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65

ADOPTION, DIFFUSION, AND SUBSTITUTION OF STRUCTURAL WOOD PANELS

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April 1998

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Executive Summary

A sizable literature concerned with technological substitution modeling exists within the domain of forest products. These models have generally been used to develop market share forecasts for various forest products and their substitutes based on relative product prices. Substitution models usually assume that the potential market size is known and that products can freely substitute for one another. A small but growing literature concerned with the diffusion of new innovations also exists within the domain of forest products. This diffusion literature typically focuses on factors affecting consumer acceptance for product innovations and forecasting the level of demand growth without constraining the potential market size. In this paper, we examine the dynamic sales behavior of three and four successive generations of structural wood panel products using varying forms of a multigeneration diffusion model. The multigeneration diffusion model introduced here, which encompasses the elements of diffusion and substitution modeling, assumes that a new structural wood panel product will diffuse through a population of potential consumers over time and that market share competition will be introduced with successive generations of structural wood panels.

Estimation results indicate that market share competition between various structural wood panel products are differentially affected by substitution and diffusion effects. The model results reveal that the aggregate market share growth and decline for southern pine plywood can be attributed mostly to substitution effects (*i.e.*, substitution between western and southern pine plywood), while the aggregate market share growth of oriented strandboard can be attributed to diffusion effects.

The model results also suggest that structural wood panel products act as complements rather than as substitutes to one another. Caution should be used, however, in interpreting these results since we evaluate the structural wood panel market in the aggregate rather than evaluating specific end-use markets. Nevertheless, market aggregate complementarity has been found in other research examining the market share competition between structural wood panel products.

In the near-term, the multigeneration diffusion model suggests that the southern pine plywood market has reached its peak production level over the past five years, with production forecast to decline slowly but steadily over the next decade. Western plywood is forecast to continue its downward production and market share trand. Oriented strandboard is expected to remain entrenched in a growth phase over the next five to ten years.

We explore several managerial implications of the model results and suggest alternative multigeneration diffusion models that could be developed for structural wood panel products.

Keywords: adoption, diffusion, substitution, market share competition, forecasting, technological progress, industry evolution, product life cycle, plywood, oriented strandboard, waferboard

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Introduction

Technological progress typically results in the introduction of new technologies, including both processes and products, which directly compete with older ones. Historical examples of new technologies substituting or completely replacing older ones abound. Automatic automobile transmissions, for instance, have substituted for standard transmissions, while board lumber has been effectively replaced by various wood panel products in such end uses as wall and roof sheathing in the residential construction market. The time interval between successive generations of new products has considerably decreased in the past few decades, especially in the high-technology electronic hardware and software product markets (*e.g.*, Microsoft's Windows® 3.1, Windows® 95, Windows® 98). A reduction in the time between successive generations of new technologies has also occurred in the forest products industry. This is evidenced by the market penetration of several new types of engineered wood products (*e.g.*, various configurations of wood I-beams substituting for 2x8 and 2x10 solid wood joists). As time intervals between the introduction of new technologies become compressed, the importance of understanding the impact of recent technologies on earlier ones increases.

In most cases, an older technology is not completely replaced by a new technology; the older technology continues to retain a hold on some portion of the market. Therefore, a process of diffusion is set into motion for the new technology. Diffusion models have typically been used in situations where a new technology exhibits a perceptible technical improvement over an older technology. However, most diffusion research has focused on forecasting the sales or acceptance of the new technology while dismissing the fact that the old technology remains available and competes with the new technology.

A new technology can potentially expand the overall size of the market by supporting end-use applications that may not have been feasible previously. Additionally, a new technology can provide the opportunity for purchasers of the older technology to substitute the new technology for the earlier one. These substitution effects ultimately reduce the market potential, as well as the actual sales, of the earlier technology in one of two ways. First, some consumers will adopt the new technology when they would otherwise have adopted the older one. Second, some consumers who have already adopted the older technology may switch to the new one. If the time interval between technologies is relatively short, then the older technology may continue to diffuse through a population of potential adopters even as the substitution process is under way. Consequently, the demand for an earlier technology could grow even as the substitution process for the new technology occurs.

The objective of this study is to present a multigeneration forecasting model that explains the process of diffusion for a first generation technology and the process of substitution between various successive generations of this technology. Our focus is on multiple generations of structural wood panel products; namely, western plywood, southern pine plywood, waferboard, and oriented strandboard. We develop a multigeneration diffusion model for the structural wood panel industry in the United States. The model provides a basis for assessing and forecasting the influence of successive generations of structural wood panel products on earlier ones. We extend the multigeneration diffusion modeling research conducted by Mahajan and Muller (1996), Norton and Bass (1987, 1992), and Speece and MacLachlan (1992, 1995) in several ways. Norton and Bass were the first to introduce and test a multigeneration diffusion model. Their model, as well as the model developed by Mahajan and Muller, was presented in the context of high-technology industries, while the multigeneration model developed by Speece and MacLachlan was in the context of the packaging industry. We present an example that indicates that multigeneration models also have application in industries generally associated with commodity products. Additionally, we explore the use of various utility-adjusted price functions in the estimation of our model.

The Structural Wood Panel Market

The model that is developed in this study examines successive generations of structural wood panel products in the United States. Specifically, we examine the diffusion and substitution of western plywood, southern pine plywood, waferboard, and oriented strandboard. These products are typically used in such structural applications as floor, roof, and wall sheathing, underlayment, and the webs of wood I-beams. Prior to developing the multigeneration diffusion model, we briefly outline the historical evolution of each of these four types of structural wood panel products. This historical overview, primarily discussed in the context of the evolution of the United States structural panel industry, will provide insight into the factors that influence the substitution and diffusion of successive generations of structural wood panel products.

Western Plywood

Plywood is the generic name applied to a product that is composed of an assembly of thin veneers that have been cross-aligned, usually at 90 degree angles, and glued together. Relative to solid wood, plywood has the advantages of exhibiting properties along its length that are nearly equivalent to those along its width, high strength in proportion to its weight, high resistance to splitting, and fewer defects. One superior attribute of plywood, relative to solid lumber, is that its panel form allows for lower installation costs on a square foot basis in those end-use markets where coverage of large areas with wood are desirable (*e.g.*, wall and roof sheathing, subflooring, crates, temporary construction decking). All other structural wood panel products possess this attribute as well.

Western plywood, which includes plywood produced from western inland species, can trace its roots to 1905 and the Portland Manufacturing Company, located in Portland, Oregon. This company produced a "glued veneer stock for factory use;" the primary use being panel stock for doors, drawer bottoms, and trunks (Anonymous 1905a, 1905b, 1949). The next fifteen years of the western plywood industry were intimately tied to the vertically integrated door manufacturing industry, with an insignificant volume of plywood being directed into structural end uses. A multitude of factors can be attributed for western plywood's slow market acceptance; however, the lack of product standardization, inconsistency in product quality, and a high cost relative to lumber were the primary factors hindering western plywood's acceptance in the structural (*i.e.*, residential construction) market (Petit 1957b).

Western plywood first began making inroads into structural end uses in the residential construction market around 1920 (Anonymous 1931; Buskirk 1955; Perry 1952). On September 5, 1924, a group of western plywood manufacturers formed the Pacific Coast Plywood Manufacturers Association (a forerunner to today's APA - The Engineered Wood Association). This association was initially formed with the goals of devising standards for a fir plywood grading system, developing the fir plywood market, and researching plywood production and distribution costs. In May of 1925, at a meeting on the campus of the University of Washington, it was decided that the members of the association would begin to target the home construction market specifically (Buskirk 1955; Cour 1955). This decision has had a lasting impact on the structural wood panel industry since the home construction market has remained a primary target for structural wood panels.

The growth of the western plywood in the United States market was quite stable up to World War II, as evidenced in Figure 1. After the war, however, western plywood production increased at very high rate until it reached its peak production output of 7.899 billion square feet (1/2" thickness basis) in 1965. In fact, the western plywood industry led all other individual industrial sectors in growth in the United States on an annual basis from 1950 to 1965 (Sherman 1965). During this time, the industry grew at an average annual rate of 14%.

Total production of western plywood began a steady decline starting in 1965, and has yet to stabilize. Western plywood's market share of the United States structural wood panel market, as displayed in Figure 2, declined from 100% in 1963, to 50% in 1978, to approximately 10% in 1997. One of several factors contributing to western plywood's market share decline in the structural wood panel market was the introduction of a competing product—southern pine plywood. Other factors have been the continued use of older, less efficient processing technology and higher harvesting costs relative to other geographic areas of North America (Spelter 1997).

Southern Pine Plywood

The second generation product that entered the United States structural wood panel markets was southern pine plywood. Initial research examining the commercial production of southern pine plywood began in 1943, when Crossett Company (later purchased by Georgia-Pacific Corporation) delivered second-growth southern pine logs to the USDA's Forest Products Laboratory in Madison, Wisconsin (Fassnacht 1964). The properties of these logs and their veneer were compared with western peeler logs as a raw material for plywood. The results of tests at that

