the optimal market prices in both the net exporting and importing countries of the model. The component wise interpretation of these K-T conditions leads to relationships that govern optimal expressions for production, consumption, quantity flows and efficient market pricing conditions. Conditions 4.16 and 4.17 deal with optimum production with the latter showing that if there is positive production, which means that condition 4.16 is binding, then the sum of the marginal cost of new capacity plus marginal cost of production must be equal to the market price in that country. The interpretation of the K-T conditions 4.16 and 4.17, therefore make economic sense as they indicate that the sum of marginal costs should be greater than or equal to the optimal market price for capacity expansion and production to take place in a country. In the event production is zero, it must be that a country's supply price exceeds the market price in that country.

The optimum consumption condition is given by equations 4.20 and 4.21. If consumption is positive, equation 4.21 implies that 4.20 is binding and the delivered price of coal in the importing country is equal to the optimal market price. If quantity demanded is zero, this means that 4.20 is not binding and the market price is greater than the price in the importing country or region. A more intuitive interpretation of this condition is to begin by noticing that when equation 4.20 is binding, this means that the marginal benefit from a unit of consumption is equal to its shadow price. In the event that consumption is zero, then it must be that the market price is greater than the marginal benefit from a unit of steam coal imported. A simple manipulation of equations 4.18 and 4.20 leads to the locational price equilibrium condition that says that the optimal market price differential between two spatially separated markets must equal the cost of transportation for any positive quantity shipped and is less than these costs for a zero shipment.

This condition rules out arbitrageurs or speculators who would not find it profitable to buy the product in one market and sell it in another market as all of their profit margin would be used up to pay for transportation costs. The locational price equilibrium condition is shown in equation 4.29.

$$(c_{ikt} + c_{kjt}) + \lambda_{Sit} + \lambda_{Vk,t} \geq \lambda_{D_{jt}} \tag{4.29}$$

The pair of equations 4.22 and 4.23, and 4.24 and 4.25 are efficient market pricing conditions. The interpretation of these conditions is that a positive market price induces production that is both for the domestic and export markets. In the event the market price is zero, then there exists an excess of supply of exports in the region. In the importing countries, a positive price ensures that condition 4.25 is binding and imports are in balance with demand. If the price is zero, this condition would no longer be binding and hence there would be excess supply.

4.6 Formulation of the Empirical Model

The formulation of the empirical model is that of a model with elastic supply and inelastic demand. The elastic supply functions are derived from the estimation of long run marginal cost functions for net exporters of steam coal in the model while the inelastic demand is the forecast quantities of steam coal imports by the net importing countries in the model and the forecast domestic demand for steam coal by the net exporting countries. The existing international steam coal trade models are based on marginal cost functions that are derived from engineering cost data that normally are not readily available to researchers. The spatial and dynamic model developed in this work employs time series data specific to the supply of and demand for steam coal in the selected countries in the model to estimate the long run marginal cost functions for the net exporters in the model. This function is then transformed into the quantity formulation for incorporation into the objective function of the spatial and dynamic model. Integration over the linear long run marginal cost function yields the variable supply cost, which is quadratic in the quantity supplied (see equation 4.9 above). The advantage of using a quadratic programming approach is that the model solves endogenously for optimal supply quantities, capacity additions, trade flows and supply prices, across space and time.

4.7 The Supply and Demand Components

In this section we present the specification and estimation of the country supply and demand functions and the long run marginal cost functions for the net exporting countries of the model.

4.7.1 Specification of Country Supply and Demand Functions

There are two possible approaches for modeling the export supply and import demand quantities for steam coal. The first involves the direct estimation of steady state regional export supply and import demand functions (see Lord 1991). Such an approach results in non-linear supply and demand functions that do not readily lend themselves to the quadratic programming approach that is widely applied in spatial price equilibrium models. The second approach begins with the econometric estimation of country supply and demand functions. In this approach, some researchers have invoked assumptions of inelastic supply with the result that the demand functions are then estimated using ordinary least squares (OLS) methods. Examples include Hashimoto’s (1979) model of world iron and steel economy, econometric model of the copper industry (Bozdogan and Hartman, 1979, Mikesell, 1979, and Fisher, Cootner and Bailey, 1972) and Toweh and Newcomb’s (1991) model dealing with the spatial equilibrium analysis of the world iron ore trade.

In this study, we estimate the country supply and demand functions under the context of a non-spatial time dependent econometric model of the world steam coal trade following similar approaches to those by Labson (1997) and Meyers, Devados and Helmar (1989). The purpose of this non-spatial econometric model approach is two-fold: 1) to model the domestic demand and supply functions for all countries to determine the forecast demands in the net exporting countries and also the forecast import demands in the net importing countries of the model, and 2) to model the long run marginal cost of steam coal supply in the net exporting countries of the model. The forecast domestic and import demands are then used in the spatial and dynamic model to determine which countries would respond by adding production capacity under a decision criterion that minimizes the discounted sum of capital costs, variable supply costs, rail transportation and maritime transportation costs over a given time horizon. This model is applied towards analyzing a variety of coal trade issues relevant to policy decisions in Botswana.

The model differentiates coal only on the basis of its heat content (Btu) and for this reason the coal supply and demand data are converted to metric tons of coal equivalent (mtce). Similarly, all price and cost variables are reported on a per mtce basis.

4.7.2 Estimation of Country Supply and Demand Functions

Microeconomic theory informs us that the supply function for a firm is derived from the first order conditions for a profit maximizing firm. In the short run, when the firm is faced with a fixed level of capacity, the quantity supplied is explained by input and output prices. In the long run, however, the firm is able to adjust its capacity to meet increased demand. This means that a properly specified model of the long run supply function should include a variable for capacity as provided in equation 4.30 below. The long run marginal cost functions for each of the net exporters are obtained by estimating the inverse long run supply functions as specified in equation 4.33 below. In this form, each net exporter's long run marginal cost function is obtained by a regression of the steam coal price on input prices, output supply and production capacity.

The demand for steam coal, like all input demands, is a derived demand. Such demand equation is obtained from the first order conditions for cost minimization by a firm subject to a given level of output. In this case, we are considering the demand for steam coal in electricity generation, and this is derived from the first order conditions for a cost minimization problem in which electric utilities choose levels of fossil fuels to minimize total costs of generating electricity. The demand equations to be estimated are specified in equation 4.31 below.

The supply, demand and long run marginal cost functions are specified within the structure of a non-spatial econometric model of the world steam coal trade. This is the approach used by Labson (1997) and Meyers, Devados and Helmar (1987). The market clearing condition in equation 4.32 is not invoked in the econometric modeling of the supply, demand and long run marginal cost functions and is presented here for the sake of completeness of the non-spatial econometric model only. For each of the countries in the model, the supply and demand equations that will be estimated are of the form:

Country Supply: $$S_{it} = g_i(W_{it}, R_{it}, P_{it}, S_{it-1}, K_{it},) \qquad (4.30)$$

Country Demand: $$D_{it} = f_i(P_{it}, P_{oil,t}\, P_{gas,t}, D_{it-1}, GDP_{it}, Trend) \qquad (4.31)$$

World Steam Coal Market Clearance: $$\underbrace{\sum_{i=1}^{n+m} S_{it} + S_{ROW\ t}}_{\text{Sum of supply}} = \underbrace{\sum_{i=1}^{n+m} D_{it} + D_{ROW\ t}}_{\text{Sum of demand}} \qquad (4.32)$$

where: P_{it} - is the end user real price of coal in country i and year t in base year 2000

in US Dollars per metric ton of coal equivalent (mtce). Australia data assumed export and end user prices are the same;

D_{it}, D_{it-1} - domestic demand for coal in mtce for region i for periods t and $t-1$ (000s mtce)

S_{it}, S_{it-1} - domestic supply of coal in mtce for region i for period t and $t-1$ (000s mtce)

S_{ROWit} - rest of world supply in period t (000s mtce)

D_{ROWit} - rest of world demand in period t (000s mtce)

W_{it} - is the real hourly mine labor wage in year 2000 US $ for country i in period t;

R_{it}, - is the real cost of capital, (real interest rate) in period t;

$P_{oil,\, t}$ - is the end user price of oil in year 2000 US $ per mtce in period t;

$P_{gas,\, t}$ - is the end user price of gas in year 2000 US $ per mtce in period t;

GDP_{it} - is the real gross domestic product for country i in time period t, (US $ 2000)

K_{it} - is the coal production capacity in exporting country i in period t in (000's mtce)

$(n+m)$ - total of countries in the model (net exporters plus net importers), and

Trend - is the time trend.

The above econometric model is dynamic but not spatial. This means that it does not estimate trade flows among countries in the model. The difference in estimated values for domestic supply and demand indicate each country's position as either a net exporter or importer of steam coal.

For each country in the model, equations 4.30 and 4.31 are estimated using data for the period 1980 to 1997. The ex-post forecast period is 1998 to 2000, while the ex-ante period is 2000 to 2010. In any econometric forecasting, the performance of a model can be measured by the goodness of fit for the within-sample period as interpreted from significance of the adjusted R-squared, low forecast error for the out-of-sample period and other parametric and non-parametric tests. As we plan to employ the models to forecast future values, our priority in this study is to select a model with good explanatory power and low forecast error.

The minerals industry has been modeled frequently using partial adjustment models to take into account the slow speed of adjustments due to both supply and demand side rigidities (Fisher, Cootner and Bailey, 1972, Bozdogan and Hartman, 1979 and Mikesell, 1979). Supply side rigidities derive from the long time required to build capacity, which, once it is in place, presents certain operational constraints of its own. For instance, during periods of depressed prices, a mine will maintain its output as long as this price is equal to the short run average variable cost of production. On the demand side, there are rigidities in the adoption of processes that employ substitutes in the production of final goods. There is therefore a difference in elasticities between the short and long run periods. For these reasons, the models estimated would combine both the structural and partial adjustment form to include variables that provide the model with economic explanation as well as accounting for the slow speed of adjustment between the short and long run periods. It has been found that the simple autoregressive models sometimes out-perform multivariate models in forecasting. We keep this fact in mind when selecting the best models for estimating country supply and demand functions.

There is need to pre-test the data series for stationarity before we can estimate equations 4.30, 4.31 and 4.33. This is done to avoid spurious regression of one trending variable on one or more trending variables as well as more severe problems. This testing is easily achieved by running the Augmented Dickey-Fuller (ADF) unit root tests on the data variables for each country in the model. There has been an evolution of the approaches that can be used to correct trended data series to achieve stationarity (see Hunt, Judge and Ninomiya, 2003, Harvey 1997 and Gujarat 1995). All variables of the econometric model are first differenced and the ADF unit root test is conducted once again on the differenced series to confirm stationarity.

4.7.3 Estimation of the Long Run Marginal Cost Functions

The inverse long run marginal supply function described above is as shown below in equation 4.33 with the explanation of the variables as already provided. In the event there is simultaneity between price and quantity at the country level, this equation can be estimated with equation 4.31 with the identity shown in equation 4.32 above using two stage least squares, otherwise it is estimable as a single equation for each net exporting country.

$$P_{it} = f_i\,(W_{it}, R_{it}, S_{it}, P_{it-1,} K_{it,}) \tag{4.33}$$

The estimated linear long run marginal cost functions, with all other identifying variables collapsed into the intercept term, are of the form shown below with the constraint that both α_{it} and β_i be non-negative.

$$P_{it} = \alpha_{it} + \beta_{i*} q_{it} \tag{4.34}$$

In this study, we consider the marginal cost function in the long run when the firm can adjust its capacity to meet changes in demand. For this reason, there is a need to model variation in capacity over time. Since such capacity data are lacking, a surrogate was devised based on the observation that in any year during which prices are high or there is a disruption in supply from other exporters, the level of operation would be near full capacity. Since data were not available for all years, the missing observations had to be estimated. The years for which full capacity is assumed together with a brief explanation for their selection are as follows:

1. 1981/82 – The strike by Polish coal miners in 1981 disrupted Poland’s coal exports to Western Europe, such that US steam coal exports expanded to fill the gap. (Coal Information 1996, p I.20),
2. 1984/85 – The strike by UK coal miners led to all the major steam coal exporters increasing their exports to Western Europe to fill the gap,

3. 1992 – Industrial action in the US affected steam coal exports and therefore other exporters expanded to fill the gap (Coal Information 1996, p I.20), and
4. 2000 – the matching of demand and supply at full capacity led to a recovery in steam coal prices (Coal Information 2001, p I.130).

In using the long run marginal cost function, we make the assumption that this is equal to the minimum acceptable selling price of steam coal for each of the net exporters in the model. This assumption means that no producer is earning any rent. This assumption has also been invoked in coal trade models by the Macal (1979) and Dutton (1982) and derives from economic theory that in the long run all economic factors are paid their market price and firms realize zero economic profit.

4.8 Spatial and Dynamic Optimization

The second stage of this model incorporates the transformed long run marginal cost functions from the first stage into a spatial and dynamic optimization model of the world steam coal trade that has a quadratic objective function. In the second stage, we rely on a cost minimization decision criterion to determine which exporters would expand their production capacities to meet the exogenous demand for steam coal. The forecast demand for steam coal facing the net exporters in the model includes both the domestic and export demand.

The estimated long run marginal cost functions are transformed into a quantity formulation (see equation 4.34 above) and incorporated into the objective function of the spatial and dynamic optimization model. The other terms of this objective are: capital expenditure costs, variable supply costs, rail transportation and sea freight costs. Appendix H provides the indicative and estimated costs for rail and maritime costs respectively. The model is solved using the GAMS MINOS 5.5 solver (Brooke et. al., 1998). The salient features of this model are:

1. inelastic domestic demand in the net exporting countries of the model,

2. inelastic import demand in the net importing counties of the model,
3. elastic supply functions for net exporters derived from their estimated long run marginal cost functions, and
4. a quadratic objective function which derives from the variable supply costs which are quadratic in quantity supplied for each of the net exporters in the model.

This model is therefore capable of solving for the optimal values of capacity additions over the given simulation or forecast periods, optimal supply quantities by the net exporters, export and import quantities, optimal trade flows, and supply prices over space and time.

4.9 Data

The data sources for this study are presented in table 4.3 below.

Table 4.3 Sources of Data for the Model

Data Variables	Source
Steam coal production, consumption, exports, imports	Coal Information, 1988, 1990, 1996 and 2001
End user prices for steam coal, natural gas and heavy fuel oil	1) Coal Information, 1988, 1990, 1996 and 2001 2) Energy Prices and Taxes, Quarterly Statistics, 2nd Quarter 2001
Maritime freight rates	Coal Trade Freight Report, Rodriguez and Sons Co. cited in International Coal Review Monthly
Rail transportation costs	Coal Information, 1988, 1990, 1996 and 2001
Macro data on real gdp, interest rates, exchange rates and CPI	International Financial Statistics, May 2001.
Hourly wage rates	International Labor Organization's Washington branch web site: http://us.ilo.org
Heat content of coals	US Energy Information Administration's web site www.eia.doe.gov

4.10 Expected Results

The spatial and dynamic optimization model is expected to provide useful information on the likely timing and scale of new coal development in Botswana’s Mmamabula coalfield. The results of the multi-period spatial linear programming model show that there exist opportunities for coal production from the Mmamabula coal field would be competitive in the world markets. Specifically, if Botswana had capacity and rail links already in place, then these results show that the country’s coal would have been traded internationally in the year 2000. The main model will then determine whether this advantage ceases to exist once order of magnitude cost estimates for capacity additions are included in the model. In the event that the results show no immediate cost advantage for Botswana coals, it is expected that within the forecast horizon, coals from Botswana would become competitive as indicated by the linear programming model, which indicates that the port of Walvis Bay would have long term cost advantages in the Western European steam coal market.

4.11 Conclusions

This chapter has provided the theoretical approach to modeling the competitiveness of Botswana’s coal in the seaborne steam coal trade. This approach relies first on the econometric modeling of the world steam coal trade to obtain the following: forecast domestic demand for steam coal in net exporting countries, the derived steam coal imports in the net importing countries and finally, long run marginal cost functions for each of the net exporting countries in the model. As we are dealing with time series data, each country’s data series was tested for stationarity using the Augmented Dickey-Fuller unit root test. These tests are necessary to avoid spurious regressions in which the models might give high levels of goodness of fit even when there is no ruling economic relationship.

The second stage of the proposed model involves spatial and dynamic optimization in which the objective function is to minimize the discounted sum of capital costs, variable supply costs, rail transportation costs and maritime transportation costs over a given time horizon.

A simple multi-period linear spatial allocation model was simulated to determine the impact of the declining rail and sea freight costs on the competitiveness of Botswana’s coal (Appendix G). The results from this model demonstrate that if the rail transportation rates charged on South African coal exports are applied to steam coal exports from Botswana, and if there were railway lines to Matola and Walvis Bay for transporting this coal, then Botswana’s coal would be competitive in the world steam coal markets. This simple transportation model also demonstrates that in 2000, Botswana’s coal would have been competitive for exporting through Richards Bay. These results are very encouraging and justify a furthering of the model to include capital costs for capacity additions and variable costs of supply in the spatial and dynamic optimization model. The mathematical formulation of this model was developed and the Kuhn-Tucker conditions interpreted to confirm the proper formulation of the problem.

CHAPTER 5

EMPIRICAL RESULTS

5.1 Introduction

In chapter 4, we presented the modeling approach as that which has two stages: the first stage presents an econometric estimation of the supply and demand functions for each of the countries in the model and the long run marginal cost function for exporters in the model, and the second stage features a simulation framework consisting of a spatial and dynamic optimization model that has a quadratic objective function in variable supply costs. In the second stage, the import demand quantities from the first stage are exogenous to the optimization model which due to the inclusion of capital expenditure costs, long run marginal costs, rail transportation costs and sea freight costs is capable of solving for the following: capacity additions in the exporting countries of the model, supply prices, domestic demand, and trade flows over time and space. The model covers the periods 1995, 2000, 2005 and 2010. The results of the econometric model of the world steam coal trade are validated by both parametric and non-parametric methods. In the latter approach the computed values for exports and imports are validated by comparing the export or import quantities for each country with those from other models.

In the second stage of this study, we solve the spatial and dynamic optimization model of the world steam coal trade model to determine which of the exporting countries, with Botswana included as a possible exporter, would have responded to the import demand in the past, in 1995 and 2000, and which are likely to respond to the estimated import demand in the future, in 2005 and 2010, under a decision criterion that minimizes the sum of the discounted costs of capacity additions, variable costs of supply, rail transportation and sea freight costs. The model is then used to forecast the future of Botswana's coal for the years 2005 and 2010 from a base year of 2000.

5.2 Policy Approach

The use of coal models in formulating and evaluating energy policy has long been the accepted way of utilizing these models. In the United States, for instance, there has been a reliance on energy-economy models like the national coal model and its simpler versions such as the coal supply model in the formulation of environmental policy on coal use (Holloway, 1982, Wood and Mason 1982). Currently, the US Energy Information Administration's National Energy Modeling System consists of a Coal Market Module that is capable of producing forecasts relying on an engineering based marginal cost function. In this study, the policy focus is that of defining the obstacles to the development of an export coal industry in Botswana. As the country is landlocked, the burden of providing for rail infrastructure might present a real barrier to the development of an export coal industry. The Botswana government's policy on infrastructure provision for mining projects has always been that it would provide it and then charge user fees to recover the cost of provision over a stipulated period. In chapter 2, we gave a description of the regional initiative under the SADC protocol on Transport, Communications and Meteorology in which the region aims to approach infrastructure provision on a regional instead of an individual country basis. The mechanics of this regional cooperation include the prioritization of projects that have a regional benefit. A study like this one, could, therefore, provide economic justification for the prioritizations of rail and port infrastructure in those export corridors that offer the lowest transportation cost for exported coal.

Botswana has a long history of large scale mining and it recently revised its mining law to make it more comprehensive and investor friendly. This should provide comfort to any security of supply concerns in the markets in Western Europe and Asia. This model aims to provide a tool for the policy maker to model the likely competitiveness of Botswana's coal and to be in a position to anticipate possible future developments in world energy markets that may bear some opportunities for the development of the country's coal deposits. It is hoped that the output from this model would simplify the decision making process about whether or not conditions in the world energy markets justify much more detailed investigations at the project investment level.

5.3 Results of the Estimation of Country Supply and Demand Functions

The country level data series for steam coal demand and supply, hourly wages for the mining industry, real interest rates, real gross domestic product, end user prices for steam coal, natural gas, and crude oil, were tested for stationarity using the augmented Dickey-Fuller unit root test. The presence of a unit root and therefore, non-stationarity was detected in all the variables. These test results indicate that ordinary least squares regression would lead to spurious results due to the regressing of a trending variable on one or more trending explanatory variables. The existence of non-stationarity may also be accompanied by co-integration, a condition in which one or more variables have a long term equilibrium relationship and therefore share a similar trend. There are basically two approaches of handling non-stationary time series data: first differencing and if the variables are co-integrated, an approach that uses the error correction mechanism in the representation of the model for estimation. As the focus of this study is to forecast instead of establishing a relationship between the above variables in their levels form, the first differencing approach is used (see Gujarat, 1995 and Hunt, Judge and Ninomiya, 2003). All the data series were, therefore, first-differenced and the transformed series once again checked for stationarity. As expected, the first differencing eliminated the stochastic trend. Finally the results from the Hausmann specification test for each country's supply and demand function as represented in equations 4.31 and 4.32 indicated that there was no simultaneity between the steam coal supply price and quantity demanded or supplied. This was the expected result as the price formation in the international steam coal trade occurs at the international as opposed to the national level. In agreement with the general approach in model estimation, where it may be too restricting to assume a linear relationship between variables, in this study, a model, non-linear in the parameters, was used in estimating the country supply and demand functions. Also this non-linear functional form was transformed into a log-log form to end up with a linear in the parameters model. The results of the econometric modeling of the country supply and demand functions are presented in appendix A.

5.4 Validation of the Results for Country Supply and Demand Functions

There exist a variety of tests for validating econometric models of the type used in this study and these fall generally into two classes, parametric and non-parametric tests (see Pindyck and Rubinfeld, 1991 and Labys 1982 and 1973). The former relies on significance of the estimated parameters and the adjusted R-squared, which measures a model's goodness of fit. In addition, the estimated parameters may be shocked to simulate changes in policy variables. For instance a shock to the intercept term could simulate the imposition of taxes and consumption subsidies that affect the inverse supply and demand functions respectively. The slope parameters may also be shocked by half of the standard estimation error as suggested by Rubinfeld and Pindyck and the resulting values of the endogenous variable observed.

The performance of a model can be measured for both the with-in-sample and out-of-sample periods. Where the intention is to utilize the model for conducting out-of-sample forecasts, non-parametric tests, such as the root mean squared error, RMS, the mean absolute percent error, MAPE, and the Theil inequality coefficient, U, which is a ratio of the root mean squared error to the sum of the root mean squared values of the simulated and actual values of the endogenous variable are used to measure a model's forecasting ability. The value of the U ratio falls between 0 and 1, with values closer to zero depicting good out-of-sample performance and those nearer to 1 indicating poor model performance (Pindyck and Rubinfeld, 1991). Econometric models can also be checked for how well the models simulate turning points in the data by a graphical approach. Another approach involves a comparison of the forecast endogenous variables to those from other models.

The preceding discussion on validation approaches point to the need for the modeler to identify the kinds of tests that are suitable for the purposes of the model. If the objective is to obtain forecast values of the endogenous variable, then a low forecast error for the model takes precedence over the individual significance of the estimated parameters. This is the priority pursued in this modeling exercise. The validation of the country supply and demand functions therefore, proceeds as follows: reporting results from tests on MAPE, U, and the interpretation of bias component of U in the context of the suitability of a model for long range forecasting and comparing the forecast values for exports and imports computed from the country supply and demand equations with those from other models.

