Japanese Demand for Hardwood Lumber from the United States

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Japanese Demand for Hardwood Lumber from the United States

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ABSTRACT

Japanese imports of tropical and temperate lumber increased during the last two decades. Imports of temperate lumber comprise a small share of the Japanese market, but the United States supplies the majority of temperate lumber imports. Japan has also supplied much of its needs by sawing lumber from imported tropical logs. However, environmental pressures and policies pushing toward export of value-added products from southeast Asian sources will likely decrease the availability of inexpensive tropical logs to Japan in the future. Given the increasing environmental and export policy pressures from traditional tropical suppliers, estimates of impacts of increasing lumber prices from these sources on Japanese demand for U.S. lumber are needed. This study develops a model that allows the demand for lumber to be disaggregated by source while treating lumber as an input into a production process and not as a final good. The results suggest that, in aggregate, the U.S. hardwood lumber industry will not benefit from restrictive environmental and export policies in tropical countries. Policies that lower U.S. import prices into Japan, such as more favorable import tariff policies or exchange rates, would have a substantial impact on imports from the United States.
Japanese Demand for Hardwood Lumber from the United States

BACKGROUND

Japan is the world's largest importer of hardwood products. It comprises about a 40% share of the world import market for hardwood logs, while holding about a 10% share of the world import market for hardwood lumber. Despite an overall decline in consumption of hardwood lumber, Japan has doubled its share of the product's world imports since the early 1980s (Chang 1991).

During the last two decades, although imports have continued to rise, Japan's domestic production of hardwood lumber has declined precipitously (Figure 1). With decreases in production, real prices of domestically sawn hardwood lumber climbed. In addition, the yen appreciated against the currencies of major exporters of hardwood lumber, helping to maintain the growth of imports into Japan. Japan's high-growth consumer economy also helped spur imports of hardwood lumber products. The real value of furniture manufacturing and construction — two important markets for hardwood lumber — experienced a high rate of growth during the 1970s and 1980s (Figure 2).

One component of the hardwood log market is tropical hardwood logs. Japan has been a major importer of tropical hardwood logs, using them for the production of lumber. Indonesia, the Philippines, and Malaysia supply about 70% of the country's tropical hardwood imports. These suppliers have enacted increasingly restrictive policies on the export of logs, moving toward export of processed products (Chang 1991). By 1986, Indonesia, Peninsular Malaysia, and the Philippines had all placed full embargoes on the export of tropical logs to help alleviate tropical deforestation problems and to shift exports into value-added products (Vincent 1989). Although Peninsular Malaysia placed an embargo on the export of logs, the log export policies of two primary lumber-producing regions of Malaysia, Sabah and Sarawak, were much less restrictive than those of Peninsular Malaysia. Export of logs from Malaysia increased during the 1980s, and imports into Japan from Malaysia remained at about the same overall level during the 1980s.

Increased concerns over tropical deforestation may eventually lead to a further decline in the export of tropical lumber from these countries to Japan (Luppold and Hansen 1989). Environmental policy pressures could result in increased prices of hardwood lumber over the long term. If the availability of tropical hardwood lumber becomes limited, the need for temperate hardwood lumber imports into Japan could increase. However, inroads into the Japanese market will depend on the substitutability of hardwood products from temperate zones with tropical hardwoods. Given current efforts by producing countries to export more processed products and the potential of increasing concerns regarding tropical deforestation, estimates of the impact of changes in the prices of tropical hardwood lumber on the demand for lumber from temperate sources are needed.

The United States is Japan's primary source of temperate hardwood lumber, currently supplying about 90% of the this segment of the market (Hasegawa 1989). While imports from the United States comprise a small share of Japan's total lumber use, Japan's imports of U.S. hardwood lumber have experienced a high rate of growth. They were seventeen times greater in 1989 than in 1981 (Hansen,
Figure 1. Consumption of Hardwood Lumber in Japan, 1970–1988. (Source: Commodity Trade Statistics and Japan Statistical Yearbook.)

Figure 2. Real Value of Construction and Furniture Manufacturing and Real Value of Imports of Hardwood Lumber into Japan.

**THE JAPANESE MARKET FOR HARDWOOD LUMBER**

**Output Markets and Domestic Lumber Production**

The Japanese economy grew rapidly during the 1970s and 1980s. Real GNP grew by more than 400% between 1970 and the late 1980s. As displayed in Figure 2, the Japanese furniture and construction markets grew along with the economy. Through the 1970s and 1980s, the construction and furniture manufacturing industries experienced an average real annual growth rate of 8% and 4%, respectively. Exceptions to the overall growth rate were downturns in 1974 and in 1980. The real value of consumption of hardwood lumber also increased. The actual quantity consumed declined through the mid 1970s and mid 1980s (Figure 1), but increases in real prices of hardwood lumber pushed up the value of consumption. For example, the real national average wholesale price of lauan thick boards nearly doubled between 1970 and 1988.

The furniture market has been an important target for high grade hardwood lumber. Of the lumber used in the manufacture of furniture, the majority is hardwood. However, lumber must also compete with other materials, such as plywood, particle board, hardboard, and fiberboard, as furniture manufacturers use more of these materials. The market for plywood in Japan has primarily been supplied internally with domestically produced plywood. That Japan supplies most of its own plywood and other processed wood products needs can be explained by its tariff structure, shown in Table 1, which places tariffs on these more processed products.

Joinery is also an important market for hardwoods. Joinery includes trim on windows, doors and facings, trim work, blinds, stairs, railing, built-in furniture, and panelling. Of the lumber used for joinery, about half is hardwood.

More than 85% of Japan's domestic production of logs is coniferous. Virtually all manmade growing stock is coniferous (Matsui 1980). Japan's broadleaved forests include Japanese oak and beech (Japan Statistical Yearbook). Japanese oak is used for furniture, cabinets, joinery, and panelling (TRADA 1979). Japanese beech is used for furniture, flooring, turnery, and plywood. While Japan supplies the majority of its own lumber needs, the percentage of domestic consumption that is supplied from within Japan is declining (Figure 1). Also, the lumber that is domestically supplied is primarily from imported logs. In the 1980s, more than 80% of the logs consumed in Japan were from imported logs.

