Understanding the adoption of new technology in the forest products industry

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Abstract

In anticipating future rates of adoption of new technology in forest products, several uniquely important factors come into play. In this respect, the role of innovations imported from other industries, the effect of raw material shortages, the importance of economic factors in adoption of innovations, and the problems presented by the heterogeneity of wood raw material and finished products are discussed. The nature of the adoption process and reasons for long lags between innovation and adoption are also addressed. Certain observations carry. implications for how research and information gathering should be conducted and what priorities should be accorded activities related to technology development and research in forest products.

Many times in this century, serious timber shortages have been forecast for the forest products industry. Although the economic scarcity of some wood materials is apparently increasing (the real price of sawlogs has been rising for a long time (17)), other wood materials seem unaffected (pulpwood prices have remained relatively stable over the last four decades (28)). Thus, although numerous wood-saving technological improvements are reportedly "on the shelf" and others are adopted rapidly by the industry, slow adoption rates for some major innovations undoubtedly reflect an appropriate response to economic conditions rather than conservatism.

This paper addresses the following questions: What are some of the principal and unique influences on technological change in the forest products industry that must be understood to anticipate future rates of adoption of new technology? Do these influences currently elicit appropriate rates of technology adoption?

The paper has five major sections: 1) the importance of innovations imported from other industries (interindustry flow) and other countries; 2) the effect of raw material shortages; 3) the effect of the economic performance of innovations; 4) problems presented by the heterogeneous nature of wood raw material; and 5) problems presented by the heterogeneity of finished products. It is taken as axiomatic that the impact of technological change is not felt at the stage of invention or innovation, but when improved technologies are actually used in production. For this reason, we pay particular attention to the determinants of the adoption of new technologies.

Interindustry technology flow

Prospects for technological change in forest products are heavily shaped by 1) commitment of resources to research and development (R&D) within the private and public institutions that comprise the forest products industry and its suppliers; and 2) developments in industries that are remote from forest products. For example, the forest products sector has made considerable use of sophisticated electronics components, including computers, lasers, and computerized axial tomography scanners (on an experimental basis). Many industries depend upon other sectors of the economy for the expansion of their technological capabilities. In the United States, five sectors account for more than 75 percent of total R&D: aircraft and missiles, chemicals and allied products, electrical machinery, nonelectrical machinery, and motor vehicles. Moreover, even within these sectors, many of the most important new technologies are acquired from

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TABLE 1. — *Research and development flow for 1974.*[a]

Type of technology	Cost	
	Lumber and wood products	Papermill products
	------- ($ million, U.S.) -------	
Total own industry R&D	72.6	202.3
Process[b]	64.2	86.4
Products coming from other industries[c]	66.9	119.6
Products going to other industries[d]	7.9	74.7
Final consumer products[e]	2.8	73.3

[a] Source: (24).
[b] Own industry R&D embodied in equipment used by the industry.
[c] Other industry R&D embodied in equipment purchased by forest products industries.
[d] Own industry R&D embodied in equipment used mainly by other industries.
[e] Own industry R&D embodied in final consumer products.

outside. For example, the aircraft and missiles sector accounts for the largest amount of total R&D spending of any industrial sector. Yet, that industry is a massive importer of computer technologies from other sectors. Although aircraft and forest products may seem to be very remote from one another, both have greatly benefited from metallurgical improvements and electronic and computer innovations.

Perhaps of greater relevance to the forest products industry has been the experience of another "traditional" industry that has been regarded as technologically conservative — the clothing industry. The clothing industry is also being shaped by the importation of high technologies. Computers have taken over many manual operations (e.g., the use of robots) and are used to monitor the manufacturing process (21). For several decades, the chemical industry has been expanding the range of synthetic fibers, which are now a more important input into the clothing industry, in dollar terms, than are natural fibers. In addition, the clothing industry is absorbing a number of innovations from electronics and laser technology.