The econometric models for the country supply and demand functions were evaluated for their performance in the out-of-sample period of the data from 1997 to 2000 only, due to the limited time series data. The test statistics are reported in full in Appendix A. In this study, the import demands are computed as differences in domestic supply and demand. Next, we present only the statistics on the demand side, that is, for the net importing countries, to demonstrate the validity of the model and its usefulness for long range forecasting.

The adopted forecasting approach is the one step ahead forecast. This is relevant in this study as it allows actual data points to be used for solving for the predicted or forecast values. This is in contrast with the dynamic approach which forecasts future values based on forecast values from earlier periods. Obviously, in a model with low forecasting ability, the dynamically forecasted values are likely to diverge from actual values, leading to high forecast errors. For the demand equations, the MAPE is as follows: Japan (5.05%), Belgium (25.85%), France (23.62%), Germany (7.40%), Italy (12.22%), Netherlands (22.72%), Spain (12.97%) and the UK (7.87%).

These statistics infer that where there is significant steam coal consumption, there may be better reporting of data, which may explain the low errors for Germany, Japan, Spain and the UK. The high forecast error for France can be explained by the much diminished role for steam coal in electricity generation, while those for the Netherlands and Belgium may be due to the fact that these countries are entry points for steam coal imports and therefore the data may not be accurately reporting the re-exports to other Western European destinations. The Theil coefficient, U is as follows: Japan (0.03), Belgium (0.13), France (0.14), Germany (0.04), Italy (0.08), Netherlands (0.11), Spain (0.08) and the UK (0.06). These models have good explanatory power in the major demand countries of the model as indicated by the relatively high values for the adjusted R-squared. These are as follows: Japan (0.56), Belgium (0.30), France (0.10), Germany (0.49), Italy (0.29), Netherlands (0.25), Spain (0.21) and the UK (0.36). Once again, the low adjusted R-squared value for France may be an indication of the lesser role that steam coal plays in electricity generation as the country relies more on nuclear powered generation. The supply equations show values generally similar to those for the demand. While the Theil inequality coefficient values are relatively low, the existence of bias components of the U coefficient in excess of 0.2 (see Appendix A), alerts us to the limited usefulness of projecting with this model too far into the future

The next validation test for the country supply and demand models is a comparison of the computed export and import volumes with results from other models for the forecast years 2005 and 2010. In the Western European markets, the model's forecast steam coal imports are 15% and 9% below those by the International Energy Agency, while in the Asian markets, the forecasts are 7% and 13% above, for 2005 and 2010 respectively (see Table 5.4). The small difference between the model's forecast and those by the International Energy Agency provides some level of comfort in using these values in the second stage of the analysis, where the seaborne steam coal trade is simulated. The model's forecasts of exports are compared with those by three other agencies, EIA, IEA and WEFA on Table 5.3. The difference in the model's forecasts of exports and those by the EIA in the year 2005 are as follows: Australia (-5%), South Africa (+19%) and the United States (+34%). In 2010, these are: Australia (+5%), South Africa (+38%) and the United States (+67%). A comparison with the IEA projections, which do not have values for South Africa, shows the following differences in 2005: Australia (-9%) and the United States (+13%), while in 2010 these are as follows: Australia (+6%) and the Unite States (+39%). These results once again point to the fact that the country supply and demand functions estimated in this study are best suited for short forecast periods.

Table 5.1 Actual and Forecast Steam Coal Demand and Supply Quantities in Net Importing Countries of the Model (000's mtce)

Historical Period				Forecast Period			
Country	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**
Japan							
Demand	32 751	49 644	66 933	75 453	88 659	103 121	119 053
Supply	6 824	4 928	2 602	1 556	871	480	262
Imports	25 928	44 716	64 332	73 897	87 788	102 641	118 791
South Korea							
Demand [a]	76 554	54 501	39 597	52 740	61 140	70 878	82 167
Net Imp. Asia	102 482	99 217	103 929	126 637	148 928	173 519	200 958
Belgium							
Demand	6 977	6 897	5 238	6 709	8 398	10 511	13 155
Supply	1 611	436	296	144	68	32	15
Imports	5 365	6 460	4 942	6 565	8 330	10 479	13 140
Germany							
Demand	24 596	21 440	21 846	19 285	16 476	14 075	12 410
Supply	16 787	11 867	7 745	5 406	3 595	2 366	1 548
Imports	7 809	9 573	14 101	13 879	12 881	11 710	10 862
France							
Demand	14 509	11 088	12 336	10 016	7 923	6 149	4 709
Supply	8 443	6 946	4 006	2 905	2 093	1 501	1 073
Imports	6 067	4 142	8 330	7 111	5 830	4 648	3 636
Italy							
Demand	9 614	9 220	10 214	8 317	6 561	5 061	3 841
Netherlands							
Demand	8 001	7 338	8 057	7 308	6 281	5 391	4 628
Spain							
Demand	12 891	14 639	19 253	19 192	18 559	17 746	16 829
Supply	13 147	11 771	10 206	10 514	11 904	13 529	15 376
Imports	(256)	2 868	9 046	8 679	6 655	4 217	1 453
UK							
Demand	86 892	53 228	41 135	35 906	43 252	50 494	59 276
Supply	83 543	46 521	28 592	18 119	13 032	9 241	6 484
Imports	3 350	6 707	12 542	17 789	30 220	41 254	52 791
Imports Europe	39 950	46 308	67 233	64 843	72 533	83 004	93 583
Model Imports	142 431	145 525	171162	191 480	221 460	256 525	294 541

Source: Based on models estimated by the author.

Notes: [a] - South Korea's demand estimates are projections based on 5.9% growth rate from 2000 as cited in Coal Information 2001, p I.140.

Table 5.2 Actual and Forecast Steam Coal Demand and Supply Quantities in Net Exporting Countries of the Model (000's mtce)

Historical Period				**Forecast Period**			
Country	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**
Australia							
Demand	30 243	33 643	45 910	56 230	69 600	86 311	107 182
Supply	65 248	81 680	104 588	136 907	179 700	233 138	299 877
Exports	35 006	48 036	58 678	80 677	110 100	146 827	192 696
RSA							
Demand	96 692	115 407	129 710	142 060	151 355	160 463	169 498
Supply	134 215	163 678	188 836	213 187	239 526	269 118	302 367
Exports	37 523	48 271	59 126	71 127	88 171	108 655	132 868
U.S.A.							
Demand	627 375	638 844	693 489	774 799	848 535	942 735	1 029 330
Supply	658 449	661 305	704 779	799 063	874 326	971 221	1 060 258
Exports	31 074	22 460	11 290	24 265	25 791	28 485	30 928
Model Exports	103 603	118 768	129 093	176 069	224 061	283 968	356 492

Source: Based on models estimated by the author.

Table 5.3 Comparative Forecasts of Steam Coal Exports With Other Models (000's mtce)

Historical Period		**Forecast Period**	
	2000	**2005**	**2010**
Model			
: Australia	58 678	80 677	110 100
: RSA	59 126	71 127	88 171
: USA	11 290	24 265	25 791
EIA (1)			
: Australia	72 734	84 987	95 256
: RSA	57 130	59 814	63 648
: USA	19 268	18 130	15 475
WEFA(2)			
: Australia	NA	92 123	106 956
: RSA	NA	75 232	76 077
: USA	NA	9 198	9 198
IEA (3)			
: Australia	73 400	88 600	103 700
: RSA	NA	NA	NA
: USA	24 600	21 400	18 500

Source: Model values based on estimation by the author.

Notes: (1) – Table 103. World Steam Coal Flows by Importing Regions and Exporting Countries, Energy Information Administration, Annual Energy Outlook 2002, National Energy Modeling System, pp 214-215.

(2) – Table 4.8 Comparative Forecasts of World Hard Coal Exports: 2000/2010, Coal Information 2001, Part I, pp I. 156.

(3) - Table 4.7 IEA Projected Coal Trade (Mtce), Coal Information 2001, Part I, pp I. 154. The above projections for 2000 are actually for 1999.

Table 5.4 Comparative Forecasts of Steam Coal Imports With Other Models (000's mtce)

Historical Period		**Forecast Period**	
	2000	**2005**	**2010**
Model			
: Belgium			
: France	4 942	6 565	6 565
: Germany	8 330	7 111	5 830
: Italy	14 101	11 321	7 910
: Netherlands	10 214	8 317	6 561
: Spain	8 057	7 308	6 281
: UK	9 046	3 875	4 195
	12 542	17 789	30 220
Sub-total Europe	67 233	64 843	72 533
: Japan	64 332	73 897	87 788
: S. Korea	39 597	52 740	61 140
Sub-total Asia	103 929	126 637	148 928
IEA (1)			
: Belgium	6 900	7 100	7 100
: France	9 200	5 400	5 900
: Germany	16 500	22 100	22 800
: Italy	9 500	8 400	8 900
: Netherlands	12 400	8 000	6 400
: Spain	12 400	8 600	8 800
: UK	11 200	16 200	19 400
Sub-total Europe	78 100	75 800	79 300
: Japan	59 000	63 200	62 700
: S. Korea	31 600	55 100	69 200
Sub-total Asia	90 600	118 300	131 900

Source: Model values based on estimation by the author.

Notes: (1) - Table 4.7 IEA Projected Coal Trade (Mtce), Coal Information 2001, Part I, pp I. 154. The above projections for 2000 are actually for 1999.

5.5 Results and Validation of the Long Run Marginal Cost Functions

The second stage of this modeling exercise depends greatly on the validity of the estimated long run marginal cost functions for the net exporters in the model. The results of the estimation of the long run marginal cost functions are presented in Appendix B. The transformed long run marginal cost functions are provided in Table 5.1 below. The results for South Africa, and therefore, Botswana are the lowest of the four exporting countries in the model. This means that if one were to construct an industry supply curve for all countries in the model, South Africa and Botswana would occupy a position at the lower cost end of such an industry supply curve. For this reason, any sensitivity analysis on the demand side would not impact negatively the competitiveness of these low cost producers.

The validation of these models, therefore proceeds as follows: reporting results from tests on MAPE, U, and the interpretation of bias component of U in the context of the suitability of a model for long range forecasting. Lastly, we vary the starting date for the long run marginal cost function to 1983 from 1980. This last achieves a parametric variation of both the intercept and slope terms for the long run marginal cost function to check for the model's stability over time.

The MAPE for each exporting country is as follows: Australia (19.32%), South Africa (3.26%) and the United States (2.03%). The long run marginal cost function for South Africa is applied also to coal supplies from Botswana. The Theil inequality coefficients are: Australia (0.16), South Africa (0.03), and the United States (0.01). The bias proportion of the Theil inequality coefficient in excess of 0.2 indicates that these models are not suitable for long range forecasts.

Table 5.5 Transformed Long Run Marginal Cost Functions (1980 to 1997)

Period 1991 – 1995:		
	Australia:	$P = 50.90 + 7.06\text{x}10^{-5}Q^{s}$
	South Africa:	$P = 15.54 + 6.51\text{x}10^{-5}Q^{s}$
	Botswana:	$P = 15.54 + 6.51\text{x}10^{-5}Q^{s}$
	U.S.A.:	$P = 42.97 +7.32\text{x}10^{-6}Q^{s}$
Period 1996 – 2000:		
	Australia:	$P = 32.31 + 7.06\text{x}10^{-5}Q^{s}$
	South Africa:	$P = 5.01 + 6.51\text{x}10^{-5}Q^{s}$
	Botswana:	$P = 5.01 + 6.51\text{x}10^{-5}Q^{s}$
	U.S.A.:	$P = 32.19 +7.32\text{x}10^{-6}Q^{s}$

Source: Model values based on estimation by the author.

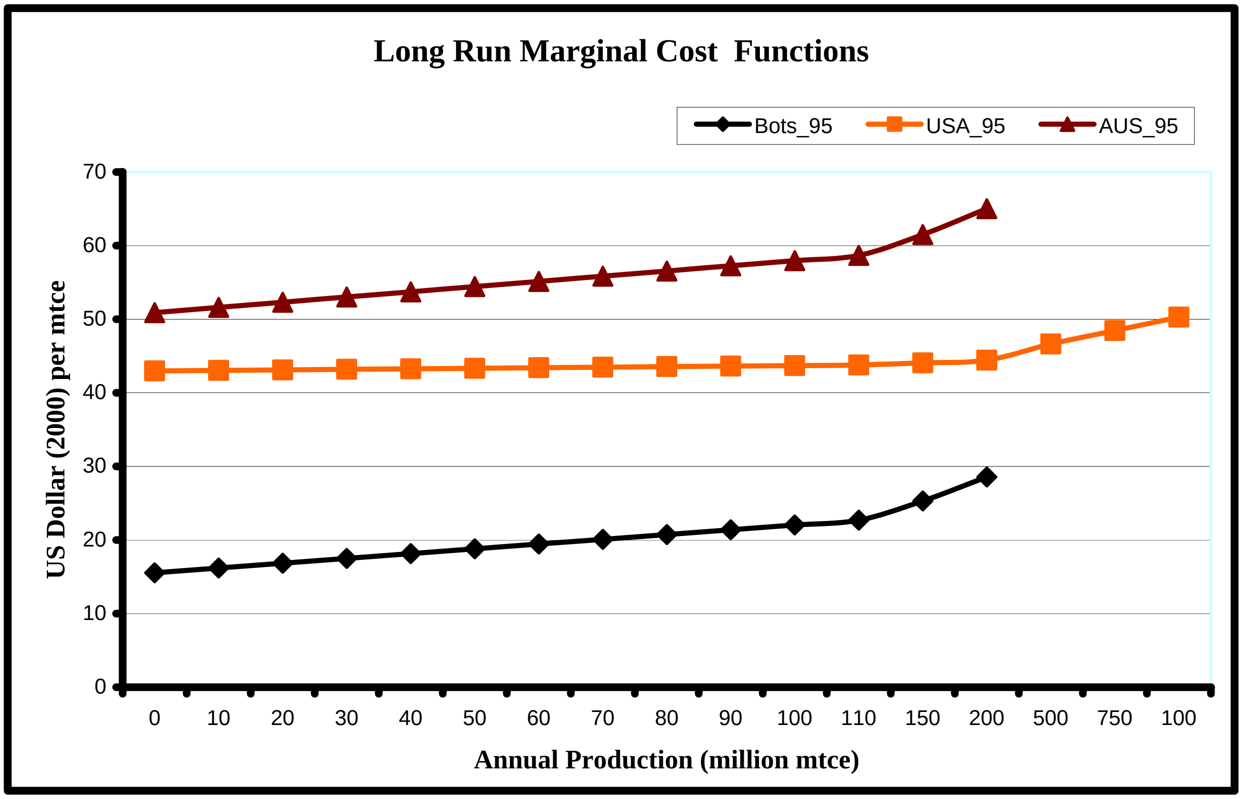

Figure 5.1 Transformed Long Run Marginal Cost Functions for Exporters
Source: Based on model estimation by the author
Note: Botswana’s function is the same as that for South Africa.

The non-negativity constraint on both the intercept and slope terms of the long run marginal cost function is observed to hold only during the sample period. For this reason, the transformed functions during the sample period are used for future periods in the model simulation and forecast stages, which is equivalent to making a further assumption that there are no supply shifts in the long run marginal cost function over the forecast period.

The validity of the long run marginal cost function is critical to the acceptance of the results of the model simulation as it determines the supply competitiveness of each of the net exporters in the model. For this reason the relatively high values for the adjusted R-squared, Australia (0.42), South Africa (0.61) and the United States (0.32), indicate that the model has good explanatory power. The parametric variation of both the intercept and slope terms for the long run marginal cost functions is achieved by varying the starting date for the long run marginal cost function to 1983 from 1980. The resulting sample period is 18 years, which is similar to the length of the original period 1980 to 1997. The varying of the start date tests the robustness of the estimated parameters over time to determine if they will maintain their signs. This method is preferred over the variation of the intercept and slope coefficients as the estimated long run marginal cost function for South Africa, and therefore, Botswana, result in the lowest intercept terms for these producers and any variation of the transformed intercept and slope variables would have to be of magnitudes that are not easy to justify in a policy context.

The sensitivity results for the long run marginal cost of supply function over the new sample period 1983-2000 are provided in Appendix B. Their adjusted R-squared values are: Australia (0.25), South Africa (0.61) and the United States (0.49). These compare very favorably with those in the original estimation. The coefficients on the supply quantity variable maintain their positive sign, which shows that the model is stable over this period and 18 observations.

5.6 Simulation With the Spatial and Dynamic Optimization Model

We now proceed to the second stage of our analysis in which we apply the spatial and dynamic optimization model of the world steam coal trade to simulate this trade and obtain the results of the base case scenario. The price equations used in this model are shown on Table 5.5 above. The rail transportation costs are the actual values for 1995 and 2000 while those for 2005 were projected from the actual values in 2000. The projected rates for 2005 were applied to 2010. Maritime transportation costs were estimated by using time series data on costs along each major seaborne steam coal trading route. This involved ordinary least squares regressions of sea freight costs per mtce on the price of crude oil, which were used as a proxy for the price of bunker fuel oil, annual steam coal quantities exported between each pair of export and import port along each route and finally on the scale of the seaborne steam coal trade. The results of this estimation are shown in Appendix C. The values for rail and maritime transportation costs are presented on Tables 5.6 and 5.7 below. This section presents the purpose of the base case simulation, the assumption for the base case, the two simulated routes for Botswana's steam coal exports, and the results of the base case simulation and their validation.

Table 5.6 Indicative Rail Transportation Costs (in year 2000 US $ per mtce)

		Historical Period			Forecast Period	
Mine to Port	**Distance** (Km)	1990	1995	2000	2005	2010
Australia	280-380	14.54	10.29	6.05	3.81	3.81
Witbank						
: Richards Bay	635	25.28	12.83	7.28	4.31	4.31
: Matola	453	18.03	9.16	5.19	3.07	3.07
: Walvis Bay	2000	79.61	40.42	22.91	13.56	8.03
Mmamabula						
: Richards Bay	1255	46.41	20.52	13.18	7.80	7.80
: Matola	1100	40.68	17.98	11.55	6.84	6.84
: Walvis Bay	1500	55.47	24.52	15.75	9.32	9.32
Appalachia						
: Hampton Roads	700	28.60	20.24	19.16	17.87	17.87

Source: Compiled from Coal Information, 1990, 1996 and 2001, International Energy Agency, Paris.

Table 5.7 Maritime Transportation Costs (in year 2000 US $ per mtce)

		Historical Period			Forecast Period	
Export to Import Port	**Distance (Nautical miles)**	**1990**	**1995**	**2000**	**2005**	**2010**
Gladstone						
: ARA	13900	16.68	16.03	17.02	13.34	13.30
: Yokohama	4200	9.98	10.44	9.08	8.95	9.35
Richard’s Bay						
: ARA	7400	12.97	12.00	11.18	7.94	7.44
: Yokohama	7600	13.74	14.36	10.45	8.27	7.63
Hampton Roads						
: ARA	3900	10.33	9.47	8.37	7.19	7.36
: Yokohama	9500	26.00	20.96	17.80	15.92	16.50
Matola						
: ARA	7400	12.97	12.00	11.18	7.94	7.44
: Yokohama	7600	13.74	14.36	10.45	8.27	7.63
Walvis Bay						
: ARA	5900	10.34	9.57	8.91	6.33	5.93
: Yokohama	9100	16.45	17.19	12.51	9.91	9.14

Source: 1) *International Coal Review Monthly*, National Mining Association, 1983 to 2000, Washington, D.C., Table 17, Single Trip Ocean Freight Rates per Long Ton of Coal
2) Shipping distances are from Mining Cost Services, March 2002, Western Mining Engineering, p TR C4

Notes: Maritime transportation costs are converted by author to US $ per mtce. The 1990 – 2000 values are actual values while those for 2005 and 2010 are econometrically predicted.

5.6.1 Base Case Simulation

The objective of the base case simulation is to determine whether or not coal from Botswana is competitive in the world steam coal markets of Asia and Western Europe, and further, to define both the temporal and spatial distribution of steam coal exports from Botswana that would have been likely in the past and also in the future. The scenario seeks to identify export routes to seaports for Botswana's coal exports and then to determine whether or not there is economic justification for the provision of rail and port infrastructure in the event that the model solution includes coal exports from Botswana.

5.6.2 Assumptions for the Base Case

The competitiveness of Botswana as an exporter of steam coal to markets in Asia and Western Europe is simulated against that of Australia, South Africa and the United States. The approach involves a reconstruction of the coal industries in these four countries beginning in 1990 and simulating the growth in production through the development of new capacity to meet both domestic and export demand for steam coal. The forecast domestic demand in the net exporting countries and import demand in the net importing countries were obtained from the econometric model of the world steam coal trade and are therefore exogenous to the spatial and dynamic optimization model. The production from new capacity is assumed to start in the fifth year in each of the five-year periods, 1991-1995, 1996-2000, 2001-2005 and 2006-2010. The model is then used to determine which countries in the model will respond by developing coal production capacity to meet both domestic and export demand for steam coal.

The spatial and dynamic optimization model has a quadratic objective function in which the objective is to minimize the sum of discounted annualized capital expenditure costs for capacity additions, long run marginal costs, both rail transportation and maritime transportation costs of internationally traded steam coal. The specific assumptions for the base case scenario are that:

1. exporters in the model build capacity to meet domestic demand and rest of world export demand first;
2. exporters face a residual demand equal to their combined market share in both of the two markets of Western Europe and Asia computed from historical data to be 62%;
3. exporters' market share in the rest of the world markets are treated in the same way as domestic demand in that they are given zero transportation costs and do not appear in the trade flows;
4. steam coal exports from Botswana are assumed to begin at 10.0 million mtce in 1995 and to follow a trajectory similar to that realized in other exporting countries such as South Africa and Australia where these grew, on average, at about 10 million mtce every five years; the port capacity constraint for the simulated ports of Walvis Bay and Matola are assumed to grow in line with Botswana's coal exports and in fact are the ones set exogenous to the model while the model solves endogenously for the addition of production capacity from Botswana's coal fields;
5. the capital cost estimate is valid for a room and pillar operation using continuous miners and rated between 2000 and 25 000 metric tons per day of coal. This translates into a mine size of 7.5 million metric tons of coal per annum. The capital cost estimate for each exporter assumes the development of multiple coal mine operations of this size to meet increased demand and therefore ignores any scale economies beyond this maximum size;
6. the real rate of discount is 15% and this applies on investment projects with a fixed life of mine of 20 years;
7. South Africa's coal exports use the Richard's Bay coal terminal even though the Matola port would be at a cost advantage because of its shorter hauling distance, and the maximum port capacity is 82 million metric tons per annum;
8. the share of rest of world exporters to the importing countries in the model is assumed to fill up the remaining share of the demand and does not enter the model;
9. the long run marginal cost of supply function is equal to the breakeven price or the minimum acceptable selling price, which means that exporters realize zero economic profits, and
10. the total export port capacity for the two simulated ports constraints rises from 10 million mtce in 1995 to 40 million in 2010 in equal increments of 10 million mtce in each five year period.

5.6.3 The Two Simulated Routes for Botswana's Coal Exports

The two simulated routes are: 1) Mmamabula – Lobatse – Ghanzi – Gobabis - Walvis Bay, in Namibia, and 2) Mmamabula – Ellisras – Pretoria – Matola in Maputo, Mozambique. The first route would use existing rail from Mmamabula to Lobatse, a distance of about 200km and a simulated railway line from Lobatse to Ghanzi, along the same corridor as the Trans-Kalahari Highway on the Botswana side, a distance of about 700 km and that from Ghanzi to Gobabis to join an existing railway line in Namibia. The total estimated length of this haul would be 1500 km. The second route links Mmamabula to the line that is currently being used to export steam coal from ISCOR's Grootegelug mine near Ellisras. The approximate total length of this haul is 1100 km. These routes are shown in Figure 5.2 below.

