THE POTENTIAL FOR SHORT LENGTH LUMBER IN THE FURNITURE AND CABINET INDUSTRIES

By

Janice K. Wiedenbeck

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Approved:

R. L. Youngs, Chair

P. A. Araman

M. P. Deisenroth

D. E. Kline

F. M. Lamb

E. M. Wengert

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Blacksburg, Virginia

ABSTRACT

The primary purpose of this study was to evaluate short length lumber (less than 8 feet long) utilization opportunities within the furniture and cabinet industries. In the first part of the study a data bank of mapped red oak lumber was used to search for differences in lumber characteristics between lumber length groups. The same data was used to evaluate opportunities for improving the value of a piece of lumber by trimming a lower grade, longer length piece to obtain a shorter, higher grade board. The defect data indicated that wane makes up a slightly higher percentage of the total defect area for short boards than for long boards but the degree of crook deviation for short boards is significantly less than for long boards. The value improvement analysis indicated that fifteen percent of the 1 Common, and 49 percent of the 2A Common, 8 and 9 foot long boards could be trimmed to a higher grade, higher value short board.

The effect of lumber length on random width dimension yields was examined using the CORY lumber cut-up program. For 10 of the 18 cutting bill combinations examined, the regression between total yield and lumber length was significant. In the significant crosscut-first relationships total yield decreased with increasing lumber length. In the significant rip-first relationships total yield decreased as lumber length increased. The variable which showed the strongest and most consistently significant relationship to lumber length was the average volume of parts produced per furniture rough mill sawing operation; the regression of board feet per sawing operation was significantly and negatively related to lumber length in 14 of the 18 cutting bill combinations tested. Regression results indicated that as crook decreases, total cutting yield, average cutting length, part volume per sawing operation, and part value tend to increase.

Short and longer length lumber yields were also compared in mill studies. The mill studies were conducted at a crosscut-first furniture rough mill and at a rip-first cabinet rough mill. Total yield, the yield of the longest length cutting on the cutting bill, the percentage of total yield made up of the three longest length cuttings, average cutting length, and crosscut and rip saw rates were investigated. The only significant regression relationships detected were: 1 - for the crosscut-first, 2A Common analysis the percentage of total yield made up of the three longest length cuttings was inversely related to lumber length, and 2 - for the rip-first, 1 Common and 2A Common analyses the ripsaw volume throughput rate improved with increasing lumber length.

Simulation studies based on models of these same two rough mills indicated that the volume and value of parts cut from short length lumber in a crosscut-first rough mill compares favorably with the volume and value recovery obtained from longer length lumber. In the "worst case" crosscut-first production alternative the breakeven short length lumber price was only $129 less per thousand board feet than the going market price for longer length lumber. For the rip-first model the volume and value of parts produced from short lumber was only 60 percent that of the longer length lumber. The breakeven short length lumber prices calculated for this model ranged between $373 and $653 per mbf.

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INTRODUCTION

Section 1

Problem Statement

Procurement and production personnel associated with the eastern U.S. hardwood lumber industry frequently state that high quality logs of preferred species are much more difficult to obtain today than was the case a couple of decades ago. This is the prevailing opinion despite the fact that Forest Survey data indicates that hardwood quality is improving (Beltz 1991) and the inventory of select hardwood species is increasing (de Steiguer et al. 1989a, Araman 1987a). The perception that the availability of the more highly valued hardwood logs is decreasing is not unfounded, however. Supply constraints related to timber accessibility, timber stand operability, and stocking levels limit the effective availability of a significant proportion of the larger diameter trees and select species (Tansey 1988). Timberlands that are not subject to such constraints have been high-graded to the extent that the remaining hardwood stand is composed largely of smaller stems, lower grade timber, and less highly demanded species. The hardwood processing industry must address the problem of how best to adapt its timber conversion methods to better utilize the available resource.

The management prescription for returning these high-graded timberlands to productive forests requires that large quantities of small diameter and lower quality stems be cut to reduce overstocking and stagnation (Irland 1988). As cost effective practices are established to utilize this material, the incidence of high-grading-type harvest activities will diminish, the volume and quality potential of many of these stands will improve, and the timber supply concerns of primary processors will be reduced (Wengert et al. 1986, Irland 1988, Tansey 1988).

One of the proposed methods for converting the lower grade hardwood resource into a high value product involves cutting high quality short length lumber (less than 8 feet long) or dimension parts out of short hardwood bolts (Ringer 1975, North Carolina Division of Forest Resources [NC-DFR] 1979, Rosen et al. 1980). Wengert et al. (1986) discussed short length lumber processing problems that exist in five manufacturing areas: 1-log grading, 2-log breakdown, 3-lumber drying, 4-lumber grading, and 5-manufacturing. When asked about the problems they associated with short length lumber, several hardwood lumber manufacturers stated that their inability to find markets for short length lumber was a much greater deterrent to the production of short length lumber than was any technological aspect of short length lumber production.

The major high value markets for hardwood lumber produced in the U.S. are the domestic furniture, cabinet, and dimension industries, and the export industry. Hardwood lumber utilization by the U.S. furniture, cabinet, and dimension industries equaled approximately 27 percent of total U.S. hardwood lumber consumption in 1987 (Luppold 1991). These are the market segments on which the largest number of lumber producers focus their marketing attentions. Hardwood sawmills will be more likely to adopt procurement and processing methodologies for short length lumber if a high value, high volume, end-user market (such as the furniture market) can be established.

At present, most eastern hardwood sawmills produce very little lumber shorter than eight feet in length. Short length lumber that is generated in the process of sawing longer logs is most often converted into relatively low value hardwood chips (~ $20/ton). Modifications to present sawmilling practices, such as recovering lumber from logs with swollen butts or end-trimming a longer length No 2A Common board to produce a shorter length No. 1 Common or Selects board could produce additional volumes of short length lumber. When chips are produced from material that has the potential to yield short, high quality lumber, value recovery goes down and raw material costs rise.

Before the furniture industry will accept short length hardwood lumber, several obstacles must be overcome. These obstacles include: cutting yield uncertainties, handling problems and costs, and the furniture industry's lack of experience with short lumber (Wengert et al. 1986). If short length lumber yield and processing cost estimates were available, the potential value of short length lumber to the furniture industry could be estimated. This information could then be used by lumber manufacturers to help them design a short length lumber manufacturing and marketing strategy.

Objectives

1. To compare and contrast short length red oak (genus: Quercus; subgenus: Erythrobalanus) lumber with longer length red oak lumber for certain properties which affect material utilization.
2. To establish potential furniture cutting yields from short length red oak lumber via both simulation and actual mill studies and to compare these with yields from longer length lumber.

3. To determine the change in operating efficiencies and costs that might be expected when processing short length lumber in both a rip-first cabinet-type rough mill and a crosscut-first furniture-type rough mill.

Literature Review

The Hardwood Lumber Industry

Size and Importance:

According to United States Department of Commerce - Bureau of Census (USDC-BOC 1982) figures the U.S. hardwood lumber industry consisted of 840 establishments in 1982. These establishments spent an estimated $650 million on raw materials and produced $1,136 million worth of shipments. The average number of employees per hardwood establishment is estimated to be fewer than ten (de Steiguer et al. 1989a).

The actual number of hardwood lumber establishments is thought to be substantially larger than Bureau of Census figures indicate; Hammett et al. (1991) tallied 2,225 active hardwood sawmills in seven Southern Appalachian states using state Forest Products Industry directories. The discrepancy in these figures is probably the result of inadequacies associated with the Bureau of Census' method of estimating the number of establishments with fewer than five employees (Bratkovich and Passewitz 1991). The hardwood industry is comprised of many such small establishments. Hardwood lumber production was an estimated 10.024 billion board feet in 1986 (Luppold and Dempsey 1989). This production figure includes the production of the smallest hardwood sawmills which Census data fails to capture.

Hardwood sawmills are typically much smaller than their softwood counterparts with average outputs being approximately one-quarter the average for softwood sawmills (Dempsey 1987; Bush and Sinclair 1989). The average 1982 production of hardwood sawmills in Kentucky, West Virginia, and Pennsylvania was 1.385 MM bf (Dempsey 1987). The hardwood sawmill capacity of the southern Appalachian states (North and South Carolina, Georgia, Tennessee and Virginia) is approximately 20 percent of the national capacity (de Steiguer et al. 1989a). Less than 10 percent of hardwood lumber volume is produced by operations owned by large forest products companies (de Steiguer et al. 1989b).