<table>
<thead>
<tr>
<th>Product</th>
<th>Import tariff percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumber</td>
<td>10 (1972) 8 (1987)</td>
</tr>
<tr>
<td>Plywood</td>
<td>20 (1972) 17.5 (1987)</td>
</tr>
<tr>
<td>Logs</td>
<td>0 (1970) 15.0 (1988)</td>
</tr>
</tbody>
</table>

Input Suppliers

Tropical Hardwoods

Despite logs quotas and bans put in place by two of the three major tropical log exporters — the Philippines and Indonesia — more than 90% of logs imported into Japan came from South Seas sources during the 1980s. This is due in part to Malaysia’s constant flow of exports to Japan (Yearbook of Forest Products Prices).

Hardwood products exported from South Seas sources to Japan are from the Dipterocarpus and Shorea genera, and these species are traded under the names lauan, apitong, meranti, and keruing (Takeuchi 1974). Lauan is the name for a group of species of Shorea, Parashorea, and Pentacme from the Philippines. Red lauan is used for veneers, furniture, panelling, and cabinets (TRADA 1979). White lauan is used for veneer, plywood, furniture, cabinets, and interior joinery. Apitong, found throughout the Philippines, is used for building construction, framing, and flooring. Meranti is the group name for species of Shorea found in Malaysia, Sarawak, Brunei, and Indonesia. Meranti is used for joinery and construction, plywood, interior framing, and drawer sides and backs of furniture. Keruing is used for heavy and light construction, flooring, and sills. Keruing is found in Malaysia, Indonesia, Sarawak, and Sabah.

About 60% to 80% of logs imported from the South Seas are used in the manufacture of plywood (Vincent 1989; Booth 1980). With the possibility of diminishing supplies, processors of thick structural plywood turned to alternative sources, such as softwood logs. During the 1980s, Japan lowered its tariffs on plywood from 20% to 17% (Vincent 1989).

Other potential future suppliers of tropical hardwood logs include Papua New Guinea and Latin America. Japan has also imported tropical lumber from Singapore, Thailand, and Brazil. However, each of these sources either held a small share of the market or was a sporadic supplier to Japan. The Philippines, Malaysia, and Indonesia have the advantage over other tropical hardwood-producing regions because these countries’ stands are high density, of uniform species mix, and in close proximity to the Japanese market (Takeuchi 1974).

Temperate Hardwoods

The United States supplies the majority of Japan’s imports of temperate hardwood lumber (Hasegawa 1989). Japan imports a wide species mix of hardwood lumber from the United States, including red alder, yellow poplar, and ash (Hansen, Luppold, and Thomas 1990). Other species of some importance are red oak and white oak. Maple has seen a declining export market into Japan, falling from nearly 40% of the market in 1981 to less than 3% during the late 1980s. Red alder is used for turnery, furniture, corestock, and plywood (TRADA 1979). Yellow poplar is used in furniture, flooring, and joinery. Ash is used in interior joinery, cabinets, and furniture.

Other sources for temperate hardwood lumber included Canada, China, the European Community (EC), North and South Korea, and the former USSR. However, imports from each of these sources have held a small percentage of the market or have been sporadic.

Objectives

This study measured the impacts of price changes within the lumber sector on the demand for U.S. lumber in Japan. Other studies have examined the demand for lumber in Japan; however, they have focused on softwood lumber demand or aggregated softwood and hardwood lumber together, or have used an ad hoc specification of demand for lumber within the framework of larger sectoral models. This study examined price changes including changes in lumber prices from competing sources, changes in prices of outputs using lumber, and changes in the
prices of other inputs used with lumber. As a result, this study also estimated Japanese demand for U.S. hardwood lumber within a framework that is consistent with how the lumber is used as an input into other production processes.

A two-stage, multiproduct, profit-maximization model was employed that allowed the demand for lumber to be disaggregated by source while treating lumber as an input into a production process and not as a final good. Because the model is disaggregated by import source and type of lumber, the substitutability between lumber from the alternative sources and between types of lumber can be measured with elasticities.

**PREVIOUS STUDIES OF LUMBER DEMAND AND MARKETS**

Several studies have examined the demand for lumber imports into Japan. The studies of import demand for lumber have either used highly aggregated data or have not modeled the demand for imported lumber as a derived demand for other production processes.

Vincent (1987) examined the trade between the South Seas nations (Indonesia, the Philippines, and Malaysia) and Japan in hardwood logs, lumber, and plywood using data spanning 1970–1983. Vincent treated the South Seas nations as individual trading regions because the countries do not have identical forest resources or industries. The study used a spatial equilibrium model to model trade, with supply and demand equations for lumber from each of the regions. While lumber supply and demand equations for each region are estimated, estimates of separate demand equations for the hardwood product imports from each region into Japan are not presented. The study does not model lumber as an input for other specific production processes. Hardwood lumber demand in Japan was hypothesized to be a function of lumber price, gross domestic product (GDP), and a dummy variable shifter. The estimate of own-price elasticity of demand for nonconiferous lumber in Japan was \(-0.49\).

McKillop (1973) modeled trade between the United States and Japan for softwood products using a more disaggregated model than did Vincent. However, simple linear demand equations were based on an *ad hoc* specification. Japanese demand for U.S. lumber was hypothesized to be function of the price of U.S. lumber, price of Canadian lumber, price of domestic lumber in Japan, price of wood imports from other sources, level of residential construction, and level of industrial output.

Buongiorno and Chang (1986) examined demand for forest products, including hardwood lumber, using pooled data from ten OECD countries, including Japan, between 1961 and 1981. The demands for the forest products were conditional factor demands using highly aggregated data. The conditional factor demands were a function of GDP and the price of the forest product. The GDP deflator was used as a proxy for the price index of all other inputs used along with forest products in producing GDP. The weighted price of imports and exports was used as a proxy for domestic price of the forest product. The demand models were assumed to be distributed lags of first logarithmic differences of income and price in each country and year. Buongiorno and Chang found that the own-price elasticity of demand for hardwood lumber was \(-0.16\), and the elasticity of demand for hardwood lumber with respect to GDP was 1.26.