The routes from export to import ports are assumed to be the same as those for South Africa's coal exports to Western Europe and Asia. The Richard's Bay port is approximately equidistant from markets in Asia and Western Europe at 7400 and 7600 nautical miles respectively (Western Mining, 2002,Table 6 p. TR C4). A computation of the reduction in the sea voyage from using Walvis Bay instead of the East facing ports of Southern Africa shows that this would be about 20%. A port such as Walvis Bay would, therefore, be about the same distance from the Western European steam coal markets as exports ports for South American exporters.

5.6.4 Results of the Base Case Simulation

The results of the base case simulation scenario are shown below in Tables 5.8, 5.9 and 5.10. These results show that Botswana would have ranked first in competitiveness in the Western European steam coal market, followed by South Africa, the United States and finally

Australia. In the Asian market, Botswana would have ranked third after Australia and South Africa but ahead of the United States. The market shares for Botswana in Western Europe, expressed as a percentage of total model exports to this market, would have been 35% in 1995, 48% in 2000, 0% in 2005 and 62% in 2010. South Africa's market share would have risen from 27% in 1995 to 52% in 2000, 100% in 2005 and 0% in 2010. The US' market share in Western Europe would have begun at 38% in 1995, declined to zero in the intervening years and rebounded to 38% by 2010.

The loss of market share by South Africa in Western Europe is made up for by the gain of market share in Asia, where its share would have risen from 47% in 1995 to 62% in 2010 at the expense of that for Australia, which would have declined from 54% in 1995 to 21% in 2010. Botswana's share of the Asian market would have been 39% in 2005 and 17% in 2010 (see Figures 5.3 and 5.4). The base case assumes a residual demand of 62% to be faced by the four exporters in the model. It is therefore a straightforward exercise to express the resulting simulated market shares in terms of the world seaborne steam coal trade. The market shares reported on this basis are given on Figure 5.4 below and once again these are in general agreement with the actual values for 2000 for the existing exporters. On this basis, Botswana's simulated share of the seaborne steam coal trade would have been 7% in 1995, 12% in 2000, 16% in 2005 and finally 19% in 2010. In tonnage terms, this would have been 10.0 million mtce in 1995 and doubling over each five-year interval to end the simulation period at 40.0 million mtce. The country's competitiveness would have ranked it in the second position after South Africa and ahead of Australia, which would have been in the third position, while the United States would have occupied the last position among the four exporters in the model.

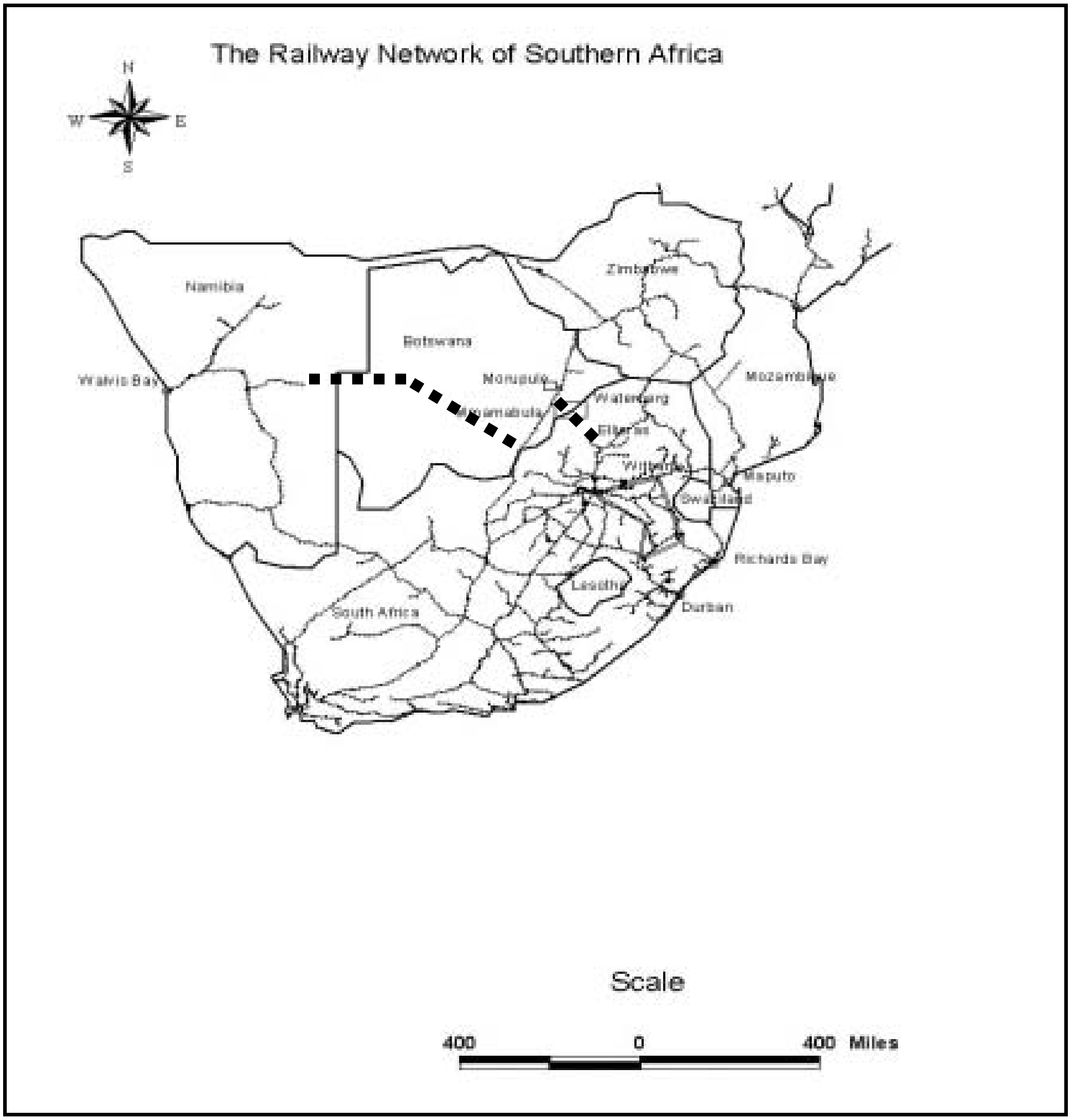

Figure 5.2 Simulated Railway Lines (bold dashed pattern) to Seaports With the Existing Railway Network of Southern Africa

Source: Compiled by author from GIS database files retrieved on April 19th, 2002 from: http://www.maproom.psu.edu/dcw/

Note: Coal deposits location is not geo-referenced and is therefore only illustrative.

Table 5.8 Simulated Gross Steam Coal Exports (000's mtce)

	1995	2000	2005	2010
Australia	32 759	40 324	32 227	18 887
South Africa	59 736	70 283	82 281	82 231
United States	19 643	14 163	14 271	29 287
Botswana	10 033	20 033	30 033	40 033

Source: Based on model simulations by the author.

Table 5.9 Simulated Flow of Steam Coal From Mine to Export Seaport (000's mtce)

	1995	2000	2005	2010
Queensland to Gladstone	32 755	40 258	32 219	18 886
Appalachia to Hampton Roads	10 743	0	0	14 991
Witbank to Richard's Bay	36 000	45 000	57 000	57 000
Mmamabula to Richard's Bay	0	0	0	0
Mmamabula to Matola	10 000	20 000	30 000	40 000
Mmamabula to Walvis Bay	0	0	0	0

Source: Based on model simulations by the author.
Note: These coal flows are net of those to rest of world markets. The difference between the gross simulated steam coal flows in table 5.6 and the above simulated net flows is the flows to rest of world markets.

Table 5.10 Simulated Flow of Seaborne Steam Coal From Export to Import Port (000's mtce)

	1995	2000	2005	2010
Gladstone to ARA (1)				
Gladstone to Yokohama	32 755	40 258	32 219	18 886
Hampton Roads to ARA	10 743	0	0	14 991
Hampton Roads to Yokohama	0	0	0	0
Richard's Bay to ARA	7 737	21 342	11 337	0
Richard's Bay to Yokohama	28 263	23 658	45 663	57 000
Matola to ARA	10 000	20 000	0	24 297
Matola to Yokohama	0	0	30 000	15 704
Walvis Bay to ARA	0	0	0	0
Walvis Bay to Yokohama	0	0	0	0

Source: Based on model simulations by the author.
Notes: (1) – Amsterdam, Rotterdam and Antwerp, which are taken as in ports of entry for steam coal into the modeled countries in the region.

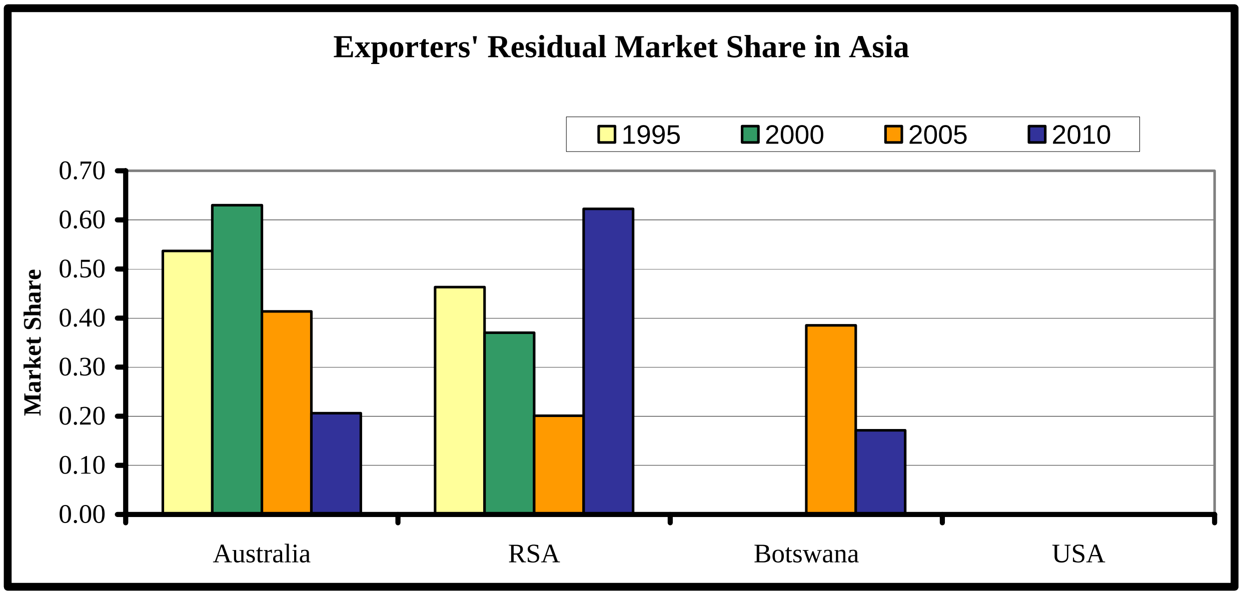

Figure 5.3 **Simulation Results of the Base Case Scenario for the Exporters' Residual Market Share in Asia**

Source: Based on model simulation by the author.

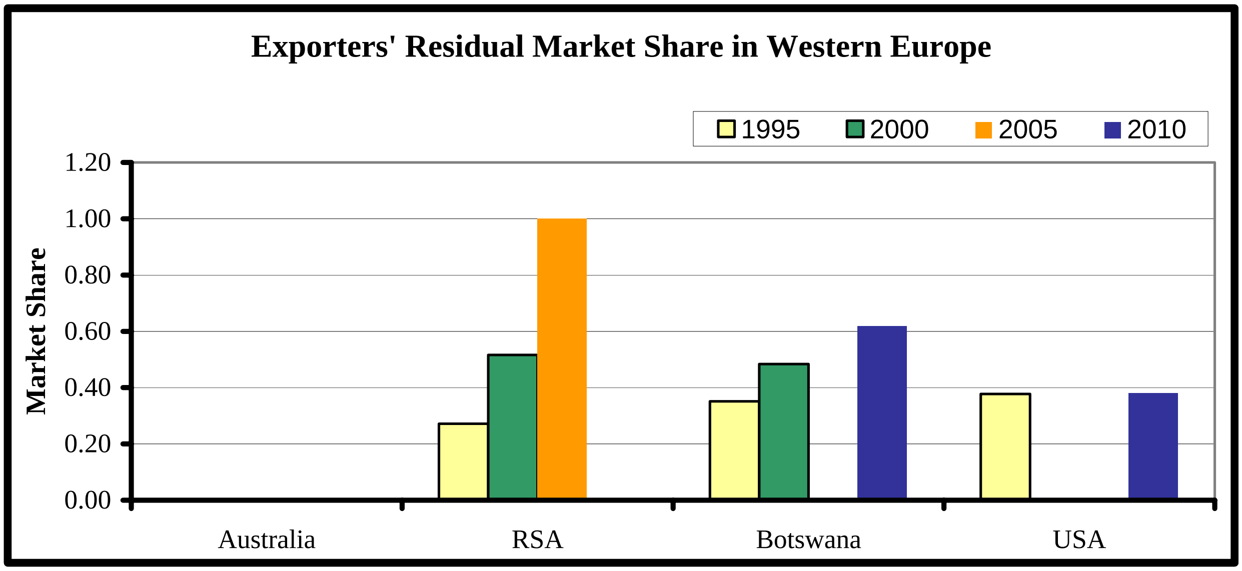

Figure 5.4 **Simulation Results of the Base Case Scenario for Exporters' Residual Market Share in Western Europe**

Source: Based on model simulation by the author.

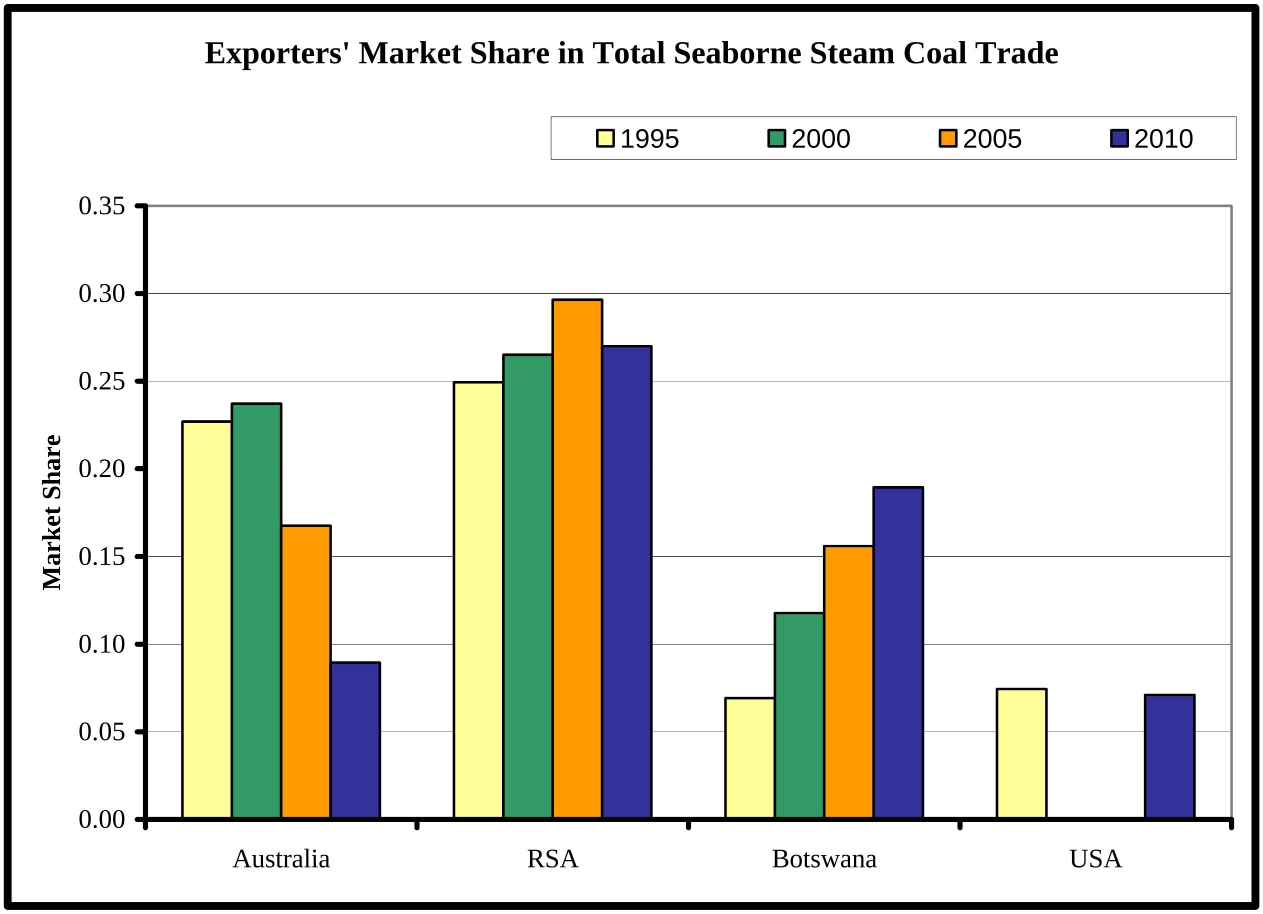

Figure 5.5 **Simulation Results of the Base Case Scenario for Exporters' Market Share of the World Seaborne Steam Coal Trade**

Source: Based on model simulation by the author.

5.6.5 Validation of the Results of the Base Case Simulation Scenario

To extend the validation process of the model, one useful approach is to assess the response surface of the model. Programming models are difficult to validate and as developed by Yang and Labys (1981), one can confirm with statistical significance the appropriate response qualities of a model. The approach used normally involves analysis of variance based on some form of experimental design. We therefore adopt two approaches for validating the spatial and dynamic optimization model used in this study. The first involves comparison with historical values to determine how closely the model represents the actual activity being modeled (see Gruver and Giarratani, 2002 and Yang, Hwang, and Sohng, 2002). The second approach is based on experimental design methods. The validation of this model proceeds as follows: (1) a comparison of optimal and historical values of exports and their distribution between origin-destination pairs and, (2) an experimental design approach that determines the response surface for Botswana's simulated optimal exports to changes in capital expenditure costs, variable supply costs, rail and maritime transportation costs for the years 1995, 2000, 2005 and 2010.

5.6.5.1 Comparison With Historical Supplies and Flows

Tables 5.10 and 5.11 provide comparisons between the optimal and historical values of steam coal exports and their distribution between origin-destination pairs respectively. The exclusion of Botswana from among the suppliers from these tables reproduces the existing state of the world steam coal trade among the selected exporters, Australia, South Africa and the United States. While the validity of the econometric model was first validated in section 5.5 above, one aspect of this exercise included varying the starting period for the estimation period, leading to a new estimation horizon of 1983 to 2000. The price equations for the 1983-2000 are shown in Table 5.11 and when these are substituted into the optimization model, they reproduce the base case simulation results shown above in Tables 5.8, 5.9 and 5.10. This is due to the new long run marginal cost functions for South Africa having lower intercepts than in the base case scenario.

The difference between the optimal export volumes and the actual values for 1995 are: Australia (-7%), South Africa (+24%) and the United States (-30%), while in 2000 these are: -4%, +24% and -27% for Australia, South Africa and the United States, respectively (see Table 5.12 above). These values indicate good model performance.

Next we determine how well the model predicts the temporal and spatial distribution of this trade by comparing the models optimal trade flow values with the actual values for 1995 and 2000. The temporal and spatial distribution of this trade is provided in Table 5.13 below. The model performs well in depicting trade flows between the major suppliers and demanders and does poorly in explaining trade links with low traded volumes. For instance, the differences between the model's optimal trading volume between South Africa and Western Europe are -7% and +38% in 1995 and 2000 respectively while that to Asia, which is not a major market for South Africa, these differences are +327% and –6% for 1995 and 2000 respectively. A similar observation is made for differences in Australia's exports to the Asian market where the errors are 3.8% and 8% in 1995 and 2000 respectively, while for exports to Western Europe, the errors are as high as –100% in both 1995 and 2000. As the United States is a marginal supplier to both markets, by virtue of having the highest marginal cost function among these exporters, its exports volumes are quite erratic. The differences in the model's prediction of exports to Western Europe are -24% and -100% in 1995 and 2000. The model predicts no US exports to Asian markets.

Table 5.11 Transformed Long Run Marginal Cost Functions (1983 to 2000)

Period 1991 – 1995:

Australia: $P = 44.05 + 1.37\text{x}10^{-4}Q^{s}$

South Africa: $P = 6.37 + 9.87\text{x}10^{-5}Q^{s}$

Botswana: $P = 6.37 + 9.87\text{x}10^{-5}Q^{s}$

U.S.A.: $P = 44.32 + 5.87\text{x}10^{-6}Q^{s}$

Period 1996 – 2000:

Australia: $P = 19.85 + 1.37\text{x}10^{-4}Q^{s}$

South Africa: [(a)] $P = 9.87\text{x}10^{-5}Q^{s}$

Botswana: $P = 9.87\text{x}10^{-5}Q^{s}$

U.S.A.: $P = 33.17 + 5.87\text{x}10^{-6}Q^{s}$

Source: Model values based on estimation by the author.
Notes: [(a)] – The computed intercept value is negative in 1996, therefore a zero intercept term is used to meet the non-negativity conditions in the mathematical programming model.

Table 5.12 Simulated Gross Steam Coal Exports Excluding Botswana (000's mtce)

Historical Period			Forecast Period	
	1995	**2000**	**2005**	**2010**
Australia				
: Actual	45 923	62 622		
: Model	42 793	60 358	62 222	48 849
: Difference %	-7.0	-4.0		
South Africa				
: Actual	48 271	59 126		
: Model	59 736	70 283	82 281	82 231
: Difference %	+24.0	+19.0		
U.S.A.				
: Actual	27 989	19 421		
: Model	19 643	14 163	14 271	39 287
: Difference %	-30.0	-27.0		
Botswana	0	0	0	0

Source: Based on model simulations by the author.

Table 5.13 Simulated Seaborne Steam Coal Flows Excluding Botswana (000's mtce)

Historical Period			**Forecast Period**	
	1995	**2000**	**2005**	**2010**
Gladstone to ARA (1)				
: Actual	4 427	6 674		
: Model	0	0	0	0
: Difference %	-100.0	-100.0		
Gladstone to Yokohama				
: Actual	41 496	55 948		
: Model	42 755	60 258	62 181	48 849
: Difference %	+3.0	+8.0		
Hampton Roads to ARA				
: Actual	14 176	2 838		
: Model	10 743	0	0	24 954
: Difference %	-24.0	-100.0		
Hampton Roads to Yokohama				
: Actual	4 889	3 085		
: Model	0	0	0	0
: Difference %	-100.0	-100.0		
Richard's Bay to ARA				
: Actual	19 090	30 059		
: Model	17 737	41 342	41 300	14 258
: Difference %	-7.0	+38.0		
Richard's Bay to Yokohama				
: Actual	5 581	3 877		
: Model	18 263	3 658	15 700	42 742
: Difference %	+327	-6.0		
Matola to ARA	0	0	0	0
Matola to Yokohama	0	0	0	0
Walvis Bay to ARA	0	0	0	0
Walvis Bay to Yokohama	0	0	0	0

Source: Based on model simulations by the author.
Notes: (1) – Amsterdam, Rotterdam and Antwerp, which are taken as entry ports for steam coal imports into the modeled countries in the Western European region.

5.6.5.2 Response Surface Methodology

The use of experimental design approaches has proven to be a valuable tool for the design and quality improvements of products in many industrial activities. The principal concept is that of the response surface methodology (see Myers and Montgomery, 1995, Kleijnen, 1974 and 1975, Ogawa, 1974 and Naylor, 1971). The response surface methodology permits the observation of interaction factors and therefore extends the sensitivity analysis wherein only one factor is varied at a time. Some typical objectives of response surface methodology as found in Myers and Montgomery include: 1) response optimization, 2) optimal selection of operating conditions to meet product specification and 3) analysis of a response surface of a region of interest. In this study, our objective is more in line with the last of these three (see also Labys and Yang, 1981).

