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A World Trade Model with Bilateral Trade Based on Comparative Advantage

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Abstract

This paper describes an extension of Duchin's World Trade Model to include the explicit representation of transportation costs, permitting the endogenous determination of bilateral trade flows and region-specific prices. The original model is a linear program that, based on comparative advantage and the minimization of factor use, determines regional production and trade flows as well as world prices and scarcity rents for m regions, n good, and k factors. The new World Trade Model with Bilateral Trade achieves its objectives by introducing transportation services and geographically dependent transportation requirements for each traded good and each pair of potential trade partners. The formulation of this model and its major properties are presented, and results from a preliminary analysis with 11 regions, 8 goods, 4 transportation sectors, and 6 factors of production are reported and compared with corresponding results from the World Trade Model. On the basis of this comparison, we conclude that transportation costs have little impact on a region's total imports or exports of a given commodity.

Keyword

input-output model, comparative advantage, world trade model, bilateral trade

JEL Codes: C61, C67, F19

1 Introduction

Duchin's World Trade Model (WTM) was developed to evaluate worldwide and region-specific economic and environmental implications of alternative assumptions about production and consumption in different regions of the world, taking their imports and exports endogenously into account (Duchin, 2005). However, that model does not explicitly associate traded goods with the means by which they are transported and the cost of this transportation. To represent the transportation of traded goods, one needs at the outset to know their origins and destinations. The objective of this paper is to present a model that generalizes the WTM by directly incorporating transportation requirements. In this way the new model is able to determine both bilateral trade flows and the region-specific prices of traded goods.

Identifying bilateral trade flows and associating them with production requirements extends the analytic power of the modeling framework. Increasingly, researchers are concerned to identify bilateral trade flows for two reasons. First, transportation is a major use of energy and source of greenhouse gases, with the quantities dependent on the modes of transport and the distances traveled. Second, these bilateral flows are needed to distinguish the factor contents and emissions associated with a region's production from those associated with its consumption. To do so requires production information for its trading partners. Embedded emissions and other environmental loads associated with imports cannot be quantified without this knowledge. When scenarios about the future are analyzed, it is vital to have the ability to identify likely changes not only in volumes of trade but also in trade partners.

In the absence of transportation-related transaction costs, a region would be indifferent (at least from an economic point of view) to the origin of its imports. In this paper bilateral trade flows are determined by taking these transaction costs explicitly into account. Inter-regional transportation requires physical inputs of labor, energy and capital and involves costs that are related to the nature and weight of what is carried, the mode of transport, and the origin and destination. Transportation costs constitute a non-negligible share of the total cost of some goods, and related emissions account for a significant portion of total emissions associated with that good.

Duchin's World Trade Model, WTM, is a linear programming model(LP)that determines inter-regional trade flows and world prices based on comparative advantage by minimizing factor use subject to region-specific factor constraints

(Duchin, 2005). The WTM has features that make it a desirable framework for investigating the economic and environmental significance of alternative scenarios about production and consumption activities. This paper presents an extension of the WTM that explicitly includes transportation activities and on this basis is able to determine bilateral trade flows and region-specific prices. These features substantially extend the model's ability to analyze the environmental and economic implications of production and consumption in a global economy. The World Trade Model (WTM) has m regions, n sectors, and k factors of production and was applied by Duchin to a database for 11 regions, 8 sectors, and 3 factors. The purpose of the present paper is to extend the capabilities of the WTM by distinguishing a region's imports by their source regions and distinguishing its exports by their destinations. This is achieved by making inter-regional transportation costs both explicit and endogenous in the model, yielding a World Trade Model with Bilateral Trade, or WTMBT. Data are collected to represent several maritime transport sectors, which carry the bulk of international goods, in this first implementation of the new model.

Empirical results from computations of the WTMBT with the expanded database for 1990 are reported as well as results for the same year using the WTM. Based on comparisons of properties of the two models and of the empirical results obtained with them, we conclude that the WTMBT has all the desirable properties of the original input-output model of the world economy (Leontief, Carter, and Petri, 1977), augmented by the ability to make production assignments, trade flows, and world prices endogenous on the basis of comparative advantage of the WTM (Duchin, 2005) and the determination of bilateral trade flows and region-specific prices that include transportation costs.

The WTM operationalizes the concept of comparative advantage familiar from textbook treatments of 2 regions, 2 sectors, and 1 or 2 factors for the general case of m regions, n goods, and k factors. This is achieved by assigning production of a good to the region that is the relatively lowest cost producer. In the general case, the region is unable to satisfy total world demand for the good; when it runs up against one or more factor constraints, the next relatively lowest-cost producer enters production, and so on, until all demand is satisfied (or all limiting factors are exhausted before total demand can be satisfied). The unique contribution of the WTM is the determination of relatively low-cost producers by comparing cost structures simultaneously across all regions and all sectors. An importing region is indifferent to all features of exporting regions except their production cost structures.

The concept of comparative advantage is expanded in the World Trade Model with Bilateral Trade, WTMBT, where, as in reality, the economic advantage of a region that has low cost structures will be offset if it is geographically remote from potential trade partners or has inadequate or costly transportation and communication infrastructure (for example, if it is landlocked). Similarly, a somewhat higher-cost producer will benefit from a more central location and favorable infrastructure. Cost comparisons from the points of view of importing regions now include not only the cost of the product but also the cost of transporting it, represented here by the good-specific cost of maritime transport from the origin to the destination. Now the identification of the relatively lowest-cost producer depends not only on production characteristics but also a number of other considerations including the location of the major markets. It is shown both conceptually and empirically that results obtained with the two models are similar for the common variables, but the WTMBT has additional capabilities.