In a study on the interindustry flow of new technologies, Scherer (24) revealed the sources of recent innovations in the forest products industry (Table 1). He developed a technology flow matrix for the U.S. economy for the year 1974, based upon company-financed R&D expenditures (that is, excluding inventions from government and university laboratories). By combining data on R&D expenditures with patent information on anticipated uses of inventions, Scherer constructed a matrix showing the "exchanges" of new technologies among industries. He found that the forest products industry was heavily dependent upon outside sources of technological change. In contrast, the computer and farm machinery industries were large-scale technology exporters. Lumber and wood products firms were identified as the main user of $67 million of R&D performed in other industries and $64 million of R&D performed inside the industry (1974 dollars). For the pulp and paper sector, the figures were $120 million. and $86 million, respectively.

In addition, many important forest product innovations have originated abroad, especially in Scandinavia and Germany. Significant innovations may come from Japan in the future. Several countries have been increasing their financial support for forestry research more rapidly than the United States (12).

The significance of external sources of technological change needs to be understood. At the very least, an enlarged monitoring activity should examine new directions and developments in other industries and countries for their potential relevance for forest products. The forest products industry might benefit from institutional innovations that would make such monitoring and evaluation more systematic and explicit or more readily available to the industry as a whole. A step was taken in this direction in 1982, at a meeting of corporate R&D managers to discuss future technological developments (27), but much more is needed in this area.

In *Wood Use: U.S. Competitiveness and Technology* (29), the Office of Technology Assessment (OTA) offered the following reasons for the low level of R&D expenditures by the forest products industry: 1) The industry is mature in the sense that wood products are well developed and have been used in essentially the same form for a long time; and 2) Wood products are not high technology and, therefore, are not likely to be subject to revolutionary technological breakthroughs in their manufacture and use.

Such reasoning is parochial and unconvincing. The world is full of old. "mature" industries and products that have been completely revitalized by "revolutionary technological breakthroughs," as suggested by the adoption of robots, synthetic fibers, and lasers in the textile industry — surely a mature industry. Agriculture and medicine are also mature industries, and yet they have both been transformed by revolutionary technological breakthroughs within the past 50 years.

Improving the monitoring and searching activities at the interfaces between forest products and high technology industries and between domestic and foreign industries may facilitate forecasting as well as the transfer of valuable technologies in the years ahead. As we will discuss, the problem in the forest products industry is not maturity. Rather, many of the industry's difficulties in achieving technological improvements stem from the heterogeneity of raw materials and the wide variety of requirements for finished wood products. Moreover, the adoption of new technologies is often precluded by economic considerations.

Response to raw material scarcity

The direction of technological change in the forest products industry, as elsewhere, is not a purely random or exogenous phenomenon, even though the industry may be affected by events that originate entirely outside the industry. Rather, technological change is influenced by the changing structure of costs of manufacturing (labor, capital, and raw materials) and the prices of competing products (plastics, steel, and concrete). Technological innovations in the forest products industry tend to have a strong labor-saving bias (11,25), suggesting that the industry tends to increase its competitiveness through improvements in labor productivity. We acknowledge that labor and capital scarcity must be considered because they strongly influence technological change. However, many innovations unique to forest products have been triggered by raw material shortages. In this section, we focus on

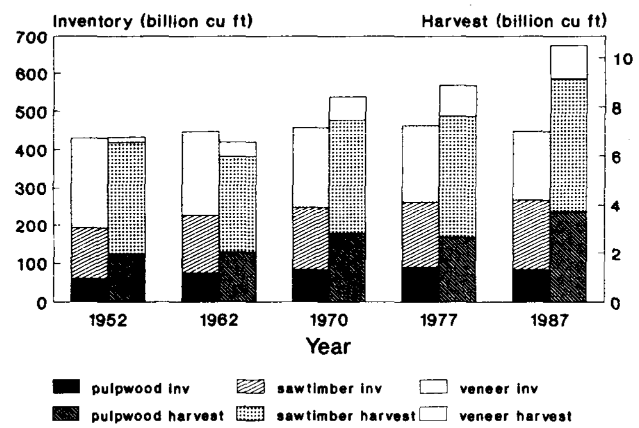

Figure 1. — Composition of inventory and harvest of softwood growing stock by size class from 1952 to 1987 (30-34).