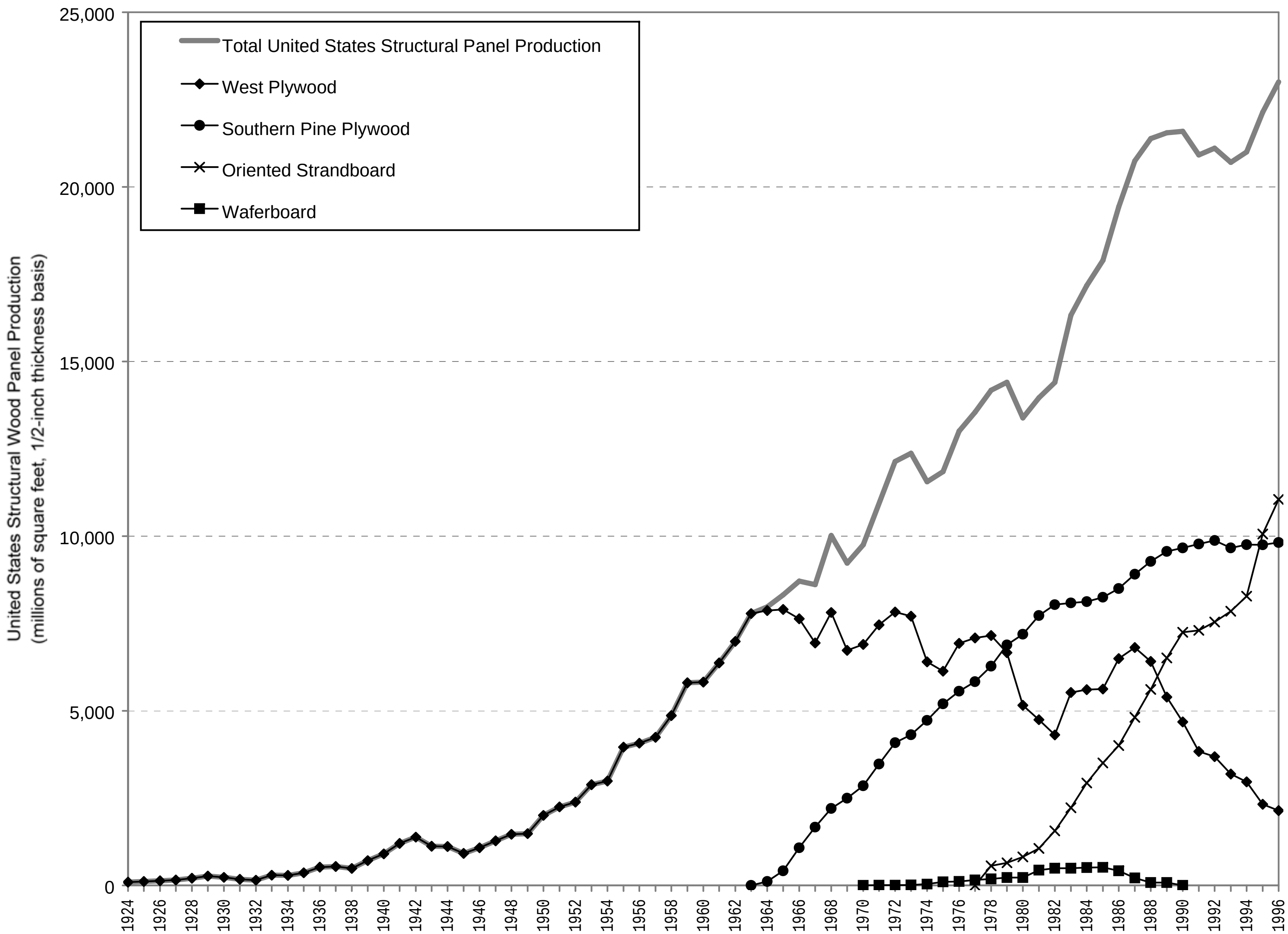

Figure 1. United States structural wood panel production by panel type on a 1/2-inch thickness basis, 1924-1996.

Sources: Spelter (1984), Sudbury (1981), *Random Lengths Yearbook*, APA—The Engineered Wood Association, Structural Board Association

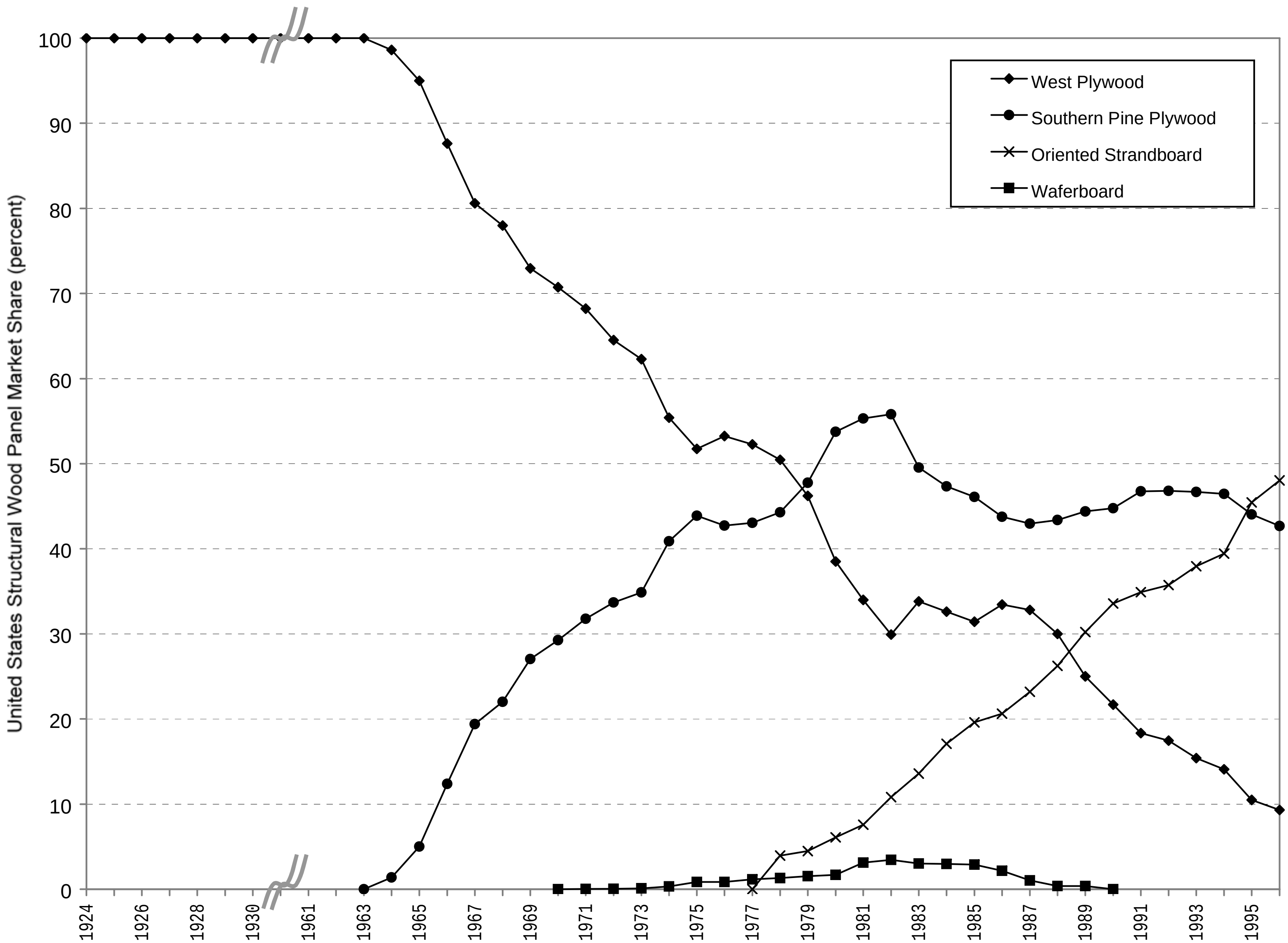

Figure 2. Structural wood panel market shares by panel type based on 1924-1996 United States production data.

time indicated that southern pine was not a feasible raw material for the production of structural plywood. It has been documented that a few hardwood plywood producers were producing structural southern pine plywood in the 1940s and 1950s; their total production, however, was negligible (Anonymous 1963; Fassnacht 1964). Furthermore, these producers were manufacturing custom southern pine plywood that was not certified by any grading agency for structural end-use purposes.

A combination of circumstances around 1960 led to a serious reevaluation of southern pine as a raw material for structural plywood. First, the supply of high-grade Douglas-fir peeler logs in Oregon, Washington, and British Columbia fell below the volume required to supply the installed industry capacity beginning in the late 1940s (Anonymous 1963; McKellar 1948; Norman 1964; Petit 1957a; Schrader 1951; Stanford Research Institute 1954). This shortfall was further exacerbated by peeler-grade log exports to Japan that increased in the United States from an inconsequential volume in 1960 to over 1.5 billion board feet in 1967 (Gunn 1992; Holley 1969). Concurrently, the South's "second forest" was producing a large increase in reasonably high-quality southern pine logs in sizes suitable for veneer production. Further, prior to the 1960s, the South lacked economies of scale in plywood production; the western and Canadian plywood industry had a comparative advantage in that they were utilizing larger diameter logs that substantially reduced the number of bolt changes that had to be made during veneer processing (Burrell 1965). Processing equipment manufacturers, however made several important technological breakthroughs in the 1950s and early 1960s that allowed for the feasible production of structural plywood from small-diameter southern pine logs (Gilligan 1992). The most notable technological advances included high-speed spindleless lathes, retractable lathe chucks, automated clippers, and improved veneer handling and drying systems (Mullins 1992; Spelter and Sleet 1989). These technological advances allowed southern pine manufacturers to produce a continual flow of veneer from logs ranging in size from 8 to 20 inches in diameter (Haskell, *et al.* 1966). Interestingly, at the outset of the commercial southern pine plywood industry in 1963, Georgia-Pacific Corporation and Champion International Corporation "found that it cost no more to produce southern plywood than it did to produce western plywood," and "that in the long run it would cost less to produce southern plywood" (Federal Trade Commission 1978).

The initial speed at which the southern pine plywood industry grew is evident in the dramatic increase in the number of production plants operating commercially between 1963 and 1967. According to Holley (1969), only one of the 156 structural plywood plants (less than 1%) operating in the United States in 1963 was producing southern pine plywood. By 1967, southern pine plywood plants represented 34 of the 184 American structural plywood-producing plants (18.5%). Substantial credit to southern pine plywood's rapid market acceptance can be attributed to the Douglas-fir Plywood Association (DFPA), which changed its name to the American Plywood Association in 1964 the better to reflect the introduction of a new species being used in commercial structural plywood production. The DFPA began certifying southern pine plywood equally with western plywood in the early 1960s. As a result, American consumers (*i.e.*, designers, specifiers, builders, homebuyers) of structural plywood were assured of southern pine plywood's quality from its initial introduction into the market (Norman 1964).

As Figure 2 indicates, it took less than 16 years for southern pine plywood to surpass western plywood as the structural wood panel market share leader in the United States (market share being based on square feet of production on a 1/2-inch thickness basis). Southern pine plywood maintained the top market share position in the United States from 1979 to 1995, when it was surpassed by oriented strandboard, the fourth generation structural wood panel product. It is interesting to note that at the time of southern pine plywood's introduction into the structural wood panel market, some industry experts were predicting that it would not pose a serious threat to the western plywood industry's future growth (Norman 1964). These experts reasoned that the South could not supply enough southern pine peeler logs to meet the growing market demand for structural wood panels. These forecasts, however, failed to consider the technological advances that would be made in the production of southern pine veneer and plywood (*e.g.*, spindleless lathes, veneer drying systems, high moisture resin technology), as well as a developing trend toward higher-value lumber and peeler log production rather than pulpwood production.

