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A COMPARISON OF PRODUCT DIFFUSION AND DISTRIBUTED LAG MODELS FOR ESTIMATING WOOD/NON-WOOD SUBSTITUTION IN THE US WINDOW MARKET

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Abstract

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Jeff Moffett

Product substitution is defined as a shift in market shares between two competing products. Relative prices are hypothesized to determine wood/non-wood substitution patterns in the US residential window market. The study reviews each of two different models for estimating substitution. One model is based on diffusion theory. The second model is a partial adjustment model based on distributed lag theory. Each model is applied to the window market. Both models provide the same static analysis of the window market, however they differ in their representations of the dynamics of the market share changes. The results of each approach are considered in terms of their respective assumptions. Each model allows for the derivation of the own-price and cross-price market share elasticities of wood windows. While the diffusion approach provides more detailed information about price elasticity trends over time, the restrictive functional form brings the results into question. The partial adjustment model provides average elasticity estimates. The environmental impacts associated with wood/non-wood substitution are also discussed.

Executive Summary

A Comparison of Product Diffusion and Distributed Lag Models for Estimating Wood/Non-wood Substitution

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Wood product markets are subject to substitution by lower cost non-wood materials. Alternative materials such as aluminum and vinyl are generally more fossil fuel intensive and have different environmental impacts from renewable wood resources. Increased attention to environmental impacts has drawn increased attention to substitution of wood by non-wood products.

This study surveys the available research on explanations for substitution related to economic and technological change, then models substitution within a particular end-product market. The question of whether substitution can be explained by prices or technological change almost independent of prices is an important factor in analyzing the impacts of policies on the environment.

This report uses as a case study the United States residential window market, where wood and aluminum windows have been competing for the past five decades. Prior to World War II, wood windows dominated the window market. Since then aluminum windows have increased market share. By 1982, wood windows held only 26 percent of the market. Throughout much of this period, not only were wood windows more expensive than aluminum windows, but the price differential steadily increased.

Substitution models based on distributed lags of relative prices appear to provide more accurate and detailed information on market share changes than models that rely on arbitrary technological innovation formulations. While the short-run own-price and cross-price market share elasticities may be low, the long-run elasticities suggest that direct substitution between competitive products, such as wood and aluminum windows, can exceed 1.0. The case study shows a 1.7 percent change in wood window market share in the long-run for every one percent change in relative price. This high long-run price elasticity of substitution may have significant implications for carbon mitigation analysis and other environmental policy issues.

The primary differences between wood and non-wood alternatives used in residential and light commercial construction are the energy requirements involved and carbon emissions related to fossil fuel consumption in production. When all of the aspects of extraction, transportation, processing and production were considered, wood products were found to require less energy in manufacture (CORRIM, 1976). The exact amounts differed for each end-product.

Several studies have examined the environmental impacts arising from the production of wood, plastics, aluminum, steel and concrete. Each of these industries has substantial extraction impacts. The manufacturing of steel, aluminum and plastics was judged to create more significant problems than sawn-wood and cement (Alexander and Greber, 1991). Furthermore, wood has the unique attribute of being a renewable resource which can be managed over many rotations.

The most significant effect of forest management on the level of carbon dioxide in the atmosphere will come from the substitution of wood materials for more energy-intensive materials. New approaches to forest production and more intensive forest management practices requiring forest investment would be necessary to increase the production of higher-quality logs needed in order to increase the substitution of wood for non-wood products. While shortages of wood products due to forest preservation constraints may reduce wood demand and forest investment on one hand, carbon taxes on fossil fuels could have the impact of increasing demand and forest investment resulting in the substitution of wood for non-wood products on the other. In effect, environmental policies need to consider substitution issues which are likely to show a strong advantage for the use of renewable resources.

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I. Introduction

A. The Issue of Substitution

Many products traditionally made with wood have been replaced by products made from lower-cost, non-wood materials. The question is: what is the driving factor behind this process of wood/non-wood substitution? The shift in consumption from wood to non-wood products leads to a corresponding shift in the environmental impacts associated with each product's life-cycle. Thus, environmental concerns have increased the need to understand wood/non-wood substitution.

For the past five decades the United States' window market has been characterized by the competition between wood and aluminum windows. Although style, size and quality changes have occurred, the general product categories have remained consistent through this period, making a useful case study for substitution research.

Wood/non-wood product substitution is defined as a shift in market shares between two competing products, one wood and the other non-wood. The process of substitution involves the replacement of an existing product with a new product or innovation, all else being equal. Because wood/non-wood substitution occurs within particular product end-use markets, it is a process of product substitution.

Substitution has takes place in virtually all end-use markets. Market share trends indicate the extent of the substitution that has taken place in each particular market. Steel and aluminum doors are now common in the exterior door market. Fiberglass doors have been introduced to the Canadian market. Steel studs have the potential to substitute for lumber in the residential framing market. Again in Canada, concrete railway ties have significantly penetrated the tie market.

There are several reasons for substitution to occur. Regulations such as fire codes have required the use of non-flammable materials. In other cases, the substitute products are regarded as offering better performance. Prices also drive substitution. In construction markets, less expensive substitute products allow builders to lower their costs. This study applies to the markets where relative prices have driven substitution.

B. Problems with Measuring Substitution

Although the significance of wood/non-wood substitution is often discussed in contemporary literature (Alexander and Greber, 1991; Forintek, 1989; Koch, 1991; Lippke, 1991; McKillop, *et al.*, 1978; McKillop, *et al.*, 1980; Spelter, 1985a; Woodbridge, Reed & Associates, 1989), these studies have not examined substitution directly, nor with regard to specific products in end-use markets. Many studies of wood products industries have primarily focused on estimating the demand for softwood lumber. Although softwood lumber represents the largest portion of wood product production, it is difficult to define clearly the markets where lumber and non-wood products are substituted for one another. For example, steel products have substituted for wood products in some markets, but not others, making it difficult to analyze wood/steel substitution in the aggregate. This study attempts to improve on this ambiguity by analyzing a specific end product market where substitution has clearly taken place.

Gathering data for a specifically-defined products presents problems for substitution research. As substitution is only a recent concern, and applies to many product markets, the necessary data has not been systematically collected in a single source. Market share surveys--a potential source of substitution data--are not often conducted on a periodic basis. The US Bureau of the Census and other agencies usually report production in terms of value, rather than number of units, making it difficult to extract market share changes based on quantity measures. Price index categories are occasionally redefined, creating a problem in maintaining consistency over time. Thus, a significant challenge for substitution research involves gathering and organizing the required data.

C. Comparison of Methods for Deriving Substitution Elasticities

As a result of comparing methods for deriving substitution elasticities, this study also derives a price elasticity measure from each of two methods. One method employs a product diffusion model. The other method utilizes a partial adjustment model based on the concept of a distributed lag.

The price elasticity is useful for estimating substitution, and is defined as the percentage change in production associated with a one percent change in prices. Thus, these two methods were compared on the basis of estimating market share responses to relative price trends. The derivation of own-price and cross-price demand elasticities is an important part of econometric research in the forest products sector. Since market models can be used to predict price changes, knowing product price elasticities allows future consumption patterns to be projected.

The product diffusion and partial adjustment models differ in their assumptions regarding how market shares adjust over time. This study controls for some of the variation in the results and emphasizes the importance of the assumptions of each model by using the same data with each model.

D. Organization of the Paper

Section two describes the study approach that provides a basis for estimating elasticities of substitution using the two models. The third section outlines the product diffusion and partial adjustment models by describing recent applications of each of these approaches in the forest products sector. In section four, each model is estimated for the US window market. The fifth section presents the results. The paper concludes with a discussion of the environmental ramifications and suggestions for future research.

II. Study Approach

A. Working Hypotheses

This study postulates a relationship between market shares and relative product prices whereby prices drive substitution. This leads to the supposition that the technological innovation of producing windows from aluminum was developed because of its cost advantage over wood and that wood costs drove the technological innovation. Economic theory suggests that increasing input product prices leads producers to look for substitute inputs. Previous research has concluded that the feasibility of any particular substitution depends largely on the relative prices of the alternative materials (CORRIM, 1976).

The time frame for measuring elasticities is an important consideration. Short-run supply (one-year) responses are usually found to be less elastic as producers are constrained by existing contracts, inventories and plant capacities--the lower the elasticity, the smaller the percentage change in production for a given price change. As more time passes these factors can change, producing more elastic supply responses in the long-run.