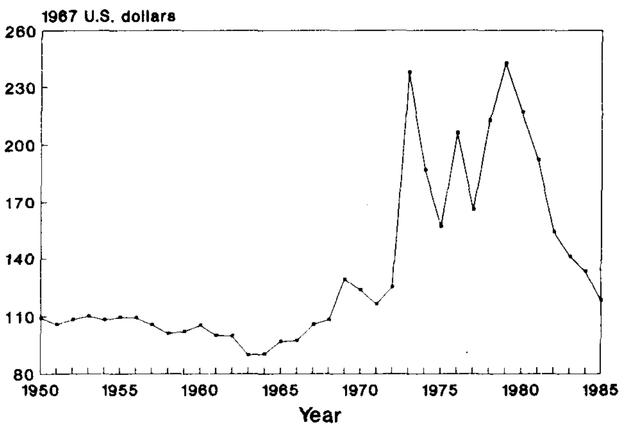

Figure 2. — Price of Douglas-fir veneer logs in western Washington and Northwest Oregon from 1950 to 1985 (28).

the influences of wood shortages on the development and adoption of technological innovations in the forest products industry.

The role of predictability of supply

In both the public and private sectors, research responds to expectations concerning future availability of raw materials. The forest products industry has a peculiar advantage in anticipating the future availability of one of its essential raw materials, timber.

Although certain trends in raw materials can be extrapolated into the future, projecting consequences of trends may be difficult. As the price of a raw material increases, a wide range of economic and social adjustments may then be called into play, such as simple conservation measures, changes in product design, and possible substitution of more abundant materials. Substituting more abundant materials for scarcer materials involves a range of technological changes that facilitate substitution or that simply reduce the need for the scarce material in the first place.

The recent technological history of forest products must be told in terms of how the increasing physical scarcity of timber, primarily the rising cost of large logs, has induced innovations that have facilitated the use of smaller logs and "inferior" timber sources. In the case of softwood timber (Fig. 1), an increasing output has been harvested from a relatively constant timber inventory. At the same time, the character of the inventory has changed (toward smaller trees), along with the character of finished products (less lumber, more panels, and more flakeboard).

Examples of major technological developments that were motivated by resource scarcity can be found in the structural panel and pulp and paper sectors. The basic ideas underlying new structural panels date back at least as far as the 1950s. The introduction and rapid acceptance of new structural panels in the 1970s and 1980s owed much to research and improved technological capabilities that could utilize low-cost hardwood resources. However, a powerful triggering mechanism was undoubtedly the sharp rise in the price of softwood veneer logs (Fig. 2), which placed plywood at a considerable cost disadvantage (14). On the other hand, in the pulp and paper sector, fluctuations in the price of softwood pulpwood have played a less obvious role in developing pulping processes that expanded the variety of tree species used as raw materials. Instead, consistently lower prices for hardwood pulp wood, woodmill residue, and recycled paper contributed to the introduction of processing techniques that could exploit these materials. The proportion of hardwood pulpwood grew from 15 percent in the early 1950s to 31 percent in 1986 (35,36). Wood residues from sawmills and plywood mills now account for over 40 percent of woodpulp sources. Finally, the use of recycled paper rose from 12 million short tons in 1970 to 15 million short tons in 1981 (29); recycled paper comprised about 24 percent of fiber inputs in paper and paperboard production in 1987 (20).

Problems with projection models

Failing to take adjustment mechanisms into account **was** responsible for the naive "models of doom" energy forecasts of the 1970s (9,19). Such models were baaed on narrow and unrealistic behavioral assumptions. They did not take into account how a regime of flexible prices would create strong incentives to utilize alternative energy sources, such as wood. The years immediately after the 1973 to 1974 Arab oil embargo and the drastic rise in energy prices gave rise to a rapid expansion in the use of wood as an energy source. This experience provides valuable evidence of the impressive speed with which the forest products industry and consumers can respond to a clear set of price signals (29).

The lesson for the forest products industry is clear. Long-term extrapolations of increasing raw material scarcities are likely to be of no value — or worse, of negative value — unless they explicitly take into account the dynamics of technological changes induced by the scarcities themselves, as well as the nature of user responses to rising prices of inputs.