Waferboard

Waferboard, the third generation structural wood panel product, is a nonveneered structural wood panel that is produced almost exclusively from aspen roundwood. Standard waferboard is produced utilizing wafers that have not been oriented. While waferboard can be produced utilizing wafers that have been partially oriented and layered, oriented waferboard is distinct from oriented strandboard and possesses structural characteristics that more closely resemble standard waferboard than oriented strandboard.

Waferboard was first produced on a very small commercial scale in 1955 by the Pack River Lumber Company in Sand Point, Idaho (Clark 1955, 1981). This venture was short-lived, however, and no commercial waferboard production occurred again in the United States until 1971.[1] Only one waferboard producer existed in the United States between the years of 1971 and 1979. After 1979, considerable expansion occurred in the nonveneered structural wood panel industry, and this expansion had a significant impact on the entire structural wood panel industry (Fuller 1984a). Waferboard production in the United States peaked in 1982, before declining to the point where no waferboard has been produced in the United States since 1990.

Waferboard's early market acceptance in the United States has been attributed to its mechanical properties and price differentials relative to the low grade plywood (*e.g.*, CDX) used in the roof decking markets of the northeastern and north central regions (Vajda 1980). Specifically, while 3/8-inch thick plywood was being increasingly specified by builders for roof decking in the late 1970s and early 1980s, builders found that the 3/8-inch product was much more flexible ("bouncy") than the 1/2-inch thick plywood that they had used in the past. As an alternative, builders began to specify 7/16-inch waferboard based on the existing building code regulations. The 7/16-inch waferboard product offered a compromise because it was stiffer than the 3/8-inch thick CDX plywood, but considerably less expensive than 1/2-inch thick CDX plywood.

Waferboard gained increased market acceptance in the United States because of several physical and economic advantages that it possessed relative to plywood. At the time of waferboard's introduction in the marketplace, Canadian, western, and southern pine plywood were generally decreasing in overall quality and grading standards were being widened with respect to the type and number of defects allowed (Guss 1987). Waferboard offered an alternative product that possessed two good sides and contained few voids or gaps. Additionally, waferboard could easily be manufactured in sizes larger than the traditional 4x8-foot plywood panel, which was a desirable product attribute for such large-size panel consumers as mobile home and factory-built home manufacturers (Gall 1981).

Waferboard also possessed a production cost advantage relative to softwood plywood. Most waferboard in the United States and Canada was produced using aspen, which historically had been an underutilized species with a very low stumpage value. Furthermore, forest managers incurred relatively low regeneration costs since aspen is an asexually reproducing species. Given that there were large areas of aspen forests in several geographical regions in the northern United States, manufacturers were able to establish production facilities in proximity to both the raw material resource and numerous large consuming markets. Despite waferboard's higher shipping weight relative to plywood, manufacturers, shipping on the basis of delivered cost, and consumers, purchasing from the mill FOB, realized considerable savings in transportation costs due to shorter freight hauls (Fuller 1983). A final economic factor favoring waferboard was technologically related; the waferboard production process was considerably more automated than softwood plywood production, thereby reducing labor costs (Constantino, *et al.* 1989).

Despite the fact that waferboard provided a low-cost alternative to plywood, particularly in sheathing applications, growth of the waferboard market was slow. Several factors inhibited the market share growth for waferboard. First, waferboard possesses a nonveneered appearance, which was considered by consumers as a somewhat radical divergence from plywood. Waferboard also possessed inferior strength properties relative to western and southern pine plywood (given equivalent thickness), which contributed to problems in gaining building code acceptance in some regions of North America. Furthermore, wholesalers and retailers incurred higher expenses by having to carry structural wood panel inventories of both plywood and waferboard. Finally, production problems experienced by some of the first manufacturers of waferboard were highly publicized (Guss 1987; Montrey and Utterback 1990). Most of these problems were related to resin, panel delamination, and product availability. The combination of these factors contributed to increased consumer risk and uncertainty in using waferboard in structural end-use applications.

Although waferboard as a product was relatively short-lived and never represented a substantial share of the United States structural wood panel market, as evidenced in Figure 2, its importance in influencing market acceptance for

[1] Waferboard was being produced on a commercial scale in Canada beginning in 1966 (Pistorius and Utterback 1995).

the fourth generation of structural wood panels—oriented strandboard—should not be overlooked. Waferboard provided consumers with a knowledge base concerning the attributes that structural nonveneered wood panels possessed relative to western and southern pine plywood.

Oriented Strandboard

Oriented strandboard (OSB) represents the fourth and latest generation of structural wood panel product. OSB is similar to waferboard in that it is a nonveneered panel. A factor that spurred product and process development and commercialization of OSB was the inherently low structural stiffness and strength characteristics that waferboard offered relative to plywood (Montrey and Utterback 1990). For instance, given equivalent thickness, the modulus of elasticity (MOE) in flexure for a waferboard panel is approximately one-third of that for western plywood.

OSB is produced with a minimum of three layers of aligned strands. These strands resemble the wafers used in waferboard production, but possess a substantially greater length-to-width ratio. The length of the strands is in the natural direction of the grain. Similar to plywood production, the face layers of OSB are aligned parallel to one another while the core layer is aligned in the cross-panel direction. The strand alignment of the face layers provide panel stiffness and strength whereas the cross-alignment of strands in the core layer provides cross-panel dimensional stability. As a result of OSB's physical configuration, it possesses structural properties that are nearly equivalent to plywood.

At the time of OSB's market entrance in 1977, some observers of the structural wood panel market commented that although waferboard had an advantage over OSB due to its "known appearance, acceptance, and technology," it would have to be improved in order to retain its market share (Montrey and Utterback 1990; Vajda 1980). Very few marketable improvements were made to waferboard, however, and OSB soon began making very rapid inroads into the North American structural wood panel market, eventually displacing waferboard almost entirely.

The relative success of OSB versus waferboard in the structural wood panel market can be attributed to superior product attributes and a similar method of production, including economies of scale (Spelter 1997). As Figure **3** reveals, the average nominal price of OSB has been lower than that of both western and southern pine plywood since 1980 (given equivalent thickness). While the average nominal price of OSB has always been greater than that of waferboard, this difference has been marginal. Furthermore, comparing the price differential between OSB and waferboard fails to account for the value, or utility, that consumers receive from each of the products' attributes; the value that consumers receive from nearly every OSB product attribute generally exceeds that received for waferboard (Seward and Sinclair 1988a). This product attribute value concept will be further explored in the development of the price functions used in the multigeneration diffusion model.

In less than 17 years, OSB has become the market share leader in the United States structural wood panel market, as evidenced in Figure 2. In 1995, OSB represented a market share in the structural wood panel market of 45.4%, as compared to southern pine plywood's 44.0% and western plywood's 10.5%. OSB took one year longer to become the structural wood panel market share leader than it took southern pine plywood to overtake western plywood. Note, however, that southern pine plywood is not nearly as radical in appearance and production from western plywood as OSB is from western and southern pine plywood. Therefore, the ability of southern pine plywood producers to piggy-back on consumer perceptions of western plywood were probably much greater than that of OSB producers.

Alternative Structural Wood Panel Forecast Models

Several models have been developed to forecast the demand for structural wood panels, and, for the most part, these have been technological substitution models and combined factor and cross price elasticity of demand models. Constantino, *et al.* (1989), developed one of the most comprehensive technological substitution models that strives to capture the market share competition between structural plywood and nonveneered wood panels (*i.e.*,

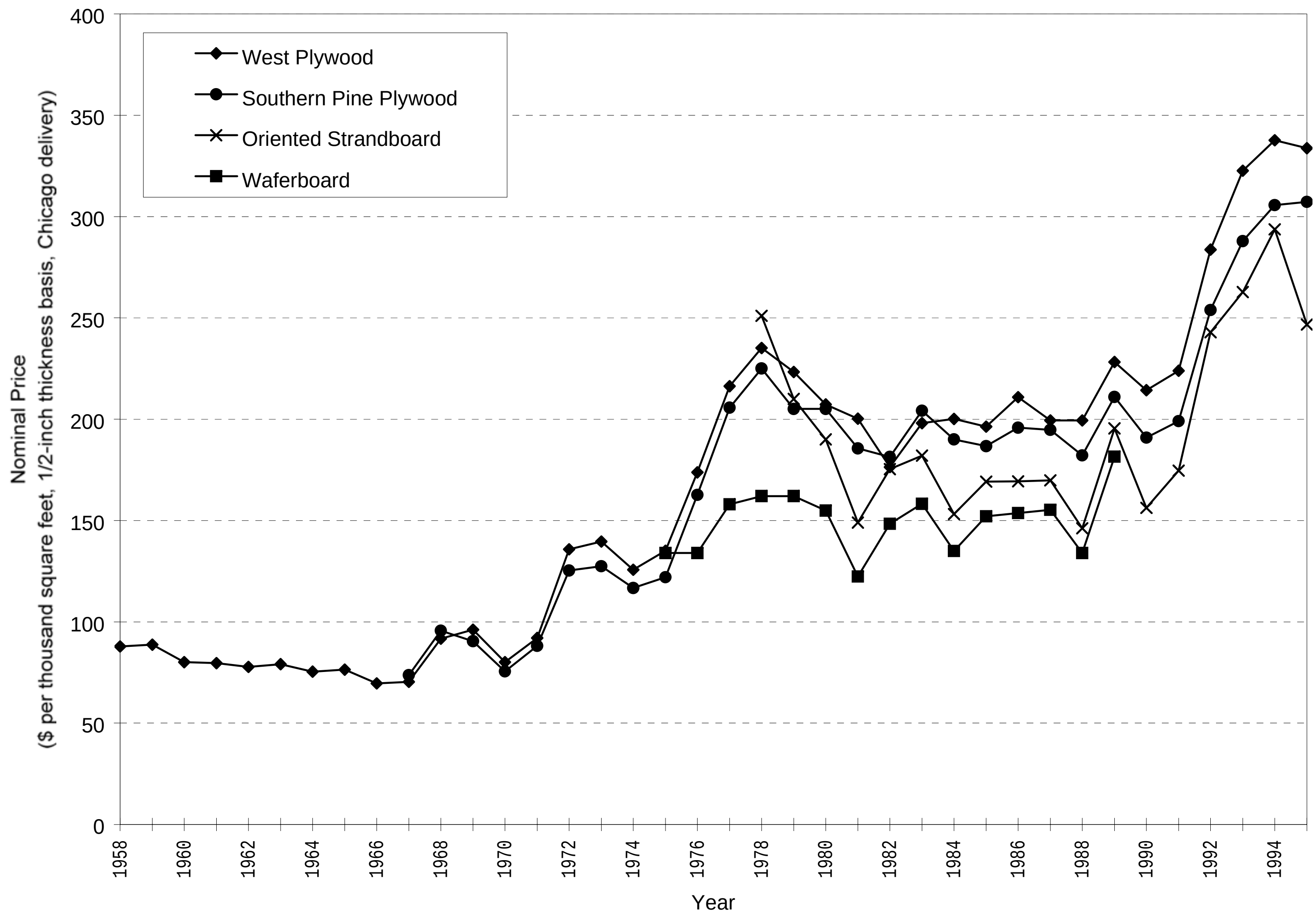

Figure 3. Nominal yearly prices of structural wood panels on a 1/2-inch thickness basis delivered to Chicago, 1958-1995.