Hardwood sawmills can generally be categorized as being either grade mills, industrial product mills, or part-time mills (de Steiguer et al. 1989b). While most hardwood sawmills cut a wide variety of species, the primary species cut are red and white oak (34 percent and 16 percent of total annual lumber production; Bush et al. 1991). Industrial product mills, which most often cut pallet lumber and railroad ties, tend to be more productive (bf/labor hr) than grade mills which cut higher value lumber products. Part-time mills frequently shut down during periods of low lumber demand and restart during market upswings. They have low capital investments and are generally debt-free (de Steiguer et al. 1989b).

Material costs are the largest cost item in the hardwood lumber industry. Average material costs (including the costs of logs, energy and miscellaneous supplies) for the hardwood lumber producers of West Virginia, Kentucky, and Pennsylvania ranged from 65 to 68 percent of total costs in 1982 (Dempsey 1987).

The Resource Base and Raw Material Consumption Trends:

Ninety percent (275 billion cubic feet) of the total U.S. hardwood growing stock volume is found in the eastern United States (Sheffield and Bechtold 1990). Oak species comprise 28 percent of the growing stock in the North and 44 percent in the South (Sheffield and Bechtold 1990). Of the total oak growing stock volume, Select white and Select red oaks (those oak species that are of particularly good form and quality) make up approximately 45 percent of the oak volume. Eastern hardwood growing stock inventories have steadily increased in all diameter classes over the last 3+ decades (Sheffield and Bechtold 1990). This increase is due to the fact that net annual growth has consistently exceeded removals throughout the region. Sheffield and Bechtold (1990) cite a ratio of growth to removals for eastern hardwood inventories in 1986 of 1.8 to 1. More recent data from individual states shows a decrease in the gap between growth and removals from that which was evident in previous inventories (Sheffield and Bechtold 1990). There are certain regions and certain species for which the growth to removals ratio is very much different than the average for the east as a whole. For instance, over the period 1975 to 1989 the ratio of average annual growth to removals was 3.78 to 1 for hardwood growing stock in West Virginia (DiGiovanni 1990).

Several factors are involved in making a significant portion of the hardwood growing stock essentially unavailable for harvest. For example, in the Southern Appalachian timber supply region, one-third of the hardwood growing stock inventory is found growing on slopes of at least 61 percent (de Steiguer et al. 1989b). Fifty-four percent of the red oak growing on National Forests in the Southern Appalachian timber supply region is located on these extreme slopes or is located more than 1,500 feet from an access road (de Steiguer et al. 1989b). Environmental protection of fragile and high impact regions threatens to further reduce the available timber supply. Consequently, annual hardwood removals are equivalent to less than one-half of one percent of hardwood inventory for National Forests in the Southern Appalachian timber supply region (de Steiguer et al. 1989b). This is a particularly relevant statistic given the fact that despite controlling only 18 percent of the Southern Appalachian timber supply, National Forest timberlands contain 34 percent of the select red oak growing stock volume (de Steiguer et al. 1989b).

The physical availability of timber growing in non-industrial private forest ownerships (NIPF) is generally not as limited by road access and slope. On farmer-owned NIPF lands annual hardwood removals represent slightly more than 1 percent of hardwood inventory. Approximately three-quarters of the hardwood growing stock volume in the east is held by non-industrial private forest owners (Sheffield and Bechtold 1990). A major concern related to these timberlands is the recent trend toward fragmentation of NIPF ownerships. The smaller sized timber tracts that result from fragmentation can lead to increased logging costs, accessibility problems related to right-of-way agreements, and land-use conflicts between neighbors.

The demand for hardwood roundwood is expected to increase over the next fifty years by 73 percent in the South and 66 percent in the North (Phelps and Darr 1990). Increases are expected in all hardwood roundwood product categories. Most notable, however, are the anticipated increases in demand for hardwood pulpwood (130% increase), hardwood fuelwood, and hardwood roundwood used in the production of oriented strand board and waferboard. The higher valued roundwood products (veneer and sawlogs) are expected to comprise a smaller fraction of the total hardwood roundwood market, declining from 27 percent to 23 percent over the period 1988 to 2040 (Phelps and Darr 1990). The demand for hardwood lumber is expected to increase to 13.2 billion board feet by 2040.

Increases in hardwood removals and hardwood stumpage prices associated with the projected increases in demand for hardwood roundwood are likely to be very unevenly distributed. Increases in pulpwood demand and roundwood demand for oriented strand board and waferboard production will be evident in areas proximal to the pulp and paper and particleboard mills. Increases in fuelwood demand will be most evident in areas proximal to urban centers. Many regions will still lack markets for the smaller size and lower grade hardwood stand components.

Hardwood Lumber Markets:

The volume of hardwood lumber consumed by U.S. hardwood industries in 1987 was approximately 11.3 billion board feet (Luppold 1991). Ninety-seven percent of the hardwood lumber consumed in the U.S. is purchased by industrial consumers (Spelter and Phelps 1984). In addition, small quantities of hardwood lumber are used in residential and nonresidential construction and small, but increasing quantities of hardwood lumber are sold to individual consumers through home center retailers.

Luppold's (Luppold 1989, cited by Bush 1989; Luppold 1991) adaptation of Bureau of Census data highlights several distinctive hardwood market trends (Table 1). Comparisons of 1977 and 1987 hardwood lumber consumption volumes by industry segment reveals that six segments expanded their use of hardwood lumber over the

Table 1. Hardwood lumber consumption by major end-use products.

USER GROUP	1977	1987	% CHANGE
	Volume (million board feet)		
Pallets and Containers	2,627	4,425	68
Dimension	1,080	1,359	26
Flooring	304	476	56
Wood Household	1,250	1,058	-15
Millwork	372	713	92
Kitchen Cabinets	358	612	71
Rail Ties	1,000	635	-37
Exports	240	543	126
Commercial Furniture	221	427	93
Upholstered Furniture	254	309	22
Plywood/Structural Memb-ers/ Prefab Buildings	552	703	27
Total Consumption	8,258	11,260	36

Source: Luppold 1991.

period by more than 50 percent. In addition, three hardwood industry segments increased their hardwood lumber usage by less substantial margins between 1977 and 1987. Over the same period, only two segments saw their consumption of hardwood lumber drop. In total, hardwood lumber consumption increased by 36 percent over the ten year period.

High Value Markets for Hardwood Lumber:

Forty-two percent of the hardwood lumber consumed in 1987 was used by industries that demand predominantly, if not exclusively, 1 Common and better grade lumber. The largest markets for the upper grades of hardwood lumber are the dimension industry and the wood household furniture industry (Cardellichio and Binkley 1984; Luppold 1991). These are the market segments on which the greatest number of lumber producers focus their marketing efforts. The dimension industry and wood household furniture industry consumed 12.1 and 9.4 percent of the hardwood lumber processed by U.S. secondary manufacturers in 1987, respectively (Luppold 1991).

The millwork, kitchen cabinet, export, and commercial furniture industries also consume significant quantities of the higher grades of hardwood lumber. These industries consumed 6.3 percent, 5.4 percent, 4.8 percent, and 3.8 percent, respectively, of the total volume of hardwood lumber consumed by U.S. industries in 1987 (Luppold 1991).

Of the six industry segments that increased their hardwood lumber usage between 1977 and 1987, the export industry had the largest percentage increase in consumption (126% between 1977 and 1987; 333% between 1977 and 1990; Luppold 1991). A greater degree of value-added manufacturing is being performed by U.S. lumber producers prior to shipping to world markets, than was the case a decade ago. Twenty-three percent of the hardwood lumber volume exported in 1988 was dressed while in 1980 less than 16 percent of the volume exported was dressed (Hammett and McNamara 1991). This market segment should continue to grow as U.S. lumber producers expand their international marketing efforts.

The major export markets served by the U.S. hardwood lumber industry are Asia (34% of export volume in 1987 and 1988), Western Europe (33%), and Canada (24%; adapted from Nolley 1989). There are two major markets for U.S. hardwood lumber in Asia: Japan and Taiwan.