Other studies have modeled lumber markets under the assumption that lumber serves as an input; however, these studies often use *ad hoc* specifications of demand. Luppold (1982) developed a multiple equation model of the hardwood lumber market in the United States (1959–1978), including an equation representing hardwood lumber
demand. Luppold's model used aggregated annual observations for data within the U.S. lumber sector. The model consisted of four relationships - equations representing the demand, supply, and price of hardwood lumber, and an equilibrium identity. Luppold hypothesized that the quantity of lumber demanded was a function of lagged quantity demanded, past lumber price, past prices of other inputs used along with lumber, and current prices of output, including pallets and furniture. The quantity supplied of lumber was a function of lagged quantity supplied, price of hardwood lumber, wage rates, current and past interest rates, and time. The price of lumber was hypothesized to be a function of lagged price, quantity demanded, level of inventory, and exports. The elasticity of demand for lumber with respect to the price of lumber was -0.961. The elasticity of demand for lumber with respect to wages rates was -1.14, with respect to interest rates -0.076, and with respect to the price of output 1.76. The elasticity of supply of lumber with respect to the price of lumber was 0.648. The elasticity of supply of lumber with respect to wage rates was -0.676; to stumpage rates, -0.400; and to interest rates -1.85.

Cardellichio and Binkley (1984) also modeled demand for hardwood lumber in the United States as a derived demand. Their study focused on end-use sectors from 1950 to 1980 instead of aggregate demand levels. These end-use sectors included furniture manufacture, hardwood flooring, pallets, millwork, and other uses. Demand indicators for each were examined. For example, the demand indicator for furniture use was a furniture production index, and the demand indicator for flooring and millwork was housing starts. Cardellichio and Binkley estimated separate demand equations for each of the end-use sectors, assuming that each market was completely separate.

McKillop, Stuart, and Geisler (1980) examined the competition between softwood lumber, plywood, and substitute structural products during 1953–1974. While prior studies (McKillop 1973; Adams and Blackwell 1973) measured the impact of changing prices of competing products on the demand for wood products, McKillop, Stuart, and Geisler examined the impact of changing wood products prices on the demand for three substitute structural products — steel, aluminum, and concrete. The study used housing starts and the value of nonresidential construction as output measures. Wages were also included in the demand equations. Results indicated that lumber and steel were substitutes. Lumber and aluminum were also substitutes; however, concrete and lumber and plywood and steel were complements.

Rocknel and Buongiorno (1982) considered softwood lumber demand as a derived demand within a cost function approach. They developed a translog cost function for residential construction in the United States (1968–1977). Using duality theory, the functions for softwood lumber, plywood, hardboard, particle board, other materials, and labor were derived. Rocknel and Buongiorno used an index of building costs for residences as an index of the average cost of residential construction in the United States. The output measure was new private housing starts. The input price variables included the price of Douglas fir as a proxy for the price of softwood lumber, the wholesale price index of plywood, the wholesale price indexes of hardboard and particleboard, weighted average prices of other materials (structural steel, cement products, structural clay products, plumbing fixtures, heating equipment, and selected fabricated metal products). The price of labor was measured by the average weekly earnings of special trade construction workers. The share equations for each of the inputs were not estimated because of a lack of sufficient data. Thus, only the cost functions were estimated, resulting in some loss of efficiency.
METHODOLOGY

The model uses a two-stage, multiproduct, profit-maximization procedure within the structure of producer theory to obtain measures of substitutability by source of hardwood lumber. In the first stage, profits are assumed to be maximized. Output supplies and aggregate input demands are derived from the aggregate profit function. Output supplies are hypothesized to be furniture and construction supplies. Aggregate input demands are hypothesized to be demands for furniture manufacture labor, furniture manufacture capital, construction labor, construction capital, other wood (plywood and softwood lumber), energy, temperate hardwood lumber, and tropical hardwood lumber. The demand for lumber from different import sources is conditional on the profit-maximizing level of quantity demanded for all types of lumber determined within the first stage. The import sources for temperate lumber are the United States and other temperate suppliers. The imports sources for tropical lumber are Indonesia, the Philippines, Malaysia, Japan, and other tropical suppliers.

Assuming a multiproduct transformation function that is intertemporally and homothetically separable in the input partition \( \pi \), the multiproduct transformation function can be presented as

\[
F(q_1, \ldots, q_m, X_1, \ldots, X_n) = 0.
\]

The first stage of the profit maximization problem is then to solve

\[
\Pi(p, W) = \max_{q, X} \left[ \sum_{i=1}^m p_i q_i - \sum_{i=1}^n W_i X_i : F(q, X) \in T \right].
\]

The left side of Equation (1) is the aggregate profit function; applying Hotelling's lemma gives the output supplies and aggregate input demands

\[
\frac{\partial \Pi}{\partial p_i} = q_i = q_i(p, W) \quad i = 1, \ldots, m,
\]

\[
- \frac{\partial \Pi}{\partial W_i} = X_i = X_i(p, W) \quad i = 1, \ldots, n,
\]

which are homogeneous of zero degree in \((p, W)\) by Euler's theorem.

Because the model requires industry-level measures of input and output prices and quantities, data availability may be a limiting factor at the first stage. An unavailable price series can be handled either by employing a proxy via a perfect competition assumption or by redefining the unrestricted profit function to be the restricted (variable) profit function. In both cases, the profit (rent) quantity can be calculated. Unfortunately, an unavailable quantity series implicitly restricts the choice of functional form and restricts the modeled technology to be joint.

When a quantity variable is unavailable, Hotelling's lemma applied to the popular translog profit function yields a system of product and input share equations that cannot be defined, so the choice of functional forms is limited to a linear flexible functional form (LFFF).\(^1\) A convenient LFFF is the revenue form of the generalized Leontief

\(^{1}\)The LFFF implies that the multiproduct transformation function is input-output separable (Lopez 1985), hence production is joint (Hall 1973), except when the individual production functions are quasi-homothetic (Lau 1972). Both jointness and quasi-homotheticity are unappealing. Jointness increases the number of parameters that must be estimated within a single system. Quasi-homotheticity implies that all production functions for all outputs are identical up to a multiplicative constant. Jointness should be tested before adopting the restrictive assumption of a quasi-homothetic technology.
The revenue form yields

\[
 r_i = \sum_{l=1}^{n} \sum_{j=1}^{m} \alpha_{il} p_l p_j + \sum_{l=1}^{n} \sum_{j=1}^{m} \beta_{ij} W_j p_l \quad i = 1, \ldots, m,
\]

where by symmetry \( \alpha_{iu} = \alpha_{ui} \), \( \beta_{ui} = \beta_{ui} \), and \( \delta_{ij} = \delta_{ji} \), and linear homogeneity is implicitly imposed. In the model employed in this study, \( r_i = p_i q_i \); \( l, s = 1, 2 \) (furniture, construction); and \( r_i = -W_i X_i \), \( i, j = 1, \ldots, 8 \) (furniture labor, woodworking machinery, energy, construction materials and machinery, construction labor, other wood, temperate hardwood lumber, and tropical hardwood lumber). Table 1 lists complete variable descriptions.