Historical observations are important in developing a framework for projecting technological change in the forest products industry. Econometric models have incorporated a wide range of empirical data on the pattern of timber utilization in the American economy (1,18). These models make it possible to extrapolate the impact that changes in the growth of population, gross national product, and other economic variables will have on timber utilization. The question that needs to be considered here is how useful such models are at projecting the impact of technological change (22).

The essential point is that econometric models, even conceptually and technically sophisticated models, often take information about technologies or technological change as exogenously given and then predict the consequences upon timber markets. However, models can simulate the behavior of technological change endogenously. For example, the USDA Forest Service, Forest Products Laboratory (FPL). Pulpwood Model (15), based on a linear programming model by Gilless and Buongiorno (10), estimates technological change as an endogenous process. This model defines current and future technological processes that make various grades of paper and paperboard by specifing wood or fiber input requirements and nonfiber costs for each process. As the model operates, future processes, which represent new technologies, can be adopted. Their adoption is partly determined by regional market price equilibria for wood and recycled fiber estimated by the model.

With the exception of the FPL Pulpwood Model and the International Institute of Applied Systems Analysis model (16), forest products industry models generally do not address technological change as an endogenous behavioral phenomenon. That is, how will different sets of changes in market conditions generate different patterns of technological change in the industry?

The work of Hayami and Ruttan (13) and Binswanger and Ruttan (4) on induced innovation in agriculture also provides an approach to technological change that might well be replicated in the forest products industry. In fact, the induced-innovation hypothesis has been tested in agriculture and other fields (26), and it is surprising that this approach has not yet been fully tested (as far as we know) in the case of forest products.

Economic performance of innovations

Looking at the reasons for past technological change calls attention to a central point of this paper: Decisions to develop and adopt new technologies are ultimately based on economic and not purely technological considerations. Even though new technologies possess attractive features or reduce the cost of a specific material, the technologies are often not economically superior because all associated costs have not been considered (31).

Benefits associated with new technologies are frequently overstated, and the best improvements in the field rarely match what has been reported under ideal laboratory conditions. For example, best opening face (BOF) sawing, a computer program that selects the best first-cut in logs to make lumber, was developed by the FPL in the early 1970s. The OTA reported that under laboratory conditions, BOF yields 6 to 90 percent more lumber from 5-to 20-inch logs and averages 21 percent more lumber recovery than conventional sawing (29). However, the disparity in performance between ideal laboratory conditions and sawmills is considerable. The sense that some irrational lag is occurring in the adoption of BOF is greatly diminished when the evaluation of actual performance in sawmills shows an average increase of a mere 4 percent, not $\geq$ 20 percent, compared to conventional sawing (29). As long as this disparity remains large, reticence to adopt new technology should not be dismissed as adoption lags or slow rates of diffusion.

Similar considerations lend understanding to the apparently delayed adoption of some other major innovations in the forest products industry (e.g., oriented strandboard (OSB) and waferboard, which were technically available in the 1950s, but were not widely adopted commercially until the 1970s). When all costs are taken into account, seemingly superior technologies may be adopted slowly at first because they do not decisively reduce costs. Radically new technologies usually represent clusters of new characteristics, some positive and some negative. The innovation, therefore, involves a sorting-out process, in which negative characteristics are reduced while positive ones are enhanced. In many cases, this situation gives rise to a long and costly development period.

Often, new technologies cannot be introduced without costly new manufacturing equipment. Therefore, the economics of adoption need to be analyzed in terms of the present costs and discounted future financial returns of an investment process. Composites such as parallel-laminated veneer (PLV) and Com-Ply are attractive products because they make it possible to use lower quality materials, hardwoods, and smaller logs. However, the expensive processing equipment required cannot be readily retrofitted into existing sawmills. Introducing such equipment is much more likely to be associated with replacing depreciated equipment at existing sawmills or establishing new mills. Either action would require the right stumpage market conditions, improved prospects for the adoption of composite products, and access to financing on acceptable terms; moreover, either action would probably be taken infrequently or be delayed (29).