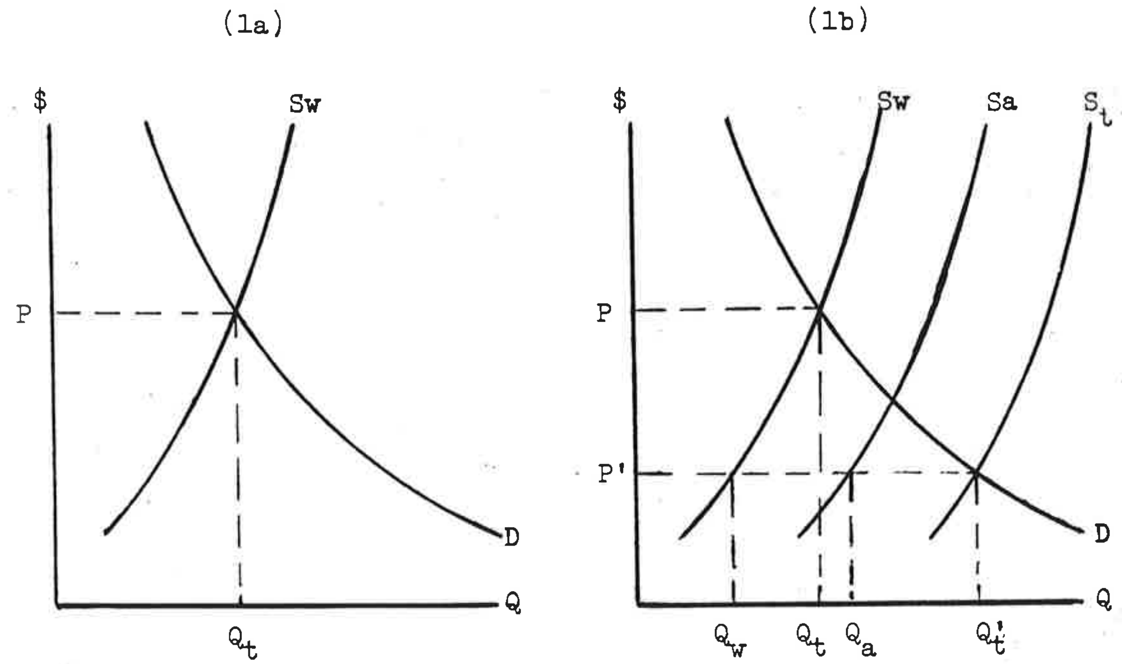
B. The Basis of Comparison

Comparative static analysis is a useful tool for understanding the outcome of the adjustments resulting from a given change in a market. Dynamic analysis considers how the changes take place, identifying the dynamic path of movement from one point of equilibrium to another. For example, model specifications need to represent responses that may be carried out over several time periods. Both static and dynamic analyses are important aspects of accurately modelling share shifts in the window industry.

In terms of a static analysis, the diffusion and partial adjustment models represent the same aggregate market changes discussed in this section. However, the two models differ in their representations of the dynamic aspects of market adjustment reflected in changing share trends. This section primarily outlines the static analysis that is common to both models and provides a basis for developing the dynamic aspects of each model that follows in section three.

In a comparative static analysis, product substitution can be portrayed in the familiar price-quantity plane. Figure 1a shows the window market, prior to the advent of metal windows, being dominated by wood windows. The wood window supply curve (S_w) is the total supply curve for the window industry. This total supply curve is derived by

Figure 1: Introduction and Adoption of Aluminum Windows in the Window Market.



summing the marginal cost curves of each firm. In equilibrium, quantity Q_t is supplied at price P.

Figure 1b shows the result of the development of aluminum windows after a given period of time. The total window supply curve has been shifted to the right as a result of the aluminum window production, representing an increase in supply. The total supply curve for the window market (S_t) is now the sum of the wood and aluminum window industry supply curves, S_w and S_a, respectively, where the industry supply curves are the marginal cost curves for each industry. The total quantity of windows Q_t' is supplied at price P', where the price level is actually a vector of prices corresponding to different styles and types of windows. All firms are assumed to produce for the appropriate price on the price array so as to maximize profits.

The increased supply lowers the equilibrium price level from P to P', which may cause higher cost producers of wood windows to leave the market in addition to inducing all wood window firms to reduce production. The quantity of wood windows supplied has declined from Q_t to Q_w at price P', while the aluminum window industry supplies Q_a at price P'.

Figures 2a and 2b show the process of substitution continuing as the result of further improvements in the aluminum window manufacturing technology and an increased raw material price in the wood window industry, respectively. Figure 2a shows an incremental rightward shift in the marginal cost curve for the aluminum window industry (cost saving technological innovation), which also shifts the total window supply curve out to S_t'. Thus, the equilibrium price level falls from P' to P". The lower price level (P") results in a further change in the market share ratios. The market share of wood windows falls from Q_w/Q_t' to Q_w'/Q_t''. Likewise there is a corresponding increase in the market share of aluminum windows to Q_a'/Q_t'' from Q_a/Q_t'.

In Figure 2b, the marginal cost curve for the wood window industry shifts to the left as the increased raw material prices (variable input) result in a decrease in supply (increase in marginal cost). The total supply curve also shifts left, resulting in a higher price (P''') and a smaller quantity of consumption (Q_t'''). The market share of wood windows falls, while the share of aluminum windows increases.

The factors affecting supply in Figure 2 are only two examples of many possible changes that could cause supply to shift. An increase in the raw material costs for the aluminum window industry would cause the marginal cost curve for that industry to shift left, reducing the market share of aluminum windows.

The fact that the lower-cost innovation does not completely displace the existing product indicates that aluminum windows are not a perfect substitute for wood windows or cannot fully supply the market at price P'. The difference in appearance and perceived differences in quality and maintenance requirements will lead some consumers to pay more for certain types of windows. Consumers range from individual homeowners remodelling one room in a house to builders developing subdivisions. Within the price vector P', it is assumed that the array of wood window prices is greater than the array of aluminum window prices. Thus, the introduction of a lower-cost alternative to the market for windows increases the relative price of wood windows. For a given relative price a certain fraction of the window demand will be met by those preferring to pay more for wood windows. As relative prices change this ratio is hypothesized to change.

Figure 3 demonstrates the effect of a shift in the marginal cost curve of the aluminum window industry on the relative price of wood windows and the resulting share shifts. It also illustrates the total market for windows as two sub-markets for aluminum and wood windows respectively; this being an implication of the imperfect nature of the substitute products. The demand for aluminum windows (D_a) and wood windows (D_w) sum to the total demand for windows (D) shown in Figures 1 and 2. If, for example, aluminum raw material prices fell, shifting the supply of aluminum windows from S_a to S_a', the price vector of aluminum windows would fall from P_a to P_a'. This results in an increase in the relative price of wood windows from P_w/P_a to P_w/P_a', as well as an increase in the

Figure 2: Incremental Shifts in the Supply of Windows.