The rest of this paper is divided into 5 sections. The new model is described in Section 2, and its properties are described in Section 3. The next sections describe the expansion of the database to incorporate a description of four maritime transport sectors. Section 5 presents the result of the model computations, and the final section summarizes and concludes.

2 The Representation of Bilateral Trade

2.1 The World Trade Model with Bilateral Trade

The World Trade Model with Bilateral Trade (WTMBT) is a linear program that endogenously determines regional output, $\mathbf{x}_i$, and bilateral trade flows, $\mathbf{e}_{ij}$, in the primal program and regional prices, $\mathbf{p}_i$, and scarcity rents, $\mathbf{r}_i$, in the dual. The WTMBT has $(n+s)m+(n+s)m(m-1)$ endogenous variables in the primal by contrast with the nm variables of the WTM. (The number of $\mathbf{x}_i$ variables in WTMBT is $(n+s)m$, and the number of $\mathbf{e}_{ij}$ variables is $(n+s)m(m-1)$). The parameters and variables of the model are listed in Table 1. The primal objective function minimizes global factor costs:

$$\min \quad z = \sum_i \pi_i' \mathbf{F}_i \mathbf{x}_i \tag{1}$$

The first sets of constraints are the regional goods balances, in which the import flows generate the demand for transportation. This is achieved by introducing a new object, the $\mathbf{T}_{ji}$ matrix, which specifies the requirements of transporting a good from region j to i. In the resulting balance equation, output, $\mathbf{x}_i$, is the sum of intermediate production requirements, $\mathbf{A}_i\mathbf{x}_i$, exports net of imports, $\mathbf{e}_{ij}$ - $\mathbf{e}_{ji}$, transport demand required for carrying imports, $\mathbf{T}_{ji}\mathbf{e}_{ji}$, and regional final demand $\mathbf{y}_i$:

$$(\mathbf{I} - \mathbf{A}_i)\mathbf{x}_i - \sum_{j \neq i} \mathbf{e}_{ij} + \sum_{j \neq i} (\mathbf{I} - \mathbf{T}_{ji})\mathbf{e}_{ji} \geq \mathbf{y}_i \quad \forall i. \tag{2}$$

The production of a given good in region i requires factor inputs, which are quantified in the $\mathbf{F}_i$ matrix. Factor use is constrained by the endowment, or in some cases the availability, $\mathbf{f}_i$:

$$\mathbf{F}_i\mathbf{x}_i \leq \mathbf{f}_i \quad \forall i. \tag{3}$$

The third set of restrictions comprise the benefit-of-trade constraints, which assure that no region exceeds its no-trade factor usage. (See (Duchin, 2005) for the rationale for this constraint.) This is achieved by requiring that the value of exports not exceed the value of imports at no-trade-prices, where the latter are found by solving a no-trade model (NTM) that is described in Appendix A along with the other relevant models.

$$\mathbf{p}_i^{*'}(\mathbf{I} - \mathbf{A}_i)\mathbf{x}_i \leq \mathbf{p}_i^{*'}\mathbf{y}_i \quad \forall i. \tag{4}$$

The dual formulation of the model, which determines prices and scarcity rents, is presented below:

$$\max.\quad z = \sum_i \mathbf{y}_i' \mathbf{p}_i - \sum_i \mathbf{f}_i' \mathbf{r}_i - \sum_i \mathbf{p}_i^{*'} \mathbf{y}_i \alpha_i \tag{5}$$

$$\text{s.t.}\quad (\mathbf{I} - \mathbf{A}_i')\mathbf{p}_i - \mathbf{F}_i' \mathbf{r}_i - (\mathbf{I} - \mathbf{A}_i')\mathbf{p}_i^* \alpha_i \quad \leq \pi_i \mathbf{F}_i' \qquad \forall i \tag{6}$$

$$(\mathbf{I} - \mathbf{T}_{ji}')\mathbf{p}_i - \mathbf{p}_j \quad \leq 0 \qquad \forall i, j \in i \neq j. \tag{7}$$

The dual maximizes the total value of final demand net of rents, subject to two price constraints. The first determines prices in regions that produce and export a given good while the second describes price formation in importing regions.

Table 1: Parameters and Variables for the WTMBT

	m		number of regions
	n		number of goods
	s		number of transport sectors
	k		number of factors of production
	i, j		indices for regions $i, j = 1...m$
Parameters	$\mathbf{A}_i$	$(n+s) \times (n+s)$	matrix of interindustry production coefficients i region i
and	$\mathbf{F}_i$	$k \times (n+s)$	matrix of factor inputs per unit of output in region i
Exogenous	$\mathbf{D}$	$m \times m$	matrix of interregional distances
Variables	$\mathbf{W}$	$(n+s) \times (n+s)$	matrix of weight of goods
	$\mathbf{T}_{ij}$	$(n+s) \times (n+s)$	matrix of requirements for transportation from i to j
	$\mathbf{y}_i$	$(n+s) \times 1$	vector of final demand in region i
	π_i	$k \times 1$	vector of factor prices in region i
	$\mathbf{f}_i$	$k \times 1$	vector of factor endowments in region i
	$\mathbf{f}_i^*$	$k \times 1$	vector of factor use in absence of trade in region i
	$\mathbf{p}_i^*$	$(n+s) \times 1$	vector of goods prices in absence of trade in region i
Endogenous	$\mathbf{x}_i$	$(n+s) \times 1$	vector of output in region i
Variables	$\mathbf{e}_{ij}$	$(n+s) \times 1$	vector of goods exported from region i to region j
	$\mathbf{p}_i$	$(n+s) \times 1$	vector of goods prices in region i
	$\mathbf{r}_i$	$k \times 1$	vector of factor scarcity rents in region i
	α_i	scalar	benefit-of-trade shadow price in region i