Many new technologies that have promised to save material have also required additional, and offsetting, doses of complementary inputs. Thus, promising new mechanical pulping technologies, which hold out the prospect of higher yields, are also burdened with the requirement of higher energy costs (16). On the other hand, the diffusion of new technologies has been accelerated when the associated complementary inputs have been positive from an economic point of view. The rate at which plywood was adopted over lumber was rapid for two reasons: The employment of plywood on construction sites proved to be labor saving, and the price of plywood had declined sharply relative to the price of lumber (8) (Fig. 3).

What is at issue is more than just a matter of eliminating “bugs.” New technologies always represent clusters of characteristics, so the industry must cope with the more fundamental matter of optimizing those characteristics, suppressing some and enhancing others, while minimizing risk and uncertainty.

In the forest products industry, one particular institutional feature may be significant in shaping the timing of the decision to adopt new technology. In the present division of research labor, the initial research is done in the public sector by institutions such as FPL, regional Forest Service research stations, and state universities. But commercial success ordinarily goes beyond what can reasonably be attained by a public agency: fine-tuning the product design and characteristics to the specific needs of specialized categories of users, as well as improving process and machinery for which the public sector has only a modest capability. The final push must come from the private sector and must therefore await the stimulus of changing prices or costs that ordinarily shape the decision to adopt. A fitting example is the implementation of the OSB-waferboard technology in the early 1980s. This technology had been available since the 1950s but became a viable option only after softwood veneer log prices rose dramatically relative to aspen prices in the late 1970s. The rapid adoption of OSB-waferboard followed a sharp relative increase in veneer log prices (Fig. 4).

In examining the adoption of new technologies, we need to consider the trajectory of slow and gradual improvement beyond the crude condition that usually characterizes the early stage of new technologies. A huge volume of literature systematically ignores this particular point. Some sociologists and economists tend to search for the evidence of first use of some new technology and then treat the subsequent delay in wider adoption as evidence of an irrational lag or excessive conservatism on the part of potential adopters. A more complicated history needs to be examined. The decision to adopt technology should be explored in the comparative context of alternative technologies. Particular focus should be placed on the progress of reducing costs, improving performance, and expanding confidence in the performance of the new technology, as well as on the systematic modification of the technology to accommodate the diverse range of needs of a heterogeneous user population (23).

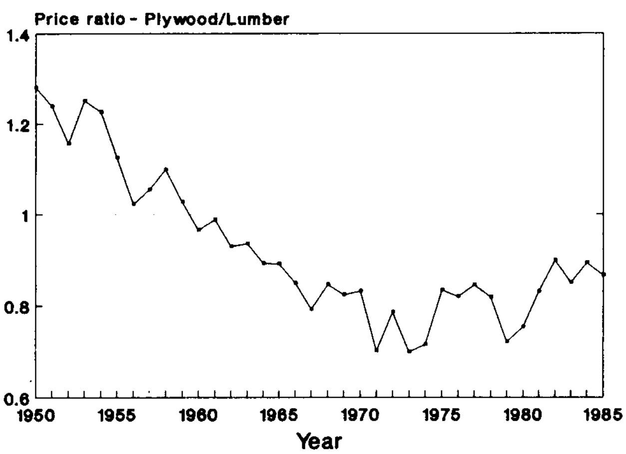

Figure 3. — Prices of softwood plywood and lumber in Douglas-fir region from 1950 to 1985 (2).

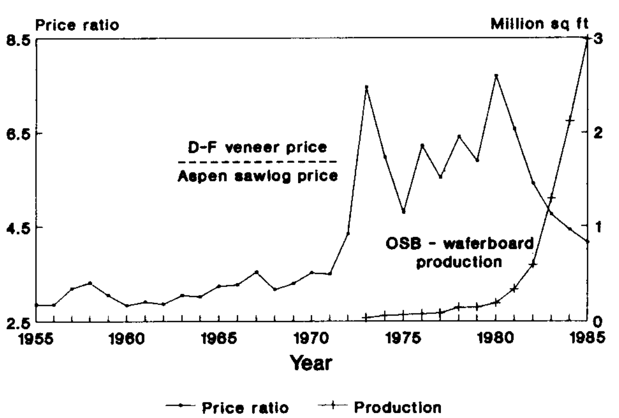

Figure 4. — Price of Douglas-fir veneer compared to price of aspen sawlogs and OSB-waferboard production from 1955 to 1985 (1,28). Note: some data were estimated.