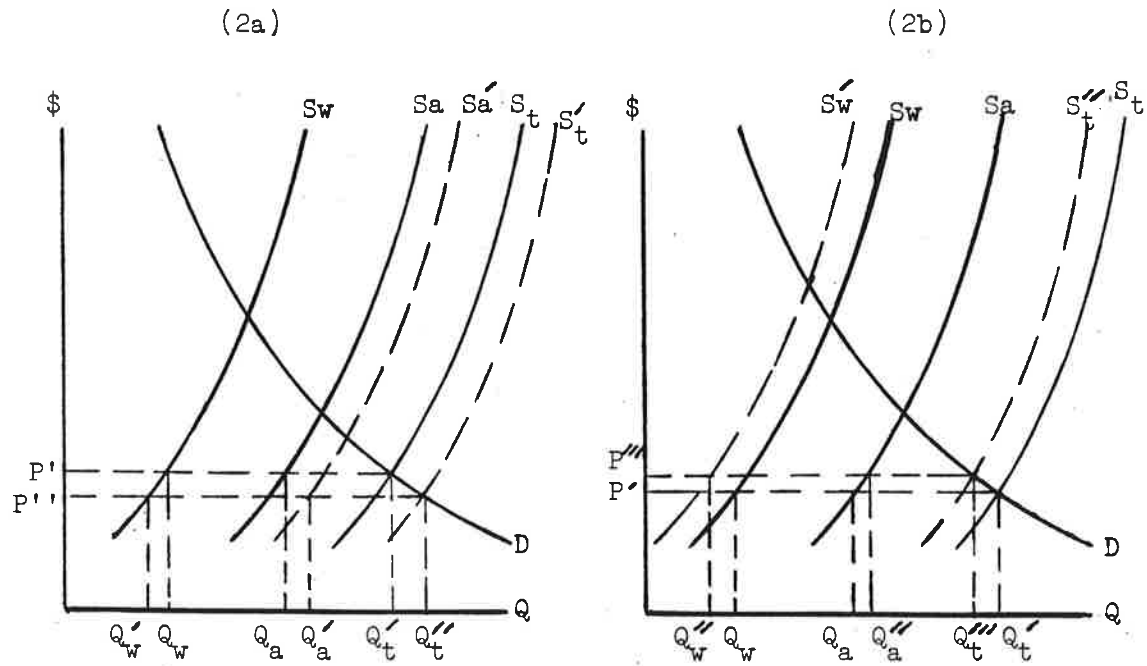
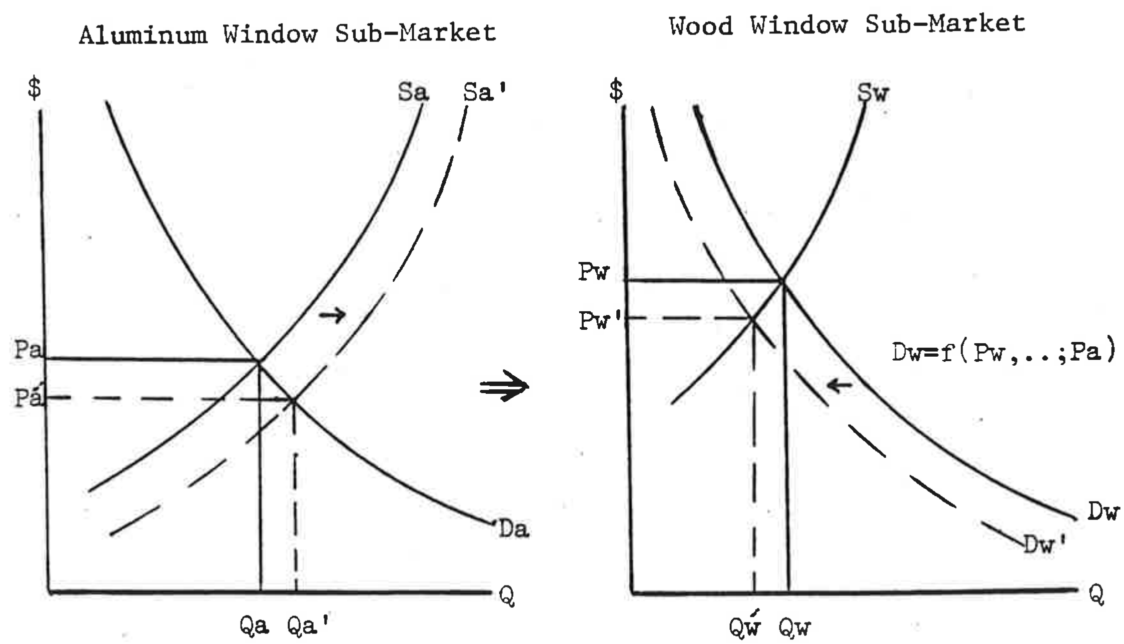


Figure 3: Price and Substitution Effects on Window Sub-markets Resulting from a Shift in the Marginal Cost Curve of the Aluminum Window Industry



quantity supplied of aluminum windows from Q_a to Q_a'. The change in the quantity of aluminum windows supplied increases the market share of aluminum windows.

However, as the demand for wood windows is partially dependent on the price of substitutes, in this case aluminum windows, the reduction in the price of aluminum windows will eventually result in a decreased demand for wood windows (D_w'). This results in a reduction in the price of wood windows from P_w to P_w', and a reduction in the quantity of wood windows from Q_w to Q_w', further increasing the market share of aluminum windows.

In Figures 1, 2 and 3 the demand shifters, other than prices, are held constant. For the purpose of the above comparative static analysis, the demand for windows has not been specified and assumed constant. However, the demand for windows has not been constant, and shifts in the demand curve will also impact market share levels. Although an increase in demand would increase the quantity of both wood and aluminum windows supplied, the share ratios would most likely change reflecting the specific supply (marginal cost) elasticities. Therefore, in modelling the market share trends in the window industry it should be noted that demand shifts are a contributing factor. However, demand changes are not explicitly considered in this study.

III. Outline of Methods

A. Product Diffusion

Diffusion in this context refers to the adoption of new products resulting from technological innovations. The diffusion approach is a useful tool for estimating product substitution because the dependent variable can be expressed as a percent of total consumption, or market share. The functional form of the diffusion model represents technological innovation and the cumulative relative price determine the rate of the diffusion of the innovation. In other words, relative prices determine the rate of adoption of the technological innovation.

The concept of product diffusion is closely related to product life-cycle theories of marketing research. The life-cycle of a product is broken down into four stages: introduction, growth, maturity, and decline (Spelter, 1985a). Products in their introduction and growth phases replace mature and declining products. Although this trend is reversible, it is generally assumed that once a product reaches the growth phase, where its acceptance proceeds at an increasing rate, the trend will continue until the product saturates the market.

1. Application of a diffusion model in the softwood lumber sector: Henry Spelter (1984, 1985a, 1985b) researched methods for integrating economic factors directly into a diffusion model of the forest products sector. Spelter saw it necessary to account for technological change in modeling the dynamics of the demand for forest products. Given the dynamic nature of technological change, Spelter maintains that fixed coefficient models--models that render only average price effects--are insufficient for accurately simulating the dynamics of market adjustments. Spelter (1984) postulated that, as markets change due to technological innovation, the effects of prices on substitution also change. Thus, the model he developed "analyzes demand in the context of distinct substitution cycles that were brought about by specific technological innovations." Spelter concluded that diffusion theory was an appropriate framework for modeling product demand in lieu of the processes of technological change.

Spelter's approach is based on the following identity for demand (Spelter, 1984):

$$Q_t \equiv \Sigma Q_{i,t} \equiv \Sigma M_{i,t} \cdot F_i \cdot S_{i,t}, \quad 0 \leq S_{i,t} \leq 1, \tag{1}$$

where Q_t is the sum of consumption in i markets at time t, $M_{i,t}$ is the market activity (market size) variable in market i at time t, F_i is the maximum market potential in market i, and $S_{i,t}$ is the product's market share. The market activity indicator is treated as exogenous.

Spelter incorporates a diffusion trend in describing the growth of the market share of a given product in its end-product market. In his 1984 study of softwood plywood and structural particle board, Spelter primarily used the Gompertz curve where $S_t = a^{bt}$, where S_t is the market share at time t. In a few sectors a logistic curve, defined as $S_t = 1/(1 + e^{a-bt})$, was estimated. In the 1985 study of softwood lumber, he primarily used the reciprocal logarithmic function, defined as $S_t = \exp(-b/t)$. In each of these functions the estimated parameters are the a and b, and the b, respectively. In traditional diffusion modeling, the time trend variable t is a cumulative variable increasing by one in each period, $t = t_{-1} + 1$.

Although diffusion theory suggests market penetration follows an exponential trend, there does not appear to be a theoretical basis for selecting a particular functional form in this model, other than selecting the form that produces the best fit. Given this limitation, Spelter's research focuses on providing an alternative to the specification of the unit increment time variable that would incorporate economic information. Spelter replaced the time trend with a price differential between the existing product and the new product or innovation,

$$t^* = t^*_{-1} + \Delta P_t, \tag{2}$$

where

$$\Delta P_t = \frac{P(e)_t - P(n)_t}{P(n)_t}, \tag{3}$$

with $P(e)_t$ the price of the existing product at time t and $P(n)_t$ the price of the new product at time t. The argument for defining t^* in this manner is that innovations are adopted when their overall costs are lowest (Spelter, 1985a). If the innovation is cost-competitive, it will be adopted in proportion to the difference in cost. If the innovation loses its cost advantage, the adoption trend reverses (Spelter, 1985b).

In order to estimate the share of lumber in its declining stage, the share function was subtracted from one (Spelter, 1985a). In other words, the share of the existing and the share of the new products sum to one. For some sectors he added an additional parameter, k_i, to the equation representing a penetration limit. Spelter's model estimates the product's end-use factor as the dependent variable, defining it as,

$$U_{i,t} = F_i \cdot S_{i,t}. \tag{4}$$

Thus, the primary function used in Spelter's softwood lumber research[1] is:

$$U_{i,t} = F_i \cdot [1 - k_i \exp(-b_i / t^*)], \quad 0 \leq k_i \leq 1. \tag{5}$$

Spelter's formulation of $S_{i,t}$ allowed him to derive the price elasticity by taking the derivative of Q_t from equation (1) with respect to $P(e)_t$, and multiplying by $P(e)_t / Q_t$. Thus, Spelter uses the definition of own-price demand elasticity given by $(\partial Q_t / \partial P(e)_t) \cdot (P(e)_t / Q_t)$, where Q_t is the quantity of the existing product. This derivation allows for the elasticity to change over time, which was one of the primary objectives of Spelter's study. Spelter argues that elasticity values change as technological trends cause structural changes in market parameters (Spelter, 1985a). The model estimated lumber demand as the sum of 18 end-use demands and achieved an overall fit indicated by an R^2 value of 0.81. The results also showed the own-price demand elasticity of lumber declining from 0.285 in 1950 to .111 in 1980.