The second-stage disaggregate input \( x_{ij} \) may be obtained by applying Hotelling’s lemma to the aggregate profit function — Equation (1) — with respect to the disaggregate inputs, so differentiating Equation (3) with respect to \( w_q \) yields

\[
 \frac{\partial \Pi}{\partial w_q} = x_q = x_q (w_q, C_i)
\]

which is the constant cost input demand function.\(^2\) The function \( x_q (w_q, C_i) \) is conditional upon the predetermined expenditure \( C_i \), and is homogeneous of degree zero in \( (w_q, C_i) \) by Euler’s theorem.

A system of equations defined by the indirect aggregator (production) function and the constant cost demand equations are estimated for the second stage. The translog is used to approximate the indirect aggregator function because it is second order flexible, does not suffer from the ‘separable inflexibility’ problem (Yuhn), and is easily interpreted within the context of aggregation and index theory.

In general, the translog indirect aggregator function for the \( X_i \) aggregate is

\[
 \ln X_i = \gamma_0 + \sum_j \gamma_{ij} \ln w_q + \gamma_i \ln C_i + \sum_j \gamma_{ijc} \ln w_q \ln C_i + \frac{1}{2} \gamma_{ii} (\ln C_i)^2 + \frac{1}{2} \sum_k \sum_j \gamma_{ijk} \ln w_q \ln w_k
\]

and by Roy’s identity

\[
 S_{ij} = \frac{\gamma_{ij} + \gamma_{ijc} \ln C_i + \sum_k \gamma_{ijk} \ln w_k}{\gamma_i + \gamma_{ii} \ln C_i + \sum_k \gamma_{ikc} \ln w_k}
\]

where \( S_{ij} = w_q X_q C_{ij}^{-1} \) is the \( ij \) cost share. The temperate sources are the United States and other temperate countries, and the tropical sources are Indonesia, the Philippines, Malaysia, Japan, and other tropical exporters. The following restrictions are implied by homogeneity and symmetry:

\[
 \sum_j \gamma_{ij} = -\gamma_i, \quad \sum_j \gamma_{ijc} = -\gamma_{ii},
\]

\[
 \sum_j \sum_k \gamma_{ijk} = -\sum_j \gamma_{ijc}, \quad \gamma_{ijk} = \gamma_{ikj}.
\]

---

\(^2\)A proof is provided in the appendix.
Furthermore the sufficient condition for two-stage budgeting is that the aggregator functions be linearly homogeneous in $C_i$, which implies that

$$\gamma_i = 1, \quad \gamma_{i_1} = \gamma_{i_1c} = 0 \quad \forall \ j.$$ 

The conditional second-stage price elasticities are

$$\eta_{jm}^c = [-\delta_{jm} + \delta_{jm}^{-1} \gamma_{jm}].$$

Because changing prices influence the first and second stages of the problem, the overall effects of prices are captured by calculating synthesized elasticities from the first and second stages of the models.

The synthesized elasticities, derivations of which are presented in the appendix, equal

\[\frac{\partial \ln x_{ij}}{\partial \ln w_{km}} = \eta_{ijkm} = \Omega_{ij} s_{ijkm} \quad \forall \ i, j, m \in I^2, i \neq k,\]

\[\frac{\partial \ln x_{ij}}{\partial \ln w_{jm}} = \eta_{ijjm} = \eta_{ijkm} + (\Omega_{ij} + 1) s_{ijm} \quad \forall \ i, j, m \in I^2, i = k,\]

\[\frac{\partial \ln x_{ij}}{\partial \ln p_{il}} = \Omega_{il},\]

\[\frac{\partial \ln q_i}{\partial \ln w_{ij}} = \Theta_i s_{ij},\]

\[\frac{\partial \ln q_i}{\partial \ln p_k} = e_k,\]

where

$$\Omega_{ik} = \frac{\partial \ln X_i}{\partial \ln W_k}, \quad \eta_{ijkm} = \frac{\partial \ln x_{ij}}{\partial \ln w_{km}} \Big|_{c_i}, \quad \Omega_{il} = \frac{\partial \ln X_i}{\partial \ln p_l},$$

$$s_{ij} = \frac{w_{ij}}{C_i}, \quad \Theta_i = \frac{\partial \ln q_i}{\partial \ln W_i}.$$ 

Equation (9) is the elasticity of the disaggregate input $x_{ij}$ with respect to factor price $w_{km}$ if the $j$th and $m$th disaggregate inputs are not in the same partition. Equation (10) is the elasticity of the disaggregate input $x_{ij}$ with respect to factor price $w_{km}$ if the $j$th and $m$th disaggregate inputs are in the same partition. Equation (11) is the elasticity of the disaggregate input with respect to output price. Equation (12) is the output elasticities with respect to the disaggregate input price. Finally, Equation (13) is the output price elasticity.

**DATA**

The data used in this study are from several sources including Commodity Trade Statistics, Yearbook of Forest Products Prices, Forest Products Prices, Japan Statistical Yearbook, and International Financial Statistics. Data prior to 1970 and following 1988 were incomplete. While the data are primarily focused on hardwood lumber imports, this study models the impact of several sectors on lumber demand; therefore, other quantity and price data are used. The variables used in the model, their definitions, and sources are summarized in Table 2.

In this study, lumber is treated as an input for other production processes, construction, and furniture manufacture. The measures of output are total construction and production of furniture and fixtures. Output and price data are from Japan Statistical Yearbook.

Lumber is assumed to be only one of several inputs going into the production process. Other broad categories of inputs are labor, capital (machinery and materials), other wood, and energy.