A somewhat perplexing and significant aspect of the slow adoption of a new technology is revealed in the use of wood trusses, which were originally designed for roof framing, later designed for flooring, and were recently designed for entire houses. In the United States today, conventional roof trusses are used for most new wood-frame houses, whereas "truss frames" (wood trusses that provide framing for the whole house) are just beginning to be used. Truss frames were originally developed in Germany approximately 150 years ago. The technique was introduced to the United States in the 1950s, but it has not received widespread acceptance, which is surprising in view of the large number of benefits claimed for trues framing. One source claims that truss frames eliminate the need for interior supports and require 30 percent less structural framing lumber than conventional construction (29). Another source estimates a 20 percent savings in the amount of wood (32).

An important feature is the uncertain economic impact of truss framing. Although an OTA table of the benefits of truss framing lists labor savings as the first item, the accompanying text is ambiguous. It states, "The truss frame system and panel assemblies often are simpler and faster to erect on site and may save labor" (29). The lack of clarity over associated labor costs probably reflects differences among designs of houses and differences in calculating associated labor costs. Because labor costs are considerably greater than material costs, uncertainty over the precise level of labor cost differences could readily swamp the purported benefit of an associated reduction in material costs.

A considerable degree of uncertainty over the economic benefit of truss framing has persisted because of the cost of labor. The "conservatism" of various agents in the building industry is easily invoked in discussions of these matters. But an appropriately conservative, even skeptical, approach may be justified when the economic benefits from a new technology are surrounded by a wide band of uncertainty.

The adoption rate of new technologies in the forest products sector needs to be understood in terms of the overall economic impact of the technologies and not baaed on a one-dimensional interpretation of a specific effect. Economic evaluations are extremely diffcult to make and the eventual outcomes are often counterintuitive. This is because genuine improvements in one part of the system give rise to less obvious but offsetting costs in other parts: for example, a deterioration in product quality, the need for a higher cost manufacturing process, more labor input, or a new design configuration to accommodate the use of a new material. Moreover, a pervasive factor complicates authoritative evaluation of new technologies. As time passes, technologies themselves pass along trajectories of performance and cost changes that may radically alter their economic efficiency. In most industries, the first generation of new technologies in most industries is typically primitive when compared to the characteristics of subsequent generations at later stages of maturity. Although this feature is shared with other industries, it may assume greater importance in the forest products industry as a result of interaction with the other sources of uncertainty and difficulties of information acquisition central to the industry.

Problems with a heterogeneous raw material

This section focuses on a distinctive characteristic of the forest products industry — the natural heterogeneity of its essential raw material, wood. If the industry is not unique, it is at least at the extreme end of a spectrum of possibilities with respect to variability or heterogeneity in physical characteristics of its primary raw material. This heterogeneity is based on the fact that wood is an organic material with a remarkable degree of natural diversity.

Such heterogeneity immensely complicates the process by which useful knowledge is accumulated and diffused within the forest products industry. Whereas research results on aluminum, iron and steel, pharmaceuticals, and electronics have the potential for some immediately wider application or even codification, and therefore for usefulness in other contexts, the results of forest products research are circumscribed by the nature of wood. The behavior of wood is highly variable from one species to another and also from one location in the log to another. The number of variables is truly immense. Consider, for example, the natural variation in wood density among species, an important feature of wood from a structural standpoint. For various species of pine, specific gravity varies from 35 to 60 lb./ft.^{3} (ovendry). In addition, the coefficient of variation for specific gravity within each species is approximately 10 percent (33).

This heterogeneity leads to a subtle interaction among many variables that generally takes a long time to sort out, whether new technology is being developed for construction or for pulping and papermaking. Technological problems are often too subtle and multivariate for scientific methodology to offer generalized results. The inherent subtlety of the information (acquisition process in forest products, not the mature stage of the industry) accounts for many of the difficulties in bringing scientific methodology more effectively to bear upon technological problems. For example, an astonishing number of elementary facts about wood are not yet established with any kind of quantitative precision, such as the chemical structure of lignin and the response of wood to various forms of chemical or biological treatment.