The major species exported to Japan in 1989, in decreasing order of importance were: 1 - alder, 2 - ash-hickory, 3 - yellow-poplar, 4 - white oak, and 5 - red oak (Luppold and Thomas 1991). The major species exported to Taiwan in 1989 were: 1 - red oak, 2 - white oak, 3 - hard maple, 4 - alder, and 5 - ash-hickory. Asian hardwood lumber markets utilize predominantly 6, 7, and 8 foot long boards and rough dimension (Araman 1987b).

Red oak comprised 39 percent of the hardwood lumber exported to Western Europe in 1988 and 59 percent of the hardwood lumber exported to Canada (Nolley 1989). White oak comprised an additional 28 percent and 5 percent of the hardwood lumber exports to Western Europe and Canada, respectively.

A study of Kentucky hardwood lumber exporters indicated that the majority of firms exported 1 Common and better grade lumber (Ringe et al. 1987). Only two of thirteen firms had developed a market for their 2A Common hardwood lumber as well.

One firm was exporting a grade called Com-Select that they were remanufacturing from 1 Common lumber. The Com-Select grade which was essentially wane-free, was being sold in lengths as short as 6 feet and widths down to 4 inches for a price comparable to that of FAS lumber (Ringe et al. 1987). Many hardwood lumber exporters are separating their lumber grades (FAS and 1 Common) in order to receive a substantial premium for their FAS bundles. Markets for clear red and white oak, cherry, and ash lumber are well established (Luppold 1987a).

The millwork and commercial furniture industries, both users of the higher grades of hardwood lumber, increased their consumption of hardwood lumber from 1987 to 1997 by 92 and 93 percent, respectively (Luppold 1991). Similarly, the kitchen cabinet industry, another user of the higher lumber grades, dramatically increased their consumption of hardwood lumber by an estimated 71 percent.

While the dimension and wood household furniture industries in combination use 21.5 percent of the hardwood lumber consumed by industry, their combined demand for hardwood lumber rose only 4 percent over the period 1977 to 1987. Hardwood lumber consumption by the wood household furniture industry decreased by 15 percent over the period. The dimension industry's demand for hardwood lumber increased by 26 percent.

A rapidly expanding market for high value hardwood lumber is the home center market. Home center hardwood board sales were predicted to increase over the period 1986 to 1991 by 138 percent in the "Top 100" (largest) home centers and by 74 percent in the "typical" firms (Cesa and Sinclair 1988). "Top 100" home centers, which cater more to the Do-It-Yourself customer and less to the professional builder than "typical" firms, carry more fixed width, fixed length boards than do "typical" firms. "Top 100" home centers carried shorter length boards with the most common length being 6 feet. Seventy-one percent of the "Top 100" home centers carried clear two-face lumber surfaced on four sides. The most important species carried was oak, followed distantly by poplar, birch, and mahogany.

Increasing demand for the higher grades of hardwood lumber will require that new raw material supplies be identified and utilized. Short, high quality logs and lumber could be used to help meet future demand. Short length lumber has already gained varying degrees of acceptance in the export and home center markets.

Lower Grade Lumber Markets:

The pallet and container industry's consumption of hardwood lumber increased 68 percent from 1977 to 1987 (Luppold 1991). Approximately 26 percent of the lumber consumed by the pallet industry was manufactured in-house (Luppold 1987a). Increases in the automation of materials handling activities led to enormous increases in demand for pallets over the last 35 years. In the 1970's many pallet producers installed primary breakdown systems and began purchasing Grade 3 sawlogs, poletimber, and pulpwood (Anderson 1986). A 1986 survey of Pennsylvania pallet producers indicated that 50 percent of the wood raw material for the industry was in the form of cants, 30 percent in the form of lumber, and 20 percent in the form of roundwood and various other miscellaneous materials (Fraser et al. 1990). The pallet industry is similar to the hardwood sawmill industry in that it is composed of many small, widely dispersed operations (Fraser et al. 1990). The pallet industry provides many rural timber owners with a market for their lower grade and smaller logs.

Since the pallet industry consumes close to 40 percent of all hardwood lumber manufactured in this country, it has a strong influence on the price of the lower lumber grades (Luppold 1991). The manufacture of pallet parts from low grade and smaller sized hardwood logs effectively sets a cap on the price of 2A Common and 3 Common hardwood lumber (Luppold 1987a).

The pallet industry is beginning to face some new pressures that may lead to a decrease in the use of hardwood lumber by the industry during the 1990's (Luppold 1991). A decrease in the use of hardwoods by the pallet industry could lead to a decrease in the utilization of lower grade and smaller logs and a corresponding decrease in the management options available to timber owners.

Other hardwood industry segments which use predominantly the Common grades of lumber are the flooring, rail tie, upholstered furniture, and prefab building segments. Consumption by these industry segments as a percentage of total hardwood lumber consumption in 1987, and the percent change in consumption from 1977 to 1987 are as follows: flooring - 4.2 percent of consumption, 56 percent increase; rail ties - 5.6 percent of consumption, 37 percent decrease; upholstered furniture - 2.7 percent of consumption, 22 percent increase; prefab buildings, structural members, and plywood - 6.2 percent of consumption, 27 percent increase (Luppold 1991; Table 1). With the possible exception of the rail tie industry, these secondary hardwood manufacturers should demand increased volumes of hardwood lumber in the 90's.

Market Intermediaries:

Wholesalers, brokers, and concentration yards play a big role in the distribution of hardwood lumber. They are particularly valuable to the small scale lumber producer and lumber user. Smaller sawmills cutting less than 5 million board feet per year sell approximately 33 percent of their production directly to the end user (Cassens and Banks 1989). The bulk of their production is channeled through an intermediary. Concentration yards and distribution yards typically perform certain processing/remanufacturing activities (grading, kiln drying, surfacing, remanufacturing to boost grade, and straight-line ripping) in addition to their distribution service.

These operations are experienced in handling a variety of lumber forms and making them available as a marketable product to either large scale users (in the case of concentration yards) or small scale users (distribution yards). Larger sawmills presently utilize intermediaries for 29 percent of their lumber volume (Cassens and Banks 1989) but could readily employ their distribution services for lumber products that accumulate slowly (e.g. short length lumber) or are hard to market locally.

Competitive Strategy in the Hardwood Lumber Industry

The competitive environment in the hardwood industry has intensified in the last decade with the entry of many low-cost international producers of consumer wood products. Market share losses by secondary hardwood manufacturers lead to reduced demand for domestically produced hardwood lumber. Steven Lawser, executive director of the National Dimension Manufacturers Association, summarized the situation in the following words (1991):

> *American and Canadian lumber producers are searching for ways to combat foreign competition. Many have already decided that survival in today's market does not depend merely on more efficiently cutting logs into lumber, with the hope that somewhere out there consumers will find uses for them. U.S. woodworkers are beginning to learn that market know-how enables other countries, including those without their own timber resources, to win customers.*

A survey of executives of 20 of the largest U.S. hardwood lumber manufacturers regarding their perspectives on the strategies and trends within the industry was recently conducted (Bush 1989). Survey results indicated that the largest hardwood lumber manufacturers tended to take a cost leadership approach to competition. The key elements of their marketing mix are competitive pricing, product availability, wide species selection, and rapid delivery (Bush 1989).

Medium-sized companies rely more on a product differentiation strategy and less on cost leadership than do the large firms. These firms produce predominantly kiln-dried rather than green lumber and are active in the export lumber market. Their attempts at differentiation are based largely on providing consistent quality, packaging, customer service, and long-term customer relationships (Bush 1989).

The largest number of hardwood lumber manufacturers fall into the small-sized category (less than 35 MMBF/year). These companies rely on channel intermediaries to market their lumber to diverse markets or they develop a close relationship with a local user. When the bulk of production goes to a single end-user the sawmill can easily become controlled by that user (a captive supplier). When brokers and wholesalers are involved in the sale and distribution of the lumber, the company loses contact with the market and thus tends away from a differentiation strategy in lieu of a production orientation (Bush 1989).