The objective function of the optimization model for the world steam coal trade developed in this study has four cost components and we define a response function that relates the level of Botswana's exports to the four cost components. We adopt a general 2^k factorial design to observe the response surface in the vicinity of the forecast optimal values obtained from the optimization model. The steps in this experiment involve screening of factors to select those that have a significant impact on the response, applying OLS regression analysis on transformed variables, and conducting the analysis of variance and the partial F-test to check for factor significance.

The factor symbols for this experimental design are: capital cost, (A), supply costs, (B), rail costs, (C) and maritime costs, (D). Table 5.14 presents the low and high levels for these factors, while Table 5.15 provides the results of the optimization for each of the runs and the effect estimates. The hypothesis testing using the partial F-test is as follows:

$$H_o : B_j = 0 \quad \text{and} \quad H_A : B_j \neq 0 \tag{5.1}$$

$$F_o = \frac{SS_R(B_j \left| B_o, B_1, ..B_{j-1}, B_{j+1}, ..B_k \right.)/1}{SS_E/(n-k-1)} \tag{5.2}$$

where the enumerator represents the regression sum of squares with factor *j* excluded divided by the degrees of freedom for the single factor *j*, which is 1. The denominator is the error sum of squares divided by the appropriate degrees of freedom. In tabular form, the partial *F*-test statistic is readily computed by taking the ratio of the mean square error with the factor included to the mean square error of the regression (see Table 5.16 below). To decide the significance of a factor, we compare F_o with the critical F value from statistical tables at the 1% and 5% levels and if F_o is greater than the *F* value from the tables, we reject the null hypothesis, H_o at the given level of significance.

The partial F-test procedure in this study is equivalent to conducting hypothesis testing using the *t* test as we are testing the marginal contribution of a single factor at a time (see Gujarat, Chapter 8 and Myers and Montgomery, Chapter 2). This is explained by the connection between the *F* and *t* tests, wherein the square of the *t* value is approximately equal to the F value for 1 and *v* degrees of freedom.

Table 5.14 Factor Level Ratios to Base Case Scenario

Factor	Low	High
Capital Costs	1.00	1.20
Supply Costs	1.00	2.00
Rail Costs	1.00	2.00
Maritime Costs	1.00	1.20

Table 5.15 A 2^4 Simulation Experiment for Botswana's Annual Steam Coal Exports (for the period 1995 to 2010, in Decimal %)

Factors						% Change from Base Case Scenario				
Run Number	A	B	C	D	Treatment Combination	1995	2000	2005	2010	Totals
1	-	-	-	-	(l)	0.000	0.000	0.000	0.000	0.000
2	+	-	-	-	a	-1.000	0.002	0.000	-0.250	-1.248
3	-	+	-	-	b	0.000	0.000	0.000	0.000	0.000
4	+	+	-	-	ab	-1.000	-0.364	-0.168	-0.376	-1.909
5	-	-	+	-	c	0.000	0.000	0.000	0.000	0.000
6	+	-	+	-	ac	0.000	-1.000	-0.801	-0.850	-3.651
7	-	+	+	-	bc	-1.000	0.000	0.000	0.000	0.000
8	+	+	+	-	abc	0.000	-1.000	-0.999	-0.998	-3.997
9	-	-	-	+	d	0.000	0.000	0.000	0.000	0.000
10	+	-	-	+	ad	-1.000	0.002	0.000	-0.250	-1.248
11	-	+	-	+	bd	0.000	-0.272	0.000	0.000	0.000
12	+	+	-	+	abd	0.000	0.000	-0.107	-0.330	-1.710
13	-	-	+	+	cd	-1.000	-1.000	-0.591	0.000	0.000
14	+	-	+	+	acd	0.000	0.000	0.000	-0.693	-3.284
15	-	+	+	+	bcd	0.000	-1.000	-0.999	0.000	-3.997
16	+	+	+	+	abcd	-1.000	0.000	0.000	-0.998	0.000

Source: Based on model simulation by the author.

Table 5.16 Analysis of Variance for the 2^4 Simulation Experiment

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F_o	F_c at 1%	F_c at 5%
A	4.089	1	4.089	9.14	9.33	4.75
C	1.214	1	1.214	2.71		
A*C	1.214	1	1.214	2.71		
Error	5.367	12	0.447			
Total	11.884	15				

Source: Based on model simulation by the author.

The analysis of effects for the above experiment identified capital costs, rail costs and the interaction term between these two variables to be factors that need to be considered in deriving the regression model to explain changes in Botswana's simulated exports over the period 1995 to 2010. The linear regression equation for the export response function is given in equation 5.1 below.

$$\hat{y} = -0.390 - 0.127\, x_1 - 0.069\, x_3 - 0.069\, x_1 x_3 \tag{5.3}$$

R^2_adjusted = 0.53   N = 64

where $\hat{y}$ is the predicted value of the percentage change in steam coal exports relative to the optimal values from the base case simulation scenario, and x_1 and x_3 are transformed capital and rail costs in the range –1.0 to 1.0, and x_1x_3 is the interaction term for capital and rail costs.

The above response function indicates that the level of exports is a declining function of capital costs, rail transportation costs and their interaction term. Figures 5.6 (a), (b) and (c) provide a graphical presentation of the main effects for capital costs, the interaction effects between capital costs and rail transportation costs, and the response surface for this experimental design. This experiment indicates that rail transportation costs have no main effect on the level of Botswana's steam coal exports but combine with capital costs to negatively impact on exports as shown on Figures 5.6 (a), (b) and (c). The sensitivity analysis that follows will therefore include scenarios for varying capital and rail transportation costs one at a time and analyzing the resulting exports and their distribution.

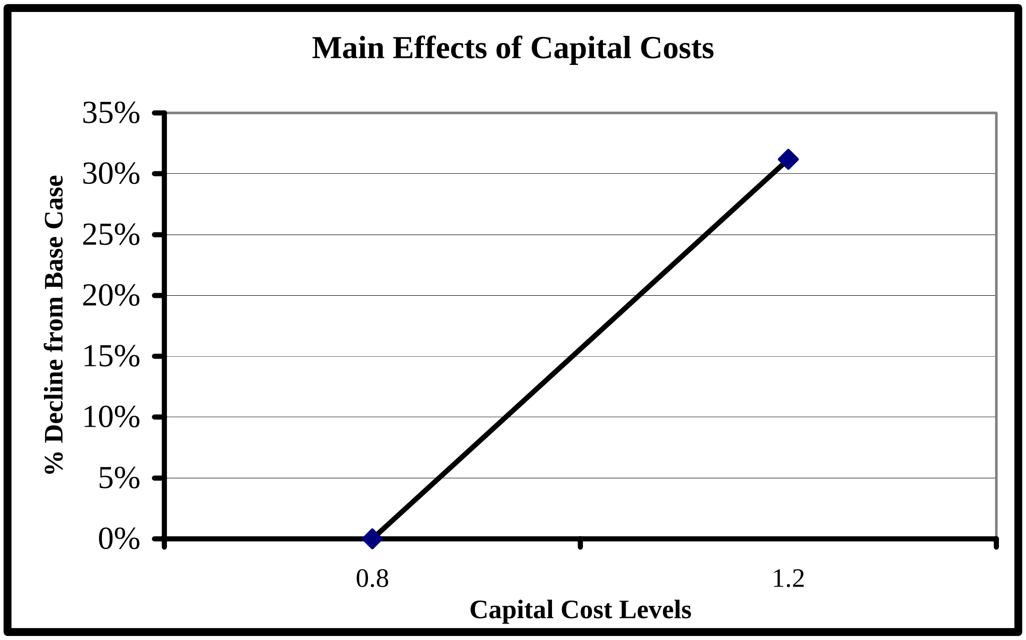

Figure 5.6 (a) Main Effects of Capital Costs on Botswana's Simulated Steam Coal Exports

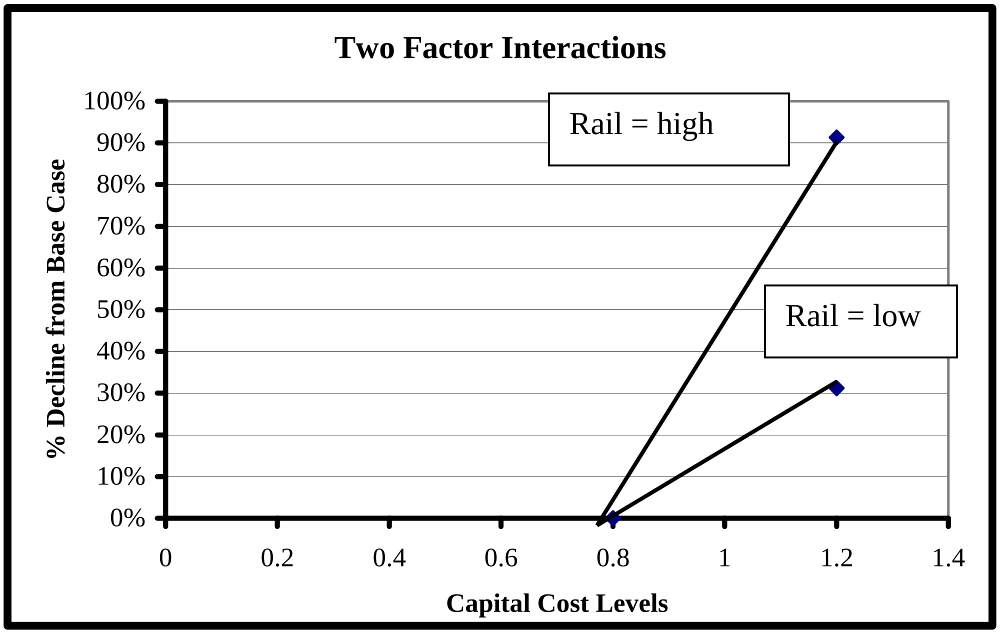

Figure 5.6 (b) Capital and Rail Costs Interaction Effects on Botswana's Simulated Steam Coal Exports

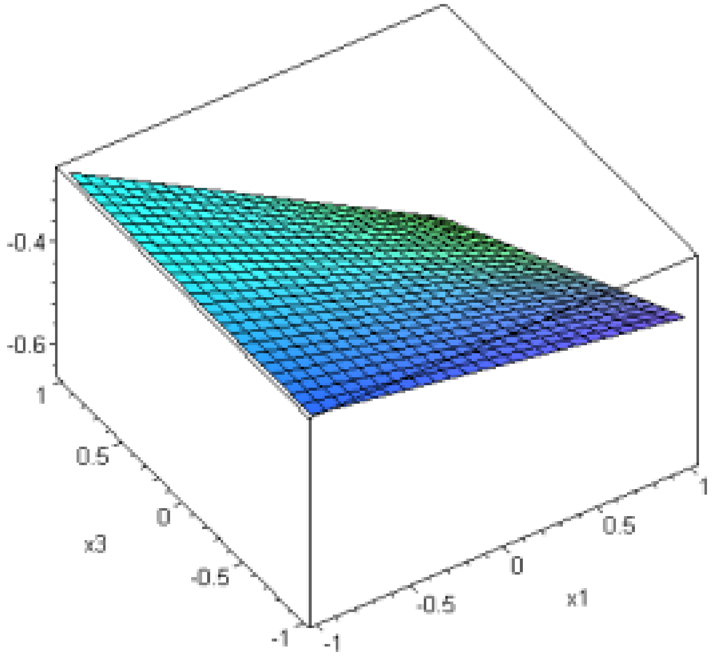

Figure 5.6(c) The Response Surface for Botswana's Simulated Steam Coal Exports

5.7 Conclusions

This chapter presented and validated the results of the econometric model of the world steam coal trade. The forecast values for export and imports from this model compare favorably with those from models by the EIA, IEA and WEFA. While the non-parametric validation tests for the out-of-sample period show low forecast errors for countries that are major coal consumers, the relatively high bias proportion of the Theil coefficient alerted us to the likelihood that the model would perform poorly if used for forecasts that are too far into the future. The relatively large values for the adjusted R-squared indicate that the model has good explanatory power. The long run marginal cost function for the net exporters in the model displayed good properties with respect to the expected signs on the slope coefficients. The validation of these functions successfully demonstrated the robustness of these results over time. As in the country supply and demand equations, these models also had good explanatory power but poor out-of-sample forecasting ability.

The results of the base case simulation scenario show that Botswana's coal would be competitive in the steam coal markets of Western Europe where it becomes the leading supplier among the four exporters in the model. The export port for this trade is Matola in Mozambique. We determined through the experimental design approach that capital costs are the significant factor explaining changes in Botswana's steam coal exports and proceeded to derive a response function that also included rail transportation costs, which were shown to have no effect on exports within the ranges studied.

In summary, the model's ability to depict the temporal and spatial distribution of the seaborne steam coal trade is quite good and is in general agreement with findings by other researchers that support the dominance of Australia and South Africa in models of the seaborne steam coal trade (see Kolstad, Abbey and Bivins, 1982 and Dutton, 1982).

CHAPTER 6

POLICY APPLICATIONS

6.1 Introduction

In this chapter, we conduct sensitivity analysis on the simulation results for the base case scenario to check the robustness of the model's solution to changes in capital costs and rail transportation costs. The other cost factors were shown to have little or no effects on the levels of Botswana's exports from the experimental design approach and are therefore not investigated further in this chapter. We then proceed to apply the model to forecast Botswana's future steam coal exports in the years 2005 and 2010 from a base year of 2000 and then determine the country's competitiveness in the steam coal markets in Western Europe and Asia during these years. The simulation results for base case scenario demonstrate that Botswana's coal exports would have been competitive in the Western European markets in the past and that they would remain competitive in this market and Asia in the future. This finding differs from that of the 1983 study, which attributed lack of competitiveness of Botswana's coal in the export markets to the cost of rail transportation to seaports.

6.2 Sensitivity Analysis

Theoretically any adverse shift in Botswana's long run marginal cost function would reduce the country's competitiveness as a supplier of steam coal to world markets. In this study, any deterministic shocking of the intercept and slope terms for Botswana's long run marginal cost function would not add any information in this case because of the low intercept and comparable slope terms to those of Australia and the United States (see Figure 5.1 or Table 5.5 above). For instance, in the period 1991-1995, Botswana's intercept term is about one-third those of Australia and the United States and the differences grows to about one-sixth in 1996-2000 period. Also recall that supply costs were found to have insignificant effects on the variability in the level of exports. This means that any adverse shifts in Botswana's supply curve would have to be of a magnitude that is not relevant to any policy variable. For instance an intercept shift of up to 200% still leaves Botswana's supply function below those of Australia and the United States.

The sensitivity analysis will therefore focus on testing the robustness of the base case simulation results on the competitiveness of Botswana's steam coal exports to changes in rail transportation costs and capital costs of expansion or new capacity as these are the factors that were retained to explain the response surface under the model validation in Chapter 5, above. We assume that no single exporter would face maritime transportation costs that diverge from those applying to other exporters once distance and other factors have been taken into account. For this reason they will not be included in the sensitivity analysis. We also know that, the validation experiment failed to select maritime transportation costs as a significant factor in explaining changes in Botswana's simulated steam coal exports. The sensitivity analysis also provides an indication of the long-term competitiveness of each of the two routes described in subsection 5.6.3 above. The scenarios studied are shown in Table 6.1 below.

6.3 Results of the Sensitivity Analysis of the Base Case Scenario Simulation

The sensitivity analysis results confirm the results from the response surface methodology that was applied to validate this model which demonstrated that rail transportation costs, at the levels that apply on South Africa's steam coal exports, do not have a significant effect on changes in Botswana's simulated exports. Table 6.2 shows the sensitivity of

Mmamabula’s coal exports to changes in the capital expenditure costs for mine development. These costs were incremented at 10%, 20% and 25%. For all increases in capital costs of 10% or less, there is no change from the results of the base case scenario. When these costs are raised to 20%, Botswana’s 1995 exports are eliminated while they remain unchanged in 2000 and 2005 but decline by 41% in 2010 relative to the base case. This decline is in the Western European market. As a result of the 20% increase in capital costs, Botswana’s lost market share in Western Europe is gained by South Africa, whose exports increase by 129% in 1995 relative to their base case levels. South Africa’s market share in Western Europe rises to 62% as compared to 27% in the base case. It remains unchanged in 2005 and 2010. As South Africa regains its market share in Western Europe, this frees up the Asian market for Australia, which realizes a rise in exports to command 70%, 94%, 80% and 53% respectively for the years 1995, 2000, 2005 and 2010. This compares to the base case scenario market shares in Asia of 54%, 63%, 41% and 21% for the same years respectively.

Finally, when capital costs for Botswana’s coal are raised by 25% relative to the base case scenario, Botswana’s coal becomes uncompetitive in both the Asian and Western European markets. South Africa and the United States share the Western European steam coal market in 1995 and 2010 with the intervening years wholly controlled by South Africa. The Asian markets are shared between Australia and South Africa with the share in 2000 very close to the historical level of 90% for Australia. The elimination of Botswana’s exports from the simulation model approximates the existing steam coal trade among the exporters in the model and is depicted on Table 5.12 above.

Table 6.1 Scenarios for Sensitivity Analyses of the Base Case Simulation Results

Scenario	Rail Transport Cost	Mine Capital Cost
1	50%	
2	100%	
3	200%	
4		10%
5		20%
6		25%

Table 6.2 Sensitivity of Trade Flow Patterns to Changes in Botswana's Capital Costs (% Change from Base Case Scenario)

	Historical Period		Forecast Period	
	1995	2000	2005	2010
Botswana's Capital Cost up 10%				
: Gladstone to ARA	0	0	0	0
: Gladstone to Yokohama	0	0	0	0
: Hampton Roads to ARA	0	0	0	0
: Hampton Roads to Yokohama	0	0	0	0
: Richard's Bay to ARA	0	0	0	0
: Richard's Bay to Yokohama	0	0	0	0
: Matola to ARA	0	0	0	0
: Matola to Yokohama	0	0	0	0
Botswana's Capital Cost up 20%				
: Gladstone to ARA	0	0	0	0
: Gladstone to Yokohama	31	0	0	0
: Hampton Roads to ARA	0	0	0	66
: Hampton Roads to Yokohama	0	0	0	0
: Richard's Bay to ARA	129	11	0	0
: Richard's Bay to Yokohama	-35	0	0	0
: Matola to ARA	-100	0	0	-41
: Matola to Yokohama	0	0	0	0
Botswana's Capital Cost up 25%				
: Gladstone to ARA	0	0	0	0
: Gladstone to Yokohama	31	50	93	159
: Hampton Roads to ARA	0	0	0	66
: Hampton Roads to Yokohama	0	0	0	0
: Richard's Bay to ARA	129	94	0	+
: Richard's Bay to Yokohama	-35	-85	0	-25
: Matola to ARA	-100	-100	0	-100
: Matola to Yokohama	0	0	-100	-100

Source: Based on model simulations by the author.

The two major unknowns in this model are the capital costs associated with the development of rail and port infrastructure. These have been accommodated by assuming that the rail charges for transporting coal in South Africa together with the port charges reflect full economic costs in which all of the factors employed in the provision of these services are paid including a provision of profit to the service providers. In the case of the port facilities, this assumption may be sufficient as these are privately owned and operated. In the case of the railway line, which is owned by the South African government, the assumption may not hold as these exporters earn much needed foreign currency and may therefore enjoy government subsidies in the form of lower rail rates to encourage such coal exports. For this reason, the model sensitivity analysis on rail costs is intentionally made to include orders of magnitude increases in these costs in an attempt to accommodate a wider range of "what if" questions on the role of rail transportation costs and hence the geographical location of the country.

6.3 Forecasting With the Spatial and Dynamic Optimization Model

The purpose of this section is to apply the spatial and dynamic optimization model to forecast the likely future development of Botswana's coal deposits beginning from a base year of 2000 and extending to 2010 in five-year intervals. The base case forecast assumptions are as follows:

1) Australia's future exports to Asia and South Africa's future exports to Western Europe do not fall below their year 2000 levels while they can take on any positive value in those markets in which these countries are marginal suppliers,
2) exports from the US are free to take on any value in both markets as the country is a marginal supplier to both markets, and
3) Botswana's exports are constrained by export port capacity, which is assumed to be 5.0 million mtce for Matola in 2005 and 20.0 million in 2010.

The first assumption preserves the existing export quantities, which may be protected from competition by long term contracts, but foresees a situation in which importers would want to minimize their future import bills by buying from the lowest cost entrants into the industry. The last assumption assumes that if a decision to proceed with an export mine where made at the end of 2002, then in the remaining time, 2003 – 2005, from the first period of forecast, Mmamabula coal could be exported through Matola after the necessary investment on mine, rail and port capacity is made. While the model mine is that for a mechanized continuous room and pillar operation, the existence of strippable reserves at Mmamabula presents a possibility for developing an export steam coal mine by 2005. Due to the distance from Mmamabula to Walvis Bay, this route is assumed to be only available in 2010.

6.3.1 Results of the Base Case Forecast Scenario

The results of the base case forecast scenario are provided on Table 6.3 and these predict the following ranking among the four exporters for exports to Western Europe: 1) South Africa, 2) Botswana, 3) the United States and 4) Australia. In the Asian market, the forecast rankings are: 1) Australia, 2) South Africa, 3) Botswana and 4) the United States. Botswana's market share in Asia would be 12% in 2010. This translates into 10.772 million mtce 2010. The export port for this coal is Matola in Mozambique. On the Western European market, Botswana's market share would be 12% and 23% in 2005 and 2010 respectively, which translates into 5.0 million and 9.228 million mtce for these years respectively. All of Botswana's coal would be exported through the port of Matola in Mozambique.

In the Asian steam coal markets, Australia's forecast residual market share declines from its actual level of 89% in 2000 to 73% and 61% in 2005 and 2010 respectively while that for South Africa rises from 7% in 2000 to 27% for both 2005 and 2010 respectively. The US is eliminated from this market, losing its 5% market share held in 2000. On the Western European markets, both Australia and the United States are eliminated. South Africa's forecast market share is 88% and 77% in 2005 and 2010 respectively and during these years, the remainder of this market share is taken up by Botswana. These results were subjected to a sensitivity analysis for scenarios shown on Table 6.5 below.

Table 6.4 provides the forecast f.o.b. steam coal prices for the net exporters in the model together with those for some of the emerging exporters for the year 2000 only. The relative competitiveness ranking based solely on the f.o.b. prices for 2000 and with the export unit value expressed in year 2000 U.S. Dollar per mtce and shown in brackets are: Indonesia ($24.22), South Africa ($26.84), Colombia ($28.10), Botswana ($28.89), Australia ($31.10) and the United States ($38.08). Over the forecast period, the competitiveness ranking of the ports for the net exporters in the model is as follows: 1) Matola, 2) Richard's Bay, 3) Walvis Bay, 4) Gladstone / New Castle and 5) Hampton Roads.

Table 6.3 Forecast Results of the Base Case Scenario Showing Exporters' Market Shares

	Australia	South Africa	Botswana	USA
Asian Market				
Actual 2000	89.0	7.0	0.0	5.0
Base Case Forecast Scenario Shares				
: 2005	73.0	27.0	0.0	0.0
: 2010	61.0	27.0	12.0	0.0
Western European Market				
Actual 2000	17.0	76.0	0.00	7.0
Base Case Forecast Scenario Shares				
: 2005	0.0	88.0	12.0	0.0
: 2010	0.0	77.0	23.0	0.0

Source: Based on model simulations by the author.

Table 6.4 Relative Competitiveness of F.O.B. Prices for Net Exporters (year 2000 US $ per mtce)

Historical Period		Forecast Period	
Route	**2000**	**2005**	**2010**
Indonesia	24.22	na	na
South Africa			
: Matola	24.75	22.68	23.15
: Richard's Bay	26.84	23.92	24.39
: Walvis Bay	42.47	33.17	33.64
Colombia	28.10	na	na
Botswana [a]			
: Matola	28.89	26.45	26.92
: Richard's Bay	30.52	27.41	27.88
: Walvis Bay	33.09	28.93	29.40
Gladstone / Newcastle	31.10	40.32	41.17
Hampton Roads	38.08	55.83	56.37

Source: Based on model simulations by the author.