One of the key points, and achievements, of this approach is that it relies on a price differential as the key determinant of substitution within the framework of the law of demand. Thus, the Spelter model is an appropriate mechanism for testing the hypothesis that relative prices have driven substitution in the window market.

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[1]In Spelter's 1984 study of plywood and particle board, he incorporated the same price differential trend, t^*, into a Gompertz curve for most of the end-markets, and a logistic or reciprocal logarithmic for the rest. He then estimated the demand in each of the end-markets and summed the results to give total product demand. The overall correlation between actual and estimated softwood plywood consumption was indicated by an R^2 value exceeding 0.98.

2. Critical analysis of Spelter's application: Aside from the selection of products considered, Spelter's results depend on the time frame chosen for each of the 18 different end-use markets in his model. In Spelter's own words, "in conventional diffusion modeling, the trend variable gets an initial value of one for the period the innovation appears." Using Spelter's model, the price differential t^* should begin cumulating from the first period an innovation is introduced. However, 16 of 18 sectors in Spelter's study are estimated from data for the period 1948 to 1981. This assumes that 16 different innovations were each introduced in 1948. In diffusion modeling, an error will arise if the trend variable does not begin cumulating in the period the innovation was introduced.

If, for example, an innovation was introduced in 1940, its market share in 1948 will be the result of eight years of share shifts. According to Spelter's specification of diffusion theory, the 1948 market share would correspond to the sum of the price differentials for the previous eight years. If the series was estimated from 1948, the cumulative 1940-1948 share shift would be considered market share change for the first period alone, corresponding to the single year price differential for 1948.

By not beginning the trend series when the innovation is actually introduced, the resulting series would differ from the actual series by a constant. The constant would be equal to the cumulative price differential for the previous periods not counted. In a nonlinear model, such a discrepancy will bias the results. This bias will be reflected in the estimated elasticities, by overestimating the magnitude of the elasticity values in the initial periods. Intuitively this makes sense as the multi-year share shift is assumed to be derived from a single year price differential in the first period alone. If this is the case, Spelter's results would overestimate the decline of the elasticity. Thus, a "corrected" diffusion model would presumably yield results similar to the results found by Adams, *et al.*, which is discussed below.

B. Distributed Lag

Tilton (1986) suggests that prices may influence material substitution the most by inducing technological change. In other words, prices drive technology which in turn drives material substitution. A feedback mechanism may also be present given that technological innovation further influences prices. If the new technology is cost effective, then the price of the new product will be reduced, further influencing the processes of technological change and substitution. Therefore, in simulating material substitution, prices can be assumed to be the driving force (Tilton, 1986; Woods and Burrows, 1980).

Tilton (1986) also points out that the short-run and long-run effects of prices can be differentiated by introducing a lag structure into the demand equation. Distributed lag models can be used to estimate both short-run and long-run price elasticities and offer a less restrictive functional form than the diffusion models for simulating the relationship between relative prices and market share changes.

One of the key issues with lag models is proportioning the influence of past prices--sometimes referred to as the form of the distribution or shape of the lag. For example, a lag model may give equal weights to each of a given number of the previous prices, or the weights may decline giving less influence to far past prices than to more recent prices.

A recent study of softwood lumber demand elasticity incorporated a lag distribution of past prices (Adams, *et al.*, 1992). The shape of the lag is determined by a partial adjustment process.[2] Using cost minimization theory, they derive the following lumber demand equation from the production function for a particular end-use Q_e:

$$\ln(L/Q_e)_{i,t}=a_{0,i,t}+a_{1,i,t}\ln(P_{IL}/P_{IO})_{i,t}+a_{2,i,t}\ln t, \tag{6}$$

where $(L/Q_e)_{i,t}$ is the lumber end-use factor in market i at time t. The end-use factor expresses the amount of lumber consumed per unit of end-use product produced. P_{IL}/P_{IO} is the price ratio of the lumber-using input and a substitute-using input, or the relative price of the lumber-using input. The time trend variable t accounts for technological change, and a_n for $n = 0,1,2$ are parameters to be estimated. This equation gives lumber demand as a function of the relative prices of lumber-using inputs and technological changes.

Finally, Adams, *et al.*, modified the demand equation with a partial adjustment mechanism to represent the "adjustment dynamics of demand" and produced the following equation,

$$\ln(L/Q_e)_{i,t}=\gamma_{i,t}\ln(L/Q_e)^*_{i,t}+(1-\gamma_{i,t})\ln(L/Q_e)_{i,t-1},\quad 0<\gamma_{i,t}\leq 1, \tag{7}$$

referring to $\gamma_{i,t}$ as a measure of firms' confidence of the realization of $(L/Q_e)^*_{i,t}$, the lumber requirements expected for the current year.

By combining equation (7) with (6) Adams, *et al.*, produced the lumber end-use demand function,

$$\ln(L/Q_e)_{i,t}=b_{0,i,t}+b_{1,i,t}\ln(P_{IL}/P_{IO})_{i,t}+b_{2,i,t}\ln t+b_{3,i,t}\ln(L/Q_e)_{i,t-1}+\varepsilon_{i,t}, \tag{8}$$

where $b_{j,i,t} = \gamma_{i,t}a_{j,i,t}$ for j = 1,2, $b_{3,i,t} = 1 - \gamma_{i,t}$, and $\varepsilon_{i,t}$ is the random error term for end-use i at time t.

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[2]The partial adjustment model was first developed by Nerlov (1958). Further descriptions of the model can be found in econometric references, including Johnston (1984), Judge, et al. (1980), and Gujarati (1988).

The results of the empirical analysis led to the elimination of the trend variable from the demand function specification. According to Adams, *et al.*, this may suggest that a simple time trend is an inadequate representation of technical shifts.

The overall objective of the Adams, *et al.*, study was to estimate the lumber demand functions using the "Kalman filter," which is an algorithm that allows the coefficients to vary freely over time. Annual data from the period 1950 to 1987 for five end-use sectors was used. The sheathing and siding market represents the residential construction sector and the data construction appears to be very comparable to Spelter (1985a), thus controlling for some of the variation in the results of the two approaches. In some sectors, including residential construction, the coefficients estimated using the Kalman filter were not significantly different from the fixed coefficients estimated using OLS. All of the fixed coefficients were found to be significant. The results showed the aggregate price elasticity of softwood lumber has declined by about 25 percent over the sample period, less than the approximately 50 percent decline found by Spelter.

C. A Comparison of the Assumptions and Limitations

1. Assumptions: Model results are only as valid as the assumptions that have been made in order to construct the model. The product diffusion model specifies the dynamic process of technological innovation and adoption in its functional form. The primary assumption is that this process can be represented by an exponential trend.

In the diffusion model, market share levels are determined by cumulative price differentials. However, even as the relative price of an existing product decreased, as long as the price of the existing product exceeded the price of the innovation, the market share of the existing product would be predicted to decrease. The use of a price differential in the diffusion model therefore assumes that the innovation is a perfect substitute for the existing product. In actuality, the existing product could maintain market share even if its absolute price exceeded the absolute price of the innovation, providing a segment of the market perceived a difference in the products. Therefore, the specification of the parameter k accounts for the fact that total market displacement may not occur (Spelter, 1985a).

The partial adjustment model assumes that the cost effects of the process of technological innovation and adoption will be embodied in the product prices. The primary assumption of the model is the dynamic adjustment process, which gives the actual market share change between two periods as a constant function of the optimal share change, or in other words, that the current share value is a weighted average of the long-run equilibrium value and the share value in the past period.

One of the key issues arising from a comparison of these models, in terms of their dynamic characteristics, is the question of how elasticities change over time. The price elasticity estimates derived from each model are in different forms. The diffusion model gives a single period, or short-run, estimate for each year, allowing the elasticity values to change over time rather than giving an average estimate as is the case with the partial adjustment model.