The focus strategy in which: "the firm focuses on a particular type of buyer, market group, or segment of the product line .... seeks to serve a particular target very well -- better than its competitors who are competing more broadly," (Bush 1989; adapted from Rich 1986), is not widely used by hardwood lumber manufacturers. The focus strategy is not an easy strategy to employ for a company that lacks marketing expertise as it requires skills in market segmentation and positioning (Bush 1989). Neither does the diversity of product types (species, size, quality) that are sawn at most mills lend itself to the focus strategy.

Three trends that sawmill industry executives expect to see impact the industry in coming years are: a shortening of distribution channels, increased specialization of orders, and movement of the inventory carrying function back toward primary processors (Bush 1989). Examples of the increased specialization that is being dictated by lumber markets include orders for: specific widths, lengths, and grade mixes of lumber (Bush 1989).

As sawmills adapt to the new market demands for specialized products they will be in good position to extend their product line into secondary products. Value-added products are being manufactured by some primary producers at present. Examples include: dimension stock, pallets, mouldings, millwork, flooring, stair case parts, picture frames, and clear cut-to-size boards for the DIY market (Lawser 1991). To-date it has been predominantly medium-sized sawmills that have ventured into the arena of secondary or value-added product manufacture, in particular dimension manufacture (Bush 1989). One of the advantages associated with secondary product manufacture is that lower value, shorter pieces and lesser-valued species can be more readily utilized by mills improving both volume and value recovery (Lawser 1991).

The Eastern U.S. Furniture and Cabinet Industry

Size and Importance

The wood household furniture industry (SIC 2511) was reported to have 2,948 establishments in the U.S. in 1987 (USDC-BOC 1987a). Other statistical sources report a greater number of establishments. The industry's consumption of hardwood lumber in 1987 was 1,058 million board feet or 9.4 percent of industrial hardwood lumber consumption (Luppold 1991). In addition, a significant fraction of the 1,359 million board feet of lumber consumed by the dimension industry was used by the wood household furniture industry (Luppold 1991). Bureau of Census statistics indicate that 70 percent of the firms producing wood household furniture employ fewer than 20 employees (USDC-BOC 1987a). A comparison of Census information for the industry from 1977 and 1987 indicates that there has been some industry consolidation: the total number of establishments decreased by 2.4 percent and the number of establishments with more than 20 employees increased by 5 percent.

The wood household furniture industry is concentrated in the southeast. North Carolina has led the nation in furniture production for the last several decades (USDC-ITA 1985; cited by Meyers 1991). Furniture industry establishments are also found in smaller concentrations in the Lake States and California. For each of the three largest wood household furniture industry product classes (wood living room, wood dining room and kitchen, wood bedroom furniture) the top three producing states in 1987, based on value of shipments were North Carolina, Virginia, and California, respectively (USDC-BOC 1987a).

The wood kitchen cabinet industry was comprised of 3,714 establishments in 1987 (USDC-BOC 1987b). The number of establishments for this industry segment increased by 65 percent between 1972 and 1982 (USDC-BOC 1985). While 70 percent of the firms in the wood household furniture industry have fewer than 20 employees, 68 percent of the firms in the wood cabinet industry have fewer than 10 employees (USDC-BOC 1985). Most of the smaller firms are custom cabinet manufacturers.

Hardwood lumber consumption by the cabinet industry in 1987 was 612 million board feet - 5.4 percent of U.S. industrial hardwood lumber consumption (Luppold 1991). Hardwood lumber consumption for the industry increased by 71 percent between 1977 and 1987 (Luppold 1991).

Consumption Trends

The U.S. wood household furniture industry consumes the following hardwood lumber grade mix according to a survey conducted by Bush et al. (1991): 60 percent - #1 Common, 24 percent - #2A Common, 11 percent - First and Seconds, 3 percent - Select, and 3 percent - other grades. The wood cabinet industry consumes: 50 percent - #1 Common, 32 percent - #2A Common, 10 percent - Select, 7 percent - First and Seconds, and 2 percent - other grades (Bush et al. 1991).

The major species consumed by these two hardwood industry segments was red oak. Twenty percent of the lumber consumed by the furniture industry and 49 percent of that consumed by the cabinet industry was red oak (Bush et al. 1990). When the wood household furniture industry, upholstered furniture industry, and the wood office furniture industry are combined red oak again is the top-ranked species with a 27 percent market share (Meyers 1991). For the furniture industry the next most important species were: yellow-poplar, white oak, and hard maple (Meyers 1991). For the cabinet industry the next most important species, in decreasing order of importance, were: white oak, hard maple, and yellow-poplar (Bush et al. 1990).

While the dimension and wood household furniture industries in combination use 21.5 percent of the hardwood lumber consumed by industry, their demands for hardwood lumber did not change substantially during the period 1977 to 1987. In fact, the hardwood lumber consumption by the wood household furniture industry decreased by 15 percent over the period. The dimension industry's demand for hardwood lumber increased by 26 percent. Luppold (1991) speculates that some wood household furniture manufacturers may have reorganized their rough mills into separate profit centers that were then reclassified as dimension mills. Thus, the consumption for these two hardwood industry segments should be pooled when studying material use trends. These two industry segments increased their use of hardwood lumber consumption by only 4 percent from 1977 to 1987.

The static state of hardwood lumber demand by U.S. wood household furniture manufacturers is due in large part to the increase in U.S. furniture imports. Between 1973 and 1986 the ratio of imports to apparent consumption rose from 5.4 percent to 22.6 percent (Araman 1987a). Another trend shaping the future for the wood household furniture industry is the increase in the market share of Ready-To-Assemble (RTA) furniture. RTA furniture's market share in 1986 based on shipments was estimated to have been between 3 and 12 percent of the total for the household furniture industry (Sinclair et al. 1990). Survey results indicate that sales for RTA furniture manufacturers increased by 24 percent from 1986 to 1987 and an additional 17 percent from 1987 to 1988 (Sinclair et al. 1990). RTA furniture uses more composite panels than does traditional wood household furniture (Sinclair et al. 1990). RTA producers anticipate that their use of industrial particleboard will increase more than their use of other wood and non-wood products (Sinclair et al. 1990).

Traditionally, higher priced furniture contains a higher percentage of parts made from hardwood lumber than does lower priced furniture. Expectations are that in the 1990's social and political changes will lead to income redistribution patterns that will put more spending power in the hands of the middle class (Luppold 1991). If this happens, the demand for higher-priced furniture will decrease and the demand for medium and lower-priced furniture will increase. Not only does less expensive furniture tend to be made from a higher percentage of composite panel products, softwood lumber, and plastics (Luppold 1987b), but the medium-priced furniture market has also been the most vulnerable to foreign competition (Luppold 1991).

A survey of over 3,500 furniture industry members painted a different picture of future material use trends: hardwood lumber usage rates are expected to grow by 26 percent in the wood household furniture industry, 37 percent in the wood office furniture industry, and 45 percent in the upholstered furniture industry over the three year period from 1989 to 1992 (Hardwood Manufacturers Association 1991).

Short Length Lumber Utilization

Barriers to the Use of Short Length Lumber

Without question, the largest barrier to the utilization of short length lumber by the furniture and cabinet industries (or any other value-added industry) is the historical availability of longer length lumber and lack of experience with short length lumber. Many of the physical problems associated with the use of short length lumber are related to system configurations which have been designed to handle lumber longer than six feet.

Several negative opinions and experiences related to the utilization of short length hardwood lumber by the furniture and cabinet industries were printed in the Weekly Hardwood Review (Weekly Hardwood Review 1989):

1. "In our plant the usage of short lumber indicated an increase in labor costs of 15%."

2. "Handling costs were increased not only on the green stacker but throughout the plant from unloading, drying and unstacking."

3. "Capital costs to change entire handling system would not justify change."

4. "We have a problem in running short lumber through the planer."

5. "I don't think many (sawmills) would separate the 6'/shorter so they could be handled separately."

6. "Studies in our plant have only indicated a 4-5% increase in lumber yield when utilizing short lumber."

National Hardwood Lumber Association Grade Rules

The hardwood lumber grades set forth by the National Hardwood Lumber Association (NHLA) are widely used in both North American and World markets as a means of determining hardwood lumber value. The rules provide the lumber user "with a standard on which (she)/he may base (her)/his purchase for a particular end use" (NHLA 1990).