Notes: [a] – Botswana's f.o.b. prices for 2000 are based on South Africa's f.o.b. prices.
- Indonesia and Colombia are added for comparison in 2000 only

Table 6.5 Scenarios for Sensitivity Analyses of the Base Case Forecast Results

Scenario	Rail Transport Cost	Mine Capital Cost	Steam Coal Import Demand
1	50%		
2	100%		
3	200%		
4		10%	
5		20%	
6		25%	
7			-20%
8			+20%

6.3.2 Sensitivity Analysis of the Base Case Forecast Results

A sensitivity analysis was conducted to observe changes to the forecast optimal market shares, choice of export port, size of mine and timing of development for Botswana's coal deposits that would result from changes in rail transportation costs, capital costs for mine development and the level of import demand (see Table 6.5 above). The results of the sensitivity analyses are as follows:

1. In scenarios 1, 2 and 3, the optimal levels of Botswana's steam coal exports are least sensitive to rail transportation costs to the extent that a 200% increase in these costs still results in Botswana's market share in Western Europe being at 12% or 5.0 million mtce, and 23% or 9.23 million mtce, in 2005 and 2010 respectively. In the Asian market, Botswana's market share declines marginally to 10% from 12% in the base case in 2010. The export tonnage in 2010 is 8.70 million mtce. The size of cumulative export mine capacity declines from 20.05 million mtce under the base case scenario to 17.97 million mtce in 2010.
2. In scenario 4, when capital costs are 10% above their base case levels, there is a 10% decline in Botswana's coal exports in 2010. This decline occurs for exports to the Asia market only. Scenario 5 shows that if these costs are 20% higher than in the base case forecast scenario, exports decline by 75% in 2010. Botswana loses its entire market share in Western Europe while in Asia its share declines to 6% from the 12% it held in the base case forecast scenario. The export mine capacity is 5.0 million mtce in 2005 and 5.04 million mtce in 2010. In scenario 6, when capital costs are 25% above the level for base case forecast scenario, Botswana's steam coal is no longer competitive in both markets and the country is eliminated out of the model (see Tables 6.6 and 6.7 below).

3. In scenario 7, when the steam coal import demand is 20% lower than estimated, this does not affect the size of export mine at Mmamabula, which remains at 5.0 million mtce in 2005 and rises to 20.0 million mtce in 2010.
4. In scenario 8, a higher demand than that estimated expectedly shows that the simulated export port capacity for Mmamabula production would become a binding constraint on the size of mine to be developed. Also the port capacity constraint for South Africa means that the additional demand has to be met by other exporters not facing any of these constraints. The model demonstrates the role of marginal supplier that the United States plays in this model. Its exports to Western Europe are 12.32 million mtce in 2010, which is the only time that the model selects US exports.
5. The port of Matola offers the advantage of serving both the Asian and Western European markets and this is the port selected by the model.

Table 6.6 Distribution of Market Share in Asia Due to Changes in Botswana's Capital Costs (%)

	Australia	South Africa	Botswana	USA
Asian Market				
Actual 2000	89.0	7.0	0.00	5.0
Base Case Forecast Scenario Shares				
: 2005	73.0	27.0	0.0	0.0
: 2010	61.0	27.0	12.0	0.0
Capital costs up 10%				
: 2005	73.0	27.0	0.0	0.0
: 2010	61.0	29.0	10.0	0.0
Capital costs up 20%				
: 2005	73.0	27.0	0.0	0
: 2010	65.0	29.0	6.0	0
Capital costs up 25%				
: 2005	80.0	20.0	0.0	0
: 2010	71.0	29.0	0.0	0

Source: Based on model simulations by the author.

Table 6.7 Distribution of Market Share in Western Europe Due to Changes in Botswana's Capital Costs (%)

	Australia	South Africa	Botswana	USA
Western European Market				
Actual 2000	17.0	76.0	0.00	7.0
Base Case Forecast Scenario Shares				
: 2005	0.0	88.0	12.0	0.0
: 2010	0.0	77.0	23.0	0.0
Capital costs up 10%				
: 2005	0.0	88.0	12.0	0.0
: 2010	0.0	77.0	23.0	0.0
Capital costs up 20%				
: 2005	0.0	88.0	20.0	0.0
: 2010	0.0	77.0	0.0	23.0
Capital costs up 25%				
: 2005	0.0	100.0	0.0	0.0
: 2010	0.0	77.0	0.0	23.0

Source: Based on model simulations by the author.

6.4 Conclusions

In this chapter, sensitivity analyses were conducted to check the robustness of the base case simulation scenario results by varying rail transportation costs and capital expenditure costs for mine development on the Mmamabula coal deposits. The results of the sensitivity analysis confirm those of the response surface methodology wherein rail transportation costs do not have a significant effect on Botswana’s exports while these are sensitive to capital costs. If capital costs are 25% higher than in the base case simulation scenario, this eliminates Botswana’s exports from the model.

The spatial and dynamic optimization model was applied to forecast the optimal market shares, choice of export port, size of mine and timing of development for Botswana’s coal deposits for the years 2005 and 2010. The forecast mine size and timing of mine development are 5.0 million mtce in 2005 and 20.05 million mtce in 2010. This was followed by a forecast sensitivity analysis of the optimal forecast steam coal exports to changes in rail transportation costs, capital costs for mine development and the level of import demand for the years 2005 and 2010. The sensitivity results confirmed the simulation results by identifying the Western European steam coal markets as the one where Botswana’s coal exports would have a competitive advantage. The analysis also selects the port of Matola over Walvis Bay for exports to both Asia and Western Europe.

CHAPTER 7

CONCLUSIONS AND FUTURE RESEARCH

7.1 Introduction

In this study, we attempted to analyze the world steam coal trade with the specific objectives of determining the scale of development and time schedule of coal exports likely to be forthcoming from Botswana and the land routes for these exports to existing and simulated ports at Matola in Mozambique, Richard's Bay in South Africa and Walvis Bay in Namibia, and to determine the appropriate policy, where such may be necessary, to encourage the development of infrastructure for exporting Botswana's steam coal.

We constructed a model of the world steam coal trade that included the major exporters and importers who account for a substantial share of this trade. The model consisted of four exporting countries: Australia, South Africa, United States and Botswana, where the latter was included in the model simulation to determine the competitiveness for export of its steam coal deposits. The demand markets for the steam coal trade included two countries in Asia: Japan and South Korea, and seven countries in Western Europe, namely: Belgium, France, Germany, Italy, Netherlands, Spain, and the United Kingdom.

This study involved two stages of analysis, the first of which was to carry out econometric modeling of demand and supply functions for each of the countries in the model and then to compute net import demand for steam coal by countries in Asia and Western Europe as defined above. This stage also involved the estimation of the long run marginal cost functions for the net exporting countries in the model.

The econometric modeling of country supply, demand and the long run marginal cost functions for the net exporters of the model, were subjected to non-parametric validation techniques involving the following: the mean absolute percent error, MAPE, the Theil inequality coefficient, U, and its bias component of the error, the adjusted R-squared, sensitivity to starting period in the case of the long run marginal cost function, and comparison of the export and import values with both the historical values and also those values obtained by other studies. These econometric models for supply, demand and the long run marginal costs function were found to have good explanatory power but limited forecasting ability. For this reason, the forecasts of supply and demand were conducted for a short out-of-sample forecast period of 10 years from 2000 to 2010.

The second stage of this study had two purposes: 1) to simulate the competitiveness of Botswana's steam coal exports in the defined markets in Asia and Western Europe, and 2) to forecast the optimal size of capacity development, timing for future mine development on Botswana's coal deposits, choice of export port among Matola in Mozambique, Walvis Bay in Namibia and Richards Bay in South Africa. The first purpose required that the long run marginal cost functions be transformed into the quantity formulation and then substituted into the objective function of the spatial and dynamic optimization model. Additional components of the objective function included: equations for estimating the capital cost of development for a model steam coal mine, rail transportation costs, and maritime transportation costs. The objective function minimizes the sum of the discounted costs of capital expenditure, variable supply costs, rail transportation costs and maritime transportation costs over a given time horizon. The use of discounting is meant to properly account for the time value of money and project risk in the objective function. This model is applied to solve for the temporal and spatial distribution of production capacity to meet domestic demand for steam coal in the net exporting countries in the model and also to solve for the flow of steam coal exports to markets in Asia and Western Europe. The model simulation period extends from 1990 to 2010, in five-year intervals as follows: 1991-1995, 1996-2000, 2001-2005 and 2006-2010. The results are stated in both market shares and physical tonnages of coal to determine Botswana's competitiveness in the steam coal markets of Asia and Western Europe.

The second purpose was to apply this spatial and dynamic optimization model to forecast the likely future development of Botswana's coal deposits beginning from a base year of 2000 and extending to 2010 in five-year intervals as in the simulation model.

7.2 Summary of Results

The simulation results for the base case scenario demonstrate that Botswana's coal would have been competitive in the Western European steam coal markets in the past and that they would have remained so in the future. The market share, based on the residual steam coal demand in the importing countries of the model, would have grown from 35% in 1995, 48% in 2000 and 62% in 2010 in the Western European markets. In 2005, all of Botswana's coal would have been exported to Asia. The country would have been the leading supplier to Western Europe. In the Asian markets, Botswana's exports would have begun in 2005 at 39% and declining to 17% in 2010. The country would have been in third position ahead of the United States in this market with Australia losing the leading position to South Africa. The export capacity for steam coal would have grown from 10.0 million mtce in 1995 to 40.0 million mtce in 2010.

An experimental design approach was adopted to validate the model by determining which of the four factors, capital costs, variable supply costs, rail transportation costs and maritime transportation costs would have a significant effect on Botswana’s exports. The results indicated that capital costs have a significant effect on the level of competitiveness of Botswana’s coal. The traditional sensitivity analysis was conducted on the results of the base case simulation scenario. The results of the sensitivity analysis confirmed those from the experimental design approach which indicate that Botswana’s steam coal exports are insensitive to rail transportation costs but are sensitive to changes in capital costs. They also indicate that Matola would be a preferred export port for both the Asian and Western European markets.

The spatial and dynamic optimization model was applied to forecast the likely future development of Botswana’s coal deposits beginning from a base year of 2000 and extending to 2010, in five-year intervals. The results of the base case forecast scenario predicts the following ranking among the four exporters for exports to Western Europe: 1) South Africa, 2) Botswana, 3) the United States and 4) Australia. In the Asian market, the forecast rankings are: 1) Australia, 2) South Africa, 3) Botswana and 4) the United States. The model selects the port of Matola for exports to both Asia and Western European over the forecast horizon. The suitability of the port of Matola for exports to both of these markets presents opportunities for Botswana to take advantage of its geographical location in relation to the two major steam coal markets in the world. The size of mine and timing of development in the base case forecast scenario are 5.0 million mtce in 2005 and 20.05 million mtce in 2010. The market shares in Western Europe are 12% in 2005 and 23% or 5.0 million and 9.23 million mtce in 2005 and 2010 respectively. The market share in Asia is 12% or 10.77 million in mtce in 2010.

The results of the base case forecast scenario were subjected to a sensitivity analysis to observe changes to the forecast optimal market shares, choice of export port, size of mine and timing of development for Botswana's coal deposits that would result from changes in rail transportation costs, capital costs for mine development and the level of steam import demand. The results are summarized below:

1. In scenarios 1, 2 and 3, the optimal levels of Botswana's steam coal exports are least sensitive to rail transportation costs to the extent that a 200% increase in these costs still results in Botswana's market share in Western Europe being at 12% or 5.0 million mtce, and 23% or 9.23 million mtce, in 2005 and 2010 respectively. In the Asian market, Botswana's market share declines marginally to 10% from 12% in the base case in 2010. The export tonnage in 2010 is 8.70 million mtce. The size of cumulative export mine capacity declines from 20.05 million mtce under the base case scenario to 17.97 million mtce in 2010.
2. In scenario 4, when capital costs are 10% above their base case levels, there is a 10% decline in Botswana's coal exports in 2010. This decline occurs for exports to the Asia market only. Scenario 5 shows that if these costs are 20% higher than in the base case forecast scenario, exports decline by 75% in 2010. Botswana loses its entire market share in Western Europe while in Asia its share declines to 6% from the 12% it held in the base case forecast scenario. The export mine capacity is 5.0 million mtce in 2005 and 5.04 million mtce in 2010. In scenario 6, when capital costs are 25% above the base case forecast scenario, Botswana's steam coal is no longer competitive in both markets and the country is eliminated out of the model.

3. In scenario 7, when the steam coal import demand is 20% lower than estimated, this does not affect the size of export mine at Mmamabula, which remains at 5.0 million mtce in 2005 and rises to 20.0 million mtce in 2010.
4. In scenario 8, a higher demand than that estimated expectedly shows that the simulated export port capacity for Mmamabula production would become a binding constraint on the size of mine to be developed. Also the port capacity constraint for South Africa means that the additional demand has to be met by other exporters not facing any of these constraints. The model demonstrates the role of marginal supplier that the United States plays in this model. Its exports to Western Europe are 12.32 million mtce in 2010, which is the only time that the model selects US exports.
5. The port of Matola offers the advantage of serving both the Asian and Western European markets and this is the port selected by the model.

7.3 Policy Implications

In the validation section of this study, we demonstrated that the variable supply costs, within the ranges studied, have no significant effect on the level of Botswana's exports. In the event there is a shift in the supply curve due to factors such as a rise in mining wages, such a shift would have to be of an order of magnitude that would not be easy to justify as shift in a policy variable such as wages or other costs of inputs. This suggests that the results of this model would hold under a scenario of rising mining wages for the Southern Africa region. The results of this study can be applied towards policy efforts aimed at encouraging the development of Botswana's coal deposits. We propose the following three areas: 1) the Botswana government policy on the provision of infrastructure, 2) the role of the SADC protocol in regional provision of infrastructure and 3) administrative efforts to disseminate information on coal deposits and also to maintain a model of this type for future policy decisions.

7.3.1 Public Provision of Infrastructure in Botswana

There are two approaches to the provision of public infrastructure; the passive strategy, in which governments provide infrastructure to eliminate excess demand, and the active strategy, whereby governments provide infrastructure ahead of private investment so as to encourage the latter (Rietveld, 1989 p255).

In the Botswana case, the provision of public infrastructure is planned under the framework of the 5-year National Development Plans. However, the provision of infrastructure for mineral sector projects is provided under the country's mineral development policy. This represents a passive strategy in which infrastructure is provided once its use is definite. This approach has the advantage of lessening the risk of under-utilization of infrastructure. The direct beneficiaries from such infrastructure are then charged user fees that permit the commercial operation and maintenance of the infrastructure. From the mining project's perspective, the provision of infrastructure by government reduces the project's upfront capital cost as it excludes infrastructure costs, resulting in more favorable financial returns to the project.

Other infrastructure projects in the transport sector, specifically the highway network, show the adoption of an active stance by government. For instance, the Trans-Kalahari highway that links South Africa's industrial heartland and traverses about 1000 km of Botswana territory provides an alternative link to Namibia and Europe through the seaport of Walvis Bay. This highway also provides a good example of a regional approach to planning infrastructure projects as it involves three regional governments.

This model indicates that Botswana’s coal would be competitive in world steam coal markets and that the lack of a rail and seaport infrastructure could be the main impediments to its exploitation. There is merit in the passive approach that the government has adopted towards infrastructure provision for the mineral industry but it now needs, on the strength of a study such as this one, to deliberately encourage the country’s sole coal producer, Morupule Colliery, to aggressively seek export markets for the country’s coal. For its part, the government could emphasize its current policy of accelerated infrastructure development for specified projects, that have a national benefit, to prospective investors.

7.3.2 The Role of the SADC Protocol on Transport, Communications and Meteorology

In Southern Africa, improved political stability has led to regional cooperation under protocols such as the Southern Africa Development Community’s (SADC) protocol on Transport, Communications and Meteorology. Articles 3.3 and 3.5 of this protocol provide mechanisms and the institutional framework to facilitate the development of infrastructure through approaches that emphasize regional over national interests. Some experiences in regional cooperation include those in the electricity sub-sector, the Southern Africa Power Pool (SAPP), which was formalized in 1995. This has resulted in inter-connections between national grids in the region, thus minimizing the investment burden that would otherwise have to be met by individual governments. A similar argument can be made to support the merits of a regional approach to the development of railway infrastructure for the exploitation of the region’s vast coal deposits.

There would be added advantages in the regional provision of coal transportation infrastructure as this might minimize the selfish rent-seeking behavior that might exist where each country sets their rail tariffs for coal exports. Many researchers have contributed in the debates regarding the role of infrastructure in industrialization and economic development. These debates agree in the main that there is a positive relationship between infrastructure and economic development but differ with regard to the magnitude of this impact (see Bell and McGuire, 1997, Munnell, 1992, for a review). These are some of possibilities that need to be factored into a decision to provide railway infrastructure for Botswana's steam coal exports under a regional as opposed to a national approach.

The Botswana government could therefore employ the results of this study towards the justification of a regional approach to the provision of both rail and port infrastructure that would make the development of Botswana's coal possible. The competitiveness results indicate that Botswana would not necessarily be weakening South Africa's export position as the region enjoys a comparative cost advantage in the supply of coal.

The next steps would include the identification by policy makers of those issues of concern to steam coal importing countries and the discovery of ways to address them. The country has accumulated a wealth of experience and success in an approach such as this one due to the recent revision of its mining law, where it was successful in obtaining quite comprehensive input concerning those sections of the law that had stood in the way of these companies' investment in Botswana's minerals sector. The provision of railway infrastructure could encourage mining companies to take advantage of the country's friendly mining law and very competitive fiscal regime to develop Botswana's coal deposits for the export markets.

7.3.3 Role of Mineral Policy Makers

The existence of a model such this one would enhance the capabilities of mineral administrators regarding both administrative and mineral policy issues. For instance, as the base forecast results of this model indicate that rail transportation costs at the levels applying to South

African coal exports would not impede Botswana’s exports, this would then force policy makers to hypothesize and identify factors that impede these exports. Also, there would be a need for maintaining current information on the country’s coal reserves. The information on the size of coal resources in Botswana is not easily available, and for this reason, it is South Africa and Zimbabwe that are perceived to host coal resources in Africa.

The government has sponsored many studies to investigate the competitiveness of Botswana’s coal and it would derive additional benefits if these reports were accessible to researchers and prospective investors.

7.4 Conclusions

We draw the following conclusions about the international competitiveness of Botswana’s coal:

1. Botswana’s coal is competitive in world steam coal markets;
2. Rail transportation costs, at rates that apply on South Africa’s steam coal would not discourage exports of coal from Botswana;
3. Variable costs at levels applying to similar mines in South Africa are not a significant factor to the level of exports. Botswana’s long run marginal cost function is such that any supply shifts due to factors such as rising wages would have to be of orders of magnitude before this advantage would be eroded;
4. The level of exports is most sensitive to capital costs and therefore this indicates that these costs would need to be defined at a greater level of accuracy to fully determine their role on the variability of exports;
5. The port of Matola is selected by the model for exports to both Western Europe and Asia;

6. There is merit in applying the results of this study towards justifying Botswana’s case for the development of rail and port infrastructure at the regional level and within the terms of the SADC protocol on Transport, Communications and Meteorology, and
7. The spatial and dynamic model developed for this study could act as a base upon which a coal model for Botswana could be built. We have shown in this study that coal models have been applied for a variety of policy issues similar to the ones that concern policy makers in Botswana. For instance, whether or not the market conditions are favorable for developing Botswana’s coal and if so what role government could play in encouraging the exploitation of the country’s coal deposits.

This study has emphasized the worrisome issue of why the country has met with very little success in developing its coal resource base of about 100 billion metric tons of coal equivalent with about 20 billion metric tons of these in the proven category. Furthermore, some of these proven steam coal reserves are strippable. This resource base translates into two-thirds of all the coal resources in Africa, a fact that should bolster the country’s attractiveness for possible new coal development projects.

7.5 Recommendations for Future Research

The choice of countries to include in the model was limited by the availability of data and with the passage of time, if data becomes available for what are termed emerging exporting countries such as Colombia, China, Indonesia, India and Venezuela, their inclusion would increase the total market share for simulation.

The model assumption of a perfectly competitive industry facilitates the specification and estimation of the country supply and demand functions, as there is no interaction among these.

This assumption has been found to hold in the case of the United States steam coal industry (Yang, Huang and Sohng, 2002). But the US steam coal industry is not driven by exports and may therefore not reflect the behavior among those countries for which the industry is export driven. It is therefore very likely that where the steam coal industry is driven by exports and there are a relatively few players of different sizes, then the assumption of a perfectly competitive industry may not hold. For this reason, future research should model the world steam coal trade under other competition models such as the Stackelberg leader follower model or non-cooperative Cournot-oligopoly competition. Solution algorithms of the variational inequality problem could then be applied to solve such problems.

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Appendix A. Results of the Econometric Estimation of the Country Supply and Demand Functions for Steam Coal (All variables in log first differences).

Variable	**Japan: Demand**	**Japan: Supply**	**Belgium: Demand**	**Belgium: Supply**	**France: Demand**
Constant	0.006 (0.216)	-0.216*** (-4.058)	0.076* (1.775)	-0.159** (-2.493)	-0.042 (-0.641)
Pcoal	-0.355 (-1.585)		1.507** (2.406)	0.094 (0.228)	1.617* (1.994)
Pgas					
Poil	0.262* (1.776)		0.122 (0.852)		
GDP	0.204 (1.058)				-1.087** (-2.342)
Dcoal (-1)			-0.215 (-0.778)		-0.4216 (-1.477)
Trend	0.361*** (4.463)	0.868*** (3.166)		0.276 (0.891)	0.647 (1.118)
Wage		0.163 (1.039)		-0.718* (-1.954)	
Interest				0.1530 (0.626)	
Scoal (-1)		(-0.823)* (-1.965)			
R^2_adj.	0.56	0.34	0.30	0.21	0.10
M.A.P.E. %	5.047	13.29	25.85	16.56	23.62
Theil I. C.	0.031	0.093	0.134	0.096	0.140
Bias	0.008	0.163	0.255	0.358	0.172
Variance	0.956	0.322	0.295	0.261	0.171
Covariance.	0.036	0.514	0.450	0.381	0.657
DW	1.77	1.98	2.07	2.12	2.24
N	16	16	14	20	16

Source: Based on models estimated by the author.
Key: (***), (**), (*) - 1%, 5% and 10 % level of significance respectively.

Appendix A. (cont'd) Results of the Econometric Estimation of Country Supply and Demand Functions for Steam Coal (All variables in log first differences)

Variable	France: Supply	Germany: Demand	Germany: Supply	Italy: Demand	Netherlands: Demand
Constant	-0.076*** (-2.300)	-0.050** (-2.533)	-0.156*** (-5.230)	-0.073 (-1.113)	-0.032 (-0.391)
Pcoal	0.295 (1.556)	-0.200** (-2.595)	-0.102 (-1.480)	-0.110 (-0.366)	-0.014 (-0.031)
Pgas		0.314* (1.944)			0.204 (0.408)
Poil		-0.207** (-2.118)		0.473* (1.984)	0.240 (1.202)
GDP		0.295 (1.525)		0.374 (1.180)	0.024 (0.059)
Trend	0.189 (1.589)		0.514*** (3.029)	0.842** (2.827)	0.840** (2.437)
Dcoal (-1)		-0.475** (-2.635)			
Wages			0.398** (2.488)		
Interest					
Scoal (-1)			-0.664*** (-3.618)		
R^2_adj.	0.10	0.49	0.49	0.29	0.25
M.A.P.E. %	6.74	7.40	6.045	12.225	22.72
Theil I. C.	0.034	0.043	0.030	0.083	0.110
Bias	0.296	0.006	0.082	0.242	0.269
Variance	0.021	0.023	0.247	0.537	0.104
Covariance	0.683	0.971	0.671	0.221	0.627
DW	2.06	2.56	2.30	2.10	2.39
N	20	19	19	17	20

Source: Based on models estimated by the author.
Key: (***), (**), (*) - 1%, 5% and 10 % level of significance respectively.