However, the functional form of Spelter's diffusion model dictates the time pattern of the elasticity change over time (Adams, *et al.*, 1992). The diffusion model requires that the elasticities increase or decrease exponentially. As long as t^* is rising, the dependent variable will decline. This restriction has no theoretical basis. Thus, although relative prices are the key explanatory variables in describing market share changes, the pattern of substitution in this model is dictated by the functional form chosen.

The partial adjustment model produces average elasticity estimates for both the short- and long-run. Although the average estimates of the partial adjustment model do not illuminate elasticity trends over time, they are less restrictive. Thus, the question becomes: is the diffusion approach an appropriate means for adding more detail to the average elasticity estimates of a fixed coefficient model?

2. Limitations: The legitimacy of the estimation results depend on the quality of the data used. In selecting the data for the sheathing and siding sector, Spelter and Adams, *et al.*, have specified ponderosa pine 1"x12" boards as the existing commodity and $^1/_2$" CDX fir plywood as the innovation. Although plywood substituted for lumber siding during this period, market surveys show that several other products including aluminum, vinyl and hardboard siding have competed in this market over the last three decades (Phelps, 1970; Bowyer, *et al.*, 1986). Nevertheless, both models found a significant correlation for the siding sector. Although this may be indicative of plywood for lumber (wood/wood) substitution, this specification provides no information regarding wood/non-wood product substitution in this market, which, according to the data, has occurred. In order for the model to represent a market accurately, all of the relevant substitute price variables need to be included.

Highly aggregated data can also present problems. An example can be found in the data Spelter gathered for the millwork and flooring end-use sectors. Spelter specified the producer price index (PPI) for softwood lumber as the existing product price and the "all commodities" PPI as a measure of new product prices. With this level of aggregation it is difficult to discern the actual substitutions taking place. This is reflected in a low R^2 value for this sector of 0.18.

IV. Estimation of Substitution in the US Window Markets

A. The Data

Product price and share data market are required for the application of this model. Wood and aluminum windows have been the primary window products for the past several decades. This study considers only on the residential construction market. New residential and repair/remodeling construction consumed 74 percent of total US window production in 1988; the balance went into non-residential construction.

In the non-residential construction sector, market share of wood is quite small. In this sector much of the substitution away from wood has been driven by non-market forces such as performance standards and fire codes (Forintek, 1989). Modelling efforts such as this are not able to account fully for factors such as regulations. Fire codes and energy efficiency requirements influence the market but are difficult to model. In the residential window market regulations do not appear to have had a major influence.

Consumption patterns are often reported in the form of market share surveys. Unfortunately, this data has not been collected on an annual basis by a single organization. To construct this series, all of the available government and private surveys had to be combined. For years not covered by these studies, estimations of market shares were derived from the US Dept of Commerce's "Census of Manufacturers" and "Annual Survey of Manufacturers." In years where share values needed to be estimated, the level of accuracy may have been reduced.

Due to the limited amount of data, it was necessary to aggregate the single family, multi-family and repair and remodeling end-use sectors into a single residential sector. The single family and remodeling sectors showed similar consumption patterns for the few years that they could be compared. As the combination of these two sectors represented most of the residential window consumption, little variation may have been lost in creating the single residential construction series.

By aggregating at the national level many regional trends have been lost. A recent study showed that aluminum windows have a greater market share in the West, while solid wood windows dominate markets in the North (Anderson and McKeever, 1988). Ideally, more extensive regional data would be available, making it possible to estimate these regions as separate markets.

The US Department of Labor's Bureau of Labor Statistics (BLS) publishes producer price indexes for a variety of products classified by the standard industrial classification (SIC) codes and the BLS commodity codes. The definition of these codes change as new products are developed, especially for more specific product groups coded at the sevenand eight-digit level. For this study, it should be noted the BLS and Census include all cladded wood windows in the definition of wood windows.

By using price data at the eight-digit commodity code level, this study has reduced some of the effects of aggregation. Nevertheless, all of the sizes and styles of windows have been grouped together. For certain years such detailed product data was not available, and values were extrapolated from trends in the aggregate price indexes, as the definitions of the more aggregated codes, such as the four digit codes, remain more consistent over time.

For both the market share and price series, data was available as of 1947. Early market surveys (Gertler, 1959) point out that metal windows were introduced during the late 1930's. Initially, steel windows dominated the metal window industry, before giving way to aluminum windows. Conventional wisdom suggests that during World War II, metals, especially aluminum, would have been in high demand for military construction purposes. Following the war, there would have been an overcapacity of metal producing and processing facilities, leading to the development of alternative metal industries.

The diffusion model requires that t^* begin cumulating in the period the innovation is introduced. Although this exact period is not known, aluminum windows appear to have been on the market prior to 1947. Therefore, a constant (d) must be estimated to represent the cumulative price differential for the period 1944-1946, immediately following the war. Although there is little basis for justifying any estimate of d, a value of zero will bias the results in this case. A value of $d = 1.65$ was estimated based on an examination of the 1947-1950 values, and its ability to predict the share shift prior to 1947. Thus, d is an estimate of the cumulative price differential for 1947-1950.

This study does not explicitly account for the most recent innovations such as solid vinyl windows. Unfortunately, only a limited amount of data on vinyl shares has been collected. Market surveys show wood and aluminum represented as much as 85 percent of the market in 1987. Therefore, 1987 is the last period considered. The methods for simulating market penetration outlined in this paper will provide a means for estimating the market penetration of vinyl windows as more and better data becomes available.

B. Estimating a Diffusion Model of the Window Market

This diffusion model of the residential window market is based on Spelter's model (1985a). A reciprocal logarithmic function was selected to represent the diffusion trend. Wood windows were specified as the existing product. The share term was specified to represent the decline in wood window market share as follows:

$$S_t = 1 - k \cdot \exp(-b/t^*), \quad 0 \leq k \leq 1, \tag{9}$$

where k is a parameter representing the limit value of market displacement, and b is a parameter to be estimated. The cumulative price differential, t^*, is defined in a fashion similar to equation (2):

$$t^* = t^*_{-1} + \frac{P(w)_t - P(a)_t}{P(a)_t}, \tag{10}$$

where $P(w)$ is the price of wood windows and $P(a)$ is the price of aluminum windows.

In order to have the model include the substitution that occurred prior to 1947, the following transformation of equation (9) was necessary:

$$S_t = 1 - k \cdot \exp\left(\frac{-b}{t^* + d}\right), \quad 0 \leq k \leq 1. \tag{11}$$

Equation (11) is the diffusion model used to analyze the data. The equation was estimated using the Micro-TSP software package. As equation (11) is nonlinear, the estimation procedure follows that of Spelter (1985a). TSP uses the Gauss-Newton algorithm for estimating non-linear least squares.

In calculating the t^* series by equation (10), it must be recognized that the price variables in index form only represent trends in each series and not absolute magnitudes. In order to compute a difference in prices, each series must be weighted by actual prices in a given year. The index base year of 1982 was weighted by price values obtained from the R. S. Means Company (Means, 1982). A new weighted series was extrapolated from these base years using the index values for each period. As t^* is a relative price differential, each price series need not be deflated, *i. e.*, any deflator value would be canceled out.

The initial estimation of equation (11) using TSP produced a good fit with a high R^2 value of .958 and an F-statistic of 909.5. However, the Durbin-Watson test statistic was .38, suggesting serial correlation problems. An incorrect estimation of d could produce this result. Given the loose justification of choosing $d = 1.65$, other values of 1, 2 and 3 were tested. Estimations based on these values of d each gave Durbin-Watson statistics of less than .38.

Based on this evidence of serial correlation, equation (11) was re-estimated with a correction for serial correlation. Since TSP does not provide an autocorrelation correction for nonlinear equations, the SHAZAM software package was used for this purpose. Nonlinear least squares in SHAZAM is based on a maximum likelihood procedure using a Quasi-Newton algorithm (White, 1990).

In re-estimating equation (11) with the autocorrelation correction term, the overall fit was improved and the Durbin-Watson statistic was raised to a value of 2.05. Table 1 outlines the results. The estimates of the coefficients were similar and remained highly significant, but their standard errors increased. The log likelihood value increased from 85.3 to 106.2.

Table 1: Estimation Results of the Diffusion Model with SHAZAM.

Coefficient		Standard Error	T-ratio
k	0.75025	0.050854	14.753
b	3.58273	0.99353	3.6061
ρ	0.87432	0.098527	8.8738

R^2	0.9852	Durbin-Watson	2.0542
Log-likelihood	106.2229	Sum of absolute errors	0.56945
Residual sum	-0.006521	Residual variance	0.000328

Further results are discussed in Section V.