The NHLA grade rules define the worst board that is acceptable in each of several grade categories. The standard grades of hardwood lumber which apply, with few exceptions, to all hardwood species are: Firsts, Seconds, Selects, No. 1 Common, No. 2A Common, No. 2B Common, Sound Wormy, No. 3A Common, and No. 3B Common. Firsts and Seconds (FAS) are commonly combined as one grade. All grades other than 3A and 3B Common have a graduated yield and cutting scale in which boards with smaller surface areas are required to have a higher yield of clear-face cuttings which is to be obtained in fewer cuttings. The graduated yield and cutting scale is designed to balance out the costs associated with processing smaller versus larger boards to give them roughly equivalent values. This graduated system means that short length boards need to be considerably clearer than longer boards to make the same grade (Table 2).

Each of the standard grade categories has minimum lumber length and width specifications. These minimums are more restrictive for the higher grades (frequently referred to as "uppers"; FAS, FAS-1F, and Selects) than for the Common grades. For the FAS grade the minimum board length is 8 feet and the minimum board width is 6 inches. For the Selects grade the minimums are 6 feet and 4 inches, respectively. For the Common grades the minimum board dimensions are 4 feet long by 3 inches wide (NHLA 1990). Prior to the most recent grade rule changes which became effective at the beginning of 1990, there also were restrictions as to the proportion of a shipment that could be composed of the shorter lengths of lumber within each lumber grade category. This change removed one of the more substantial grade-related barriers to the marketing of short length lumber.

The fact that lumber shorter than 8 feet in length cannot, regardless of its surface quality, be included in the FAS grade means that very high quality 6 and 7 foot long boards are graded as Selects, if this grade separation is being used, or as No. 1 Common. Similarly, 4 and 5 foot long, very high quality lumber cannot be graded better than 1 Common due to the rule which limits the minimum length of Selects to 6 feet. These length limitations within the upper grades, when combined with the graduated yield and cutting scale discussed previously, serve to "sweeten the pack" considerably for shorter length packs of Selects and No. 1 Common lumber. Despite the fact that

Table 2. The minimum clear surface area (percent) required in one rectangular-shaped piece, by lumber size and grade.

LENGTH	WIDTH 3"	4"	5"	6"
SELECTS				
6'	X	91.7%	91.7%	91.7%
7'	X	91.7%	91.7%	87.5%-A
8'	X	91.7%	91.7%	83.3%
12'	X	83.3%	83.3%	83.3%
16'	X	83.3%	83.3%	83.3%-2
NO. 1 COMMON				
4'	100%	100%	75%	75%
5'	100%	75%	75%	70.8%-A
6'	87.5%-A	75%	70.8%-A	66.7%
7'	75%	75%	66.7%	66.7%
8'	75%	66.7%	66.7%	66.7%
12'	66.7%	66.7%	66.7%-2	66.7%-2
16'	66.7%	66.7%-2	66.7%-2	66.7%-3
NO. 2A Common				
4'	66.7%	66.7%	50%	50%
5'	66.7%	50%	50%	50%
6'	58.3%-A	50%	50%	50%
7'	50%	50%	50%	50%-2
8'	50%	50%	50%	50%-2
12'	50%	50%-2	50%-2	50%-3
16'	50%-2	50%-2	50%-3	50%-4

Adapted from Wengert et al. 1986.

-A Represents the average of two possible clear-face cutting yields in cases where the surface measure could have been rounded either up or down.

-2 The grade rules permit 2 cuttings to get required clear-face yield.

-3 The grade rules permit 3 cuttings to get required clear-face yield.

-4 The grade rules permit 4 cuttings to get required clear-face yield.

these rules lead to the accumulation of high quality, relatively clear short boards in less expensive lumber grades, short length lumber of these grades is not popular. In fact, many large-scale hardwood lumber users write purchasing specifications that are more restrictive with regards short length lumber than are the NHLA grade rules.

Grading systems are used as an indicator of how a given board or batch of boards will meet the needs of a particular user for a particular product. The NHLA standard grades are widely used by the furniture, cabinet, flooring, moulding, millwork, pallet, and export industries. Grading systems for hardwood wall paneling, hardwood construction, piano key stock, etc. are also provided by the NHLA (1990).

A special grade called Milpak that was derived for the benefit of small-scale, custom furniture and cabinet manufacturers and traditional home centers, provides for the marketing of dried boards as short as 18" in length. At least 20 percent of the footage contained in any Milpak shipment is required to have two clear faces; decay, wane, splits, pith, and shake are not admitted in any form (NHLA 1990). Demand for this grade of material appears to be very limited. Medium and large-scale furniture and cabinet producers with automated rough mills will frequently purchase dimension to supplement their own rough part production but the length variability (± 6") within a pack of Milpak would lead to too much material waste - a critical factor given the higher cost of Milpak versus lumber.

Bingham and Schroeder (1976/1977) proposed short lumber grading rules intended for use by the furniture and cabinet industries. Proposed grade categories are Clear, Clear one side, Sound, and Paint grade (Bingham and Schroeder 1976/1977). One of the advantages this system would have over the Milpak system is that the primary length categories are in 6 inch intervals and the degree of variation within a pack of a given length is much more restrictive. Thus, a manufacturer needing to supplement their own production could pull in a pack of this material of a given length and quality and have very little material waste. This short length lumber grading system seems to very effectively address the needs of three of the major hardwood using industries: the furniture, cabinet, and dimension industries.

The batch grading scheme outlined by Wengert et al. (1986) represents another attempt to fashion a grading system that is tailored to meet the needs of a more specific user group. In a batch system material would be sold based on its ability to meet the cutting needs of various industry segments (e.g. shorter, clearer cutting needs for the cabinet industry versus longer, sound quality needs for the upholstered furniture industry).

Many industry analysts predict the primary processors will, of necessity, move toward value-added processing and more extensive material sorting in the near future (Lawser 1991). A grading system similar to that proposed by Bingham and Schroeder (1976/1977) will be more readily adapted when primary processors move in this direction. Until that time, the NHLA standard grades will remain the yardstick used by the furniture, cabinet, dimension, and other secondary hardwood processing industries to judge hardwood lumber quality and utility. Primary processors who seek to develop a market for their short length lumber within the NHLA system can focus on providing short length lumber that does a superior job of meeting all the important quality criteria that the industry has for longer length lumber.

A survey of lumber buyers for the millwork, dimension, flooring, furniture, and cabinet industries indicated that the fifteen most important lumber and supplier attributes that enter into the purchase decision are: 1 - grading accuracy, 2 - supplier's willingness to quote firm prices, 3 - within-load thickness consistency, 4 - supplier's ability to quote competitive prices, 5 - absence of surface checks, 6 - supplier's reputation, 7 - lumber straightness, 8 - moisture content accuracy, 9 - within-load moisture content consistency, 10 - general lumber cleanliness, 11 - the relationship with the supplier, 12 - absence of end splits, 13 -supplier's ability to provide rapid delivery, 14 - absence of wane, and 15 - previous business with supplier (Bush 1989). A producer of short length lumber will be better able to develop a market for their short material if they distinguish their product as being high quality within a particular market segment.

Lumber Drying Concerns

There are two general categories of potential problems associated with drying short length lumber. The first of these categories, and the one most frequently cited by industry personnel, includes problems associated with the handling of short length lumber: stacker and unstacker equipment limitations, forklift limitations, and low volumes per board which means more pieces to handle. The other category is related to drying quality; end checking and splitting are of particular concern in the drying of short length lumber. The majority of problems in both of these categories ultimately stem from industry's lack of experience in drying short length lumber. Mill and research studies have indicated that the drying of short length lumber need not be a major barrier to the utilization of short length lumber (Catterick 1973; Ringer 1975; Reynolds 1976; Simpson and Schroeder 1980).

Equipment problems exist because equipment manufacturers and mills have focused their attention on the processing of lumber longer than 8 feet in the past. The flexibility to handle pieces shorter than 8 feet does not exist in many secondary processing operations. The lack of demand for short length lumber has in turn resulted in some sawmills designing new trimmer and sorter stations which lack the flexibility to handle shorter lengths.