The $\mathbf{A}_i$ matrix augments the corresponding matrix of the WTM by adding s transportation sectors in addition to the n goods-producing sectors. Demand for transportation is generated via the $\mathbf{T}$ matrix in equation 2. $\mathbf{T}$ is defined in terms of a new object, the $\mathbf{W}$ matrix, which fulfills two functions: it represents the weights of goods and assigns each good to the transport mode that will carry it. These objectives are achieved by placing the weight of a good in the entry of $\mathbf{W}$ where the column represents the sector producing the good and the row represents the transport sector carrying it. (Combinations of transport modes and goods that are not allowed are blocked in this implementation by introducing a prohibitively large weight in the corresponding positions in $\mathbf{W}$.) The $\mathbf{W}$ matrix therefore contains non-zero entries only in the last s rows. The $\mathbf{T}_{ij}$ matrices, one for each origin-destination pair of regions, are generated by combining the $\mathbf{W}$ and $\mathbf{D}$ matrices, where the latter contains the interregional distances:

$$\mathbf{T}_{ij} = d_{ij} \cdot \mathbf{W} \qquad \forall ij \tag{8}$$

3 Properties of the Model

3.1 Primal

The WTMBT is a generalization of the WTM and inherits many of its properties, which are described in detail and proved in (Duchin, 2005) and will not be repeated here. It is also related to the no-trade model (NTM), which represents a set of mutually closed economies. The solution to the NTM is a feasible solution for the WTMBT and is approached as its optimum solution as transportation costs become arbitrarily high: elevated transportation costs act as an barrier to trade and if they are high enough, no trade will occur.

The optimal solutions of the WTM and WTMBT can be compared only in the shared dimensionality: the regional output vectors, $\mathbf{x}_i$. For the special case of zero transportation costs, the solutions are identical although, in this case, the bilateral export variables, $\mathbf{e}_{ij}$, of the WTMBT cannot be uniquely determined.

3.2 Dual

Each good has region-specific prices in the WTMBT given that transport costs are non-zero. If the transportation costs are zero there is a single world price for each good identical to the price in the WTM. If the transportation costs are infinite, there is a region-specific price for each good identical to the price of the no-trade model.

As for the WTM, the relations between the primal and dual variables are defined by the complimentary slackness theorem. The price of a good in region i is determined by one of two equations. If the region produces the good, the price is determined as the sum of all production costs including rents while an importing region pays the price in the exporting region plus the cost of transportation.

Regional prices in the WTMBT are systematically related to no-trade prices if no scarcity rents are earned. In this case, it can be shown that the price of a domestically produced good in all regions will be strictly lower than its no-trade price, and the price of an imported good is strictly lower than the lowest no-trade price of an exporting region plus the cost of transportation in the same region.

4 Representation of Transportation and Other Data

This implementation of the World Trade Model with Bilateral Trade (WTMBT) uses a database with 11 regions, 8 goods, 4 transportation sectors, and 6 factors of production, all of which are identified in Appendix B. The WTM database (Duchin, 2005) with 10 regions, 8 goods, and 3 factors was used to the extent possible. The purpose of this section is to document the additional data incorporated for the present implementation.

4.1 Regions and Resource Constraints

Because the WTMBT was designed especially for analysis of material flows, regions with major mineral deposits and resource-processing activities need to be distinguished. The 10 regions of the WTM include a residual called Rest of World that combines a number of relatively small economies on several continents. This region was redefined by extracting an independent region for Australia and New Zealand. Other Rest-of-World countries were redistributed so that the region called Latin America now includes all countries on that continent, as does the region called Africa. All countries in Asia except China and Japan are combined into one region, dominated by the Indian economy, called Other Asia, or Asia for short.

Nonrenewable resources impose evident constraints on production and earn scarcity rents like the other factors of production: land, labor, and capital. The limited availability in any given region of coal, oil, and gas is represented in this first approach like an endowment, assumed to be 1.4 times actual production in the base year of 1990. The base year production figures are shown in Table 2.

The link between the roles of the fuels as intermediate inputs and the constraint on their availability is provided by the entries in the rows of the F matrix corresponding to coal, oil, and gas. These input coefficients are set to unity (1.0), effectively constraining the volume of total production; see Equation 3.

4.2 Transportation

Freight can be carried by a variety of modes depending on geography and on cultural, political, and economic factors. The objective of this implementation of the WTMBT is to demonstrate the capabilities of the model by representing the four modes of marine transportation that carry the large majority of internationally-traded goods: oil tankers, LNG carriers, bulk transport, and container ships. Each mode is treated as a production sector in the model. In the present implementation, every region is represented by a single port, and any of the transportation sectors can carry goods between that port and the port representing any other region.