C. Estimating a Distributed Lag Model of the Window Market

The following function[3] can be used to estimate the share of wood windows as a function of relative prices,

$$S^*_t = \beta_0 RP^{\beta_1}_t e^{u_t}, \tag{12}$$

where S^*_t is the long-run equilibrium share of wood windows at time t, RP_t is the relative price of wood windows, β_0 and β_1 are coefficients to be estimated, and u_t is a random error term.[4]

Expressing equation (12) in log form expedites the estimation process and gives the share elasticity as the price term coefficient (β_1), leaving as a β_0 constant:

$$\ln S^*_t = \ln\beta_0 + \beta_1 \ln RP_t + u_t. \tag{13}$$

Since S^* is not directly observable, the following partial adjustment hypothesis is assumed,

[3]The specification of equation (12) and the following derivation is based on Gujarati (1988), pp. 527-8.
[4]In specifying the long-run equilibrium function for the dependent variable (Gujarati (1988) and Judge, *et al.* (1980), include random error terms. However, they do not specify error terms in the adjustment process relation (14). Other authors (Johnston 1984) do not include an error term in the equilibrium function, but include it in the adjustment relation. In either case, when the equilibrium function and the adjustment relation are combined, the resulting equation includes an error term (16).

$$\frac{S_t}{S_{t-1}}=(\frac{S^*_t}{S_{t-1}})^{\delta} \quad for \quad 0<\delta\leq 1, \tag{14}$$

where δ is the coefficient of adjustment.[5] Equation (14) can be rewritten in log form as,

$$\ln S_t - \ln S_{t-1} = \delta(\ln S^*_t - \ln S_{t-1}), \tag{15}$$

where S_t - S_{t-1} is the actual change in market share and S^*_t - S_{t-1} is the share change that would occur in long-run equilibrium.

Combining equations (13) and (15), then rearranging the terms, yields the following market share function:

$$\ln S_t = \delta\ln\beta_0 + \beta_1\delta\ln RP_t + (1-\delta)\ln S_{t-1} + \delta u_t. \tag{16}$$

The adjustment assumption allows for the derivation of equation (16) which gives current market share as a function of the current relative price and past prices of declining weights.

Equations (12) and (13) specify the long-run equilibrium share function, (16) represents the short-run function; in the short-run the actual market share is not necessarily equal to the long-run level (Gujarati, 1988). An advantage of this model is the nature of the disturbance term in equation (16), which is a constant multiple of u_t. If u_t is not autocorrelated, then the model is suitable for OLS estimation (Judge, *et al.*, 1980).

From the estimation of (16) an estimate of the coefficient of adjustment can be obtained, δ = 1 - (the coefficient of S_{t-1}). The long-run function can then be derived by dividing $\delta\beta_0$ and $\delta\beta_1$ by δ and dropping the lagged share term. The short-run and long-run effects can also be obtained from the estimation of (16). As the variables are in log form, the short-run price elasticity is given simply by $\delta\beta_1$ and the long-run price elasticity is $\delta\beta_1/\delta$.

Equation (16) is the basic function used to analyze the data. The relative price variable is the ratio of wood window prices to aluminum window prices. The partial adjustment model is an autoregressive model as it specifies a lagged dependent variable as an

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[5]Gujarati (1988) points out that this model assumes a constant percentage of the discrepancy between the actual and *optimal* values of the dependent variable is eliminated within each period. He then asks why this is the case but offers no explanation. Arrow and Nerlov (1958) trace the origins of this model back to Hicks' definition of the elasticity of expectations (equivalent to the coefficient of adjustment, *d*) which is assumed to be a constant. In the partial adjustment model, *d* is not dependent on the absolute value of the market share nor the magnitude of the discrepancy between the actual share and the long-run equilibrium share. Rather, *d* represents a market's rate of response to disequilibrium conditions, which is assumed constant. In addition, the adjustment relation (14) can be rewritten to show that the observed share is a weighted average of the optimal share and the share of the previous period--where *d* is the weight assigned to the optimal share (Gujarati, 1988).

explanatory variable. These models can be estimated using ordinary least squares. The Micro-TSP program was used for this purpose.

The initial results demonstrated a good fit. However, the constant and price term coefficients were not statistically significant. Dropping the constant (16), gives the following equation,

$$\ln S_t=\beta_1\delta\ln RP_t+(1-\delta)\ln S_{t-1}+\delta u_t. \tag{17}$$

This modification substantially improved the regression results, without influencing the assumptions of the model. Although there is no theoretical basis for this modification, it is plausible assuming β_0 has a value of one, which is supported by the estimation. Because equation (17) is an autoregressive model, the Durbin h test must be done in order to detect first order serial correlation (Gujarati, 1988). An h value of 0.773 was computed, which is not enough to reject the null hypothesis of no first order serial correlation. Each of the estimated coefficients is highly significant. The F-statistic is 1915.6 and the overall R^2 value is 0.98 (see Table II). Figure 4 shows the fitted curve[6] and Figure 5 displays the residual plot.

V. Results

A. The Derivation of Share Elasticities

1. Diffusion model: The share elasticity with respect to price for the diffusion model can be calculated as per Spelter (1985a). Taking the derivative of S_t with respect to $P(w)_t$ in equation (11) and multiplying by $P(w)_t/S_t$, produces the following formula for the share elasticity:

$$-\varepsilon_t=\exp\left(\frac{-b}{t^*+d}\right)\cdot\left(\frac{k\cdot b\cdot P(w)_t}{P(a)_t\cdot S_t\cdot t^*}\right). \tag{18}$$

The results show the absolute short-run, own-price share elasticity of wood windows declining from 0.20 in 1947 to 0.01 in 1987, with a mean of 0.06 (see Figure 6). In other words, the percent change in the market share of wood windows in one year with respect to a given one percent change in the real price of wood windows, in absolute terms, has been declining. Since absolute price levels are not specified in this model, the cross-price elasticity has the same magnitude but opposite sign as the own-price share elasticity. The share elasticities will correspond to the demand elasticities (Simon, 1979).

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[6]The graph values have been retransformed to the actual values from the natural log values used for estimating the model.

Table 2: Estimation Results of the Partial adjustment Model with TSP

Variable	Coefficient	Std. Error	T-stat.	2-tail sig.
lnRP	-0.207623	0.0456314	-4.549992	0.0000
$\ln S_{t-1}$	0.8801312	0.0298281	29.506821	0.0000

R^2	0.980549	Mean of dependent var.	-0.88339
Adjusted R^2	0.980037	SD of dependent var.	0.286124
SE of regression	0.040427	Sum of squared resid.	0.062104
Durbin-Watson	1.758377	F-statistic	1915.592
Durbin *h*	0.773	Log-likelihood	75.59879