Problems in wood drying

Consider a seemingly simple problem in forest products technology: optimal conditions for kiln-drying of wood. Over the past 30 years, wood drying has come to depend less on traditional air-drying and more on kiln-drying. The advantage of kiln-drying is a shorter drying time, which lowers the throughput time in the lumber production process. This advantage is particularly important for the recently developed technology of high-temperature drying, which varies greatly in effectiveness depending on tree species. Of interest is the fact that the energy requirements per unit of output seem to be lower in high-temperature kiln-drying than in normal-temperature kiln-drying. The shorter turnaround drying time allows greater flexibility in filling orders in a timely fashion and can potentially reduce capital costs of the kiln per unit of output. Shorter turnaround time also lowers the cost of holding wood while it is being dried. The final moisture content of kiln-dried wood is lower and more predictable as well as independent of ambient temperature and relative humidity. In many cases, firms use low-temperature kiln-drying and dehumidification to predry wood and then finish the drying process in a kiln at higher temperatures. While the cost per unit of drying wood is of course higher in kiln-drying than in air-drying, apparently the difference is justified by other considerations not included in the usual cost figures (37). Just how sensitive the optimal use procedure of kiln-drying is to such factors as the price of energy, capital, and labor would be interesting to know. Unfortunately, but not surprisingly, adequate data are not available for answering these questions.

Wood drying may appear to be a simple and straightforward process, but it is a deceptively tricky affair. The optimal drying procedure depends on a large number of variables such as species, season, geographic location, whether the tree was grown in a forest or on a plantation (7), size of pile, composition of pile, and precise manner of stacking the wood. Furthermore, softwoods are more amenable to high-temperature drying than hardwoods. Hardwoods respond in numerous ways to high-temperature drying applications depending on species (5).

Extensive experimentation is presently the only way to determine the optimal high-temperature drying procedure for each species under a large combination of circumstances.

Problems in developing a theoretical framework

Research activities in forest products are seldom guided by an overall theoretical framework that is applicable in all cases. Individual experiments are often of limited usefulness. For example, one cannot confidently take data from a small experimental kiln and extrapolate the data to a commercial kiln because of the effects of pile size and composition on drying rate.

The scientific information necessary for technological innovation can be obtained. However, each small bit of information typically has to be acquired at a slow pace and at a high cost. Once acquired, information cannot always be used readily in other contexts involving different species, subspecies, or locations.

A major thrust of technological change in the forest products industry has been to overcome, or at least reduce, the effects of heterogeneity. Many innovations have involved taking a diversity of low quality timber resources and converting them into products with lumber-type or plywood-type characteristics. Recent developments in structural panel products serve as examples, including waferboard and OSB. In the pulp and paper sector, note the increasing recourse to hardwoods and former waste materials. Of course, the obstacles posed by material heterogeneity are compounded by the extreme heterogeneity of the final product, which reflects, in turn, the diversity of final consumer needs.

Problems with heterogeneous products

Every final product in the wood-based construction industry is to some degree unique, not only because of the specificity of production location and environment but also because of the special constraints imposed by varied market requirements. The heterogeneity of products, the multiplicity of raw wood material, and the typically long life of many wood products in the construction industry contribute to the unusually long period needed to sort out the impact of separate variables on product performance.

In evaluating new materials or new production techniques in an industry such as electronics, experimentation can usually determine the effects of new approaches, designs, or materials very quickly, and can make immediate adjustments and adaptations accordingly. In the construction industry, by contrast, many years of observation may be needed to evaluate how a new wood-based material can withstand the abuse of weather. Surprising results are common because varying environmental conditions (temperature, humidity, sunlight, ocean spray, industrial pollution) and the peculiar complexity and diversity of the wood product lead to subtle interactions that take a long time to understand. Conflicting observations and claims combine in ways that complicate the isolation of the separate contributions of variables. For example, time is critical in thermal-moisture interactions and affects the thermal properties of new materials and designs; such matters are inherently difficult to sort out. Inevitably, time-consuming testing imposes delays upon the decision to adopt new technologies.