Labor used with lumber in the production process is measured as thousand hours worked by regular employees in the construction and furniture and fixtures manufacturing industries. The indexes of wages are constructed from hourly wages earned by
## Table 2. Variable Names, Definitions, Units of Measure, and Sources

<table>
<thead>
<tr>
<th>Name</th>
<th>Definition</th>
<th>Units of measure</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q_1$</td>
<td>Quantity of Furniture and Fixtures</td>
<td>pieces</td>
<td>JSY</td>
</tr>
<tr>
<td>$p_1$</td>
<td>Price Index of Furniture and Fixtures</td>
<td>$1970 = 100$</td>
<td>JSY</td>
</tr>
<tr>
<td>$q_2$</td>
<td>Total Construction Area</td>
<td>1000 meters$^2$</td>
<td>JSY</td>
</tr>
<tr>
<td>$p_2$</td>
<td>Price Index of Construction</td>
<td>$1970 = 100$</td>
<td>JSY</td>
</tr>
<tr>
<td>$X_1$</td>
<td>Hours Worked by Regular Workers, Furniture and Fixtures Manufacturing</td>
<td>1000 hours</td>
<td>JSY</td>
</tr>
<tr>
<td>$W_1$</td>
<td>Index of Hourly Wages, Furniture and Fixtures</td>
<td>$1970 = 100$</td>
<td>JSY</td>
</tr>
<tr>
<td>$X_2$</td>
<td>Quantity of Woodworking Machinery</td>
<td>pieces</td>
<td>JSY</td>
</tr>
<tr>
<td>$W_2$</td>
<td>Price Index of Woodworking Machinery</td>
<td>$1970 = 100$</td>
<td>JSY</td>
</tr>
<tr>
<td>$W_3$</td>
<td>Wholesale Price Index for Petroleum and Coal</td>
<td>$1970 = 100$</td>
<td>JSY</td>
</tr>
<tr>
<td>$X_4$</td>
<td>Quantity Index of Construction Materials and Machinery</td>
<td>$1970 = 100$</td>
<td>JSY</td>
</tr>
<tr>
<td>$W_4$</td>
<td>Price Index of Construction Materials and Machinery</td>
<td>$1970 = 100$</td>
<td>JSY</td>
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<tr>
<td>$X_5$</td>
<td>Hours Worked by Regular Workers, Construction</td>
<td>1000 hours</td>
<td>JSY</td>
</tr>
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<td>$W_5$</td>
<td>Index of Hourly Wages, Construction</td>
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<td>JSY</td>
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<td>$X_6$</td>
<td>Quantity Index of Other Wood Materials</td>
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<td>YFP</td>
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<tr>
<td>$X_7$</td>
<td>Quantity Index of Temperate Nonconiferous Lumber</td>
<td>meters$^3$</td>
<td>CTS</td>
</tr>
<tr>
<td>$W_7$</td>
<td>Instrumental Divisia Price Index of Temperate Nonconiferous Lumber</td>
<td>$1970 = 100$</td>
<td>CTS</td>
</tr>
<tr>
<td>$X_8$</td>
<td>Quantity Index of Tropical Nonconiferous Lumber</td>
<td>meters$^3$</td>
<td>CTS, YFP</td>
</tr>
<tr>
<td>$W_8$</td>
<td>Instrumental Divisia Price Index of Tropical Nonconiferous Lumber</td>
<td>$1970 = 100$</td>
<td>CTS, FPP</td>
</tr>
</tbody>
</table>

**Second Stage**

<table>
<thead>
<tr>
<th>Name</th>
<th>Definition</th>
<th>Units of measure</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_{6j}$</td>
<td>Quantity of Temperate Nonconiferous Lumber, $j = \text{US, Other Temperate}$</td>
<td>meters$^3$</td>
<td>CTS</td>
</tr>
<tr>
<td>$w_{6j}$</td>
<td>Price of Temperate Nonconiferous Lumber, $j = \text{US, Other Temperate}$</td>
<td>yen/meters$^3$</td>
<td>CTS</td>
</tr>
<tr>
<td>$x_{7j}$</td>
<td>Quantity of Tropical Nonconiferous Lumber, $j = \text{Indonesia, Malaysia, Philippines, Japan, Other Tropical}$</td>
<td>meters$^3$</td>
<td>CTS, YFP</td>
</tr>
<tr>
<td>$w_{7j}$</td>
<td>Price of Tropical Nonconiferous Lumber, $j = \text{Indonesia, Malaysia, Philippines, Japan, Other Tropical}$</td>
<td>yen/meters$^3$</td>
<td>CTS, FPP</td>
</tr>
</tbody>
</table>

$^a$JSY = Japan Statistical Yearbook, YFP = Yearbook of Forest Products Prices, FPP = Forest Products Prices, and CTS = Commodity Trade Statistics.
workers in the construction industry and hourly wages earned by regular workers in the furniture and fixture manufacturing industry. These data are from the *Japan Statistical Yearbook*.

A Divisia quantity index and dual Divisia price index of construction machinery and materials (capital) were formed from various types of construction machinery and construction materials other than lumber. The Divisia quantity index was constructed from the prices and quantities of construction machinery, including land preparation machinery, cranes and or excavators, concrete machinery, and construction materials, including iron and steel, hollow cement blocks, and wooden fiber cement board. The dual Divisia price index is constructed using Fisher's weak factor reversal test. Woodworking machinery was used as a measure of capital used in furniture manufacture. The price and quantity index series for capital are calculated from data in the *Japan Statistical Yearbook*. The price of energy, also found in the *Japan Statistical Yearbook*, is represented by the wholesale price index for petroleum and coal.

Other wood materials used along with lumber are assumed to be plywood and coniferous lumber. A Divisia quantity and dual Divisia price index were constructed from prices and quantities of plywood and coniferous lumber. Prices are from the *Forest Products Prices*, while quantities are from the *Yearbook of Forest Products Prices*.

The hardwood data are disaggregated by source, domestically sawn lumber, and lumber from various import sources. Imports are disaggregated into lumber imports from the United States, Indonesia, the Philippines, Malaysia, and other temperate and tropical sources. Other temperate sources include Canada, China, the former USSR, the EC, and North and South Korea. Other tropical sources include Singapore, Thailand, and Brazil. Most of the other temperate and tropical sources were intermittent suppliers or comprised a small share of the market over the time period examined and, therefore, are not considered individually. The quantities and calculated unit values are from *Commodity Trade Statistics*. The Japanese production of nonconiferous lumber is from the *Yearbook of Forest Products* and the price of domestically sawn nonconiferous lumber is from *Forest Products Prices*. The national average wholesale price of lauan thick boards is used as a measure of domestic price. The price of lauan thick boards is used as a proxy for Japanese lumber price, which is plausible because during the sample period more than 70% of logs consumed were from major tropical exporters.