Figure 4. Wood Window Market Share and the Partial Adjustment Fitted Values

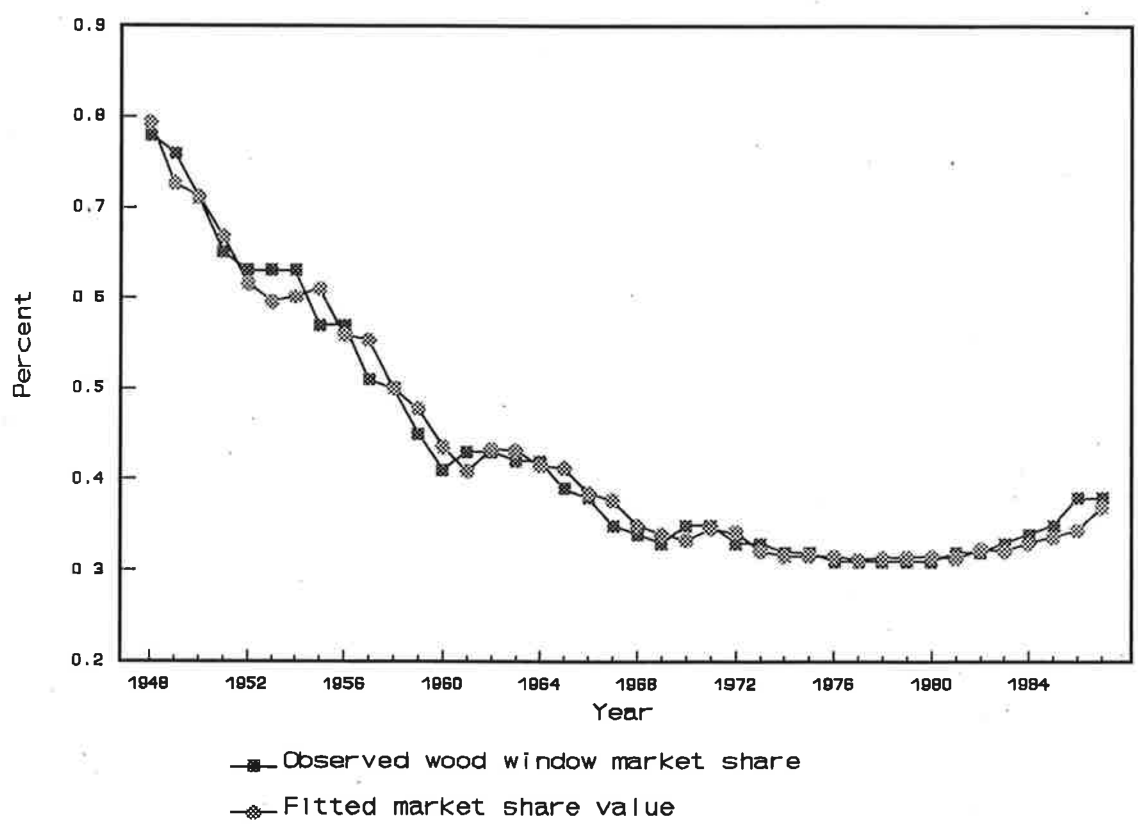


Figure 5. Residual Plot of the Partial Adjustment Model

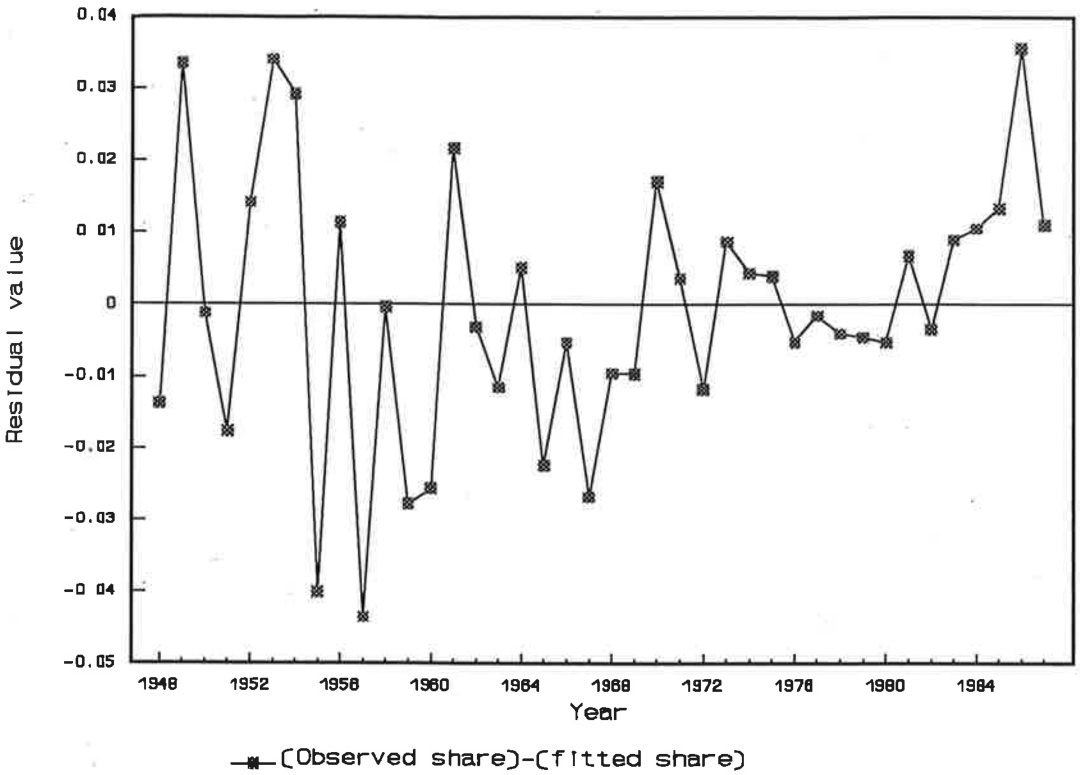
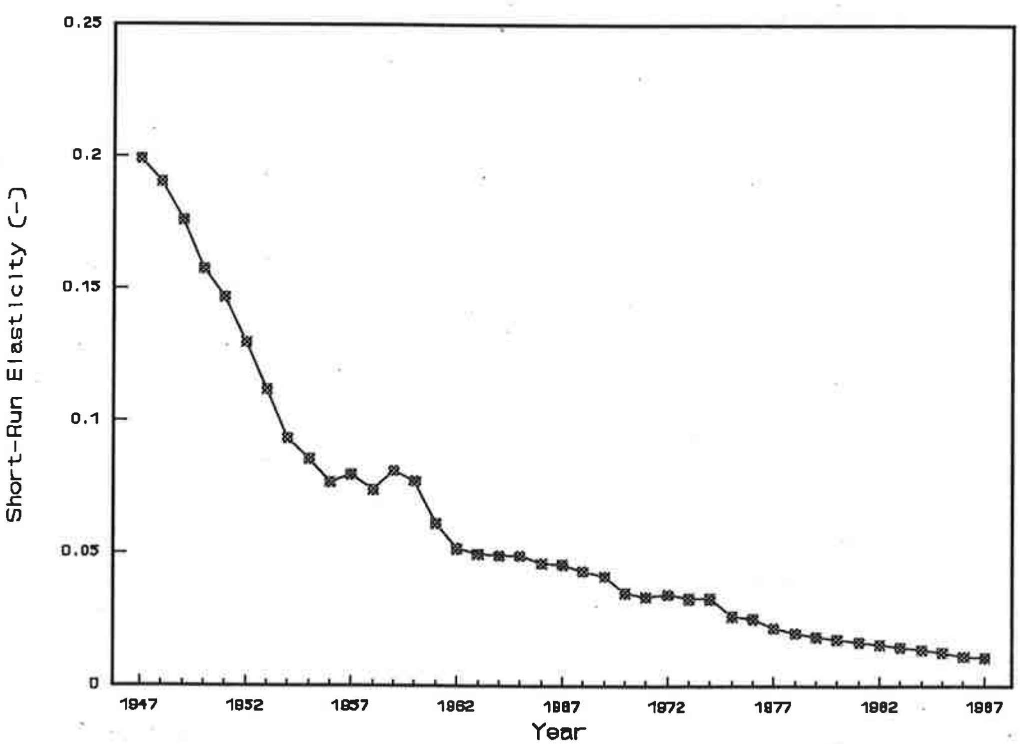


Figure 6. Wood Window Market Share Elasticity with Respect to Price: 1947-1987.



As the diffusion of aluminum windows proceeded, wood windows lost market share and have become increasingly inelastic. The trend declines exponentially as the model shows the elasticity declining at a decreasing rate over time, as expected.

Dynamic elasticities show how the price effect on wood window share changes over longer time periods. The magnitude of the market share response depends on the amount of time that has elapsed following a given price change. As the response to a price change in a given period cumulates over time, the elasticity value can be expected to grow and approach some asymptotic value (Pindyck and Rubinfeld, 1981).

In order to simulate this process, the price of wood windows was increased by one percent in 1950, 1970 and 1980. The dynamic elasticities for five year periods were then computed from the differences between these series and the fitted values from equation (11), for each of the three ranges. The results are shown in Figure 7. In each case, the fifth year elasticity is more than four times as large as the short-run elasticity of the initial year.

2. The distributed lag model: Estimation of the partial adjustment model (17) gives a value of 0.12 for the coefficient of adjustment. Because the share and price variables have been expressed in log form, the short- and long-run share elasticities can be derived from the value of the coefficients. The estimated short-run share elasticity is -0.21 and the long-run elasticity -1.73.

These estimates give the following long-run equilibrium equation:

$$\ln S^*_t = -1.73 \ln RP_t. \tag{19}$$

The long-run share of wood windows (19) can be related to the quantity demanded by using an identity similar to equation (1), and assuming M and F are exogenous. Note that $M{\bullet}F$ in this case would equal the total demand for windows. In other words, the total window demand is assumed not to influence the market shares. This assumption is less of an issue for the purpose of comparing the results of the diffusion and distributed lag models since a comparison can be made on the basis of share elasticities.