Appendix A. (cont'd) Results of the Econometric Estimation of Country Supply and Demand Functions for Steam Coal (All variables in log first differences)

Variable	Spain: Demand	Spain: Supply	UK: Demand	UK: Supply
Constant	-0.015 (-0.430)	0.015 (1.265)	0.041 (0.406)	-0.115 (-1.051)
Pcoal	0.060 (0.323)	0.134* (1.751)	2.485** (2.301)	0.821 (0.937)
Pgas	0.151 (1.007)		-0.573 (-1.294)	
Poil	0.016 (0.082)			
GDP	0.177 (1.131)		0.141 (0.122)	
Trend	0.399** (2.304)			0.506 (0.924)
Dcoal (-1)			-0.648** (-2.709)	
Wage		-0.117 (-1.407)		0.841 (1.267)
Interest		-0.024 (-1.234)		
Scoal (-1)		0.484** (2.144)		-0.359 (-1.551)
R^2_adj.	0.21	0.30	0.36	0.35
M.A.P.E. %	12.97	8.55	7.874	4.631
Theil I.C.	0.082	0.057	0.058	0.026
Bias	0.390	0.398	0.174	0.017
Variance	0.116	0.504	0.054	0.047
Covariance.	0.494	0.098	0.772	0.936
DW	2.01	2.29	2.61	2.65
N	17	16	16	19

Source: Based on models estimated by the author.
Key: (***), (**), (*) - 1%, 5% and 10 % level of significance respectively.

Appendix A. (cont'd) Results of the Econometric Estimation of Country Supply and Demand Functions for Steam Coal (All variables in log first differences)

Variable	**Australia: Demand**	**Australia: Supply**	**S. Africa: Demand**	**S. Africa: Supply**	**U.S.A.: Demand**	**U.S.A.: Supply**
Constant	0.051***	0.041	0.007	0.005	0.030	0.017
	(3.001)	(0.909)	(0.413)	(0.323)	(1.144)	(0.705)
Pcoal	-0.153*	0.135	0.0916		-0.0760	
	(-1.719)	(0.467)	(0.860)		(-0.151)	
Pgas						
Poil						
GDP			-0.129			
			(-0.794)			
Trend	-0.084	0.442***	0.188**			
	(-0.958)	(3.028)	(2.32)			
Dcoal (-1)	-0.176				-0.649***	
	(-0.754)				(-3.150)	
Wage		-0.445				
		(-1.483)				
Interest						
Scoal (-1)				-0.153		-0.608**
				(-0.643)		(-2.862)
Capacity				1.109**		0.5976
				(2.482)		(0.598)
R^2_adj.	0.04	0.32	0.21	0.22	0.36	0.32
M.A.P.E. %	1.98	6.920	3.13	1.92	4.275	4.098
Theil I.C.	0.011	0.041	0.016	0.010	0.022	0.022
Bias	0.233	0.001	0.286	0.293	0.145	0.109
Variance	0.023	0.004	0.001	0.660	0.072	0.008
Covariance	0.744	0.985	0.713	0.047	0.783	0.883
DW	1.68	2.46	2.1	2.15	2.22	2.13
N	19	20	20	20	16	16

Source: Based on models estimated by the author.
Key: (***), (**), (*) - 1%, 5% and 10 % level of significance respectively.

Appendix B. Results of the Econometric Estimation of the Long Run Marginal Cost Functions for Steam Coal (1980-1997) (All variables in first differences)

Variable	**Australia**	**South Africa**	**United States**
Constant	-7.947**	1.964	-0.860
	(-1.793)	(0.671)	(-0.840)
Wage	5.534***	4.045**	1.107
	(3.27)	(2.369)	(0.920)
Supply	7.06x10^{-5}	6.51x10^{-5}	7.32x10^{-6}
	(0.177)	(0.186)	(0.165)
Price (-1)	0.232	0.365**	0.548**
	(1.317)	(2.367)	(2.564)
Capacity	-0.000172	-0.000684	-2.69x10^{-6}
	(-0.257)	(-1.132)	(-0.506)
R^2_adj.	0.42	0.61	0.32
M.A.P.E. %	19.32	3.26	2.03
Theil	0.158	0.026	0.013
Bias	0.326	0.327	0.345
Variance	0.023	0.001	0.653
Covariance	0.651	0.672	0.002
DW	1.83	2.30	1.83
N	17	17	17

Source: Based on models estimated by the author.
Key: (***), (**), (*) - 1%, 5% and 10 % level of significance respectively.

Appendix C. Results for Time Series Estimation of Sea Freight Costs Along Trade Routes for Sea Vessels of Size Greater Than 100 000 Dead Weight Tons (All variables in log differences except for USA which is in logs)

Variable	Gladstone to Yokohama	Gladstone to ARA	Richards Bay [(a)] to Yokohama	Richards Bay to ARA	Hampton Roads to Yokohama	Hampton Roads to Yokohama
Constant	-0.124 (-1.418)	-0.159* (-2.087)	-0.277*** (-3.323)	-0.258** (-2.812)	-0.389 (-0.483)	-0.370 (-0.375)
Poil	0.344 (1.601)	0.310 (1.771)	0.181 (0.744)	0.141 (0.538)	0.552* (2.120)	0.604* (1.973)
Freight(-1)	-0.077 (-0.282)	-0.577* (-1.932)	-0.638** (-2.729)	-0.720** (-2.379)	0.375 (1.690)	0.486** (2.318)
Trade [(b)]	2.280 (1.731)	2.608** (2.249)	4.529** (2.962)	4.542** (2.684)		
Adj. R-sq.	0.24	0.41	0.62	0.50	0.36	0.42
DW	1.67	1.54	1.06	1.47	1.9	1.72
N	16	16	12	12	15	15

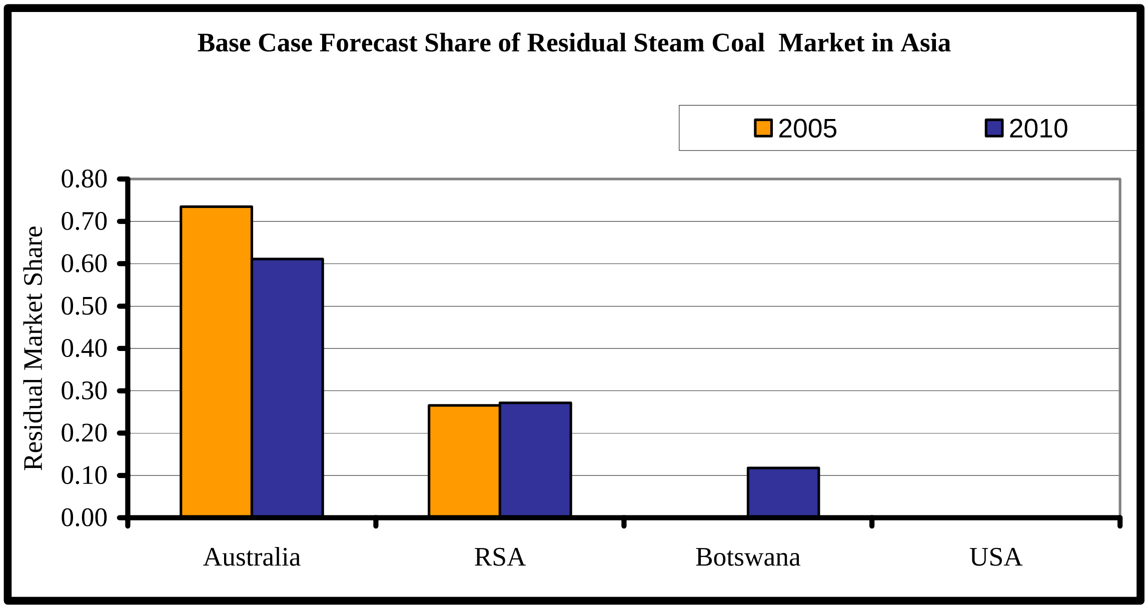
Source: Based on models estimated by the author.
Key: (***), (**), (*) - 1%, 5% and 10 % level of significance respectively.
Notes: [(a)] – This sea freight cost equation will apply to charges exported through the ports of Matola and Walvis Bay after adjusting for distances to destination from these two ports.
[(b)] – This is the volume of the seaborne steam coal trade.

Appendix D. Sensitivity Results of the Econometric Estimation of the Long Run Marginal Cost Functions for Steam Coal (1983 – 2000) (All variables in first differences)

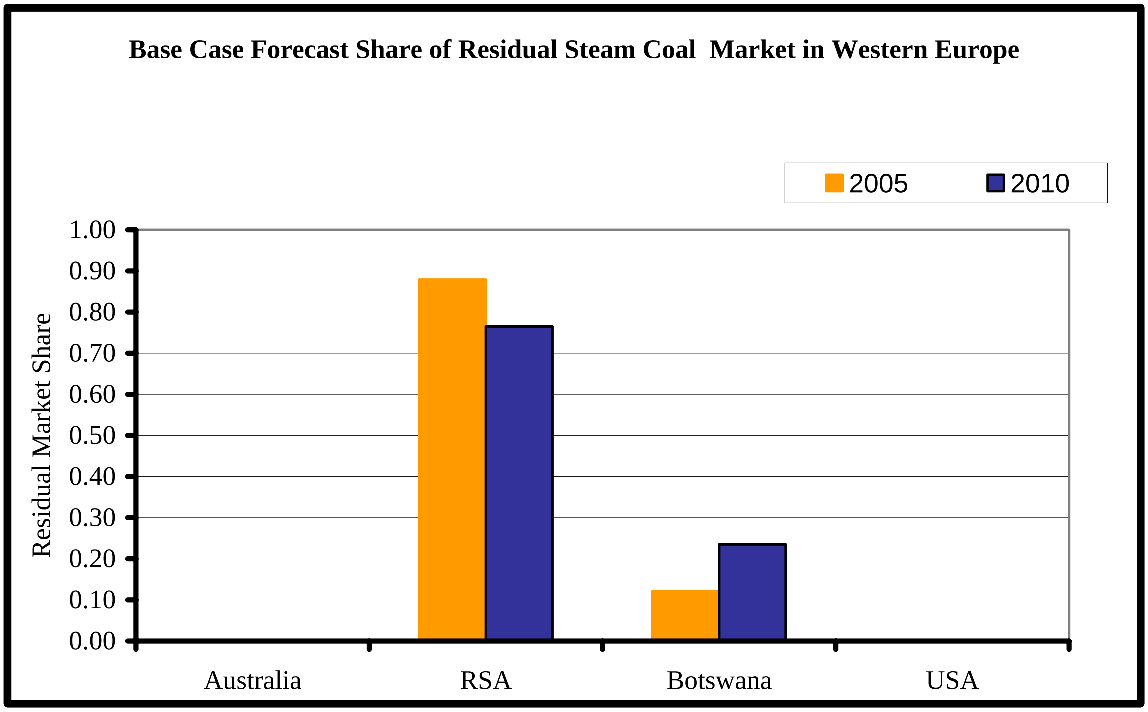
Variable	Australia	South Africa	United States
Constant	-6.330 (-1.392)	2.424 (0.829)	-0.320 (-0.480)
Wage	4.184** (2.595)	4.271** (2.511)	0.893 (1.158)
Supply	0.000137 (0.340)	9.87×10^{-5} (0.385)	5.87×10^{-6} (0.855)
Price (-1)	0.256 (1.140)	0.442** (2.649)	0.369** (2.597)
Capacity	-0.000192 (-0.269)	-0.000755 (-1.256)	-0.000122*** (-3.065)
R^2_adj.	0.25	0.61	0.49
DW	1.41	2.48	1.84
N	17	17	17

Source: Based on models estimated by the author.
Key: (***), (**), (*) - 1%, 5% and 10 % level of significance respectively.

Appendix E. Base Case Forecast Residual Market Shares for Exporters

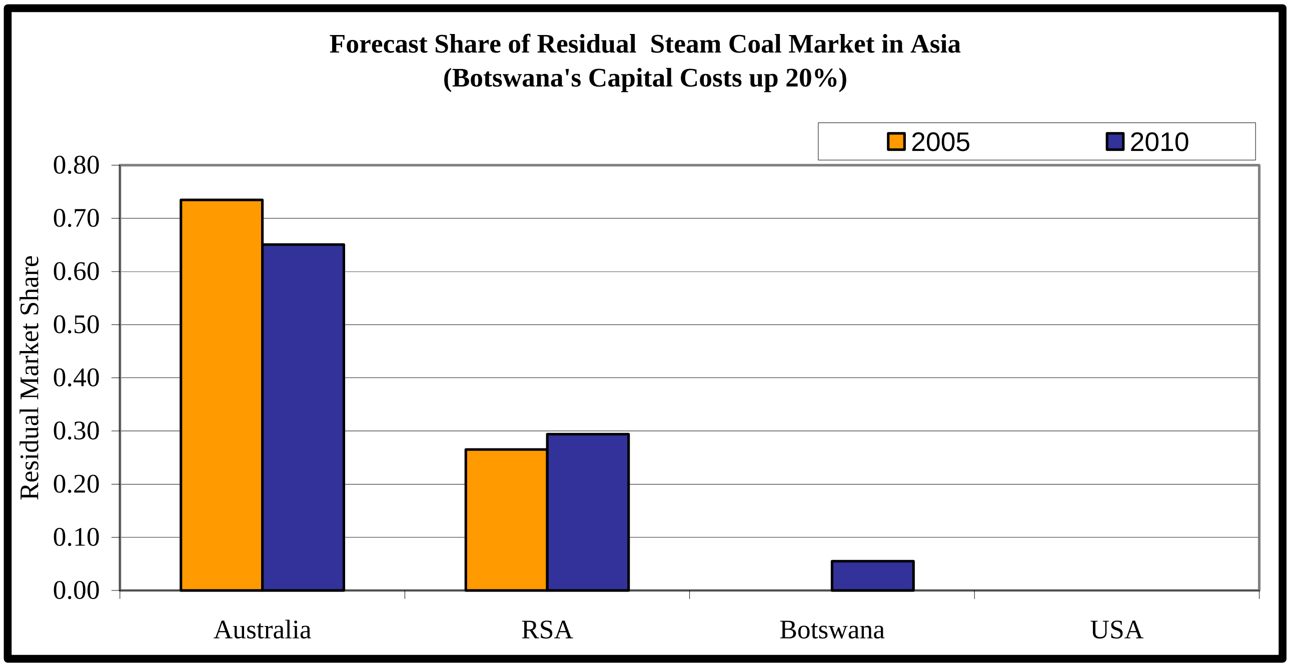

Base Case Forecast Share of Residual Steam Coal Market in Asia

Source: Based on author’s model estimation.

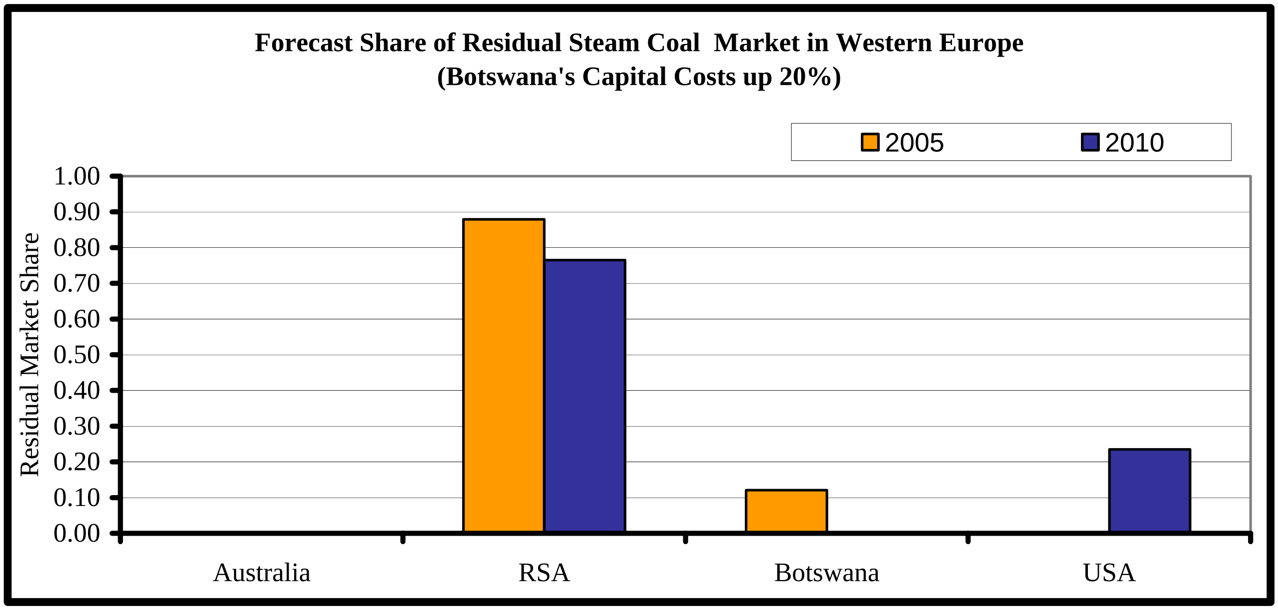

Base Case Forecast Share of Residual Steam Coal Market in Western Europe

Source: Based on author’s model estimation.

Appendix F. The Resultant Market Shares With Botswana's Capital Costs at 20% Above Their Base Case Forecast Levels



Source: Based on author's model estimation.



Source: Based on author's model estimation.

Appendix G. A Simple Multi-period Linear Programming Model of the World Steam Coal Trade

The logical starting point in the development of a spatial and dynamic model that has the four components of capacity addition, variable supply costs, and distribution costs is to begin with a multi-period linear spatial price equilibrium model. Such a model can be applied to simulate the trade flows only under a decision criterion in which the distribution costs are minimized subject to constraints for the transport problem. This is essentially an application of linear programming over a number of periods all of which are independent and could very easily be programmed individually (see Thompson and Thore 1992, p206). The advantage we gain from such an exercise is that we obtain valuable information from the marginal values, which are the Lagrange Multipliers. In an optimization problem in which the analysis is at the industry level, the marginal values represent shadow market prices at the supply and demand regions. The marginal values also provide a quick indication of the extra costs that would be incurred from an additional unit of supply at a given source and also the additional costs for transporting that unit along a given link between the origin-destination pairs.

The objective function in this cost minimization problem is to minimize the sum of rail transport and maritime transportation costs steam coal traded internationally over the period 1990 to 2010. The typical constraints are for observing material availability at the sources and meeting demand at the destination points. The transfer from land to sea-going vessels adds transshipment points with the added condition that inflows balance out with outflows at these nodes. Figure G.1 shows the existing and simulated regional supply of export coal from the Southern Africa region comprising of Botswana and South African coal mines. Almost all existing export coal mines in South Africa exploit coals on the Witbank coalfield in the Mpumalanga province. There is one large-scale colliery in the Northern province that produces coal for both the domestic and export markets. A rail link from the town of Witbank to the Indian Ocean seaport of Richards Bay, where the coal exporting companies operate a private coal handling export terminal by the same name, provides access to the only dedicated coal-handling terminal in the region. The results from this rail transportation and freight cost minimization problem are shown on tables G-1, G-2 and G-3 below.

Table G-1 shows the shadow values, which in this case represent the shadow costs of supply, for possible exports from Mmamabula declining with time so that in the year 2000, there would be no additional cost of a metric ton of coal equivalent shipped through Richards Bay while it would cost an additional $0.46 and $2.46 to export the same tonnage through Matola and Walvis Bay respectively due to the binding port capacity constraints. This result means that if there were coal available for export from Mmamabula, this would have been competitive enough to be exported through Richard’s Bay in 2000. The model also shows that from 2005 onwards, there is no additional cost for routing Mmamabula’s coal output through the port of Walvis Bay while for the other two ports, there is a slight increase in costs as the Richards Bay port capacity constraint is approached. This transportation problem shows that Walvis Bay would be a cheaper route to export to markets in Western Europe than Richards Bay. The reason for this is that while the land distance is longer than that to Richards Bay, the ocean distance is greatly reduced by exporting from Walvis Bay. This could prove to be of significant advantage as importers also value a shorter delivery time, which would be possible through the Mmamabula - Walvis Bay route (South African National Department of Transport, 1997).

In table G-2, the shadow values indicate a gradual convergence in marginal supply costs between producers in South Africa and Australia. On the other hand, an additional unit of coal produced from Appalachia would not lead to a reduction in costs. Table G-3 reflects the cost advantage that exports from Botswana would have over those from the United States and Australia in the Asian and Western European steam coal markets respectively. These preliminary results are encouraging and justify a more detailed model to take into account elastic coal supply to meet a growing demand in internationally traded steam coal. A non-linear quadratic programming model is thus used to select the timing and size of capacity additions from among the four possible supply countries in the model that would be necessary to meet the given demand for steam coal in the importing countries of the model.

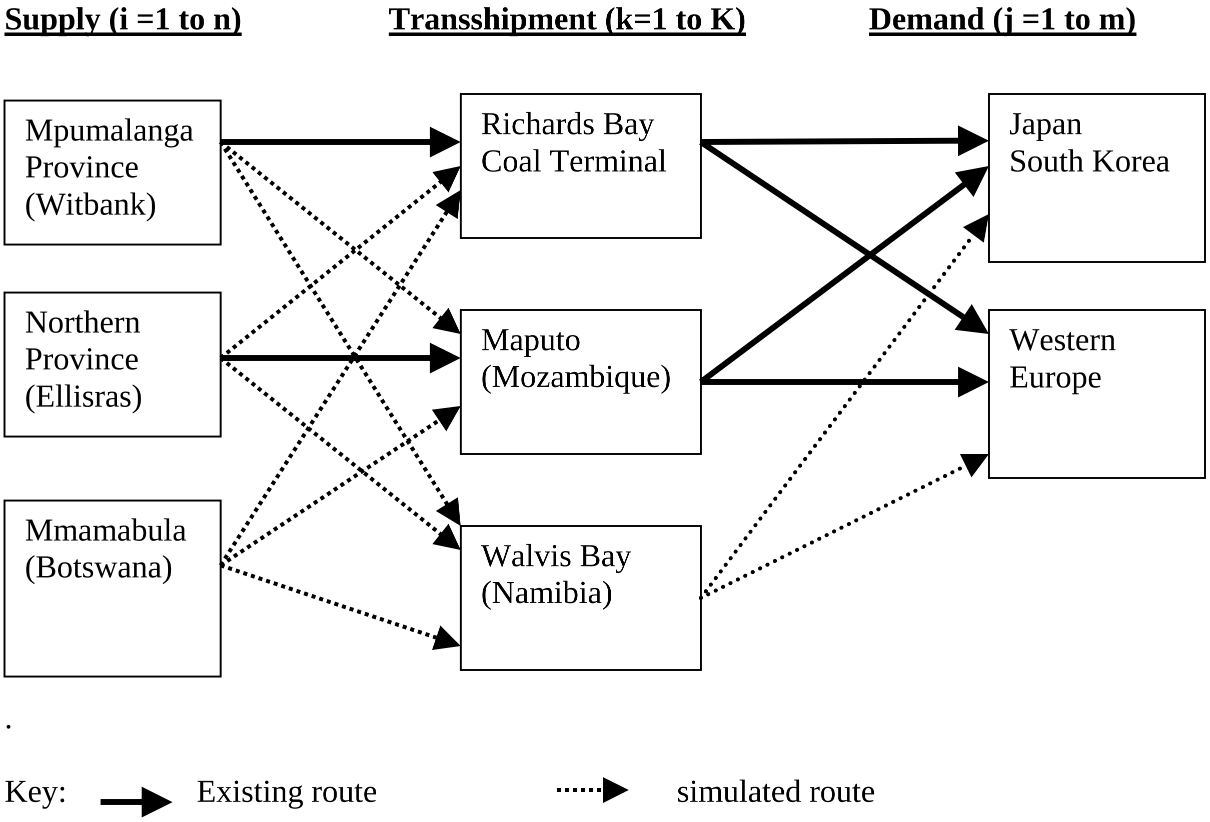


Figure G-1 Existing and Simulated Export Steam Coal Supply and Export Routes for the Southern Africa Region

Table G-1 Shadow Values for Transporting an Extra Unit of Export Coal

From/To	1990	1995	2000	2005	2010
Witbank - Matola	0.0	0.0	0.0	0.0	0.0
Witbank – Richard’s Bay	0.0	0.0	0.0	0.0	0.0
Witbank - Walvis Bay	52.19	25.61	15.46	6.63	5.83
Mmamabula - Matola	21.48	3.47	0.46	1.38	2.18
Mmamabula – Richard’s Bay	19.96	2.34	0.0	1.10	1.90
Mmamabula - Walvis Bay	26.88	4.36	2.40	0.0	0.0
Appalachia – Hampton Roads	0.0	0.0	0.0	0.0	0.0

Source: Based on model simulations by author.