Sources: Gall (1981), *Random Lengths Yearbook, Crow's Weekly Market Report of Lumber and Panel Products*, APA—The Engineered Wood Association waferboard and OSB). Four forces that influence the demand for structural plywood and nonveneered wood panels are analyzed in their model. These four forces include:

- *Output Effect* represents factors that directly impact the demand for structural wood panels used in the residential and nonresidential construction industries. These factors include changes in per capita income, housing starts, mortgage rates, and consumer tastes (*e.g.*, larger homes, more window space).
- *Price Effect* represents changes in the relative prices between products. Substitution between various types of products will be reflected in the magnitude of relative price changes and the technology being employed (*i.e.*, cost effect).
- *Technical Change Effect* represents substitution between products that cannot be explained by relative changes in prices or other measurable variables. Examples of this effect would be changes in building codes and the organizational changes within construction firms.
- *Adjustment Effect* represents the diffusion of innovation based on its acceptance in the consuming industry. Based on the diffusion of innovations theory (*cf.* Rogers 1995), this effect simply states that a certain amount of time is required for consumers to learn about a new product and acquire the skills necessary to use the product.

The analysis by Constantino, *et al.*, of the structural wood panel market yields several interesting results. First, their results indicate that plywood and nonveneered structural wood panels behave as complements in response to price changes; that is, if one of the two product types decreases in price as the other product's price remains constant, then more of both products will be potentially consumed. They note that this price effect is very small, however. Nevertheless, their research finding is quite interesting since the various types of structural wood panel products are typically considered to be direct substitutes for one another. Second, their results indicate that a substantial amount of the demand growth for nonveneered structural wood panels is due to unexplained technical changes at the expense of structural plywood. Finally, their results suggest that nonveneered structural wood panels will continue to gain market share at the expense of structural plywood due to a substantial adjustment effect. In other words, the process of diffusion of nonveneered structural wood panels has a significant effect on market shares over time. The output effect was found to influence both structural plywood and nonveneered wood panels equally.

Batten and Johansson (1984), Baudin and Solberg (1989), and Spelter (1984) also assess the demand for various structural wood panel products using technological substitution models. In all three studies, the authors attempt to incorporate the effects of structural changes on the cross price elasticities of demand for the structural wood panels through the use of several basic mathematical diffusion functions (*e.g.*, Gompertz, logistic, reciprocal logarithmic). While the results obtained are insightful and provide considerable forecasting improvement over simple cross price elasticity of demand models, they fail to incorporate more than one generation of technology in the analysis explicitly. As a result, the effects of diffusion, price substitution, and dynamic product sales behavior over time are not effectively accounted for in these studies (Bass 1986, Norton and Bass 1987, 1992).

Some further comment should be made with regard to the price data that has been used to develop cross price elasticity of demand forecast models for structural wood panels in the United States. Nearly all of these cross price elasticity of demand forecast models have utilized price data that was obtained from *Random Lengths* and/or *Crow's* (*e.g.*, Spelter 1984). In 1977, however, there was a substantial change in how the price of structural wood panels was reported in these two trade publications, which brings into question the reliability of the cross price elasticity values that were calculated in these studies. All structural wood panel prices prior to 1977 were quoted as the delivered prices based on the actual freight rates computed from Portland, Oregon, regardless of the actual mode of transportation used to deliver the product or the origin of product shipment. After 1977, however, prices are based on free-on-board mill prices. This change reflects the modification in the structural wood panel industry's pricing structure following a Federal Trade Commission complaint pertaining to the industry's use of basing-point pricing (Federal Trade Commission 1978).

At issue with basing-point pricing is that it fails to account for the true transportation cost of shipping structural wood panels to a particular geographical market. In 1972, for example, a consumer in New Orleans who purchased 1,000 square feet of southern pine plywood from a mill 60 miles away in Holden, Louisiana, was required to pay the 2,500 mile Portland, Oregon, rail shipping rate of $764 dollars, despite the fact that the true cost of delivery by truck was only \$80 (Gilligan 1992). The Holden mill collected a phantom freight of \$684, which is the difference between the fictitious (*i.e.*, the Portland rail rate) and actual (*i.e.*, Holden truck rate) transportation cost.

Comparison of price data for western plywood and southern pine plywood clearly indicates a demarcation in the variability in price difference data for these two products as a result of the FTC-mandated pricing changes in 1977. The average annual price difference between western and southern pine plywood from 1967 through 1976 was \$6.25, with a standard deviation of \$6.09. The average annual price difference between western and southern pine plywood (delivered to Chicago) from 1977 through 1995 was \$15.26, with a standard deviation of \$11.65. These differentials should have a significant impact on the calculation of cross price elasticities of demand for the various structural wood panels. Although we were unable to find any literature examining the effect of the 1977 price reporting changes on cross price elasticity of demand calculations for structural wood panels in the United States, it is expected that those calculations using pre-1977 price data will result in elasticity values that are considerably more inelastic than those calculations using data from 1977 onward. As a result, researchers will obtain considerably different results in the forecasts generated in forest products cross price elasticity of demand models depending on the time window incorporated in the various studies. We attempted to lessen the reliance on cross price elasticity of demand calculations in forecasting structural wood panel demand in our multigeneration diffusion model.

A final note should be made concerning structural wood panel forecast models not based on mathematical algorithms and functions. These models are generally based on simple algebraic formulations that make assumptions concerning industry capacity, capacity utilization rates, and expected future market conditions (*e.g.*, Adair 1997; Spelter, *et al.* 1997). This Delphi-type of forecast model is typically used to predict near-term consumption patterns (*i.e.*, one to three years) that are expected to take place within the market. These models generally do quite well in forecasting near-term consumption patterns, especially when the general economy is growing steadily and price volatility is relatively low. However, these models can provide poor estimates of future market consumption since they do not reliably capture long-term substitution effects between various panel types (*e.g.*, southern plywood versus western plywood).

Development of the Multigeneration Diffusion Model

The fundamental objective of any mathematical diffusion model is to estimate the rate of spread of an innovation among a set of prospective adopters over time (Mahajan, *et al.* 1990). Mathematical diffusion models aim to depict the successive increases in the number of adopters and forecast the continued development of the diffusion process. In the product rather than process innovation context, mathematical diffusion models focus on the development of a life cycle curve and serve the purpose of predicting the first-purchase sales of products. Diffusion models, therefore, are by definition concerned with representing the growth of a product category over time.

Bass (1969) was first to introduce the mixed-influence innovation diffusion model, which has become one of the most frequently-referrenced and -modified models in the marketing arena. Unlike basic mathematical diffusion functions, the Bass model incorporates an underlying behavioral component that is consistent with the general theory of adoption and diffusion of innovations developed in the marketing and sociology literature (*e.g.*, Mahajan, *et al.* 1990; Rogers 1995). The Bass model assumes that both innovators and imitators adopt a new product. Innovators are not considered to be influenced in their purchase timing by the number of individuals who have already adopted the product. The innovators, however, can be influenced to adopt the product by factors outside their immediate environment and social system. Such external influences include promotional messages, product reviews in the media, and academic articles, among others. The number of innovators in the market diminishes monotonically with time as the diffusion process continues. Imitators are influenced to adopt when they see others in their immediate environment adopting the product. Imitators are said to be internally influenced to adopt, and their numbers in the market increase relative to the number of innovators as the diffusion process continues over time.

The model presented here closely follows the notation and specification of the multigeneration diffusion models developed by Mahajan and Muller (1996), Norton and Bass (1987, 1992), and Speece and MacLachlan (1992, 1995). First, the cumulative percent of the market that has adopted the new product is defined as $F(t)$.