The slowness with which essential information about new technologies accumulates in the forest products sector is not confined to construction. Similar problems are endemic in the pulp and paper sector, as well. Many years of study may be needed to clarify something as elementary as the energy requirements associated with a new pulping technology, partly because of heterogeneity among wood materials but also because of varied performance requirements of the pulp. In thermomechanical pulping, for example, problems of quality control (achieving acceptable levels of brightness) and problems associated with operating the refiners were encountered after the first commercial pressurized refining system for producing news-grade pulp was introduced in Eastern Canada in 1964. But far more surprising was that the industry was unable to sort out conflicting claims over energy requirements for almost a decade. One example is the claim that energy requirements for pressurized refining were significantly lower than those for refiner mechanical pulping (an older system) (3). Such claims eventually proved to be spurious. Essential scientific knowledge for the success of new technologies seems to grow very slowly in the forest products industry.

In summary, major reasons for the slow adoption of some important new technologies in forest products are 1) the body of technologically relevant information is highly fragmented; 2) the stock of information relevant to any given use is expanded very slowly; 3) the feedback loops from use and experience are much less significant as diffusers of useful information than is the case in other industries; and 4) over a wide range of productive uses, scientific theory, although valuable, cannot play a very effective role in providing information tailored to the particularities of local use conditions.

Conclusions

Several key factors influence the process of technological change in the forest products industry. That straightforward policy recommendations can be, or ought to be, drawn from our analysis is not obvious. For example, relevant information accumulated by the forest products industry and needed for technological improvements encounters difficulties to a degree not encountered in many other industries. It does not follow, however, that information-gathering activities beyond those already in place are desirable. The FPL, as presently constituted, already studies some peculiar problems of the wood products industry. Moreover, a network of federal and university wood utilization researchers addresses manv problems caused by the heterogeneity of knowledge about solid wood processing. Federal and state utilization specialists play a significant role in transferring technology by helping firms solve technical problems and by facilitating the feedback and diffusion of useful information derived from working with the problems of the industry. Given these peculiarities, however, additional resources devoted to research or information and technology transfer would not necessarily yield higher social returns in the forest products industry compared to other industries.

Certain observations in this paper do carry implications for the manner in which research and information gathering ought to be conducted and the priority that ought to be accorded the following processes: 1) monitoring and evaluating the developments in other industries; 2) monitoring the developments in other countries; 3) focusing on the internal dynamics of technological change; and 4) studying the economics of adoption and diffusion of new technologies in the forest products industry.

More systematic attention needs to be given to monitoring and evaluating developments in other industries that may be relevant to the forest products industry. At present, some attention seems to be given on an individual and haphazard basis.

External monitoring should include more attention to ongoing developments in other countries as well as in other domestic industries. Several countries have been increasing their financial support for forestry research more rapidly than the United States. Imported technologies promise to play an even more important role in forestry-based activities in the future.

More attention needs to be devoted to understanding the internal dynamics of technological change, as opposed to constructing econometric models that simply spell out implications of historical trends. In particular, attempts to determine future adequacy of timber resource supplies need to examine the internal behavioral mechanisms that influence the adoption of new technology within the industry, including trends in all major factors of production (such as raw materials, labor, and capital).

Studies of the economics of technology adoption and diffusion within the forest products industry should receive more attention. Much research has been devoted to identifying potential performance improvements of new technologies, especially their wood-saving consequences, without systematically considering the costs of implementing these new technologies. The impression has often been given that new and technologically superior innovations have been sitting on the shelf because of some innate (or regulation-induced) "conservatism" in industry decision makers. A closer examination of such shelved technologies often reveals perfectly sound economic reasons for postponing adoption of the technology, reasons embedded in low levels of expected profitability (6). Thus, for the forest products industry, like other industries, the decision to adopt new technologies is inescapably an investment decision. Consequently, the same economic variables that are ordinarily consulted in such decisions need to be examined to justify past decisions and to guide future decisions to adopt new forest product technologies.

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