Demand for marine transportation, generated by the import of goods, is measured in ton-kilometers [tkm]. It is the product of 3 variables: the volume of the imported good [measured in any unit] times the weight of the good [tons/unit] times the distance traveled [km]. (See Equation 8.)

The sector transporting crude oil is assumed to operate Suezmax class tankers, the LNG carrier is a 140,000 m^3 vessel, bulk goods are assumed to be transported by Capesize vessels (ranging between approximately 80,000-175,000 deadweight

Table 2: Factor Endowments

Units: Land 10^6hectares, labor 10^6workers, capital 10^9 1970 US dollars , Fuels: 10^6 tce

	NA	WE	FSU	Asia	China	Japan	ME	EE	LA	Africa	ANZ
Land	345	141	256	322	140	8	14	56	740	755	89
Labour	145	198	147	552	675	65	62	50	173	169	11
Capital	6114	7880	1570	3101	2651	3610	609	628	2336	1081	427
Coal	1199	422	656	313	1085	9	2	348	44	210	221
Oil	1018	435	1125	317	277	0	1704	16	750	637	58
Gas	1120	331	1368	198	26	0	182	56	153	120	46

Sources: Land (United Nations, Food and Agricultural organization (FAO), Land and Water Division, 2000)

Labor and capital(Duchin, 2005), fossil fuels (British Petroleum, 2004). Regions are identified in Appendix B tons), and containers are transported by a 4,000TEU (twenty-foot equivalent unit, or 20-foot dry-cargo) container ships. The data for representing the input structures are assembled from a variety of sources: see Table 3 for the numerical figures and Appendix C for the sources.

Each transportation sector is represented by a column of input coefficients in the A matrix and a column of factor requirements in the F matrix. In this implementation, differences in regional transportation technologies and efficiencies are ignored, so that a given transportation sector has the same input structure (but distinct factor prices) in each region. These inputs are shown in Table 3.

Each traded good is assigned to one or more modes of transportation. Crude oil is transported by crude tankers only, and all natural gas is transported using LNG carriers. Agricultural goods use both bulk and container transport. Bulk transport is used for mining products and coal. Manufactured goods are assumed to be transported by container ships. The weights of the fossil fuels are derived from their physical properties. For mining, agricultural and manufacturing goods, average weights are taken from UNCTAD trade statistics (United Nations Conference on Trade and Development, 2004). Table 4 shows

Table 3: Intermediate and Factor Requirements per Unit of Output for 4 Modes of Marine Transportation

Units: All goods and factors in 10^3 2003 US dollars per 10^9 tkm, except oil, in 10^3ton per 10^9 tkm, and labor, in workers per 10^9 tkm

	Crude Carrier Suezmax Class	Bulk Carrier Capesize Class	Container Vessel 4000TEU	LNG Tanker $140000m^3$
Oil	0.57	0.52	2.32	1.56
Manuf.	32.4	32.9	20.3	74.6
Serv.	8.1	8.2	5.1	18.7
Labor	2.1	1.5	2.8	3.7
Capital	4.3	3.8	7.1	27.9

Source: Data from C1-C7 in Appendix C (United Nations, International Labour Office (ILO), 1990) and (United Nations Conference on Trade and Development, 2003) the weights and transport modes for all traded goods. Note that transshipment of goods (as discussed by (Dantzig and Thapa, 2003)) will not occur since we have assured that the direct path between two regions is always the shortest and that there is a world price for each transportation mode.

The distances between the ports, found in navigational tables (Maritime Safety Information Division, 2001), are shown in Table 5. An effort was made to select ports that avoid unrealistic distances between an origin region and multiple destinations. The nature of the problem is exhibited by the case of North America, where the harbor selected is next to the Panama Canal to assure plausible distances to both Asia and Europe. The Black Sea port of Novorossiysk is selected for the former Soviet Union as a compromise among similar considerations.

Many simplifications relied upon for this representation are easily relaxed. Several connection points could be included for each region and distinguished by good and/or by trade partner. Multiple transport modes including air and land transport could be included so that, for example, natural gas is transported from Russia to Europe by pipeline, as it actually is, rather than by tanker. The operations research literature provides extensive insight into methods for com-

Table 4: Weights and Transportation Modes for Traded Goods

Units: Fuels in ton per tce and others in kg per 2003 US dollars

	Transport Mode	Weight
Coal	Bulk	1.00
Oil	Crude	0.70
Gas	LNG Tanker	0.65
Mining	Bulk	1.2
Agric.	Bulk and Container	4.5
Manuf.	Container	3.5

Source (United Nations Conference on Trade and Development, 2004) plex and detailed logistics modeling; see, for example, (Bramel and Simchi-Levi, 1997). However, the advantages of incorporating greater detail for a particular study need to be balanced against the added complexity.