Differentiating $F(t)$ with respect to time yields the percentage of the potential market that adopt at time t. This percentage is proportional to both the external influence on individuals who have yet to adopt the new product and the internal influence, which is dependent on the interaction between the those individuals who have adopted the new product and those who have not. Mathematically, this function is written as:

$$\frac{dF(t)}{dt} = \left[p + qF(t)\right]\left[1 - F(t)\right]. \tag{1}$$

Variables p and q are constants of proportionality. When the right-hand side of this equation is expanded, the external influence portion of the model is represented by $p[1 - F(t)]$. The constant p, interpreted as the coefficient of innovation, is generally very small since the proportion of innovators within a population is quite small. Again, when the right hand side of this equation is expanded, the internal influence of the model is represented by $qF(t)[1 - F(t)]$. This internal influence reveals the interaction between the adopters of the new product, $[F(t)]$, and those in the potential population who have not adopted the new product, $[1 - F(t)]$. The constant q, interpreted as the coefficient of imitation, should be greater than the constant p since the order of magnitude between innovators and imitators in a population is usually substantial. Given an initial condition $F(t_0 = 0) = 0$, the differential equation has a closed form solution:

$$F(t) = \frac{\left(1 - e^{-(p+q)^t}\right)}{\left(1 + \frac{q}{p} e^{-(p+q)^t}\right)}. \tag{2}$$

Utilizing the same notation as Norton and Bass (1987), the mathematical forms of sales of successive generations of products are written as:

$$\begin{aligned}
S_1(t) &= m_1 F(t)\left[1 - F(t - \tau_2)\right], \\
S_2(t) &= \left[m_2 + m_1 F(t)\right] F(t - \tau_2)\left[1 - F(t - \tau_3)\right], \\
S_3(t) &= \left[m_3 + F(t - \tau_2)\left[m_2 + m_1 F(t)\right]\right] F(t - \tau_3)\left[1 - F(t - \tau_4)\right], \text{ and} \\
S_4(t) &= \left[m_4 + F(t - \tau_3)\left[m_3 + F(t - \tau_2)\left[m_2 + m_1 F(t)\right]\right]\right] F(t - \tau_4).
\end{aligned} \tag{3}$$

The values of $S_i(t)$ represent the cumulative sales of each generation i, while the time of introduction of successive generations of products in the product class is represented by τ. The model presented here assumes that $\tau_1 = 0$ for the first generation product, western plywood. All m parameters represent the incremental market potential in any given time period t of generation i over the potential of the $(i - 1)$ generation. Using the United States structural panel market as an example, m_1 is interpreted as the maximum one-period sales potential of the first generation product, western plywood. The market potential in any period for the next generation product, southern pine plywood, will be the sales of the first generation, $m_1F(t)$, and some increment m_2. This implies that the market potential ceilings are always rising with the introduction of successive generations of structural wood panel products. Increased market potential ceilings can be attributed to the new uses that successive generation products make possible due to the technological advances that they embody relative to older generation products. Given this ever-increasing expansion of the market potential ceiling, the total market demand for the product class that the products represent (*e.g.*, structural wood panels) is anticipated to expand.

The cumulative distribution function from the Bass (1969) mixed-influence model is denoted by $F(t - \tau_i)$, which represents the cumulative percentage of potential adopters of generation i who have adopted by time t. Potential sales of the first generation can therefore be denoted as $m_1F(t)$, but the actual sales $S_1(t)$ have been reduced by some proportion of buyers who decided to purchase the second generation product instead. $S_2(t)$ and $S_3(t)$ are modeled in a similar manner as $S_1(t)$. $S_4(t)$ is not reduced in our study since there is no fifth generation product currently available on the structural wood panel market.

The multigeneration diffusion model makes the assumption that the coefficients of innovation and imitation, p and q, do not vary as successive generations of products arrive on the market. These coefficients remain constant in the cumulative distribution function across all product generations being modeled. The model deals with four generations of structural wood panels, but only one market can choose among the panel types available. The assumption is that the inherent characteristics of this one market would not change with regard to innovativeness, imitation, or price sensitivity given that they are all part of the same decision process. The assumption of constant p and q has been tested in the modeling efforts reported in Norton and Bass (1987). In their article, they state (p.1076) that "…the data and the model are in such a high degree of correspondence that we may assert that the data do not reject the notion that the assumption of constant p and q for all generations is reasonable." More recent research reported by Islam and Meade (1997) and Norton and Bass (1992), however, has found that in a limited number of cases the assumption of constant p and q across product generations may not hold.

Similarly to Speece and MacLachlan (1992, 1995), we incorporate pricing, P, into our model by multiplying a price function by the cumulative distribution function $F_i(t)$ for each product generation, G_i. This results in a cumulative distribution function that is represented by the function:

$$F_i\left(t-\tau_i\right)=\frac{\left(1-e^{-(p+q)(t-\tau_i)}\right)}{\left(1+\frac{q}{p}e^{-(p+1)(t-\tau_i)}\right)}G_i\left(P\right). \tag{4}$$

Also similarly to Speece and MacLachlan (1992, 1995), we incorporate two alternative multiplicative pricing functional forms for each generation of product, G_i. These two forms of $G_i(P)$ are:

$$G_i\left(P\right)=\left(\frac{P_i}{P}\right)^{-\eta}\text{, and} \tag{5}$$

$$G_i\left(P\right)=\exp\left[-\eta\left(\frac{P_i}{P}\right)\right]. \tag{6}$$

The variable P_i represents the price of the product in generation i. The market price is denoted as P, and it is interpreted as the production (R_i) weighted average of prices (P_i) of the product from all four generations, or:

$$P=\frac{P_1R_1+P_2R_2+P_3R_3+P_4R_4}{R_1+R_2+R_3+R_4}. \tag{7}$$

The use of production weighted data rather than sales weighted data was chosen since considerable variability exists in the apparent consumption data (*i.e.*, total production plus imports less exports) reported across various sources, while relatively minor variability exists in the total production data. Furthermore, the use of structural wood panel production data as a proxy for consumption is not unique to this study (*e.g.*, Anderson 1977; Bessom 1965). As such, production data in our model serves as a proxy to sales (apparent consumption) data.

The parameter η in the price function is a measure of price sensitivity. This parameter remains constant over successive generations of products since it is an inherent characteristic of the consuming market and not of an individual product generation.

New generations of products are generally thought to be improvements over old-generation products. Improvements include increased overall product quality, greater product consistency, enhanced product attributes, among many others. Consequently, the utility that a consumer derives from a newer generation product should theoretically be greater than the utility derived from any older generation products. The multigeneration diffusion model accounts for this factor by allowing increasing increments on the ceiling for potential sales across generations. Price alone is not likely to be the only consideration influencing a consumer's decision of which generation of product to purchase. Instead, consumers are likely to use a ratio of utility to price, which provides them with a measure of value (*e.g.*, Aaker and Shansby 1982; Burns 1986; Martilla and James 1977; Nagle and Holden 1995). Following Stern, *et al.* (1975) and Speece and MacLachlan (1992, 1995), we incorporate a price function in our model that adjusts for the utility the consumer is expected to gain from purchase of a particular generation of structural wood panel product. We utilize published survey results (Seward and Sinclair 1988a, 1988b) that report the attributes that retailers and manufacturers of structural wood panel products use in evaluating different panel types (*i.e.*, plywood, waferboard, OSB) to develop a set of importance weights for these attributes. We use two forms of utility-adjusted price functions; one functional form uses a utility adjustment in which the attribute importance weighting scale is linear, while the other functional form uses a logarithmic attribute importance weighting scale. The linear attribute importance weighting scale (*e.g.*, Likert-like importance scale ranging from 1=not important at all to 7=extremely important) is the traditional scale form used in studies of perception. However, research has shown that a logarithmic weighting system may be subconsciously utilized in the consumer decision-making process (Stern, *et al.* 1975). Appendix I contains a detailed overview of the utility-adjusted weighting schemes that are used in the development of the price functions in the multigeneration diffusion model.

Data

The data in this study has been compiled from Spelter (1994), Sudbury (1981), and various issues of *Random Lengths Yearbook*. Additional data was obtained from the databases of the Structural Board Association and the APA—The Engineered Wood Product Association. Discrepancies in the data were resolved by averaging across the data sources. This data was generally reported on a square-foot basis at a given board thickness. A consistent board thickness measure was not utilized across the data sources, however. Therefore, all production data has been standardized to a 1/2-inch thickness prior to estimating the United States models and to a 3/8-inch thickness for the North American models.

Price data for our analysis has also been collected from a variety of sources. The majority of the price data is compiled from various issues of *Random Lengths Yearbook* and *Crow's Weekly Market Report of Lumber and Panel Products*. Additional price data was obtained from the APA — The Engineered Wood Product Association and Gall (1981). In our analysis, western plywood price data is based on the price of 4/5-ply 1/2-inch interior Douglas-fir plywood. Southern pine plywood price is based on the price of 4/5-ply 1/2-inch panels. Finally, OSB and waferboard price data is based on 1/2-inch panels.

Data Fitting and Model Forecasts

A fifth equation was added to the other four $S_i(t)$ equations in the estimation of structural wood panel production in the United States. This equation represents the total production of all four types of structural wood panels, namely:

$$S_5(t) = S_1(t) + S_2(t) + S_3(t) + S_4(t)\,. \qquad (8)$$

$S_5(t)$ is a linear combination of the other four $S_i(t)$ equations (*i.e.*, an identity function). The inclusion of $S_5(t)$ allows for an estimation of total structural wood panel production.

Data from the years 1964 to 1993 was used to fit the equations; the years of 1994 and 1995 were held out from the estimation in order to check the accuracy of the short-term forecasts of the model. The nonlinear three-stage least squares regression procedure SYSNLIN in SAS® (1988) was used to estimate the parameters in this system of five equations. The results from the estimation of western plywood, southern pine plywood, waferboard, and oriented strandboard yielded rather poor results. Further investigation and model manipulation indicated that the relative lack of data for waferboard was having a profound influence on the estimation results. Therefore, the models were estimated again by omitting waferboard data. In other words, a system of four equations was fit rather than five. This new system of equations can be written as:

$$\begin{aligned}
S_1(t) &= m_1 F(t)\left[1 - F(t - \tau_2)\right], \\
S_2(t) &= \left[m_2 + m_1 F(t)\right] F(t - \tau_2)\left[1 - F(t - \tau_3)\right], \\
S_3(t) &= \left[m_3 + \left[m_2 + m_1 F(t)\right] F(t - \tau_2)\right] F(t - \tau_3), \\
S_4(t) &= S_1(t) + S_2(t) + S_3(t).
\end{aligned} \tag{9}$$

In this system of four equations, $S_1(t)$ represents time period production of western plywood, $S_2(t)$ represents time period production of southern pine plywood, $S_3(t)$ represents time period production of oriented strandboard, and $S_4(t)$ is the identity function representing the total structural wood panel time period production less waferboard. Again, the SYSNLIN procedure in SAS® and 1965 to 1993 data were used to fit the parameters in this system of four equations. The multigeneration model parameter estimation results for the basic no price model (referred to as Model 1), as well as all the remaining models containing a price function, are displayed in Table 1. All parameters in each of the seven models, with the exception of η in all models containing a price function, were statistically significant with p-values ≤ 0.0163. The signs on these parameters were also in the expected direction.