A portion of the import data is converted from metric tons to cubic meters. The conversion factor, 1.43 cubic meters per metric ton, is from the *Yearbook of Forest Products Prices*. Several of the price series are converted from U.S. dollars into Japanese yen. The exchange rate is from *International Financial Statistics*.

**ESTIMATION AND RESULTS**

A recursive estimation approach was used. The second stage was estimated first, then the first stage was estimated. Each stage was estimated using Zellner's iterated seemingly unrelated regression (ITSUR) method. The usual assumptions of symmetric separability, and using second-stage results to construct instrumental variables for the first stage, this approach is equivalent to full information maximum likelihood (Fuss 1977).
metry, adding up, and homogeneity were imposed where appropriate and the consistency conditions for two-stage budgeting were tested. Neither weak separability nor linear homogeneity in the aggregator functions could be rejected. Therefore, an aggregate of lumber from temperate sources and an aggregate of lumber from tropical sources could be used in the first stage, and two systems were estimated in the second stage— a temperate system and a tropical system.

The second-stage systems were estimated for tropical and temperate lumber using Equations (7) and (8). The singularity problem was handled by dropping the other temperate share in the temperate system and by dropping the Japanese share in the tropical system. In each system, tests failed to reject linear homogeneity in \( C_i \) at the 5% level. Therefore, all systems satisfied the sufficient conditions for two-stage optimization.

The parameter estimates for the temperate and tropical systems, with linear homogeneity in \( C_i \) imposed, are displayed in Table 3, along with their asymptotic t-statistics. Many of the parameters are significantly different from zero. From these estimates, the conditional (second stage) price elasticities were calculated. The conditional demand elasticity matrix is shown in Table 4. All own-price elasticities are negative except for those from the Philippines. Many of the cross-price elasticities in the tropical block are negative, suggesting that

### Table 3. Parameter Estimates from the Temperate and Tropical Second-Stage Systems

<table>
<thead>
<tr>
<th>Equation</th>
<th>Estimated parameters: (^{ab})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Intercepts</td>
</tr>
<tr>
<td>US</td>
<td>-.849 (.22.39)</td>
</tr>
<tr>
<td>I</td>
<td>.028 (6.26)</td>
</tr>
<tr>
<td>P</td>
<td>-.017 (3.35)</td>
</tr>
<tr>
<td>M</td>
<td>.003 (1.33)</td>
</tr>
<tr>
<td>OTR</td>
<td>.009 (6.39)</td>
</tr>
<tr>
<td>Temperate</td>
<td>6.663 (574.79)</td>
</tr>
<tr>
<td>Tropical</td>
<td>6.043 (1468.47)</td>
</tr>
</tbody>
</table>

\(^{a}\)US = United States, OTM = Other Temperate Sources, I = Indonesia, P = Philippines, M = Malaysia, and OTR = Other Tropical Sources.

\(^{b}\)Values in parentheses are the absolute values of the asymptotic t-statistics.
Table 4. Elasticity Estimates from the Temperate and Tropical Second-Stage Systems

<table>
<thead>
<tr>
<th></th>
<th>US</th>
<th>OTM</th>
<th>I</th>
<th>P</th>
<th>M</th>
<th>OTR</th>
<th>J</th>
</tr>
</thead>
<tbody>
<tr>
<td>US</td>
<td>-1.294</td>
<td>-.034</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OTM</td>
<td>.042</td>
<td>-1.042</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>-3.863</td>
<td>-.764</td>
<td>-1.366</td>
<td>-1.018</td>
<td>6.011</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>-.914</td>
<td>1.917</td>
<td>-.386</td>
<td>-1.121</td>
<td>-.496</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>-1.404</td>
<td>-.331</td>
<td>-.895</td>
<td>-.631</td>
<td>2.261</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OTR</td>
<td>-.932</td>
<td>-.857</td>
<td>-.562</td>
<td>-1.045</td>
<td>2.396</td>
<td></td>
<td></td>
</tr>
<tr>
<td>J</td>
<td>.052</td>
<td>-.004</td>
<td>.019</td>
<td>.023</td>
<td>-1.091</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*US = United States, OTM = Other Temperate Sources, I = Indonesia, P = Philippines, M = Malaysia, and OTR = Other Tropical Sources. The elasticities are calculated at the means. Mean cost shares are US = 0.5491, OTM = 0.4519, I = 0.0084, P = 0.0070, M = 0.0082, OTR = 0.0092, and J = 0.9672.

...
Table 5. First Stage Parameter Estimates of Output Revenue and Factor Expenditure Equations