Table 5: Regional Ports and Inter-regional Distances

Units: kilometers

Port	Region	NA	WE	FSU	Asia	China	Japan	ME	EE	LA	Africa	ANZ
Christobal	NA	0	5020	6560	9305	8960	8130	9548	5980	4289	7242	7717
Marseilles	WE		0	1834	4590	8825	9558	4816	1164	5130	6090	9845
Novorossiysk	FSU			0	4320	8555	9288	4552	1568	6530	5819	9580
Mumbai	Asia				0	4655	5353	1537	4315	7863	3900	6025
Shanghai	China					0	1148	6037	8509	10877	6968	4636
Tokyo	Japan						0	6749	9221	11535	7679	4348
Kuwait	ME							0	4577	8396	4450	7424
Rijeka	EE								0	5885	5839	9590
Rio de Janeiro	LA									0	4100	7635
Durban	Africa										0	5895
Sidney	ANZ											0

Source: (Maritime Safety Information Division, 2001). Regions are identified in Appendix B

5 Empirical Results

Now we compare the results from the World Trade Model with Bilateral Trade to those from the World Trade Model. The global results are shown in Table 6, which reports world production (in the first two columns) and total exports (in the next two columns) for each good. The last section of the table reports the calculated prices. For the WTM there is a single world price for traded goods, while a maximum and a minimum price are reported for the two non-traded sectors, electricity and services. Since WTMBT has region-specific prices for both traded and non-traded items, 2 columns of prices are shown, a maximum and a minimum.

Global factor costs (the primal objective function) for the WTMBT are less than 1% higher than for the WTM. Therefore, it is not surprising (see Table 6) that global levels of output under the WTMBT are very close to those of the WTM (within about 1%), except for a noticeably higher value for oil. Increased use of oil is to be expected since it is the fuel used by the four transportation sectors. The global export levels for both models are very close for all sectors except fuels: total fuel exports (in tons of coal equivalent) are 5% higher under the WTMBT, and there is a shift from trade in gas to trade in oil. We conclude that the introduction of transportation allows for bilateral trade flows to be determined but does not affect the overall results substantially, at least at the global level. A solution to the dual of the WTMBT includes a region-specific price for each good that depends upon the weights of the region's imports and the distance they are transported. Two conclusions can be drawn from the last three columns of Table 6. First, the range of prices[1] across regions for traded

[1]The original version of this database was compiled in 1970 US dollars, and this unit is

goods under the WTMBT is relatively narrow, and second, these prices are close to the world price of the WTM, except for a higher price for oil. This price differential reflects the entry into production and export of relatively higher-cost producers and, for this reason, higher scarcity rents for the lower-cost producers.

The regional distribution of production for each good under the two models is shown in Table 7, where the first figure in each cell is for the WTMBT and the figure in parentheses is the difference between the solutions to the two models (i.e., the sum of the two figures is the value for the WTM). It can be seen that, for the most part, each region produces similar levels of the same goods in both models.

Detail on bilateral trade flows is shown in Table 8. For each good, the first 2 columns of the table identify each exporter and that exporter's price before transportation. In the following columns, each destination served by an exporter is identified followed (in subsequent columns) by the quantity exported, the transportation cost to the importer, the total price to the importer, and the cost of transportation as a percentage of the importer's total price.

To illustrate the nature of the results, we use the case of natural gas. Seven regions produce this product, of which four are exporters. The former Soviet Union is the largest producer followed by North America and Western Europe. The smaller producers are the Middle East, Africa, Australia and China, which jointly account for less than 20% of the quantity produced in the former Soviet Union. The regions exporting gas are the former Soviet Union, Western Europe, China and Australia. Further production in all of the exporting regions is constrained by the availability of gas (i.e., a binding factor constraint). The

retained for reporting purposes.

Table 6: World Output, Exports, and Prices for the WTMBT and WTM

Fossil fuels in 10^6tce. All other goods in 10^6 1970 US dollars

	Output		Export		Unit Prices		
	WTMBT	WTM	WTMBT	WTM	WTMBT	WTMBT	WTM
Coal	3037	3079	1128	1091	0.030	0.027	0.030
Oil	4748	4069	3120	2819	0.057	0.056	0.050
Gas	2462	2462	554	663	0.037	0.033	0.039
Elec.	236	235	0	0	8.52	1.80	8.8/1.9
Mining	59	58	58	58	0.51	0.50	0.51
Agric.	690	689	147	150	3.49	3.37	3.48
Manuf.	3196	3190	404	414	1.49	1.38	1.49
Serv.	4242	4233	0	0	2.79	1.44	2.9/1.5

Source: Own computations

Table 7: Output by Good and by Region for the WTMBT and WTM

Fossil fuels in 10^6tce. All other goods in 10^6 1970 US dollars

	NA	WE	FSU	Asia	China	Japan	ME	EE	LA	Africa	ANZ	World
Coal	1075	0	656	0	1085	0	2	0	0	0	221	3037
	(42)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(42)
Oil	0	435	1125	0	277	0	1704	16	496	637	58	4748
	(0)	(-183)	(0)	(0)	(0)	(0)	(0)	(0)	(-496)	(0)	(0)	(-679)
Gas	498	331	1368	0	26	0	182	0	0	11	46	2462
	(-165)	(0)	(0)	(0)	(0)	(0)	(0)	(56)	(0)	(109)	(0)	(0)
Elec.	73	48	40	12	14	17	4	11	8	3	5	236
	(0)	(0)	(0)	(-2)	(1)	(0)	(0)	(0)	(0)	(0)	(0)	(-1)
Mining	0	0	0	0	0	0	0	0	0	0	59	59
	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(-1)
Agric.	26	153	0	112	140	7	9	49	117	58	21	690
	(-26)	(0)	(0)	(0)	(0)	(24)	(0)	(0)	(2)	(-1)	(0)	(-1)
Manuf.	1350	606	473	135	93	341	0	198	0	0	0	3196
	(69)	(7)	(0)	(-51)	(29)	(-59)	(0)	(-2)	(0)	(0)	(0)	(-6)
Serv.	1493	917	465	206	203	331	53	266	168	71	69	4242
	(1)	(-1)	(0)	(-9)	(5)	(-2)	(0)	(0)	(-2)	(0)	(0)	(-9)