The handling of short length lumber packages by forklifts may pose a problem for some companies. The large size forklifts that are required for handling longer length green lumber typically have an optimal fork spacing in which the forks are separated by 4 feet or more. This spacing must be reduced to allow these large lifts to readily pick up short length lumber packages. The movement of the forks can be both time consuming and physically demanding. The incorporation of hydraulic fork positioners by forklift manufacturers would eliminate this problem. Once the forks are properly positioned another problem arises. Many large forklifts have such a substantial boom that the vision of the operator is blocked for operations that are straight-ahead and low to the ground. The precision required in picking up short packages with these big lifts would pose a considerable challenge.

Many companies that dry hardwood lumber also operate smaller forklifts. This is particularly true for secondary hardwood processing operations but may not be true for some sawmills. These forklifts can readily handle most smaller package sizes. Their small size also enables them to maneuver in smaller spaces. It has been suggested that short length lumber, especially if packaged in even length packages and moved by small forklifts, will contribute to improved space and kiln utilization (Bingham and Schroeder 1976/1977). Package densities for short length lumber that is sorted by length are considerably higher than for conventionally packaged longer length lumber (90 percent versus 70 percent; Bingham and Schroeder 1976/1977). Dry kiln control and moisture content variation could be improved if the placement of short length lumber stacks within the kiln serves to reduce air bypass (Bingham and Schroeder 1976/1977).

A major problem encountered in drying oak lumber and the other "refractory" or hard-to-dry species is the tendency for these species to check and split during the early stages of drying. End checks occurring on short boards have a greater impact on yield percents than is the case for checks occurring on longer length lumber (Bingham 1976). Three inch long checks occurring on each end of a 12 foot long board, when crosscut out, reduces the potential part yield of the board by 4.2 percent. The same length end checks on a 4 foot long board reduce the potential part yield of the board by 12.5 percent.

The results of two case studies in which short lumber was manufactured from short bolts then dried and processed into furniture parts indicate that short length parts can be dried quite satisfactorily with minimal effort above and beyond that which is normally required in drying standard length lumber (Reynolds 1976; NC-DFR 1979). In both of these cases the short lumber was sticker-stacked as it was pulled from the sawmill green chain. In one case a Saw-Dry-Rip (SDR) approach was taken in which the unedged red oak boards were stacked and dried (NC-DFR 1979). Special stacking carts were configured for this operation which contained jigs for sticker alignment (NC-DFR

1979). In the second short length lumber drying operation edged yellow-poplar boards were sticker-stacked then banded with polypropylene strapping. As the stacks dried the banding was tightened to hold the pack together during subsequent handling operations (Reynolds 1976).

In the red oak drying operation the short lumber stacks were air-dried then kiln dried using the Forest Products Lab's T4D2 schedule (NC-DFR 1979). Warp and cupping were noted for the longer length lumber that was produced in the operation but only rarely for the shorter lumber (≤7'; NC-DFR 1979). This effect was attributed to the fact that the stacking of the short length lumber was done with great care given to sticker placement particularly at the ends of the boards (NC-DFR 1979). The quality of the stacking job also minimized the occurrence of end checks. The only seasoning defect that was pronounced in the short length lumber was honeycomb. Honeycomb was evident in some, but not all kiln charges, and seemed to occur when there was a large variation in the initial moisture content of the lumber (NC-DFR 1979).

Information of a more quantitative nature than is provided by these two case studies is available from three research studies that looked at the drying of short length hardwood pieces. In one of these studies mixed hardwood dimension parts which ranged in length from 14 inches to 82.2 inches were dried using six different treatment combinations: mild, conventional, or accelerated kiln schedules; with or without end-coating (Simpson and Schroeder 1980). Neither the kiln schedule nor the end treatment was found to have a significant effect on the rate of rejection of the parts for interior frame manufacture (Simpson and Schroeder 1980). It should be noted however that the period of time between when the parts were cut and the samples were end-coated may have been on the order of hours or days rather than minutes since the treatment samples were assembled prior to end-coating. Immediate end-coating has been determined to be much more effective in reducing checking than is delayed end-coating (Wengert and Lamb 1990).

Differences in drying times between the short and long cuttings were noted for pieces dried using the intermediate kiln schedule (Simpson and Schroeder 1980). The 14 inch cuttings reached final moisture content in 21 days while the 82 inch cuttings required 24 days to dry to an average nominal moisture content of 7 percent (Simpson and Schroeder 1980). Most notably, part length was found to have a statistically significant effect on the rate of rejection of parts (Simpson and Schroeder 1980). Approximately 40 percent of the longest length cuttings were rejected, mostly due to crook. In contrast, less than 4 percent of the parts that were shorter than 20 inches were rejected (Table 3). No parts were rejected due to end checking (Simpson and Schroeder 1980).

In the second research study No. 2A Common, air-dried, red oak lumber was purchased from a sawmill and divided into three samples (Rice 1964). In two of the three treatments the boards were cut into clear one-face dimension parts and then kiln-dried. One of these treatments was end-coated. As with the previously discussed research study, the end-coating was applied too late to be maximally effective. The third group of boards was kiln-dried prior to being cut into dimension parts. All three sample groups were dried using the Forest Products Lab's T4D2 schedule. The yield of usable parts was 41 percent for the group in which dimension parts were dried without the application of end-treatment. The group which was end-treated yielded 46 percent usable parts.

Table 3. The effect of cutting size on the rate of rejection of cuttings caused by drying defects.

CUTTING SIZE		REJECTION RATE
LENGTH	WIDTH	
(INCHES)	(INCHES)	(PERCENT)
14	1-1/4	3.9
14-7/16	1-1/8	3.2
16-1/2	2	0.7
21	3-1/2	2.6
22-1/2	1-1/8	2.9
26-7/16	3-1/8	1.8
28-7/16	2	9.5
29-1/2	2-3/4	7.9
31	5-1/4	25.9
80	2	40.0
80	3-1/8	34.2
82-3/16	2-3/4	45.7
82-3/16	3-1/4	39.0

Source: Simpson and Schroeder 1980.

The difference between these yields was statistically significant. The yield for the third group in was also 46 percent but the yields within this treatment were so variable that the yield was not significantly different from either treatment in which dimension parts were dried.

One of the advantages of drying dimension parts and short lumber is that the dry kiln's space is occupied by a higher percentage of usable material. Rice (1964) estimated the cost differences between the three treatments in his study. The results indicate that the costs associated with drying parts are lower per volume of usable parts than are the costs associated with drying the No. 2A Common lumber.

In the third research study short length red oak lumber was dried using recommended kiln practices which included end-trimming to length, end-coating, stickering at ends of boards, and surfacing to an even 1-7/16 inch thickness (Ringer 1975). Two-hundred and thirty-nine boards were defect-mapped prior to kiln drying so that an analysis of potential clear two-face cutting yields could be performed using the program YIELD cut-up simulator. After the boards were dried to a nominal 6 percent moisture content they were reevaluated. Thirty-six of the 239 boards developed end splits that had an affect on cutting yield but the yield difference attributable to the end splits was less than 10 percent in all but 7 of these boards (Table 4). Fifty-two percent of the end checks which developed during drying were removed by end-trimming one inch off the ends of the boards. By trimming 3 inches off the ends another 22.6 percent of the boards with end checks were successfully defected.

The four, five, and six foot lumber lengths were also measured for the various forms of warpage (Ringer 1975). More of the 4 foot boards were warped than were the

Table 4. Number of boards out of a total of 239 boards with reduced cutting yield due to various drying-related defects.

Yield Loss	Shake	Pith or Heart	End Splits	Checks with Defects	Surfac e Checks
1-5%	5	11	22	10	3
5-10%	2	4	7	3	1
10-20%	6	12	3	2	4
20% +	6	3	4	1	3

Source: Ringer 1975.

5 and 6 foot boards but the degree of individual board warpage was not considered severe. The warpage of the 4 foot boards was attributed to the fact that these boards were located at the top of the kiln stacks (Ringer 1975). While the 4 foot lumber was more frequently bowed and twisted than was the longer length lumber, the 6 foot lumber had the greatest occurrence of crook. Only in a few cases did the crook affect the cutting yield by more than 10 percent.

Material Handling Equipment

The most frequently cited problem associated with the use of short length lumber by secondary hardwood manufacturers is the inability of existing material handling equipment to stack/unstack/surface/cut/convey the short pieces. Handling equipment limitations may also be a problem for some primary producers.