In all seven estimated models, p was consistently less than q, which was also expected. The magnitude of p was less than the 0.03 average for p reported by Sultan, *et al.* (1990), in their meta-analysis of 213 diffusion applications utilizing either a Bass or modified Bass mixed-influence diffusion model (*cf.* Bass 1969) across a variety of product categories. The low estimated values of p in this study suggest that slightly less innovativeness exists among consumers in the structural wood panel industry relative to other industries. The estimated values of q in all seven models were also substantially less than the average value of q reported in the Sultan, *et al.*, meta-analysis, which was 0.38. These small values of q imply that consumers are less inclined to imitate in the structural wood panel market. The magnitudes of p and q in our study, however, are consistent with the average magnitudes of p and q reported by Sultan, *et al.*, for Bass mixed-influence models using nonlinear estimation procedures.

With the exception of the no price model (Model 1), the values of m_i are positive and increasing. Increasing values of m_i indicate that each successive generation can fulfill and extend the market “expectations” and “requirements” of the previous generation, and that a substitution effect exists from earlier to later generations of structural wood panel products. Interestingly, the m_i’s do not increase monotonically; the rather marginal increase between m_2 and m_3 indicates that oriented strandboard did little to expand the market ceiling for structural wood panel products. The price sensitivity factor, η, was not significant in any of the models containing a price function parameter (Models 2 through 7). If the products were considered to be direct substitutes for one another, then we would expect the price sensitivity factor to be significant with a negative coefficient, indicating that product demand decreases with higher prices.

The (pseudo) R^2 values for the estimated model fits, displayed in Table 2, are extremely high for southern pine plywood, oriented strandboard, and the total market, and somewhat low for western plywood. Visual inspection of the R^2 values reveal that the model estimated with no price (Model 1) yielded the best overall fit. The differences between estimated models containing a price function were marginal; however, the linear utility-adjusted model

Table 1. Summary of United States multigeneration model parameter estimation results fit to 1964 to 1993 data.

Parameter	Parameter Estimate[a]	Approximate Standard Error	*T* ratio	Approximate Probability >|*T*|
Model 1 - no price function				
p	0.017670	0.001122	15.75	0.0001
q	0.046311	0.009216	5.02	0.0001
$m1$	9336.91	248.1	37.63	0.0001
$m2$	14488.18	1219.3	11.88	0.0001
$m3$	9660.34	1261.9	7.66	0.0001
Model 2 – unadjusted price function $G_i(P) = (P_i/P)^{\eta}$				
p	0.016042	0.000758	21.16	0.0001
q	0.033858	0.008396	4.03	0.0012
$m1$	8898.51	364.4	24.42	0.0001
$m2$	17757.76	1567.4	11.33	0.0001
$m3$	18992.04	1701.3	11.16	0.0001
η	-0.094593	0.16218	-0.58	0.5690
Model 3 – unadjusted price function $G_i(P) = \exp[\eta(P_i/P)]$				
p	0.017175	0.001580	10.87	0.0001
q	0.037489	0.013740	2.73	0.0163
$m1$	9602.09	1427.5	6.73	0.0001
$m2$	18475.31	2355.6	7.84	0.0001
$m3$	19901.22	2480.8	8.02	0.0001
η	-0.103316	0.19352	-0.53	0.6018
Model 4 - linear utility-adjusted price function $G_i(P) = (P_i/P)^{\eta}$				
p	0.016068	0.001446	11.11	0.0001
q	0.031874	0.007548	4.22	0.0009
$m1$	8889.40	368.4	24.13	0.0001
$m2$	18144.89	2202.8	8.24	0.0001
$m3$	20274.09	5409.9	3.75	0.0022
η	0.036849	0.18428	0.20	0.8444
Model 5 - linear utility-adjusted price function $G_i(P) = \exp[\eta(P_i/P)]$				
p	0.016077	0.001565	10.27	0.0001
q	0.031711	0.007439	4.26	0.0008
$m1$	8528.90	2075.7	4.11	0.0011
$m2$	17438.40	2517.9	6.93	0.0001
$m3$	19341.40	1643.1	11.77	0.0001
η	0.041313	0.23260	0.18	0.8616
Model 6 - logarithmic utility-adjusted price function $G_i(P) = (P_i/P)^{\eta}$				
p	0.016453	0.000654	25.16	0.0001
q	0.033127	0.008064	4.11	0.0011
$m1$	8931.43	370.4	24.11	0.0001
$m2$	17274.09	1586.4	10.89	0.0001
$m3$	17757.05	3333.8	5.33	0.0001
η	-0.097495	0.23782	-0.41	0.6880
Model 7 - logarithmic utility-adjusted price function $G_i(P) = \exp[\eta(P_i/P)]$				
p	0.016432	0.000665	24.70	0.0001
q	0.033069	0.008031	4.12	0.0010
$m1$	9728.60	2693.2	3.61	0.0028
$m2$	18873.62	4588.6	4.11	0.0011
$m3$	19732.01	2846.7	6.93	0.0001
η	-0.085944	0.26550	-0.32	0.7509

[a] m_1, m_2, and m_3 are in millions of square feet (1/2-inch thickness basis).

Table 2. Summary of United States multigeneration model R^2 results fit to 1964 to 1993 data.

Model[a]	Western Plywood R^2	Southern Pine Plywood R^2	Oriented Strandboard R^2	Total Panel Market R^2
Model 1 - no price function	0.5135	0.9892	0.8135	0.9205
Model 2 - unadjusted price function $G_i(P) = (P_i/P)^{\eta}$	0.3087	0.9684	0.9787	0.8579
Model 3 - unadjusted price function $G_i(P) = \exp[\eta(P_i/P)]$	0.3070	0.9680	0.9791	0.8586
Model 4 - linear utility-adjusted price function $G_i(P) = (P_i/P)^{\eta}$	0.3144	0.9689	0.9782	0.8586
Model 5 - linear utility-adjusted price function $G_i(P) = \exp[\eta(P_i/P)]$	0.3140	0.9690	0.9783	0.8584
Model 6 - logarithmic utility-adjusted price function $G_i(P) = (P_i/P)^{\eta}$	0.3089	0.9687	0.9783	0.8576
Model 7 - logarithmic utility-adjusted price function $G_i(P) = \exp[\eta(P_i/P)]$	0.3095	0.9686	0.9781	0.8574

[a] R^2 values in three stage least squares nonlinear regression estimation are pseudo values and biased in this study since the model will correctly predict zero values for all periods prior to product introduction.

Table 3. Model forecasting results for United States structural wood panel 1994 and 1995 data.

	Millions of Square Feet (1/2-inch thickness basis)					
	Western Plywood		Southern Pine Plywood		Oriented Strandboard	
	1994	1995	1994	1995	1994	1995
Actual Data	2962.5	2325.0	9757.5	9750.0	8284.5	10060.5
Model 1 - no price function	3550.6	3390.7	9804.7	9752.9	8017.3	8700.1
Model 2 - unadjusted price function	4051.1	3932.3	9948.8	9851.9	9305.2	10087.7
Model 3 - unadjusted price function	4114.5	4001.7	9933.9	9821.2	9292.3	10059.7
Model 4 - linear utility-adjusted price function	4108.1	3989.3	9896.0	9967.5	9316.2	10027.7
Model 5 - linear utility-adjusted price function	4111.0	3991.9	9899.9	9968.5	9315.3	10036.9
Model 6 - logarithmic utility-adjusted price function	4068.2	3912.8	9927.9	9892.0	9331.6	10087.1
Model 7 - logarithmic utility-adjusted price function	4070.8	3918.1	9923.2	9899.3	9338.9	10072.0

	Sum of Squared Error (1994-1995)		
	Western Plywood	Southern Pine Plywood	Oriented Strandboard
Model 1 - no price function	1481693	2234	1922020
Model 2 - unadjusted price function	3768343	46986	1042540
Model 3 - unadjusted price function	4138374	36180	1015748
Model 4 - linear utility-adjusted price function	4082312	66509	1065441
Model 5 - linear utility-adjusted price function	4097726	68046	1063210
Model 6 - logarithmic utility-adjusted price function	3743703	49203	1097209
Model 7 - logarithmic utility-adjusted price function	3766266	49757	1111946