The first figure for each good in each region is the quantity of output for the WTMBT; the figure in parentheses shows the amount by which it is exceeded for the WTM. Source: Own computations. Regions are identified in Appendix B effective unit price for gas varies across regions by about 10% from the price in the lowest-cost producer, the former Soviet Union, to the highest price in Japan, which is entirely reliant on imports. The resource rents are highest in the former Soviet Union, the relatively lowest-cost producer, where they constitute about 2/3 of the price. In Australia and China, rents account for about half the price and in Western Europe, 10%.

For the regions importing gas, transport accounts on average for 6.1% (unweighted) of the effective price. In the case of Japan, the cost of transport varies from 1.4% for imports from China to 11.5% for imports from the former Soviet Union. The case of coal also illustrates the systematic variation in transport costs, which range up to 8% of the importer's total price but only 1% for coal imported from China to Japan and only slightly more for coal transported from the former Soviet Union to Eastern Europe.

6 Conclusion

The objective of the research reported here was to extend an existing model of the world economy by determining bilateral trade flows and region-specific prices. These features capture the costs of increased transport of goods associated with globalization and the economic significance of geographic location. The new model, called the World Trade Model with Bilateral Trade or WTMBT, introduces transport requirements associated with imports into the comparisons that form the basis for determining comparative advantage.

The properties of the model are described and compared with those of the World Trade Model or WTM, on which it is based (Duchin 2005), and a model

Table 8: Exports, Imports, Prices, and Transport Costs by Good and by Region

The units of fossil fuels are in 10^6tce. All other goods in 10^6 1970 US dollars

Good	Exp.	Exp. Price	Imp.	Quantity	Transp. Price.	Imp. Price	Transp/Imp. Price
Coal	NA	0.0281	WE	385.2	0.0012	0.0294	4.2
		0.0281	EE	33.3	0.0015	0.0296	4.9
	FSU	0.0292	EE	100.6	0.0004	0.0296	1.3
	China	0.0275	Asia	220.0	0.0011	0.0287	4.0
			EE	186.6	0.0021	0.0296	7.0
			Japan	62.2	0.0003	0.0278	1.0
			ME	1.6	0.0015	0.029	5.1
	ANZ	0.0273	LA	68.5	0.0019	0.0291	6.4
			Africa	35.5	0.0014	0.0287	5.0
			EE	34.4	0.0023	0.0296	7.9
Oil	FSU	0.056	WE	401.9	0.0003	0.0563	0.5
			EE	101.3	0.0003	0.0563	0.4
			NA	45.4	0.0010	0.0571	1.8
	China	0.0565	Japan	112.5	0.0002	0.0566	0.3
	ME	0.0556	Asia	928.2	0.0002	0.0558	0.4
			NA	437.3	0.0015	0.0571	2.7
			Japan	227.5	0.0011	0.0566	1.9
			ANZ	6.8	0.0012	0.0567	2.1
	LA	0.0564	NA	311.1	0.0007	0.0571	1.2
	Africa	0.0559	NA	547.9	0.0012	0.0571	2.0
Gas	WE	0.0334	NA	46.0	0.0023	0.0357	6.4
	FSU	0.0327	NA	218.8	0.0030	0.0357	8.4
			EE	107.1	0.0007	0.0334	2.1
			Asia	80.0	0.0020	0.0346	5.7
			Japan	39.3	0.0042	0.0369	11.5
			LA	28.2	0.0030	0.0356	8.3
			ME	24.3	0.0021	0.0347	5.9
	China	0.0364	Japan	6.2	0.0005	0.0369	1.4
	ANZ	0.0349	Japan	4.7	0.0020	0.0369	5.4
Mining	ANZ	0.4983	NA	15.7	0.0114	0.5097	2.2
			WE	11.4	0.0145	0.5127	2.8
			FSU	12.3	0.0141	0.5123	2.7
			Japan	7.2	0.0064	0.5047	1.3
			EE	3.5	0.0142	0.5125	2.8
			Asia	3.3	0.0089	0.5072	1.8
			China	3.2	0.0068	0.5051	1.3
			LA	0.7	0.0112	0.5095	2.2
			Africa	0.4	0.0087	0.5069	1.7
			ME	0.2	0.0109	0.5092	2.1
Agric.	WE	3.4206	NA	10.2	0.1222	3.5428	3.4
			FSU	27	0.0446	3.4652	1.3
	EE	3.4245	FSU	10.0	0.0381	3.4626	1.1
	LA	3.4314	NA	41.3	0.1044	3.5358	3.0
	China	3.3732	Japan	17.6	0.028	3.4012	0.8
			Asia	9.4	0.1133	3.4866	3.3
	Africa	3.3878	ME	15.6	0.1081	3.496	3.1
			NA	1.8	0.1763	3.5642	4.9
	ANZ	3.3808	NA	14.6	0.1879	3.5687	5.3
Manuf.	NA	1.3799	WE	52.5	0.0729	1.4527	5.0
			L.A.	108.5	0.0623	1.4421	4.3
			Africa	44.6	0.1051	1.4850	7.1
			ANZ	48.2	0.1120	1.4919	7.5
	FSU	1.4261	WE	3.8	0.0266	1.4527	1.8
			Asia	31.9	0.0627	1.4888	4.2
			ME	44.4	0.0661	1.4922	4.4
			EE	4.8	0.0228	1.4489	1.6
	ME	1.6532	Africa	29.1	0.1147	1.7678	6.5
	Japan	1.4502	China	65.4	0.0167	1.4668	1.1