Equipment problems exist because equipment manufacturers and mills have focused their attention on the processing of lumber longer than 8 feet in the past. The flexibility to handle pieces shorter than 8 feet does not exist in many secondary processing operations. The lack of demand for short length lumber has in turn resulted in some sawmills designing new trimmer and sorter stations which lack the flexibility to handle shorter lengths.

The most common equipment limitation in both sawmills and furniture and cabinet rough mills is the spacing between chain sections on chain conveyors. The solution to this problem is clearly a matter of adding one or two appropriately spaced chain sections that will keep short pieces from skewing and dropping through. Another frequently cited problem is the difficulty in transporting small lumber packages with large forklifts. Some manufacturers sidestep this problem by putting 8 foot long boards on the bottom layer of a package of short length lumber. The short lumber is then either box-piled or packaged with short boards butted end-to-end. A more extensive discussion of forklift options for handling short length lumber is included in the previous section: "Lumber Drying Concerns."

The number of problems associated with handling short lumber in any operation depends on the number of processing operations which the lumber goes through, the degree of automation, and the level of specialization of the system's equipment for longer lumber. If short length lumber is cut on the sawmill's headrig, many machine centers in the mill must be adapted to handle the short lumber. If short length lumber is generated at the trimmer, then only the trimmer and sorting line, and forklift need to be able to handle the short material. In a rip-first furniture or cabinet rough mill the length of the lumber remains an issue until the lumber gets to the chop saws. In a crosscut-first furniture rough mill all operations that follow the crosscut operation are adapted to handling parts; lumber length distinctions are lost as soon as the crosscut operation has been performed.

Automatic sorting systems are becoming somewhat more commonplace in the hardwood sawmill industry with the growing demand for more grade and length-based sorts for high-value markets. Both capital and labor would probably be needed to adapt these systems to handle lumber shorter than 8 feet. In contrast, a manual sorting system should be much more readily converted over to handle short lumber. In the rough mill of a secondary processing operation the adoption of short length lumber as a raw material source will likely require more changes for systems in which chains and belts perform most of the transport operations rather than people and batch-loaded carts.

For the most part, the equipment which is being used which is not readily able to process short lumber is relatively new equipment. At a time when most industries are discovering the value of flexible manufacturing systems, the hardwood industry is making capital investments that lead to less flexible operations. Visits to various drying and rough mill operations have suggested that the following equipment limitations may be commonplace:

1. Planer/surfacer hold down systems not designed for short material lead to problems with boards stalling in the machine and may represent a safety hazard to operators in some cases.
2. Stacking and unstacking hoists have supports (knees) that are spaced to handle lumber longer than 8 feet (NC-DFR 1979).
3. Stick guides on automatic stackers may not be optimally spaced to allow placement of sticks within the last couple inches of short boards.
4. Limit switches (electronic eyes) on some equipment are unable to detect 4 and 5 foot lumber which can lead to misfeeds and handling problems.
5. Stops on accumulating conveyors that are widely spaced can cause short boards to skew when pressure, due to accumulation, is applied.

It is the general consensus of industry process control experts who have studied the feasibility of short length lumber utilization, that in most cases these equipment problems could be fixed quite readily (Reynolds 1976; Bingham and Schroeder 1976/1977). In some cases the equipment manufacturer might have to be brought in to make the necessary modifications. However, in the majority of cases the remedy would be little more than a few weekends of shop and/or maintenance work.

Processing Rates

Very little has been written about the effect of lumber length on processing rates and production costs in secondary hardwood processing operations. With short lumber more boards must be handled to obtain a given volume of parts. It is generally agreed that this has the effect of increasing production costs per unit of output volume (Bingham 1976; Wengert et al. 1986). Bingham's (1976) discussion of the handling problem is very descriptive:

> *With short lumber averaging four feet in length there are three times the number of pieces to handle than with the same volume in lumber averaging twelve feet in length. There are more pieces to be graded, counted, stacked and fed into the cut-off saw.*

One offsetting factor to consider when looking at handling rates and costs, is that the manual handling of short pieces can be performed more quickly and with less fatigue and strain than would be required in handling long lumber (Bingham 1976). Another factor which may be very hard to assess but which could be very valuable in high production rough mills is the potential for using short length lumber at times when long length lumber is backing up at various machine centers. For example, the insertion of a pack of 4 or 5 foot lumber when the rip saws in a crosscut first rough mill are backing up the system, could serve to smooth production flow.

Although no quantitative information pertaining to the effect of lumber length on processing rates and costs has been published, it has been determined that production costs in a crosscut-first furniture rough mill increase as part length decreases (Anderson 1983). The inverse relationship between part length and cost exists for the second stage of production within the rough mill which Anderson (1983) has defined as being from the length sorting operation to finished rough sizing. It seems fair to expect that various lumber processing operations would exhibit the same length-cost relationship as the ripsaw operation in Anderson's simulated rough mill: short parts are more costly per board foot to produce since more pieces need to be handled to obtain a given finished rough part volume.

Yield Expectations

Secondary hardwood manufacturers' lack of experience with short length lumber contributes to the notion that short length lumber yields are not as good as long length lumber yields. As has been discussed previously, end checks and splits have a greater impact on yield for short boards than for long. In addition, the potential cutting yield of short lumber may be lower than that of long lumber for some cutting bills given the fact that with short cutting bills there are fewer potential cutting combinations that can be extracted from the board. This makes it much more difficult with some cutting bills to efficiently place cuttings on shorter boards (Wengert et al. 1986). This points to the importance of using discretion in matching lumber input and cutting needs. The furniture industry has been cited for its failure to use such discretion in choosing the best lumber grade to input for given cutting bills to obtain maximum value yield over time (Helmers 1979).

In fact, it appears that cutting yields from short length lumber are at least as good as those from longer lumber. In one rough mill in which short lumber produced on a bolter saw was being processed into furniture frame stock the yield of the short length lumber was equal to or higher than that of No. 2A Common long length lumber in six of the seven quarters surveyed (NC-DFR 1979). Several factors contributed to this result: the short material off the bolter saw was unedged, it had fewer drying defects, and it was straighter-grained than the longer length lumber (NC-DFR 1979).

The results of a more controlled study conducted at the same mill provide a grade-based breakdown of the yield from short length lumber (4, 5, 6 feet long; Ringer 1975). The yields of clear two-face cuttings were 69.4 percent for the No. 1 Common, 58.4 percent for the No. 2A Common, and 48.4 percent for No. 3A lumber. No differences in yield were observed between the 4, 5, and 6 foot lumber. A comparison was made of these yields with those expected for standard length lumber. Standard length lumber yields were obtained from the Forest Products Lab nomograms. Both the nomogram yields and the short length lumber yields were based on simulation runs using program YIELD. Cutting yields from the short length lumber were higher in each grade category but the differences were not statistically significant. In a similar study the yield obtained from short lumber ranged from 70 to 85 percent versus 60 percent for longer length No. 1 Common red oak (Huffman 1973, Huber and Kroon 1974; cited in Bingham 1976).

Concerns about the yield of short length lumber are often more appropriately expressed as concerns about the yield of longer length parts from short length lumber. These concerns were initially addressed by Bingham and Schroeder (1976/1977) who surveyed the cutting needs of several furniture manufacturers over time. Their results indicated that a large percentage of the cutting needs were in lengths shorter than 42 inches.

A larger-scale and more structured survey of major furniture and cabinet manufacturers gave similar results (Araman 1982). Solid wood furniture cutting length information provided by the survey respondents indicated that 62 percent of their cutting needs were 3 feet long and shorter (Table 5). Approximately 60 percent of the cutting length needs for veneered furniture are equal or shorter than 3 feet. The lengths needed for upholstered furniture span a larger range but again, are predominantly (75%) shorter than 3 feet in length. One-hundred percent of the parts required in the manufacture of recliners are less than or equal to 3 feet in length. Cutting length requirements for kitchen cabinets, like upholstered furniture, span a wide range of lengths with the majority (80%) being 3 feet or shorter. These results indicate that most furniture and cabinet industry manufacturers cut only a small percentage of parts that are clearly too long to be obtained from lumber that is 4 to 7 feet in length.

Information on the relationship between lumber length and the yield of various length parts is very limited. In one yield study the yield of the longest length cuttings (31") in a cutting bill was found to be independent of lumber length, however only a very narrow range of lumber lengths were tested (Ringer 1975). In a second study, the yield of short (less than 40") versus long (greater than or equal to 40")

Table 5. Wood furniture and cabinet industry cutting length needs.