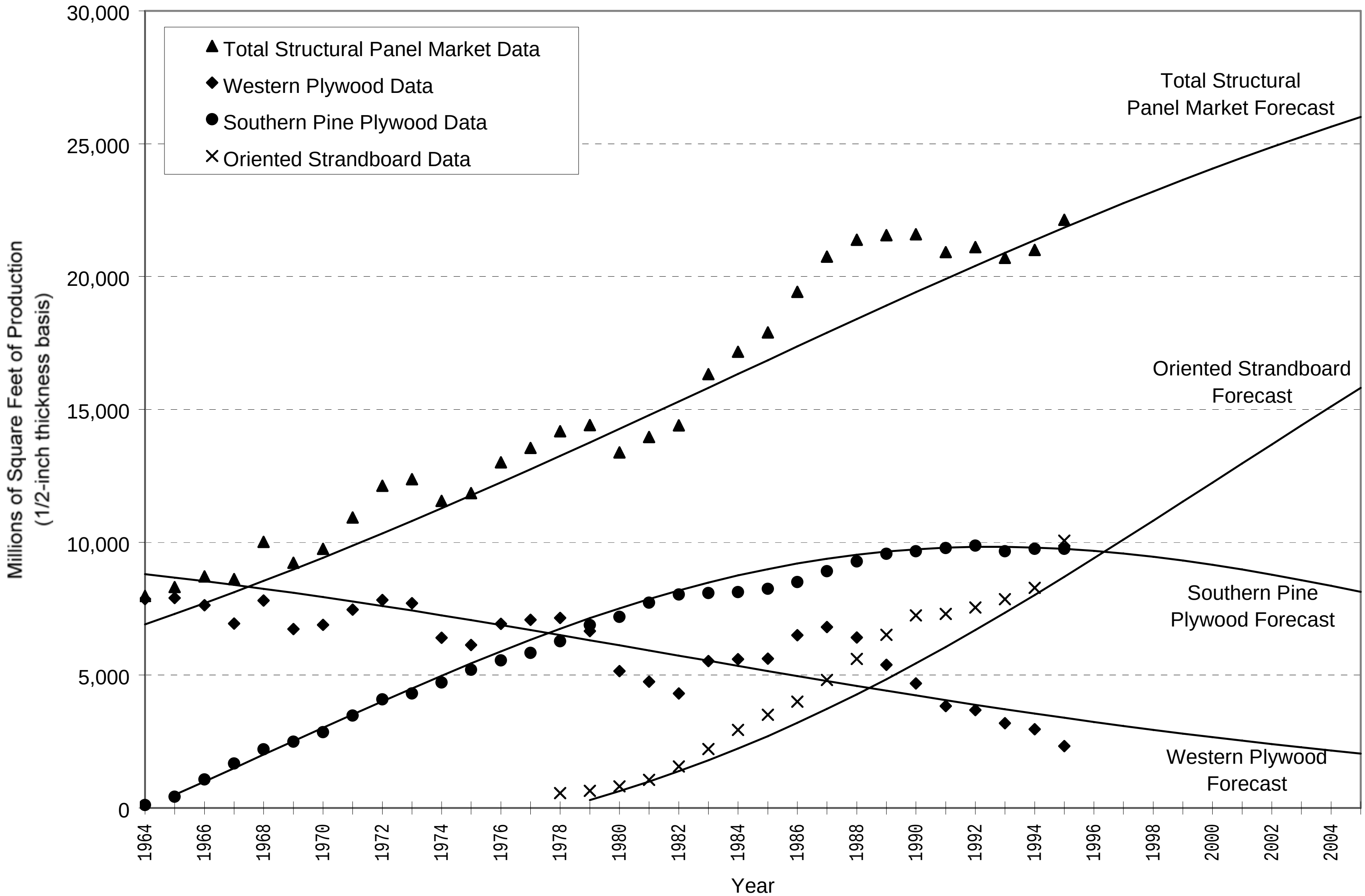

Figure 4. Multigeneration diffusion model fit to United States structural wood panel data, 1964-2005.

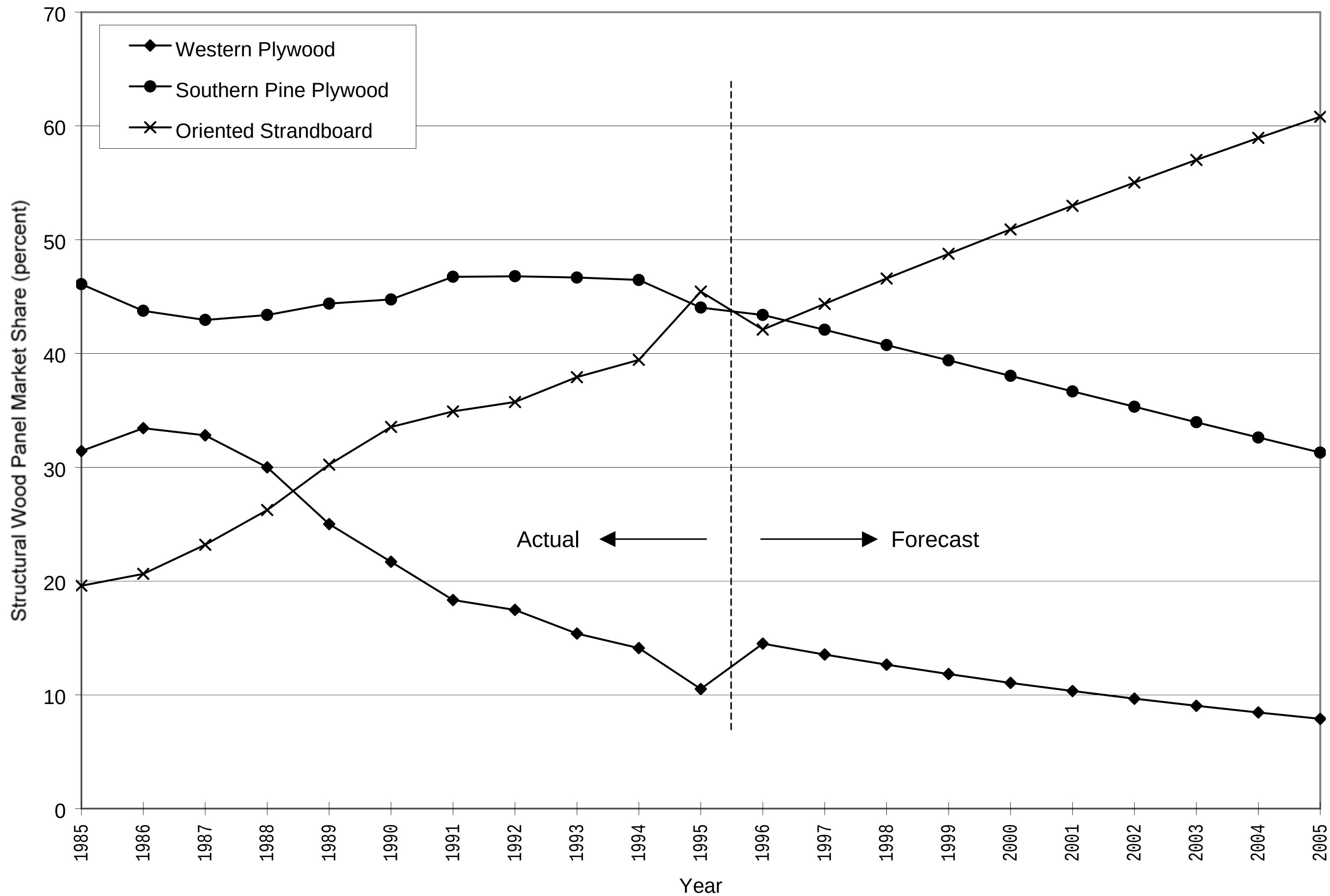

Figure 5. Actual and forecast market shares of United States structural wood panels by panel type, 1985-2005.

(Models 4 and 5) did fit western plywood slightly better than the unadjusted price models (Models 2 and 3) and the logarithmic utility-adjusted models (Models 6 and 7).

An investigation of the short-term forecasting abilities of the models was conducted by examining the model fits to 1994 and 1995 data. The actual and forecast production of the three structural wood panel products and their associated sum of squared error calculations for 1994 to 1995 data are shown in Table 3. Overall, none of the models incorporating a price function (Models 2 through 7) does as well as the model containing no price function (Model 1), which is consistent with the results of Speece and MacLachlan (1992, 1995). However, the no price function model does a rather poor job at forecasting the production of oriented strandboard relative to any of the models incorporating a price function. Examination of the various price function models indicates that there is relatively little difference in their forecasting accuracy. In Figure 4, we provide a graphical representation of the structural wood panel production forecast using the model containing no price function (Model 1) from 1964 through 2005. Figure 5 displays the actual and forecast market shares computed using the no price model (Model 1) from 1985 through 2005.

Discussion

The insignificant nature of the price sensitivity parameter, η, suggests that the demand for structural wood panel products may not be affected by incremental price increases as much as one would expect despite the commodity nature of the structural wood panel market. In fact, the model results indicate that structural wood panel products are complementary to one another, which is consistent with the findings of Constantino, *et al.* (1989). Since the model estimated in this study examines the United States market in aggregate, the lack of significance of η does not necessarily imply that complementarity exists between various types of structural wood panel in specific end-use markets (*e.g.*, wall sheathing, roof sheathing, underlayment). Further research will have to be conducted to determine if complementarity indeed exists in some specific end-use markets. For example, residential construction builders may consistently use plywood for roof sheathing and oriented strandboard for wall sheathing, disregarding substitution of the products based on relative price changes.

The values of the incremental market potential parameters, m_i, also provide evidence that market share growth can be attributed more to diffusion effects (*i.e.*, technological progress) than to price substitution effects. If product substitution is the driving force behind market share growth in the structural wood panel market, then the values of m_i should increase sequentially with the addition of each new product type. The magnitude of change between the values of m_1 and m_2 in the models containing a price function indicate that price substitutability does exist between western plywood and southern pine plywood. The magnitude of change between m_2 and m_3, however, suggests that diffusion processes explain the overall market share growth of oriented strandboard.

Similar to the results reported by other researchers using the Bass mixed-influence diffusion model, the ratios of p to q reported here suggest that the diffusion process for structural wood panel products is affected mostly by such factors as word-of-mouth effects, advertising, and promotions. Innate innovativeness among the consuming market does not appear to contribute substantially to the diffusion process for structural wood panel products.

While running various model simulations in this study, it was found that parameter stability increased substantially when a single generation of structural wood panel product reached a turning point in the market, which is consistent with the multigeneration diffusion modeling results reported by Norton and Bass (1987) for integrated circuits. These results provide support for Norton and Bass' conclusion (p.1085) that multigeneration diffusion models are "well suited to deal with industries undergoing rapid change." For instance, multigeneration diffusion models can be used to provide strategic information concerning the phasing out of products that are experiencing continual declines in their market share to other product generations within the same product category. From a corporate perspective, the determination of the appropriate time to exit a particular product market (*e.g.*, western plywood) has significant implications in the allocation or reallocation of scarce firm resources.

In the near-term, the multigeneration diffusion models developed here suggest that southern pine plywood has reached its peak production level over the past five years, with production forecast to decline slowly but steadily over the next decade. Western plywood is forecast to continue its downward production and market share trend. The short-term forecast also indicates that oriented strandboard is well entrenched in a growth phase.

The long-term results of the multigeneration diffusion models developed in this study indicate that the total market for structural wood panel products is expected to grow monotonically to the year 2010, when it is then expected to begin growing at a decreasing rate. The aggregate structural wood panel market is forecast to begin stabilizing around year 2030 at approximately 33,000 million square feet of production per year (1/2-inch thickness basis). Barring the inclusion of a new generation of structural wood panel product and/or new end uses that could considerably expand the market, the long-term forecast indicates that oriented strandboard will continue increasing market share at the expense of southern pine and western plywood.

Conclusion

The model used in this study provides an understanding of the diffusion process and rate of technological change within the structural wood panel industry. The model incorporates the proven reliability of the Bass mixed-influence diffusion model with the concept that an older generation of structural wood panel product has direct impact on the diffusion pathway of new products. Furthermore, the model can be used to forecast product category growth (or decline) and relative market shares of the products.