Source: Own computations. Regions are identified in Appendix B of no-trade or self-sufficiency. When transportation costs are equal to zero, the solution of the WTMBT is identical to that of the WTM; as transportation costs become very large, the solution approaches that of the no-trade model. Another new feature introduced in this paper is the treatment of the 3 fuels as factors of production with limited availability.

Four modes of sea transportation are introduced to carry imports, and the demand for each transport service is related to the quantities and distances for the carriage of specific goods. Each region is represented by a single harbor. Data for the input requirements of the transport sectors, weights of goods, and distances between harbors are incorporated into the database. The WTMBT is implemented for 11 regions, 8 goods, 4 transportation sectors, and 6 factors of production.

The results obtained with the new model for global factor costs and regional outputs are very close to those of the WTM, except for a notably higher output of oil due to explicit transportation requirements that were formerly ignored. In addition, the bilateral trade flows and region-specific prices are explicitly and uniquely identified, achieving the main objective of this research. Prices across regions for traded goods exhibit a relatively narrow range, indicating that transportation costs do not dominate the prices. For each traded good, the minimum price for the WTMBT is close to the single world price of the WTM while the maximum prices are higher than the WTM price because of transport costs. Results about the production and trade of natural gas are examined in detail to illustrate the nature of a solution to the WTMBT. A more extensive and more robust database will be required for empirical results with direct policy significance, and we believe that such a database will not be long delayed.

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A The World Trade Models

This Appendix presents a no-trade model (NTM) and the World Trade Model(WTM, which, like the WTMBT, have m regions, n sectors and k factors of production. Finally, a simplified two-region implementation of the World Model with Bilateral Trade (WTMBT) is shown.

A.1 The No Trade Model

For a thorough introduction to the NTM, see (Duchin, 2005). The primal takes the following form:

$$\begin{bmatrix} (I-\mathbf{A}_1) & & 0 \\ & \ddots & \\ 0 & & (I-\mathbf{A}_m) \\ -\mathbf{F}_1 & & 0 \\ & \ddots & \\ 0 & & -\mathbf{F}_m \end{bmatrix} \begin{bmatrix} \mathbf{x}_1 \\ \vdots \\ \mathbf{x}_m \end{bmatrix} = \begin{bmatrix} \mathbf{y}_1 \\ \vdots \\ \mathbf{y}_m \\ -\mathbf{f}_1 \\ \vdots \\ -\mathbf{f}_m \end{bmatrix} \tag{9}$$

The dual is as follows:

$$\begin{bmatrix} (I-\mathbf{A}'_1) & & 0 & -\mathbf{F}'_1 & & 0 \\ & \ddots & & & \ddots & \\ 0 & & (I-\mathbf{A}'_m) & 0 & & -\mathbf{F}'_m \end{bmatrix} \begin{bmatrix} \mathbf{p}^*_1 \\ \vdots \\ \mathbf{p}^*_m \\ \pi_1 \\ \vdots \\ \pi_m \end{bmatrix} = \begin{bmatrix} 0 \\ \vdots \\ 0 \end{bmatrix} \tag{10}$$

$$\mathbf{y}'_i \mathbf{p}^*_i = \pi'_i \mathbf{F}_i x^*_i = \pi'_i f^*_i \quad \forall i \tag{11}$$

A.2 The World Trade Model

The primal linear program of the World Trade Model is presented in standard form as follows (see (Duchin, 2005)):

$$\text{Minimize} \quad z = \sum_i \pi_i' \mathbf{F}_i x_i \qquad \text{subject to}$$

$$\begin{bmatrix} (I - \mathbf{A}_1) & \dots & (I - \mathbf{A}_m) \\ -\mathbf{F}_1 & & 0 \\ & \ddots & \\ 0 & & -\mathbf{F}_m \\ -\mathbf{p}^*(I - \mathbf{A}_1) & & 0 \\ & \ddots & \\ 0 & & -\mathbf{p}^{*'}(I - \mathbf{A}_m) \end{bmatrix} \begin{bmatrix} \mathbf{x}_1 \\ \vdots \\ \mathbf{x}_m \end{bmatrix} \geq \begin{bmatrix} \sum_i \mathbf{y}_i \\ -\mathbf{f}_1 \\ \vdots \\ -\mathbf{f}_m \\ -\mathbf{p}^{*'}\mathbf{y}_1 \\ \vdots \\ -\mathbf{p}^{*'}\mathbf{y}_m \end{bmatrix} \tag{12}$$

with $\mathbf{x}_i \geq 0 \quad \forall \quad i$

The dual takes the following form:

$$\text{Maximize} \quad z = \sum_i \mathbf{y}_i' \mathbf{p}_0 - \sum_i \mathbf{f}_i' \mathbf{r}_i - \sum_i \mathbf{p}_i^{*'} \mathbf{y}_i \alpha_i \qquad \text{subject to}$$