<table>
<thead>
<tr>
<th>Equation</th>
<th>Furniture</th>
<th>Construction</th>
<th>Furniture labor</th>
<th>Furniture capital</th>
<th>Energy</th>
<th>Construction capital</th>
<th>Construction labor</th>
<th>Other wood</th>
<th>Temperate lumber</th>
<th>Tropical lumber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Furniture</td>
<td>-.272</td>
<td>-.149</td>
<td>.100</td>
<td>-.043</td>
<td>-.087</td>
<td>.058</td>
<td>.531</td>
<td>.295</td>
<td>-.231</td>
<td>.132</td>
</tr>
<tr>
<td></td>
<td>(1.866)</td>
<td>(2.804)</td>
<td>(2.031)</td>
<td>(1.263)</td>
<td>(1.263)</td>
<td>(.679)</td>
<td>(.5622)</td>
<td>(.614)</td>
<td>(.716)</td>
<td>(.918)</td>
</tr>
<tr>
<td>Construction</td>
<td>-.041</td>
<td>.074</td>
<td>.335</td>
<td>-.043</td>
<td>.099</td>
<td>.182</td>
<td>.074</td>
<td>.077</td>
<td>-.077</td>
<td>.081</td>
</tr>
<tr>
<td></td>
<td>(2.804)</td>
<td>(2.195)</td>
<td>(1.371)</td>
<td>(1.526)</td>
<td>(2.267)</td>
<td>(3.808)</td>
<td>(1.465)</td>
<td>(.562)</td>
<td>(.780)</td>
<td></td>
</tr>
<tr>
<td>Furniture labor</td>
<td>-.525</td>
<td>-.102</td>
<td>.029</td>
<td>.111</td>
<td>.077</td>
<td>.078</td>
<td>.310</td>
<td>.074</td>
<td>-.310</td>
<td>.074</td>
</tr>
<tr>
<td></td>
<td>(9.985)</td>
<td>(4.328)</td>
<td>(1.038)</td>
<td>(2.172)</td>
<td>(1.689)</td>
<td>(1.548)</td>
<td>(2.512)</td>
<td>(.645)</td>
<td>(.645)</td>
<td></td>
</tr>
<tr>
<td>Furniture capital</td>
<td>.478</td>
<td>-.170</td>
<td>-.139</td>
<td>.057</td>
<td>-.182</td>
<td>-.482</td>
<td>-.154</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(5.361)</td>
<td>(1.36)</td>
<td>(4.286)</td>
<td>(1.101)</td>
<td>(4.608)</td>
<td>(2.132)</td>
<td>(2.742)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Construction capital</td>
<td>.003</td>
<td>-.033</td>
<td>.002</td>
<td>.030</td>
<td>.170</td>
<td>.034</td>
<td>(.034)</td>
<td>(.024)</td>
<td>(.024)</td>
<td>(.130)</td>
</tr>
<tr>
<td></td>
<td>(.034)</td>
<td>(.549)</td>
<td>(.024)</td>
<td>(.130)</td>
<td></td>
<td>(.1299)</td>
<td>(.1299)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Construction labor</td>
<td>-.1802</td>
<td>.005</td>
<td>-.139</td>
<td>.416</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>(20.787)</td>
<td>(.082)</td>
<td>(.595)</td>
<td>(3.66)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Other wood</td>
<td>.110</td>
<td>-.006</td>
<td>-.567</td>
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<td>(1.144)</td>
<td>(.026)</td>
<td>(4.03)</td>
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</tr>
<tr>
<td>Temperate lumber</td>
<td>.695</td>
<td>.214</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tropical lumber</td>
<td>-.308</td>
<td>(.661)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Wald test: nonjointness 108.73\textsuperscript{b}

\textsuperscript{a}Values in the parentheses are the absolute values of the asymptotic t-statistics.

\textsuperscript{b}Significant at $\alpha = .00001$. 

Tennessee Agricultural Experiment Station
### Table 6. First Stage Elasticity Estimates

<table>
<thead>
<tr>
<th></th>
<th>Furniture</th>
<th>Construction</th>
<th>Furniture labor</th>
<th>Furniture capital</th>
<th>Energy</th>
<th>Construction capital</th>
<th>Construction labor</th>
<th>Other wood</th>
<th>Temperate lumber</th>
<th>Tropical lumber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Furniture</td>
<td>-.765</td>
<td>-.214</td>
<td>.139</td>
<td>-.045</td>
<td>-.122</td>
<td>.058</td>
<td>.733</td>
<td>.307</td>
<td>-.225</td>
<td>.139</td>
</tr>
<tr>
<td>Construction</td>
<td>-.232</td>
<td>-.593</td>
<td>.166</td>
<td>.055</td>
<td>-.098</td>
<td>.156</td>
<td>.404</td>
<td>.122</td>
<td>-.119</td>
<td>.136</td>
</tr>
<tr>
<td>Furniture labor</td>
<td>-.093</td>
<td>-.103</td>
<td>.208</td>
<td>.100</td>
<td>-.039</td>
<td>-.106</td>
<td>-.104</td>
<td>-.077</td>
<td>.287</td>
<td>-.074</td>
</tr>
<tr>
<td>Furniture capital</td>
<td>.030</td>
<td>-.034</td>
<td>.100</td>
<td>-.881</td>
<td>.017</td>
<td>.100</td>
<td>.055</td>
<td>.138</td>
<td>.341</td>
<td>.117</td>
</tr>
<tr>
<td>Construction capital</td>
<td>-.172</td>
<td>-.425</td>
<td>-.467</td>
<td>.444</td>
<td>.535</td>
<td>-.508</td>
<td>.137</td>
<td>-.061</td>
<td>-.089</td>
<td>.542</td>
</tr>
<tr>
<td>Construction labor</td>
<td>-.157</td>
<td>-.080</td>
<td>-.033</td>
<td>.017</td>
<td>.067</td>
<td>.009</td>
<td>.270</td>
<td>-.001</td>
<td>.041</td>
<td>-.134</td>
</tr>
<tr>
<td>Other wood</td>
<td>-.086</td>
<td>-.316</td>
<td>-.322</td>
<td>.580</td>
<td>-.025</td>
<td>-.005</td>
<td>-.023</td>
<td>-.523</td>
<td>.018</td>
<td>1.783</td>
</tr>
<tr>
<td>Temperate lumber</td>
<td>.138</td>
<td>.067</td>
<td>.264</td>
<td>.315</td>
<td>.133</td>
<td>-.018</td>
<td>.117</td>
<td>.004</td>
<td>-.916</td>
<td>-.139</td>
</tr>
<tr>
<td>Tropical lumber</td>
<td>-.194</td>
<td>-.174</td>
<td>-.154</td>
<td>.244</td>
<td>.326</td>
<td>.254</td>
<td>-.865</td>
<td>.883</td>
<td>-.313</td>
<td>-.010</td>
</tr>
</tbody>
</table>

*The elasticities are calculated at the mean values of the variables in Equations (4) and (5).*
temperate hardwood with respect to Indonesia, the Philippines, Malaysia, and other tropical sources are also equal. The synthesized elasticities show little difference from the conditional elasticities primarily because of the small cost shares. All own-prices are of the correct sign, except for the Philippines. Hardwood lumber from the United States and from other temperate sources are substitutes, and overall hardwood lumbers from each tropical source are substitutes with Japanese lumber. All other sources are complementary.

**CONCLUSIONS**

This study measures the impacts of price changes within the Japanese lumber sector on the demand for U.S. lumber in Japan and attempted to estimate demand for U.S. hardwood lumber in Japan within a framework that is consistent with lumber being used as an input into other production processes. The model used in the study was a two-stage multiproduct profit maximization. Its primary disadvantage was that extensive industry-level price and quantity data were required at the first stage. The unavailability of an energy quantity series limited the technology to be joint.