Table G-2 Shadow Values for an Additional Unit of Supply

Source	1990	1995	2000	2005
Witbank	1.17	5.35	11.17	11.80
Mmamabula	0.0	0.0	5.27	9.40
Appalachia	0.0	0.0	0.0	0.0
Australia	26.31	18.36	20.55	11.72

Source: Based on model simulations by the author.

Table G-3 A Comparison of Shadow Values for Shipping an Extra Unit of Export

From / To	1990	1995	2000	2005	2010
Walvis Bay - ARA	0.0	0.0	0.0	0.0	0.0
Walvis Bay - Yokohama	4.78	6.58	11.54	4.59	5.12
Matola - ARA	0.0	0.0	0.0	0.0	0.0
Matola - Yokohama	0.0	0.0	10.04	0.0	0.0
Gladstone - ARA	6.56	5.77	0.0	3.38	2.04
Gladstone - Yokohama	0.0	0.0	0.0	0.0	0.0
Hampton Roads - ARA	0.0	0.0	0.0	0.0	
Hampton Roads - Yokohama	12.04	9.98	17.37	9.74	11.05

Source: Based on model simulations by the author.

Appendix H. The GAMS Code and Output for the Base Case Simulation Scenario of Spatial and Dynamic Optimization Model of the World Steam Coal Trade

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GAMS Rev 121  Windows NT/95/98                04/18/03 17:50:36  PAGE     1
General Algebraic Modeling System
Compilation
   3
   4  * This nonlinear program solves for international trade flows for the major
   5  * exporting and importing countries and simulates whether coal exports from
   6 * Botswana are competitive in this trade. Steam coal demand is econometrically
   7  * estimated outside the model. The model determines the supply necessary to
   8  * meet domestic and import demands in the countries of the study.
   9
  10  option limcol = 0;
  11  option limrow = 0;
  12
  13  SETS
  14   I     Coal Supply countries or regions /Australia,USA,Witbank,Mmamabula/
  15   K     Export region ports /Matola,RBCT,Wbay,Gladstone,Hroads/
  16   J     Export and demand region ports /ARA,Yokohama/
  17   T     Time period /1990,1995,2000,2005,2010/
  18   Theta Number of years per period /1*5/
  19   TE(T) Time period for expansion /1995,2000,2005,2010/
  20   M_to_P(I,K)    Supply region port combination /Australia .Gladstone,
  21                  USA .Hroads,
  22                  Witbank .(Matola,RBCT,Wbay),
  23                  Mmamabula .(Matola,RBCT,Wbay)/
  24
  25   EP_to_IP(K,J)   Export and import port combination
  26         /(Matola,RBCT) .(ARA,Yokohama),
  27         (Wbay,Gladstone,Hroads) .(ARA,Yokohama)/;
  28
  29  ALias (K,Ke),(TE,TPE),(T,TP);
  30
  31  SCALAR    rho    discount rate          / 0.15 /
  32          lom   life of investment(yrs)   / 20 /
  33          Ecmax Maximum equipment cost for 25000 tpd /26998162.68/
  34          Lcmax Maximum labor cost for 25000 tpd /5581791.254/
  35          Scmax Maximum supply cost for 25000 tpd /3694717.002/
  36          Wd    Maximum number of days worked in a year /300/
  37          CI    cost index ratio of 2000 to 1994      /0.9090/
  38          share residual demand   /0.615/
  39          Sea    sea freight sensitivity factor  /1.0/ ;
  40  PARAMETER
  41          Denom   expression for the denominator in the period discount
                                              factor
```

```
      Dis      expression for the fixed period discount factor
      Delta(T) discount factor for periods GT five years: years 6 to 20 years
      Sigma  capital recovery factor
      TSE(TE,TPE) time summation matrix over expansion period
      TS(T,TP)  time summation matrix;


Denom = ((1 + rho)**5)+((1+rho)**4)+((1+rho)**3)+((1+rho)**2)+(1+rho);
Dis = (1/Denom);
Delta(T) = (Dis/(1+rho)**(5*(ORD(T)-1)));
Sigma = (rho/(1 -((1+rho)**(-(lom)))));
TS(T,TP) = 1$(ORD(T) GE ORD(TP));
TSE(TE,TPE) = 1$(ORD(TE) GE ORD(TPE));

Display TS,TSE,Dis,Delta,Sigma,M_to_P, EP_to_IP;


PARAMETERS

   F_rail(I)     rail cost sensitivity factor
           /Australia 1.0
            USA       1.0
            Witbank   1.0
            Mmamabula 1.0 /

   F_price(I)    price intercept term sensitivity factor
           /Australia 1.0
            USA       1.0
            Witbank   1.0
            Mmamabula 1.0 /

   F_capex(I)    capital cost sensitivity factor
           /Australia 1.0
            USA       1.0
            Witbank   1.0
            Mmamabula 1.0 /

   Traj(TPE)    trajectory for Botswana's coal exports
           /1995    10000
            2000    20000
            2005    30000
            2010    40000 /
```

```
*These go with the original model
 B(I)  supply price slope coefficients
              / Australia .0000706
               USA 0.00000732
               Witbank  0.0000651
              Mmamabula 0.0000651 /

 So(I) supply in base year

         /Australia   65248
          USA        658449
          Witbank    134215
           Mmamabula     800 /;

* This table goes with the base model
TABLE
    A(I,TPE) supply price equation intercepts
                    1995     2000     2005     2010
         Australia 50.90     32.31    32.31   32.31
         USA       42.97     32.19    32.19   32.19
         Witbank   15.54     5.01      5.01    5.01
         Mmamabula 15.54     5.01      5.01    5.01;


*This table goes with sensitivty 1983 to 2000
*TABLE
*     A(I,TPE) supply price equation intercepts
*                   1995     2000     2005     2010
*          Australia 44.05     19.85    19.85   19.85
*          USA       44.32     33.17    33.17   33.17
*          Witbank   6.37       0.00     0.00    0.00
*          Mmamabula 6.37       0.00     0.00    0.00 ;

TABLE
    Cap(K,T) Table of port capacity constraints for period shown
                        1990   1995     2000     2005           2010
         Gladstone 200000  200000  200000   200000    200000
         Hroads    200000  200000  200000   200000    200000
         RBCT      22500   36000   45000    57000     57000
         Matola      0     10000   20000    30000     40000
         Wbay        0     10000   20000    30000     40000;
```

```
TABLE
   C(I,K,T)  Table of rail transportation costs US 2000 Dollars per mtce
                          1990   1995    2000    2005   2010
 Australia .Gladstone     0.00    0.00    0.00   0.00    0.00
 USA       .Hroads        28.60   20.24   19.16  17.87  17.87
 Witbank    .Matola       18.03   9.16     5.19   3.07   3.07
 Witbank    .RBCT         25.28   12.83    7.28   4.31   4.31
 Witbank    .Wbay         79.61   40.42   22.91  13.56  13.56
 Mmamabula  .Matola       40.68   17.98   11.55   6.84   6.84
 Mmamabula  .RBCT         46.41   20.52   13.18   7.80   7.80
 Mmamabula  .Wbay         55.47   24.52   15.75   9.32   9.32;

TABLE
  F(K,J,T)  Table of Sea freight costs to markets in US 2000 Dollars per mtce
                          1990    1995    2000   2005   2010
 Matola  .ARA             12.97   12.00   11.18  7.94   7.44
 Matola  .Yokohama        13.74   14.36   10.45  8.27   7.63
 RBCT    .ARA             12.97   12.00   11.18  7.94   7.44
 RBCT    .Yokohama        13.74   14.36   10.45  8.27   7.63
 Wbay    .ARA             10.34    9.57   8.91   6.33   5.93
 Wbay    .Yokohama        16.45   17.19   12.51  9.91   9.14
 Gladstone .ARA           21.99   18.11   17.02  13.34  13.30
 Gladstone .Yokohama      13.15   11.79    9.08  8.95   9.35
 Hroads  .ARA             10.33    9.47   8.37   7.19   7.36
 Hroads  .Yokohama        26.00   20.96   17.80  15.92  16.50 ;

Table
      W(I,TPE) Ratios of other suppliers hourly wages to USA wages
                 1995   2000   2005  2010
      USA          1.00   1.00   1.00  1.00
      Australia    1.03   1.14   1.14  1.14
      Witbank       0.38   0.28   0.28  0.28
      Mmamabula      0.38   0.28   0.28  0.28;
TABLE
      Z(I,T)  Annual Domestic demand by country or region I in 000s mtce
                 1990    1995    2000      2005     2010
     Australia    30243   33643    45910    56230     69600
     USA         627375   638844   693489  774799    848535
     Witbank      96692   115407   129710   142060    151355
     Mmamabula     800    837.5     875     875        875;
Table
      D(J,T)  Annual import demand by country or region J in 000s
                                           mtce: Model
                1990    1995    2000    2005    2010
     ARA            39950   46308   67223   67215   63881
     Yokohama        102482   99217  103929  126637  148928 ;
```

```


TABLE
        Row(I,T)  Rest of world exports from country i in 000s mtce
                       1990    1995     2000     2005     2010
       Australia      0       0         0        0        0
       USA          33200   8900    14000    14000    14000
       Witbank      14600   23600    25200    25200   25200
       Mmamabula      0      0          0         0                0;

*Table
*
* D(J,T)  Annual import demand by country or region J in 000’s of mtce: IEA
*                                1990    1995    2000    2005    2010
*       ARA                      39950   46308   78100   75800   79300
*       Yokohama         102482   99217   90600   118300  131900 ;


VARIABLES
TC     Objective function is Present Value of Total Costs: 000's US Dollar 2000;


POSITIVE VARIABLES

  VC(I,TPE)  operating costs at mine i in period t: 000's US Dollar
  S(I,TPE)   quantity of coal supplied by country I in period t: 000's mtce
  X(I,K,TPE) quantity shipped from supply S to port K in period t: 000's  mtce
  H(I,TE)    capacity addition at source i in period t:1000 tpd
  Y(Ke,J,TPE)   quantity shipped from port K to demand J in period t: 000's mtce
  Cumcapex(I,TPE) cumulative annualized capital expenditure: 000's US 2000 $;

EQUATIONS

  OBJECTIVE      Minimize the discounted sum of development, supply plus delivery costs
  Supply(I,TPE)    supply constraint at time t
  Minesize(I,TPE)  constranit on capacity expansion: 000's mtce
  Demand(J,TPE)    demand constraint at time t: Residual demand facing exporters
  Trans(K,TPE)     transshipment constraint at all ports at time t
  Capconstr(K,TPE) port capacity constraint
  Cap_rbct(K,TPE)  port constraint at RSA ports net of ROW tonnage
  RSAcapex1(I,TPE) annulized capital costs of expansion:1995 RSA
  RSAcapex2(I,TPE) annualized capital costs of expansion:2000 RSA
  RSAcapex3(I,TPE) annualized capital costs of expansion:2005 RSA
  RSAcapex4(I,TPE) annualized capital costs of expansion:2010 RSA

  Auscapex1(I,TPE) annualized capital costs of expansion:1995 Australia
```

```
 Auscapex2(I,TPE) annualized capital costs of expansion:2000 Australia
 Auscapex3(I,TPE) annualized capital costs of expansion:2005 Australia
 Auscapex4(I,TPE) annualized capital costs of expansion:2010 Australia

 USAcapex1(I,TPE) annualized capital costs of expansion:1995 USA
 USAcapex2(I,TPE) annualized capital costs of expansion:2000 USA
 USAcapex3(I,TPE) annualized capital costs of expansion:2005 USA
 USAcapex4(I,TPE) annualized capital costs of expansion:2010 USA

 Botscapex1(I,TPE) annualized capital costs of expansion:1995 Botswana
 Botscapex2(I,TPE) annualized capital costs of expansion:2000 Botswana
 Botscapex3(I,TPE) annualized capital costs of expansion:2005 Botswana
 Botscapex4(I,TPE) annualized capital costs of expansion:2010 Botswana

 Phi(I,TE)         annual supply costs
 RSAper1(I,TPE)    RSA cumulative supply at the end of 1995
 RSAper2(I,TPE)    RSA cumulative supply at the end of 2000
 RSAper3(I,TPE)    RSA cumulative supply at the end of 2005
 RSAper4(I,TPE)    RSA cumulative supply at the end of 2010

 USAper1(I,TPE)    USA cumulative supply at the end of 1995
 USAper2(I,TPE)    USA cumulative supply at the end of 2000
 USAper3(I,TPE)    USA cumulative supply at the end of 2005
 USAper4(I,TPE)    USA cumulative supply at the end of 2010

 AUSper1(I,TPE)    AUS cumulative supply at the end of 1995
 AUSper2(I,TPE)    AUS cumulative supply at the end of 2000
 AUSper3(I,TPE)    AUS cumulative supply at the end of 2005
 AUSper4(I,TPE)    AUS cumulative supply at the end of 2010

 Botsper1(I,TPE)   Bots cumulative supply at the end of 1995
 Botsper2(I,TPE)   Bots cumulative supply at the end of 2000
 Botsper3(I,TPE)   Bots cumulative supply at the end of 2005
 Botsper4(I,TPE)   Bots cumulative supply at the end of 2010
 RSA_map(I,K,TPE)  constrains RSA exports to Maputo to zero
 RSA_wbay(I,K,TPE) constrains RSA exports to Wbay to zero
 Bots_mat(I,K,TPE) constrains Mmamabula exports to export trajectory
 Bots_rich(I,K,TPE) constrains Mmamabula exports to export trajectory
 Bots_walv(I,K,TPE) constrains Mmamabula exports to export trajectory
 Mbal(TPE)         market balance constraint at time t;

S.lo("Australia",TPE)= Z("Australia",TPE)+Row("Australia",TPE);
```

```
S.lo("USA",TPE)= Z("USA",TPE)+Row("USA",TPE);
S.lo("Mmamabula",TPE)= Z("Mmamabula",TPE)+Row("Mmamabula",TPE);
S.lo("Witbank",TPE)= Z("Witbank",TPE)+Row("Witbank",TPE);


H.lo(I,TPE) = .125;

OBJECTIVE..  TC =E= (SUM(I,Cumcapex(I,"2010"))*CI)+SUM((I,TPE),VC(I,TPE))+
      SUM((I,K,TPE)$M_to_P(I,K),Delta(TPE)*F_rail(I)*C(I,K,TPE)*X(I,K,TPE))
       +SUM((Ke,J,TPE)$EP_to_IP(Ke,J),Delta(TPE)*Sea*F(Ke,J,TPE)*Y(Ke, J,TPE));


RSAper1("Witbank","1995").. S("Witbank","1995")=e= So("Witbank")+
                    Wd*H("Witbank","1995");
RSAper2("Witbank","2000").. S("Witbank","2000")=e= S("Witbank","1995")+
                    Wd*H("Witbank","2000");
RSAper3("Witbank","2005").. S("Witbank","2005")=e= S("Witbank","2000")+
                    Wd*H("Witbank","2005");
RSAper4("Witbank","2010").. S("Witbank","2010")=e= S("Witbank","2005")+
                    Wd*H("Witbank","2010");

Botsper1("Mmamabula","1995").. S("Mmamabula","1995")=e= So("Mmamabula")+
                    Wd*H("Mmamabula","1995");
Botsper2("Mmamabula","2000").. S("Mmamabula","2000")=e= S("MMamabula",
                                    "1995")+
                    Wd*H("MMamabula","2000");
Botsper3("Mmamabula","2005").. S("Mmamabula","2005")=e= S("Mmamabula",
                                    "2000")+
                    Wd*H("Mmamabula","2005");
Botsper4("Mmamabula","2010").. S("Mmamabula","2010")=e= S("Mmamabula",
                                    "2005")+
                    Wd*H("Mmamabula","2010");

AUSper1("Australia","1995").. S("Australia","1995")=e= So("Australia")+
                    Wd*H("Australia","1995");
AUSper2("Australia","2000").. S("Australia","2000")=e= S("Australia",
                                    "1995")+
                    Wd*H("Australia","2000");
AUSper3("Australia","2005").. S("Australia","2005")=e= S("Australia",
                                    "2000")+
                    Wd*H("Australia","2005");
```

```
AUSper4("Australia","2010").. S("Australia","2010")=e= S("Australia",
                                            "2005")+
                    Wd*H("Australia","2010");

USAper1("USA","1995").. S("USA","1995")=e= So("USA")+ Wd*H("USA","1995");
USAper2("USA","2000").. S("USA","2000")=e= S("USA","1995")+ Wd*H("USA",
                                            "2000");
USAper3("USA","2005").. S("USA","2005")=e= S("USA","2000")+ Wd*H("USA",
                                            "2005");
USAper4("USA","2010").. S("USA","2010")=e= S("USA","2005")+ Wd*H("USA",
                                            "2010");



Supply(I,TPE).. -SUM(K$M_to_P(I,K),X(I,K,TPE))=G= -S(I,TPE)+Z(I,TPE)
                                          +Row(I,TPE);
Demand(J,TPE)..     SUM(Ke$EP_to_IP(Ke,J),Y(Ke,J,TPE))=G= share*D(J,TPE);
Capconstr(K,TPE)..  -SUM(I$M_to_P(I,K),X(I,K,TPE))=G= -Cap(K,TPE);
Trans(K,TPE)..SUM(I$M_to_P(I,K),X(I,K,TPE))-SUM(J$EP_to_IP(K,J),Y(K,J,TPE)
                                             )=E=0;
Mbal(TPE).. SUM(I,S(I,TPE))-SUM(I,Z(I,TPE))-SUM(I,Row(I,TPE))-
          SUM(J,share*D(J,TPE))=E=0;
Minesize(I,TPE).. -H(I,TPE)=g=-100000;

Cap_rbct("RBCT",TPE)..  -SUM(I$M_to_P(I,"RBCT"),X(I,"RBCT",TPE))=G=
                -Cap("RBCT",TPE);
RSA_map("Witbank","Matola",TPE)..  X("Witbank","Matola",TPE)=E=0;
RSA_wbay("Witbank","Wbay",TPE)..  X("Witbank","Wbay",TPE)=E=0;
Bots_mat("Mmamabula","Matola",TPE).. -X("Mmamabula","Matola",TPE)-
     X("Mmamabula","Wbay",TPE)-X("Mmamabula","RBCT",TPE)=G= -Traj(TPE)
                                              ;

Bots_rich("Mmamabula","Wbay",TPE).. -X("Mmamabula","Matola",TPE)-
     X("Mmamabula","Wbay",TPE)-X("Mmamabula","RBCT",TPE)=G= -Traj(TPE)
                                              ;

Bots_walv("Mmamabula","RBCT",TPE).. -X("Mmamabula","Matola",TPE)-
     X("Mmamabula","Wbay",TPE)-X("Mmamabula","RBCT",TPE)=G= -Traj(TPE)
                                              ;

Phi(I,TPE)..     VC(I,TPE)=E= Delta(TPE)*F_price(I)*(A(I,TPE)*S(I,TPE))
         +0.5*Delta(TPE)*B(I)*(S(I,TPE)*S(I,TPE));

RSAcapex1("Witbank","1995").. Cumcapex("Witbank","1995")=e=
F_capex("Witbank")*(Delta("1995")*sigma*Ecmax*(H("Witbank","1995")/25)+
Delta("1995")*W("Witbank","1995")*sigma*Lcmax*(H("Witbank","1995")/25)+
```

```
Delta("1995")*sigma*Scmax*(H("Witbank","1995")/25));

RSAcapex2("Witbank","2000").. Cumcapex("Witbank","2000")=E=
Cumcapex("Witbank","1995")+
F_capex("Witbank")*(Delta("2000")*sigma*Ecmax*(H("Witbank","2000")/25)+
Delta("2000")*W("Witbank","2000")*sigma*Lcmax*(H("Witbank","2000")/25)+
Delta("2000")*sigma*Scmax*(H("Witbank","2000")/25));

RSAcapex3("Witbank","2005").. Cumcapex("Witbank","2005")=E=
Cumcapex("Witbank","2000")+
F_capex("Witbank")*(Delta("2005")*sigma*Ecmax*(H("Witbank","2005")/25) +
Delta("2005")*W("Witbank","2005")*sigma*Lcmax*(H("Witbank","2005")/25) +
Delta("2005")*sigma*Scmax*(H("Witbank","2005")/25));

RSAcapex4("Witbank","2010").. Cumcapex("Witbank","2010")=E=
Cumcapex("Witbank","2005")+
F_capex("Witbank")*(Delta("2010")*sigma*Ecmax*(H("Witbank","2010")/25)+
Delta("2010")*W("Witbank","2010")*sigma*Lcmax*(H("Witbank","2010")/25)+
Delta("2010")*sigma*Scmax*(H("Witbank","2010")/25));


AUScapex1("Australia","1995").. Cumcapex("Australia","1995")=e=
F_capex("Australia")*(Delta("1995")*sigma*Ecmax*(H("Australia","1995")/25)
                                                                +
Delta("1995")*W("Australia","1995")*sigma*Lcmax*(H("Australia","1995")/25)
                                                                +
Delta("1995")*sigma*Scmax*(H("Australia","1995")/25));

AUScapex2("Australia","2000").. Cumcapex("Australia","2000")=E=
Cumcapex("Australia","1995")+
F_capex("Australia")*(Delta("2000")*sigma*Ecmax*(H("Australia","2000")/25)
                                                                +
Delta("2000")*W("Australia","2000")*sigma*Lcmax*(H("Australia","2000")/25)
                                                                +
Delta("2000")*sigma*Scmax*(H("Australia","2000")/25));

AUScapex3("Australia","2005").. Cumcapex("Australia","2005")=E=
Cumcapex("Australia","2000")+
F_capex("Australia")*(Delta("2005")*sigma*Ecmax*(H("Australia","2005")/25)
                                                                +
Delta("2005")*W("Australia","2005")*sigma*Lcmax*(H("Australia","2005")/25)
                                                                +
Delta("2005")*sigma*Scmax*(H("Australia","2005")/25));

AUScapex4("Australia","2010").. Cumcapex("Australia","2010")=E=
Cumcapex("Australia","2005")+
```

```
F_capex("Australia")*(Delta("2010")*sigma*Ecmax*(H("Australia","2010")/25)+
Delta("2010")*W("Australia","2010")*sigma*Lcmax*(H("Australia","2010")/25)+
Delta("2010")*sigma*Scmax*(H("Australia","2010")/25));


USAcapex1("USA","1995").. Cumcapex("USA","1995")=e=
F_capex("USA")*(Delta("1995")*sigma*Ecmax*(H("USA","1995")/25)+
Delta("1995")*W("USA","1995")*sigma*Lcmax*(H("USA","1995")/25)+
Delta("1995")*sigma*Scmax*(H("USA","1995")/25));

USAcapex2("USA","2000").. Cumcapex("USA","2000")=E=
Cumcapex("USA","1995")+
F_capex("USA")*(Delta("2000")*sigma*Ecmax*(H("USA","2000")/25)+
Delta("2000")*W("USA","2000")*sigma*Lcmax*(H("USA","2000")/25)+
Delta("2000")*sigma*Scmax*(H("USA","2000")/25));