Similarly to Speece and MacLachlan (1992, 1995), we extend Norton and Bass' (1987) multigeneration diffusion modeling efforts by incorporating a price function into our model. We further extend the multigeneration diffusion modeling work of Speece and MacLachlan by examining the impact of using a logarithmic utility adjustment to prices. Given our modeling efforts for structural wood panel products, we conclude that a logarithmic utility adjustment to prices does not improve model fit over the use of traditional linear utility adjustment to prices or unadjusted prices. Furthermore, the use of linear utility adjustments to prices did not improve model fit over the use of unadjusted prices. Note that utility adjustment to prices by Speece and MacLachlan improved their model fit for various types of fluid milk packages, however.

Similar to all other classes of forecasting models, the model presented here omits several important variables. Managerially, however, the model provides a remarkably reliable and accurate generalization of the growth and decline of specific structural wood panel products over time. Moreover, our results indicate that the collection of price series data is not required in order to forecast a multigeneration diffusion model for structural wood panels reliably. Nonetheless, the incorporation of a price function into an estimated model can be used in forecasting the influence that various pricing situations (*e.g.*, adjustment of margins) will have on the relative sales and market shares of different generations of the product.

A clearly noticeable limitation of this study is the omission of waferboard data in the estimation of the model. As a result, waferboard's influence on the diffusion processes for western plywood, southern pine plywood, and oriented strandboard is unknown. Utilizing waferboard data in fitting the model, however, typically resulted in estimation difficulties within the realms of matrix singularity, insignificant parameters across all seven of the estimated models (especially for parameters p and q), and negative R^2 values. Negative R^2 values are possible in nonlinear three-stage least squares estimation in cases where there are low degrees of freedom and/or poor model fit. These unreliable results are consistent with nonlinear models estimated by other researchers using limited series of data (*e.g.*, Draper and Smith 1981; Heeler and Hustad 1980; Srinivasan and Mason 1986).

The use of United States production data rather than apparent consumption data in model estimation is another limitation of this study. Our model is developed under the rationale that production is equivalent to apparent United States consumption. Obviously, this rationale is flawed since we make no correction for imports and exports of structural wood panels. Given the wide variability reported across sources in the apparent consumption data for structural wood panel products, however, we feel that the production data has more validity as a data source in model estimation than does apparent consumption data.

Finally, bias is likely to exist in the utility adjustment price functions due to the nature of the information extracted from Seward and Sinclair's (1988a, 1988b) structural wood panel product attribute articles. The utility adjustments made to prices in this study were identical for southern pine and western plywood since no distinction between these two product types was made in the Seward and Sinclair studies. It was also assumed that the utility adjustments to price based on 1988 product attributes have been stable over the past nine years. This assumption clearly lends bias to the utility adjustment of prices since manufacturers of structural wood panel have improved various product attributes over this time span. The relative impact of product attribute improvements on utility-adjusted prices has not been captured in our model.

Note that the models in this study can also be estimated utilizing other types of data (Table 4). Our models were estimated using annual production figures and average annual prices. Published statistics are available to estimate the model using monthly or quarterly time series data. There is substantial variation in the data across the various sources of this information, however, while there is considerable consistency across the annual data reported by these same sources. Despite this fact, the use of monthly or quarterly data in the estimation of the multigeneration diffusion model may result in model output for waferboard, which was not possible here when using a limited series of annual data.

Table 4. Examples of potential variables for use with the multigeneration diffusion model for assessing adoption, diffusion, and substitution of structural wood panel products.

Alternative Parameters	Alternative Industries	Alternative End-use Markets
Margins rather than prices	Single-family construction	Roof sheathing
Utility-adjusted prices	Multifamily construction	Wall sheathing
Housing starts	Nonresidential construction	Underlayment
Supply constraint variables	Mobile home manufacturing	I-joist webs
	Repair and remodel	
	Industrial (*e.g.*, packaging, pallet)	
	Export market	

The examination of diffusion and substitution of various structural wood panel products in specific end-use markets with a multigeneration diffusion model also appears feasible. For example, detailed information is available with regard to the amount of various types of structural wood panel products used as wall sheathing, roof sheathing, and other end uses on a quarterly basis. Rather than evaluating the structural wood panel market in its entirety, managers may gain more strategic information of how the various structural wood panels diffuse in particular end-use markets by developing several specific end-use multigeneration diffusion models. Consequently, managers could more effectively and efficiently develop their firm's strategic marketing and corporate plans to reflect the forecast changes in the specific end-use markets. An even more refined multigeneration diffusion model could be developed for a specific firm's structural wood panel product mix, assuming that the firm produces more than one type of structural wood panel product (*e.g.*, southern pine plywood and oriented strandboard). Comparisons then could be made between the forecasts for the firm's product mix and the structural wood panel industry.

Several extensions of the basic Bass mixed-influence diffusion model have been made that could also be applied to the multigeneration diffusion model presented in this study. Extending the model to include parameters representing known causal factors affecting structural wood panel demand (*e.g.*, housing starts) and raw material supply may allow for improved forecasting ability, thereby broadening the applicability and use of multigeneration diffusion models as forecasting tools in the forest products industry.

Finally, note that the engineered wood products market has become increasingly dynamic. New engineered products are being developed and commercialized at a greater rate than ever before. Our forecasts have been based on adoption, diffusion, and substitution between structural wood panel products. Other engineered wood products compete directly for the raw material used in producing structural wood panels. For instance, laminated veneer lumber has been experiencing substantial growth in the 1990s, and a slow-down in its growth is not expected in the foreseeable future. Laminated veneer lumber market growth has led to increased competition for high grade softwood veneers over the past several years (Baldwin 1997; Keil 1997; Spelter 1997). The effect of veneer competition between laminated veneer lumber manufacturers and structural plywood manufacturers has not been captured in our models. Given the strong market growth of laminated veneer lumber, however, it is probable that structural plywood market share may be substantially less than our models have forecast in the future.

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APPENDIX I

Calculation of Linear and Logarithmic Utility-adjusted Price Functions

Two separate utility-adjusted price functions are developed in this study: one functional form uses a utility adjustment in which the attribute importance weighting scale is logarithmic, while the other functional form uses a linear attribute importance weighting scale. These functions are developed utilizing published survey results of structural wood panel manufacturers and retailers examining product attribute importance and performance characteristics of plywood, waferboard, and oriented strandboard (Seward and Sinclair 1988a, 1988b). The two utility-adjusted price functions are constructed similarly, and involve a three-step procedure (*cf.* Stern, *et al.* 1975).

Step 1 — Identification and rating of relevant product attributes and performance characteristics of each competing product. This step involves the compilation of product attributes and performance characteristics that can affect the consumption of structural wood panels. Based on the list that is compiled, each product is then qualitatively rated by "experts" to determine the degree to which it possesses each product attribute and performance characteristic. Due to our use of secondary data, which has already identified relevant structural wood panel product attributes and performance characteristics, this step is modified in our study. We utilize data reported in Table 6 of Seward and Sinclair (1988a) to construct a product rating by product attribute matrix, as shown here in Table 5. Note that plywood is not separated by western and southern pine categories. In this study, it is assumed that product attributes of western plywood are identical to southern pine plywood.

Table 5. Structural wood panel product attribute ratings.

	Structural Wood Panel Ratings[b]		
Product Attributes[a]	Plywood[c]	Waferboard	Oriented Strandboard
Low price	1	3	2
Strength and stiffness	2	1	3
Dimensional stability	2	1	3
Durability	2	1	3
Panel weight	3	2	1
Surface uniformity	2	1	3
Impact resistance	3	1	2

[a] Attribute rating data adapted from Seward and Sinclair (1988a).

[b] Ratings are based on how each product rates on each product attribute relative to competing products. The following rating system was used: 1 = "product possesses attribute to the least degree", 2 = "product possesses attribute to a considerable degree", and 3 = "product possesses attribute to the greatest degree".

[c] Given the nature of the secondary data used in generating the linear and logarithmic utility price functions, there is no distinction made between western plywood and southern pine plywood.

Step 2 — Develop measures that identify the relative degree of importance that users of the products place on each identified attribute. This step requires that users of the products qualitatively rate each of the attributes in step one into a numerical value. For this step, we utilize data presented in Table 7 of Seward and Sinclair (1988b); however, some changes were made to this Table's data. First, we reversed the linear scale so that the anchors of the scale represent 1 = "not important at all" to 5 = "extremely important". Second, in order to develop a logarithmic scale, we recoded the Table's values of 1, 2, 3, 4, and 5 to 0, 2, 4, 8, and 16, respectively. Utilizing the percentage of responses reported in each product attribute by product rating cell, we calculated weighted average linear and logarithmic scores, which are displayed here in Table 6.

Step 3 — Multiply product rating scores by product attribute importance ratings to obtain an overall utility factor for each product. The utility factors are then normalized so that the first generation structural wood panel product, western plywood, equals one. The utility factor for southern pine plywood is also considered to equal one since no differentiation was made between western and southern pine plywood in the development of utility-adjusted price functions. The aggregate and normalized utility factors are displayed here in Table 7.

The normalized utility factors are then applied to the unit price, P_i, in Equations 5, 6, and 7 for each structural wood panel product to obtain a utility-adjusted price of a particular product relative to its predecessor(s) or competing product(s) at a given point in time.

Table 6. Weighted average product attribute importance scores.

	Product Attribute Importance Scores	
Product Attributes[a]	Linear Scale[b]	Logarithmic Scale[c]
Low price	4.317	11.796
Strength and stiffness	4.158	10.316
Dimensional stability	4.102	10.100
Durability	3.842	8.738
Panel weight	3.635	8.218
Surface uniformity	3.580	7.374
Impact resistance	3.001	5.900

[a] Attribute importance data adapted from Seward and Sinclair (1988b).
[b] The linear measure is based on a 5-unit incremental scale with anchors of 1 = "not important at all" and 5 = "extremely important".
[c] The logarithmic measure is based on a 5-unit logarithmic scale with anchors of 0 = "not important at all" and 16 = "extremely important" and intermediate values of 2, 4, and 8.

Table 7. Aggregate and normalized structural wood panel product utility factors.

	Structural Wood Panel Product Utility Factors		
Functional Form	Plywood[a]	Waferboard	Oriented Strandboard
Linear - aggregate	140.285	69.802	214.716
Linear - normalized	1.000	0.498	1.531
Logarithmic - aggregate	102.552	77.816	144.976
Logarithmic - normalized	1.000	0.759	1.414

[a] Given the nature of the secondary data used in generating the linear and logarithmic utility price functions, there is no distinction made between western plywood and southern pine plywood.