The first-stage elasticities indicate that temperate hardwood lumber demand is impacted on more by changes in furniture prices than by changes in construction prices. These results are as expected. Most of the signs of the input elasticities are unexpected. The first-stage elasticities also indicate that other wood products are weak substitutes for temperate hardwood lumber and are stronger substitutes for tropical hardwood lumber. This result is expected because, for example, tropical hardwood lumber is often used for construction purposes, as is softwood lumber.

The own-price elasticities of demand synthesized from the first and second stages for the United States, other temperate sources, Indonesia, and other tropical sources all fell within the elastic range. The smallest of the own-price elasticities was for domestically sawn lumber. The cross-price elasticities within the temperate group were positive but small, indicating that lumbers from the United States and other temperate sources are weak substitutes. The signs and magnitudes of the elasticities suggest that...
domestically sawn lumber is a strong substitute for lumber from all of the tropical sources, but a complement for lumber from temperate sources.

The elasticities synthesized from the first and second stages indicate that, overall, tropical and temperate lumbers are complements. Several of the tropical species (e.g., apitong, meranti, and keruing) are used in heavy and light construction, and several of the temperate species (e.g., red alder, yellow poplar, and ash) are used in the furniture industry (TRADA 1979), so complementarity at this level of aggregation is reasonable.

One policy implication, as determined by the model, is that the U.S. hardwood lumber industry will not benefit from restrictive environmental and export policies in tropical countries. As with most welfare effects from trade, the distributional results (i.e., by specie) are unclear. The results also suggest that restrictive environmental and export policies may most strongly impact the market through the domestically sawn lumber segment. If environmental pressures increase and the movement by tropical log exporters toward policies that favor value-added products continues, tropical logs will likely become less available and more costly, resulting in a rise in Japanese domestically sawn lumber prices. The results from this study show that such an increase in prices of domestically sawn lumber would cause imports of lumber from tropical sources to increase greatly. During the time period examined, the price of domestically sawn lumber in Japan increased dramatically, and imports of tropical lumber were pushed upward. In particular, imports from Indonesia grew most rapidly. The own-price elasticity of demand for lumber from the United States is elastic, suggesting that imports of lumber into Japan will be very responsive to price changes, such as changes in the Japanese import tariff rate or the exchange rate. Import tariffs on hardwood lumber were lowered during the 1980s, and pressure to lower tariffs may continue if availability of logs for domestically sawn lumber declines.

LITERATURE CITED


APPENDIX
Hotelling's Lemma in Disaggregate Inputs

From the aggregate profit function — Equation (1) — and the chain rule, the following can be determined:

\[(A.1) \quad \frac{\partial \Pi}{\partial w_j} = \frac{\partial \Pi}{\partial W_i} \frac{\partial W_i}{\partial w_j} = -X_i \frac{\partial W_i}{\partial w_j}.\]

Equation (A.1) can be proven to equal \(x_{ij}\). Because of linear homogeneity of the aggregator functions,

\[(A.2) \quad W_i(w_{ij}, \ldots, w_{ij}) X_j(x_{ij}, \ldots, x_{ij}) = \sum_{m=1}^{J_i} w_{im} x_{im}.

Therefore, differentiating Equation (A.2) with respect to \(x_{ij}\) yields

\[(A.3) \quad W_i \frac{\partial X_i}{\partial x_{ij}} = w_{ij} \quad j, m = 1, \ldots, J_i.\]

Synthesized Elasticity Derivations

From the first stage of the model the following can be determined:

\[(A.6) \quad q_i = q_i(p, W) \quad i^{th} output supply;\]

\[(A.7) \quad X_i = X_i(p, W) \quad i^{th} aggregate input demand;\]

\[(A.8) \quad C_i = W_i(w_{ij}, \ldots, w_{ij}) X_i(p, W) \quad i^{th} expenditure.\]

Differentiating Equation (A.2) with respect to \(w_{ij}\), and some algebra, yields

\[(A.4) \quad \frac{\partial W_i}{\partial w_{ij}} X_i = x_{ij} + \sum_{m=1}^{J_i} w_{im} \frac{\partial X_i}{\partial x_{im}} \frac{\partial x_{im}}{\partial w_{ij}}.\]

Substituting Equation (A.3) into Equation (A.4) yields

\[(A.5) \quad \frac{\partial W_i}{\partial w_{ij}} X_i = x_{ij}.\]

Substituting Equation (A.5) into Equation (A.1) yields Equation (6) in the main body of the text.

From the second stage and by linear homogeneity of the aggregator functions,

\[(A.9) \quad x_{ij}^* = C_i f(w) \quad j^{th} constant cost input demand;\]

\[(A.10) \quad X_i = C_i h(w) \quad i^{th} indirect production;\]

\[(A.11) \quad C_i = X_i g(w) \quad i^{th} indirect cost.\]
Also, linear homogeneity and cost minimization implies from Equation (A.11),

\[(A.12) \quad \ln W_i = \ln C_i - \ln X_i,\]

so, by Shephard's lemma and \(X_i\) being predetermined,

\[(A.13) \quad \frac{\partial \ln W_j}{\partial \ln w_{ij}} = s_{ij}.\]

Now substituting Equation (A.8) into Equation (A.9), placing in log form, and differentiating yields,

\[(A.14) \quad \frac{\partial \ln x_i}{\partial \ln w_{km}} = \frac{\partial \ln W_i}{\partial \ln w_{km}} + \frac{\partial \ln X_i}{\partial \ln W_k} \frac{\partial \ln W_k}{\partial \ln w_{km}} + \frac{\partial \ln f(w_i)}{\partial \ln w_{km}}
= \Omega_{ik} s_{km} \quad j \in I^i, \ m \in I^k, \ i \neq k
\]

because the first and last terms are zero.

\[(A.15) \quad \frac{\partial \ln x_i}{\partial \ln w_{km}} = \frac{\partial \ln W_i}{\partial \ln w_{km}} + \frac{\partial \ln X_i}{\partial \ln W_k} \frac{\partial \ln W_k}{\partial \ln w_{km}} + \frac{\partial \ln f(w_i)}{\partial \ln w_{km}}
= s_{km} (1 + \Omega_{ij}) + \eta_{ij/km}^c
= j, \ m \in I^i, \ i = k.\]

Equations (11)-(13) in the main body of the text can be derived similarly.
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