USAcapex3("USA","2005").. Cumcapex("USA","2005")=E=
Cumcapex("USA","2000")+
F_capex("USA")*(Delta("2005")*sigma*Ecmax*(H("USA","2005")/25)+
Delta("2005")*W("USA","2005")*sigma*Lcmax*(H("USA","2005")/25)+
Delta("2005")*sigma*Scmax*(H("USA","2005")/25));

USAcapex4("USA","2010").. Cumcapex("USA","2010")=E=
Cumcapex("USA","2005")+
F_capex("USA")*(Delta("2010")*sigma*Ecmax*(H("USA","2010")/25)+
Delta("2010")*W("USA","2010")*sigma*Lcmax*(H("USA","2010")/25)+
Delta("2010")*sigma*Scmax*(H("USA","2010")/25)**.904);

Botscapex1("Mmamabula","1995").. Cumcapex("Mmamabula","1995")=e=
   F_capex("Mmamabula")*(Delta("1995")*sigma*Ecmax*(H("Mmamabula","1995")/25)+
Delta("1995")*W("Mmamabula","1995")*sigma*Lcmax*(H("MMamabula","1995")/25)+
Delta("1995")*sigma*Scmax*(H("Mmamabula","1995")/25));

Botscapex2("Mmamabula","2000").. Cumcapex("Mmamabula","2000")=E=
Cumcapex("Mmamabula","1995")+
F_capex("Mmamabula")*(Delta("2000")*sigma*Ecmax*(H("Mmamabula","2000")/25)+
Delta("2000")*W("Mmamabula","2000")*sigma*Lcmax*(H("Mmamabula","2000")/25)+
Delta("2000")*sigma*Scmax*(H("Mmamabula","2000")/25));

```

```
Botscapex3("Mmamabula","2005").. Cumcapex("Mmamabula","2005")=E=
   Cumcapex("Mmamabula","2000")+
F_capex("Mmamabula")*(Delta("2005")*sigma*Ecmax*(H("Mmamabula","2005")/25)
                                                                     +
Delta("2005")*W("Mmamabula","2005")*sigma*Lcmax*(H("Mmamabula","2005")/25)
                                                                     +
Delta("2005")*sigma*Scmax*(H("Mmamabula","2005")/25));

Botscapex4("Mmamabula","2010").. Cumcapex("Mmamabula","2010")=E=
Cumcapex("Mmamabula","2005")+
F_capex("Mmamabula")*(Delta("2010")*sigma*Ecmax*(H("Mmamabula","2010")/25)
                                                                     +
Delta("2010")*W("Mmamabula","2010")*sigma*Lcmax*(H("Mmamabula","2010")/25)
                                                                     +
Delta("2010")*sigma*Scmax*(H("Mmamabula","2010")/25));

MODEL PEM /ALL/;
SOLVE PEM USING NLP MINIMIZING TC;
option decimals=2;
option solprint=off;
option reslim = 200000;
option iterlim = 500000;
option optcr = 0.1;



PARAMETERS  E(I,TPE) exports from supply region or country I in period T
         Capcost(I,TPE)  cost of expansion in period t in nominal
                                                           dollars
         FOB_Mmbla(I,K,TPE) free on board price for Mmamabula coal
         FOB_Wit(I,K,TPE) free on board price for South AFrica coal
         FOB_USA(I,K,TPE) free on board price for Appalachia coal
         Price(I,TPE)    supply price in country i in time t;

Price(I,TPE) = F_price(I)*A(I,TPE)+B(I)*S.l(I,TPE);
E(I,TPE) = s.l(I,TPE)+H.l(I,TPE)-Z(I,TPE);
Capcost(I,TPE)= w(I,TPE)*405.8*(H.l(I,TPE)**0.941)+ 2943*(H.l(I,TPE)
                                                          **0.901)+
           390.7*(H.l(I,TPE)**0.904);

```

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G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m
C o m p i l a t i o n


 448  FOB_Mmbla("Mmamabula",K,TPE)=C("Mmamabula",K,TPE)+Price("Witbank",TPE);
 449  FOB_Wit("Witbank",K,TPE)=C("Witbank",K,TPE)+Price("Witbank",TPE);
 450  FOB_USA("USA",K,TPE)=C("USA",K,TPE)+ Price("USA",TPE);
 451
 452  display E,S.l,Price,FOB_Mmbla, FOB_Wit, FOB_USA,
 453          Cumcapex.l,H.l,X.l,Y.l;


COMPILATION TIME     =        0.000 SECONDS     0.7 Mb      WIN200-121
GAMS Rev 121  Windows NT/95/98                  04/18/03 17:50:36  PAGE     11
G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m
E x e c u t i o n

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G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m



               S O L V E      S U M M A R Y

     MODEL   PEM                OBJECTIVE  TC
     TYPE    NLP                DIRECTION  MINIMIZE
     SOLVER  MINOS              FROM LINE  427

**** SOLVER STATUS     1 NORMAL COMPLETION
**** MODEL STATUS      2 LOCALLY OPTIMAL
**** OBJECTIVE VALUE         10612441.9746

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    GAMS/MINOS, Large Scale Nonlinear Solver
    B. A. Murtagh, University of New South Wales
    P. E. Gill, University of California at San Diego,
    W. Murray, M. A. Saunders, and M. H. Wright,
    Systems Optimization Laboratory, Stanford University
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 Work space allocated           --    1.84 Mb

 EXIT - Optimal Solution found.


                       LOWER     LEVEL     UPPER    MARGINAL

---- EQU OBJECTIVE       .         .         .        1.000

  OBJECTIVE  Minimize the discounted sum of supply plus delivery costs

 ---- EQU Supply  supply constraint at time t

                  LOWER     LEVEL     UPPER    MARGINAL

Australia.1995 33643.000 33643.000     +INF      4.064
Australia.2000 45910.000 45910.000     +INF      2.511
Australia.2005 56230.000 56230.000     +INF      1.394
Australia.2010 69600.000 69600.000     +INF      0.822
USA      .1995 6.4774E+5 6.4774E+5     +INF      2.764
USA      .2000 7.0749E+5 7.0749E+5     +INF      2.236
USA      .2005 7.8880E+5 7.8880E+5     +INF      1.272
USA      .2010 8.6254E+5 8.6254E+5     +INF      0.695
Witbank  .1995 1.3901E+5 1.3901E+5     +INF      0.685
Witbank  .2000 1.5491E+5 1.5491E+5     +INF      0.372
Witbank  .2005 1.6726E+5 1.6726E+5     +INF      0.200
Witbank  .2010 1.7656E+5 1.7656E+5     +INF      0.099
Mmamabula.1995   837.500   837.500     +INF       .
Mmamabula.2000   875.000   875.000     +INF       .
Mmamabula.2005   875.000   875.000     +INF       .
Mmamabula.2010   875.000   875.000     +INF       .

---- EQU Demand  demand constraint at time t: Residual demand facing exporters

                  LOWER     LEVEL     UPPER    MARGINAL

ARA     .1995 28479.420 28479.420     +INF      4.669
ARA     .2000 41342.145 41342.145     +INF      2.824
ARA     .2005 41337.225 41337.225     +INF      1.531
ARA     .2010 39286.815 39286.815     +INF      0.894
Yokohama.1995 61018.455 61018.455     +INF      4.820
Yokohama.2000 63916.335 63916.335     +INF      2.800
Yokohama.2005 77881.755 77881.755     +INF      1.536
Yokohama.2010 91590.720 91590.720     +INF      0.896
```

```
---- EQU Capconstr  port capacity constraint

                LOWER     LEVEL     UPPER    MARGINAL

Matola   .1995 -1.000E+4 -1.000E+4     +INF      0.264
Matola   .2000 -2.000E+4 -2.000E+4     +INF      0.062
Matola   .2005 -3.000E+4 -3.000E+4     +INF      0.014
Matola   .2010 -4.000E+4 -4.000E+4     +INF      0.008
RBCT     .1995 -3.600E+4 -3.600E+4     +INF      2.391
RBCT     .2000 -4.500E+4 -4.500E+4     +INF      1.864
RBCT     .2005 -5.700E+4 -5.700E+4     +INF      1.137
RBCT     .2010 -5.700E+4 -5.700E+4     +INF      0.703
Wbay     .1995 -1.000E+4      .        +INF       .
Wbay     .2000 -2.000E+4      .        +INF       .
Wbay     .2005 -3.000E+4      .        +INF       .
Wbay     .2010 -4.000E+4      .        +INF       .
Gladstone.1995 -2.000E+5 -3.276E+4     +INF       .
Gladstone.2000 -2.000E+5 -4.026E+4     +INF       .
Gladstone.2005 -2.000E+5 -3.222E+4     +INF       .
Gladstone.2010 -2.000E+5 -1.889E+4     +INF       .
Hroads   .1995 -2.000E+5 -1.074E+4     +INF       .
Hroads   .2000 -2.000E+5      .        +INF       .
Hroads   .2005 -2.000E+5      .        +INF       .
Hroads   .2010 -2.000E+5 -1.499E+4     +INF       .

---- EQU Bots_mat  constrains Mmamabula exports to export trajectory

                        LOWER     LEVEL     UPPER    MARGINAL

Mmamabula.Matola.1995 -1.000E+4 -1.000E+4     +INF      2.483
Mmamabula.Matola.2000 -2.000E+4 -2.000E+4     +INF      2.037
Mmamabula.Matola.2005 -3.000E+4 -3.000E+4     +INF      1.283
Mmamabula.Matola.2010 -4.000E+4 -4.000E+4     +INF      0.774

                      LOWER     LEVEL     UPPER    MARGINAL

---- VAR TC            -INF  1.0612E+7     +INF       .

  TC  Objective function is Present Value of Total Costs: 000's US Dollar 2000

---- VAR VC  operating costs at mine i in period t: 000's US Dollar

                LOWER     LEVEL     UPPER    MARGINAL

Australia.1995      .    2.2669E+5     +INF       .
Australia.2000      .    97111.300     +INF       .
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Australia.2005      .    49672.131     +INF       .
Australia.2010      .    24707.222     +INF       .
USA      .1995      .   1.9161E+6     +INF       .
USA      .2000      .   7.8443E+5     +INF       .
USA      .2005      .   4.3854E+5     +INF       .
USA      .2010      .   2.4480E+5     +INF       .
Witbank  .1995      .   2.3831E+5     +INF       .
Witbank  .2000      .   73398.468     +INF       .
Witbank  .2005      .   43754.148     +INF       .
Witbank  .2010      .   23212.001     +INF       .
Mmamabula.1995      .    11044.043     +INF       .
Mmamabula.2000      .     3786.253     +INF       .
Mmamabula.2005      .     2943.490     +INF       .
Mmamabula.2010      .     2042.265     +INF       .

---- VAR S  quantity of coal supplied by country I in period t: 000's mtce

                 LOWER     LEVEL     UPPER    MARGINAL
Australia.1995 33643.000 66398.375     +INF       .
Australia.2000 45910.000 86168.480     +INF       .
Australia.2005 56230.000 88448.980     +INF       .
Australia.2010 69600.000 88486.480     +INF       .
USA      .1995 6.4774E+5 6.5849E+5     +INF       .
USA      .2000 7.0749E+5 7.0749E+5     +INF       .
USA      .2005 7.8880E+5 7.8880E+5     +INF       .
USA      .2010 8.6254E+5 8.7753E+5     +INF       .
Witbank  .1995 1.3901E+5 1.7501E+5     +INF       .
Witbank  .2000 1.5491E+5 1.9991E+5     +INF       .
Witbank  .2005 1.6726E+5 2.2426E+5     +INF       .
Witbank  .2010 1.7656E+5 2.3355E+5     +INF       .
Mmamabula.1995   837.500 10837.500     +INF       .
Mmamabula.2000   875.000 20875.000     +INF       .
Mmamabula.2005   875.000 30875.000     +INF       .
Mmamabula.2010   875.000 40875.000     +INF       .

---- VAR X  quantity shipped from supply S to port K in period t: 000's mtce

                           LOWER     LEVEL     UPPER    MARGINAL
Australia.Gladstone.1995     .    32755.375     +INF       .
Australia.Gladstone.2000     .    40258.480     +INF       .
Australia.Gladstone.2005     .    32218.980     +INF       .
Australia.Gladstone.2010     .    18886.480     +INF       .
USA      .Hroads   .1995     .    10742.500     +INF       .
USA      .Hroads   .2000     .         .        +INF       .
USA      .Hroads   .2005     .         .        +INF       .
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     VAR X  quantity shipped from supply S to port K in period t: 000's mtce

                      LOWER     LEVEL     UPPER    MARGINAL

USA      .Hroads   .2010      .    14991.055     +INF       .
Witbank  .Matola   .1995      .         .        +INF       .
Witbank  .Matola   .2000      .         .        +INF       .
Witbank  .Matola   .2005      .         .        +INF       .
Witbank  .Matola   .2010      .         .        +INF       .
Witbank  .RBCT     .1995      .    36000.000     +INF       .
Witbank  .RBCT     .2000      .    45000.000     +INF       .
Witbank  .RBCT     .2005      .    57000.000     +INF       .
Witbank  .RBCT     .2010      .    57000.000     +INF       .
Witbank  .Wbay     .1995      .         .        +INF       .
Witbank  .Wbay     .2000      .         .        +INF       .
Witbank  .Wbay     .2005      .         .        +INF       .
Witbank  .Wbay     .2010      .         .        +INF       .
Mmamabula.Matola   .1995      .    10000.000     +INF       .
Mmamabula.Matola   .2000      .    20000.000     +INF       .
Mmamabula.Matola   .2005      .    30000.000     +INF       .
Mmamabula.Matola   .2010      .    40000.000     +INF       .
Mmamabula.RBCT     .1995      .         .        +INF      2.291
Mmamabula.RBCT     .2000      .         .        +INF      1.854
Mmamabula.RBCT     .2005      .         .        +INF      1.139
Mmamabula.RBCT     .2010      .         .        +INF      0.703
Mmamabula.Wbay     .1995      .         .        +INF       .
Mmamabula.Wbay     .2000      .         .        +INF       .
Mmamabula.Wbay     .2005      .         .        +INF       .
Mmamabula.Wbay     .2010      .         .        +INF       .


---- VAR H  capacity addition at source i in period t:1000 tpd

                LOWER     LEVEL     UPPER    MARGINAL

Australia.1995     0.125     3.835     +INF       .
Australia.2000     0.125    65.900     +INF       .
Australia.2005     0.125     7.602     +INF       .
Australia.2010     0.125     0.125     +INF     46.167
USA      .1995     0.125     0.125     +INF    322.456
USA      .2000     0.125   163.342     +INF       .
USA      .2005     0.125   271.033     +INF       .
USA      .2010     0.125   295.757     +INF       .
Witbank  .1995     0.125   135.973     +INF       .
Witbank  .2000     0.125    83.010     +INF       .
Witbank  .2005     0.125    81.167     +INF       .
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Witbank  .2010     0.125    30.983     +INF       .
Mmamabula.1995     0.125    33.458     +INF       .
Mmamabula.2000     0.125    33.458     +INF       .
Mmamabula.2005     0.125    33.333     +INF       .
Mmamabula.2010     0.125    33.333     +INF       .

---- VAR Y  quantity shipped from port K to demand J in period t: 000's mtce

                        LOWER     LEVEL     UPPER    MARGINAL

Matola   .ARA     .1995      .   10000.000     +INF       .
Matola   .ARA     .2000      .   20000.000     +INF       .
Matola   .ARA     .2005      .         .       +INF      EPS
Matola   .ARA     .2010      .   24295.760     +INF       .
Matola   .Yokohama.1995      .         .       +INF      EPS
Matola   .Yokohama.2000      .         .       +INF      EPS
Matola   .Yokohama.2005      .   30000.000     +INF       .
Matola   .Yokohama.2010      .   15704.240     +INF       .
RBCT     .ARA     .1995      .    7736.920     +INF       .
RBCT     .ARA     .2000      .   21342.145     +INF       .
RBCT     .ARA     .2005      .   41337.225     +INF       .
RBCT     .ARA     .2010      .         .       +INF      EPS
RBCT     .Yokohama.1995      .   28263.080     +INF       .
RBCT     .Yokohama.2000      .   23657.855     +INF       .
RBCT     .Yokohama.2005      .   15662.775     +INF       .
RBCT     .Yokohama.2010      .   57000.000     +INF       .
Wbay     .ARA     .1995      .         .       +INF       .
Wbay     .ARA     .2000      .         .       +INF       .
Wbay     .ARA     .2005      .         .       +INF       .
Wbay     .ARA     .2010      .         .       +INF       .
Wbay     .Yokohama.1995      .         .       +INF      0.337
Wbay     .Yokohama.2000      .         .       +INF      0.138
Wbay     .Yokohama.2005      .         .       +INF      0.052
Wbay     .Yokohama.2010      .         .       +INF      0.024
Gladstone.ARA     .1995      .         .       +INF      0.557
Gladstone.ARA     .2000      .         .       +INF      0.230
Gladstone.ARA     .2005      .         .       +INF      0.075
Gladstone.ARA     .2010      .         .       +INF      0.033
Gladstone.Yokohama.1995      .   32755.375     +INF       .
Gladstone.Yokohama.2000      .   40258.480     +INF       .
Gladstone.Yokohama.2005      .   32218.980     +INF       .
Gladstone.Yokohama.2010      .   18886.480     +INF       .
Hroads   .ARA     .1995      .   10742.500     +INF       .
Hroads   .ARA     .2000      .         .       +INF      0.290
Hroads   .ARA     .2005      .         .       +INF      0.138
Hroads   .ARA     .2010      .   14991.055     +INF       .
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Hroads   .Yokohama.1995     .        .       +INF      0.585
Hroads   .Yokohama.2000     .        .       +INF      0.614
Hroads   .Yokohama.2005     .        .       +INF      0.272
Hroads   .Yokohama.2010     .        .       +INF      0.071


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                         0  UNBOUNDED
                         0     ERRORS

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General Algebraic Modeling System
Execution


----    452 PARAMETER E  exports from supply region or country I in period T

                     1995        2000        2005        2010

Australia    32759.21    40324.38    32226.58    18886.60
USA          19642.62    14163.34    14271.03    29286.81
Witbank      59735.97    70283.01    82281.17    82230.98
Mmamabula    10033.46    20033.46    30033.33    40033.33


----    452 VARIABLE  S.L  quantity of coal supplied by country I in period t:
                       000's mtce

               1995        2000        2005        2010

Australia    66398.37    86168.48    88448.98    88486.48
USA         658486.50   707489.00   788799.00   877526.05
Witbank     175007.00   199910.00   224260.00   233555.00
Mmamabula    10837.50    20875.00    30875.00    40875.00


----    452 PARAMETER Price  supply price in country i in time t

               1995        2000        2005        2010

Australia       55.59       38.39       38.55       38.56
USA             47.79       37.37       37.96       38.61
Witbank         26.93       18.02       19.61       20.21
Mmamabula       16.25        6.37        7.02        7.67
```

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----    452 PARAMETER FOB_Mmbla  free on board price for Mmamabula coal

                             1995       2000       2005       2010
Mmamabula.Matola            44.91      29.57      26.45      27.05
Mmamabula.RBCT              47.45      31.20      27.41      28.01
Mmamabula.Wbay              51.45      33.77      28.93      29.53
Mmamabula.Gladstone         26.93      18.02      19.61      20.21
Mmamabula.Hroads            26.93      18.02      19.61      20.21


----    452 PARAMETER FOB_Wit  free on board price for South AFrica coal

                       1995       2000       2005       2010
Witbank.Matola        36.09      23.21      22.68      23.28
Witbank.RBCT          39.76      25.30      23.92      24.52
Witbank.Wbay          67.35      40.93      33.17      33.77

----    452 PARAMETER FOB_USA  free on board price for Appalachia coal

                       1995       2000       2005       2010
USA.Hroads            68.03      56.53      55.83      56.48


----    452 VARIABLE  Cumcapex.L  cumulative annualized capital expenditure:
                     000's US 2000 $

               1995        2000        2005        2010
Australia  57260.29   554756.96   583288.29   583521.55
USA         1858.00  1208957.18  2204774.04  2733414.24
Witbank  1828285.80  2373767.85  2638946.51  2689273.36
Mmamabula 449877.88   669742.00   778644.94   832788.95


----    452 VARIABLE  H.L  capacity addition at source i in period t:1000 tpd

               1995       2000       2005       2010
Australia      3.83      65.90       7.60       0.12
USA            0.12     163.34     271.03     295.76
Witbank      135.97      83.01      81.17      30.98
Mmamabula     33.46      33.46      33.33      33.33
```

```
----    452 VARIABLE  X.L  quantity shipped from supply S to port K in period
                      t: 000's mtce

                            1995        2000        2005        2010
Australia.Gladstone     32755.37    40258.48    32218.98    18886.48
USA      .Hroads        10742.50                14991.05
Witbank  .RBCT          36000.00    45000.00    57000.00    57000.00
Mmamabula.Matola        10000.00    20000.00    30000.00    40000.00


----    452 VARIABLE  Y.L  quantity shipped from port K to demand J in period
                      t: 000's mtce

                            1995        2000        2005        2010
Matola   .ARA           10000.00    20000.00                24295.76
Matola   .Yokohama                              30000.00    15704.24
RBCT     .ARA            7736.92    21342.14    41337.22
RBCT     .Yokohama      28263.08    23657.85    15662.77    57000.00
Gladstone.Yokohama      32755.37    40258.48    32218.98    18886.48
Hroads   .ARA           10742.50                14991.05

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G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m
E x e c u t i o n



EXECUTION TIME       =        0.050 SECONDS      1.4 Mb      WIN200-121


USER: Division of Resource Management                G010529:1803AP-WIN
      West Virginia University                       DC2709

**** FILE SUMMARY

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Vita

Khaulani Fichani

Khaulani Fichani was born on August 6th, 1958 at Masunga in Botswana. He completed his secondary school education in 1977 from Moeding College and was awarded a scholarship under the Canadian International Development Agency to study towards a degree in mining engineering. In 1980 he graduated with a two year Mining Technician's Diploma from the Haileybury School of Mines in Ontario, Canada and proceeded to study at the University of British Columbia where he graduated in 1984 with a B.A.Sc. Degree in Mining and Mineral Processing Engineering.

His work experience includes more than ten years in both the private and government sectors. He spent one year as a production supervisor for underground mining operations at Botswana's large scale copper and nickel mine, BCL Ltd, in 1985/86 and two years as production foreman at the now largest diamond mine operation in Botswana, the Orapa and Letlhakane Mines from 1986 to 1988. By the time he went back for his Doctoral studies, he was a Principal Minerals Officer in Botswana's Ministry of Minerals, Energy and Water Affairs.

From mid 1990 to December 1991, Khaulani completed an MS program in Mineral Economics from the Colorado School of Mines in Golden, Colorado. Upon graduation he played key roles in the restructuring and subsequent sale of Amax Inc.'s interest in BCL in 1992; securing Sysmin assistance to Botswana's base metal mining industry in 1994; leading the first phase of the project to review Botswana's mineral legislation and policy that culminated in his presentation of the proposed fiscal regime to a select group of international mining executives in 1996 and chairing some of the roundtable discussions; secretary of the drafting committee for the new mining law in 1997, and an attachment to the Commonwealth Secretariat's Economic and Legal Advisory Services Division in London in 1998.

Since January 1999, Khaulani has been a student in the Ph.D. program in Agriculture and Resource Economics at West Virginia University. In this time, he has worked part-time as a GIS technician for the Division's Natural Resource Analysis Center and also as adjunct faculty at Fairmont State College in Fall 2002 and Potomac State College of West Virginia University in Spring 2003. I taught introductory microeconomics and principles of macroeconomics.

His areas of interest are in modeling primary fossil fuel trade at both the regional and international levels; applying economic theory to the solution to problems on global warming, and issues to do with energy, the environment, development and welfare.