$$\begin{bmatrix} (\mathbf{I} - \mathbf{A}_1') & -\mathbf{F}_1' & 0 & -(\mathbf{I} - \mathbf{A}_1')\mathbf{p}_i^* & 0 \\ \vdots & \ddots & & \ddots & \\ (\mathbf{I} - \mathbf{A}_m') & 0 & -\mathbf{F}_m' & 0 & -(\mathbf{I} - \mathbf{A}_m')\mathbf{p}_i^* \end{bmatrix} \begin{bmatrix} \mathbf{p}_0 \\ \mathbf{r}_1 \\ \vdots \\ \mathbf{r}_m \\ \alpha_1 \\ \vdots \\ \alpha_m \end{bmatrix} \leq \begin{bmatrix} \mathbf{F}_1' \pi_1 \\ \vdots \\ \mathbf{F}_m' \pi_m \end{bmatrix}$$

with $\mathbf{p}_0, \mathbf{f}_i, \alpha_i \geq 0 \quad \forall \quad i$

$$\tag{13}$$

A.3 The World Model with Bilateral Trade

In the two-region case, the primal model yields:

$$\text{Minimize} \quad z = \sum_i \pi_i' \mathbf{F}_i \mathbf{x}_i \qquad \text{subject to}$$

$$\begin{bmatrix} (I - \mathbf{A}_1) & 0 & -\mathbf{I} & (\mathbf{I} - \mathbf{T}_{21}) \\ 0 & (\mathbf{I} - \mathbf{A}_2) & (\mathbf{I} - \mathbf{T}_{12}) & -\mathbf{I} \\ -\mathbf{F}_1 & 0 & 0 & 0 \\ 0 & -\mathbf{F}_2 & 0 & 0 \\ -\mathbf{p}_1^{*'}(\mathbf{I} - \mathbf{A}_1) & 0 & 0 & 0 \\ 0 & -\mathbf{p}_2^{*'}(\mathbf{I} - \mathbf{A}_2) & 0 & 0 \end{bmatrix} \begin{bmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \\ \mathbf{e}_{12} \\ \mathbf{e}_{21} \end{bmatrix} \geq \begin{bmatrix} \mathbf{y}_1 \\ \mathbf{y}_2 \\ -\mathbf{f}_1 \\ -\mathbf{f}_2 \\ -\mathbf{p}_1^{*'}\mathbf{y}_1 \\ -\mathbf{p}_2^{*'}\mathbf{y}_2 \end{bmatrix}$$

$$\text{with } \mathbf{x}_i, \mathbf{e}_{ij} \geq 0 \quad \forall \quad i, j. \tag{14}$$

The corresponding dual formulation is:

$$\text{Maximize} \quad z = \sum_i \mathbf{y}_i' \mathbf{p}_i - \sum_i \mathbf{f}_i' \mathbf{r}_i - \sum_i \mathbf{p}_i^{*'} \mathbf{y}_i \alpha_i \qquad \text{subject to}$$

$$\begin{bmatrix} (\mathbf{I} - \mathbf{A}_1') & 0 & -\mathbf{F}_1' & 0 & -(\mathbf{I} - \mathbf{A}_1')p_1^* & 0 \\ 0 & (\mathbf{I} - \mathbf{A}_2') & 0 & -\mathbf{F}_2' & 0 & -(I - \mathbf{A}_2')p_2^* \\ -\mathbf{I} & (\mathbf{I} - \mathbf{T}_{12}') & 0 & 0 & 0 & 0 \\ (I - \mathbf{T}_{21}') & -\mathbf{I} & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \mathbf{p}_1 \\ \mathbf{p}_2 \\ \mathbf{r}_1 \\ \mathbf{r}_2 \\ \alpha_1 \\ \alpha_2 \end{bmatrix} \leq \begin{bmatrix} \mathbf{F}_1' \pi_1 \\ \mathbf{F}_2' \pi_2 \\ 0 \\ 0 \end{bmatrix}$$

$$\text{with } \mathbf{p}_i, \mathbf{f}_i, \alpha_i \geq 0 \quad \forall \quad i \tag{15}$$

B Goods, Transport Sectors, Regions and Factors

Table 9: Goods and Sectors

Code	Full Name	Units
Coal	Coal	tce - tons of coal equivalent
Oil	Oil oil distillates	tce - tons of coal equivalent
Gas	Natural gas	tce - tons of coal equivalent
Elec.	Electricity	1970 US dollars
Mining	Mineral products	1970 US dollars
Agric.	Agricultural products	1970 US dollars
Manuf.	Manufactured sectors	1970 US dollars
Serv.	Services	1970 US dollars
Crude.	Crude oil tanker transport	ton-kilometers (tkm)
Bulk.	Bulk carrier transport	ton-kilometers (tkm)
Cont.	Container ship transport	ton-kilometers (tkm)
LNG.	Liquefied natural gas carrier transport	ton-kilometers (tkm)

Table 10: Regions

Code	Full Name
NA	High Income North America
WE	Western Europe
FSU	Former Soviet Union
Asia	Asia
China	China
Japan	Japan
ME	Middle East
EE	Eastern Europe
LA	Latin America
Africa	Africa
ANZ	Australia, New Zealand

Table 11: Factors of Production

Code	Full Name
Land	Land
Labor	Labor
Capital	Capital
Coal	Raw coal
Oil	Oil in reservoir
Gas	Gas in reservoir

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