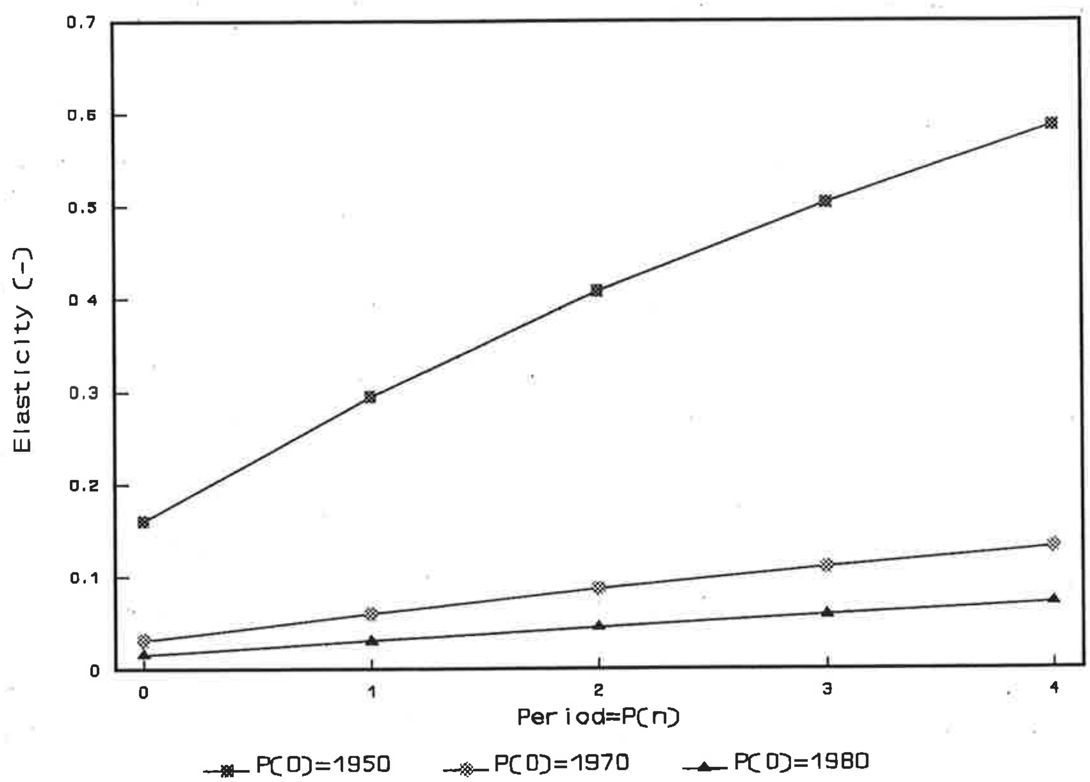
B. Comparison of Elasticity Estimates

The short-run elasticities of the diffusion model appear to approach zero. However, wood held approximately one-third of the market towards the end of the sample range. Thus, a near-zero elasticity implies that wood has a "fixed" market share, for which there is no justification.

In absolute terms, wood window own-price share elasticity declined from 0.20 in 1947 to 0.01 by 1987. As the response period increases the elasticity increases, showing that the elasticity is greater in the long-run than the short-run. However, as shown in Figure 7 the five-year responses are also inelastic.

Again in absolute terms, the short-run estimate of 0.21 for the partial adjustment model is equivalent to first period value from the diffusion approach. The long-run equilibrium estimate of 1.73 is not directly comparable to the diffusion estimates. However, 1.73 appears to be much greater than the asymptotic values approached by the 5-year responses from the diffusion model (Figure 7).

Figure 7: Wood Window Share Elasticity Adjustments Over Time for Three Five-Year Periods



The fact that both models were estimated using the same data emphasizes the significance of the model specifications and assumptions in deriving elasticity estimates. A model's results should not be considered apart from its assumptions.

Both model estimates show that in the short-run the market share of wood windows is inelastic with respect to relative price. The models also confirm the concept that the share response to a given price change will be larger given a greater amount of time for the market to adjust. In other words, the long-run elasticity is greater than the short-run elasticity. As mentioned in Section II-B, these models are capturing the effects of multiple factors in addition to prices which influence demand. The price terms in the model capture these other factors, such as shifts in demand. Thus, the actual price effects may be less than the values estimated.

VI. Discussion

A. Environmental Impacts

When products produced from different materials are substituted for one another there is a shift from one or more environmental impacts to others associated with the substitute product(s). Changes in forest and environmental management policies affect product prices, thereby changing the consumption patterns of wood and non-wood products. Furthermore, the full environmental costs associated with each material may not be included in the price of the final product. This study has outlined a means for estimating substitution for a variety of end-products. Therefore, this section briefly describes the environmental impact issues related to substitution such as the amount of energy used and carbon emissions for alternative materials.

A large share of the environmental impacts arising from various manufacturing processes occur during the extraction and primary processing phases of production. Recently, Alexander and Greber (1991) have taken a close look at a broad range environmental impacts arising during the life cycles of alternative construction materials. Although the study does not measure environmental impacts on a comparable basis, it does illuminate a wide range of impacts arising from the production of wood, plastics, aluminum, steel, and concrete.

Each of these industries has substantial extraction impacts; however, the report concluded that steel and plastics have the most lasting and toxic impacts. During the manufacturing stage steel, aluminum and plastics create more significant problems than sawn-wood and cement (Alexander and Greber, 1991). Furthermore, wood has the unique attribute of being a renewable resource. If well managed, forests will remain productive indefinitely.

The possible threat of global warming and the debate over the harvest of old-growth timber have inspired new research looking at the role of old-growth forests in the "storage" of carbon (Harmon, *et al.*, 1990; Kershaw, *et al.*, 1992). Based on the results of these two studies, it appears that the jury is still out on the issue of carbon sequestration and the conversion of old-growth timber to managed stands. The former study showed that the conversion process would increase carbon dioxide levels in the atmosphere, while the latter study concluded that carbon levels would be reduced for the first few decades. What may be of more relevance is that fluctuations in atmospheric carbon levels resulting from forest management practices are insignificant compared to the release of carbon produced by burning fossil fuels (Kershaw, *et al.*, 1992).

Thus, the most significant effect of forest management on the level of carbon dioxide in the atmosphere will come from the substitution of wood materials for more energy-intensive materials, although it may be relatively small. New approaches to forest production and more intensive forest management practices would be required to produce higher-quality logs needed to facilitate an increase in the substitution of wood for wood substitutes (Oliver, 1991). In addition, the consumption of old-growth timber for luxury goods that do not substitute for energy intensive materials is an environmental loss that does not carry an offsetting environmental gain (Oliver, 1990).

B. Economic Implications

Another important aspect of this study pertains to the fact that wood windows are a value-added wood product. The contemporary concerns for environmental protection and economic development in the Pacific Northwest have intensified the debate over forest product production policies. Many in the environmental and labor communities believe that the key to protecting the environment and creating job growth lies in producing more value-added wood products at the expense of raw log exports. To the extent that this research provides information on the nature of wood window consumption in a very competitive marketplace with possible substitutes, it will help policy makers develop realistic and effective strategies in this area.

C. Conclusion and Future Research

Over the past several decades many window products that were traditionally manufactured from wood are now being made from non-wood substitutes. Rising wood prices and an over-capacity of metal processing facilities during the middle of the century induced the innovation of non-wood windows. Less expensive window products increased market share.

This study confirms the hypothesis that product prices determine substitution. The results of each estimation method show a high degree of short-run share inelasticity for wood windows. The observed loss of wood window market share is thus explained by the cumulative effects of a prolonged price disadvantage.

Although both models fit the data extremely well, a significant fit does not justify the assumptions of a model. The restrictive and arbitrary form of the diffusion model bring this method into question. The partial adjustment approach is based on distributed lag theory and provides less restrictive estimates of market share elasticity with respect to price.

The elasticity estimates from the diffusion model imply that wood windows would need to be much less expensive (in terms of a vector of relative prices) than aluminum windows for a long period of time in order to recover lost market share. The elasticities from the partial adjustment model suggest that a more moderate cost advantage would allow wood to recover market share.

Further research should focus on developing less restrictive methods for deriving elasticities vary over time. Experiments have been done using algorithms that allow the coefficients of linear models to vary freely over time (Adams, *et al*., 1992). In addition, these methods should be applied to a variety of end product markets.

With accurate methods for quantifying substitution, existing trade models would be able to simulate the full range of environmental and economic trade-offs resulting from product substitution. Through product substitution in end-markets various environmental impacts are interrelated, because the production process of each product involves a unique set impacts. As these products are substituted, so are their environmental impacts. Product prices may not account for the full environmental impacts of each product.

Environmental policies should consider the economic aspects of the resources involved, both directly and indirectly, in order to fully protect the environment. Policies aimed at specific regions or specific impacts may increase a completely different set of impacts and/or shift the impacts to other regions.

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