Product Category	Percentage of Needs Less Than or Equal to 3 Feet	Percentage of Needs Longer Than 6 Feet
Solid Wood Furniture	62	3
Veneered Furniture	60	7
Upholstered Furniture	75	12
Recliners	100	0
Kitchen Cabinets	80	4

Adapted from: Araman 1982.

parts obtained in a non-conventional gang-rip rough mill was compared for 4 through 8 foot boards. The average yield of "long cuttings" was only 10 percent for the 4 foot lumber but the average yields for the 5 through 8 foot length categories ranged between 30 and 40 percent (Reynolds and Schroeder 1978).

Short Length Lumber Production and Utilization Opportunities

Short length lumber could conceivably be produced in a variety of ways into a variety of forms. The production of short length lumber from short bolts that would normally be left in the woods or processed into pulp would have the greatest impact on the utilization and management of eastern hardwood timberlands. This means of short length lumber production represents the largest deviation from common sawmill operating practices. Smaller quantities of short length lumber can be produced with the introduction of smaller-scale changes in sawmill practice.

Short Log Utilization

Much of the research that has been done on short log sawing has focused on the mechanics and economics of producing furniture parts rather than lumber from the short bolts (Rosen et al. 1980; Stewart et al. 1982; Huber et al. 1983). This form of processing, termed the "Tree-to-Dimension Concept" (T-D) by Bingham (1976) is a very promising approach to value-added manufacturing that is currently receiving a lot of attention. For the small primary producer equipped with a bolter saw, production rates will probably not exceed a few thousand board feet a day (NC-DFR 1979). These production levels are not high enough to keep edger and trimmer saws operating at anywhere near full utilization. If rip and cut-up saws were put in their place pieces could be produced to the quality and length specifications of one or two primary producers. These pieces would be of higher value than short length lumber since they would be cut-to-size and essentially defect-free.

One of the problems with small-scale T-D production is that small sawmills rarely have dry kilns. Lacking dry kiln capacity the sawmills will be producing green dimension and selling it to users who are drying standard lumber lengths in conventional drying systems. Short length lumber cut to even 4, 5, 6, and 7 foot lengths would likely require far fewer and less costly stacking and drying system modifications than would dimension parts of various lengths and narrower widths.

For larger mills that might be considering the short length lumber and T-D options, a consideration would have to be the present mill layout and the availability of capital. Cutting logs directly into dimension would require an existing mill that plans on continuing its production of standard N.H.L.A. grade lumber to add rip and crosscut saws which in turn might require that the sawmill's roof be expanded. It would also require retraining mill employees; they must be able to understand and adapt to the different sawing/edging/trimming treatments required for the dimension material. Cutting shorter logs into short length lumber would require a smaller capital investment. Certain quality attributes of the short length lumber could be easily changed to match the demands of customers through minor alterations in edging and trimming practices.

Most of the short log processing mills which are in operation are owned and operated by vertically integrated furniture companies (Flann 1977). The key, at present, to a successful, independently owned short log operation, would seem to be identifying potential customers, understanding their quality needs, and negotiating a contract to supply material that matches those needs. Essentially this means becoming a captive supplier for a steady customer.

As was discussed in an earlier section, secondary processors handling equipment is in many cases unable to handle material shorter than 6 or 8 feet in length. Primary producers will find a wider market for short material if they perform some of the handling and processing operations which secondary processors have problems with. Thus, short log/lumber mills that can provide high quality kiln-dried lumber/dimension will probably find customers quite readily. For mills that lack dry kilns, those that trim, stack, and bind short material to form single length stacks will find customers more readily than will those that provide conventionally packaged, short length green lumber.

Sawmill Value-added Product Opportunities

Most conventional, long-log oriented hardwood sawmills, have the potential to produce more lumber shorter than 8 feet in length than they are presently producing. In fact, many sawmill operators will tell you that they used to produce more short lumber but they reduced their output as furniture companies became less willing to buy the short material. At the majority of eastern hardwood sawmills, material that could be cut into short length lumber is being converted to chips instead.

The minimum price at which short lumber would have to be sold to obtain an equivalent value to that which would be obtained if the material were converted to green chips may be as low as $214/mbf in some situations (Barrett 1989). This figure was calculated using a green chip price of $50/ton which is close to double the price which is being received for green chips in most areas of the east. This calculation uses a delivered log cost of $80 per MBF-Doyle. The breakeven sales price for short length lumber decreases as the delivered log cost increases. Reported delivered log prices for red oak factory grade 1, 2, and 3 logs in the fall of 1988 were $449, $266, and $125 per MBF-Doyle, respectively (Nolley 1989). When similar production cost and conversion rate assumptions to those used by Barrett (1989) are combined with adjusted chip price and log price estimates, lower breakeven short length red oak lumber sale prices are obtained (Table 6). The lowest short length lumber breakeven price estimate, which incorporates a chip sales price of $20 per green ton and a delivered log price of $449 per MBF-Doyle, is $76 per thousand board feet of green lumber.

The difference between the breakeven short length lumber price and the current asking price for green hardwood lumber (e.g. $510/mbf for 4/4 No. 1 Common Appalachian red oak; Weekly Hardwood Review 1991) represents the relative value of the short length lumber versus chips. Put in different terms, this margin represents the opportunity cost associated with producing chips rather than lumber from material being processed in the sawmill.

This difference provides a margin which can be used for either short length lumber price discounts or more extensive and costly processing operations (e.g. trimming the lumber to even lengths, sticker-stacking and banding the lumber) that will help develop a market for the material. The estimated average manufacturing costs used in the breakeven analysis could vary considerably between mills. The relative cost of manufacturing green chips versus short length lumber would also vary within a mill

Table 6. Calculations of breakeven short length lumber sales prices for different log cost and chip price levels.

ANALYSIS:	Chips: $50/ton Log Price: $80/MBF	Chips: $20/ton Log Price: $449/MBF	Chips: $20/ton Log Price: $266/MBF	Chips: $20/ton Log Price: $125/MBF
CHIP ANALYSIS				
Chip Yield per MBF logs	#5800	#5800	#5800	#5800
X Chip Price per Ton	$50	$20	$20	$20
= Chip Revenue	$145	$58	$58	$58
- Chipping Cost	$20	$20	$20	$20
- Log Cost per MBF	$80	$449	$266	$125
= Chip Profit/MBF Logs	$45	-$411	-$228	-$87
LUMBER ANALYSIS				
Log Cost per MBF	$80	$449	$266	$125
÷ Lumber Yld/MBF	1160 bf	1160 bf	1160 bf	1160bf
= Material Cost/MBF	$69	$387	$229	$108
+ Manufact. Cost/MBF	$100	$100	$100	$100
= Total Cost per MBF	$169	$487	$329	$208
BREAKEVEN PRICE				
Lumber Cost/MBF Logs	$169	$487	$329	$208
+ Chip Profit/MBF Logs	$45	-$411	-$228	-$87
= Breakeven Lumber Price Per Mbf	$214	$76	$101	$121

Adapted from: Barrett 1989.

depending on which machine center produces the short lumber. If a crooked log is bucked into two shorter logs and short boards are generated from these logs, the short lumber manufacturing costs will be higher than if the short boards are generated by the headrig saw taking an extra pass through a log with a swollen butt. The least costly means of producing short length lumber is simply to complete the processing of short material that is presently being generated but is being dropped into the chipper system.

A low cost, lower value margin form of short length lumber can be generated at the trim saw. This lumber is produced by trimming a lower grade, longer length piece of lumber back to recover a higher grade, short length piece of lumber. An example of this would be trimming a 10 foot long, 6 inch wide, No. 2A Common board (approximate value = $1.20) to get a 7 foot long No. 1 Common board (approximate value = $1.78). This option only exists for sawmills that have a market for short length lumber that is comparably priced to that which they have for longer length lumber. Performing value-added trimming requires either that the grader is located in front of the trim saw, or that the trimmer operator knows the basics of the N.H.L.A. grade rules and has time to apply this knowledge. It also requires that the trim saw has the flexibility of trimming short lengths by removing footage off either end of the board. The manufacturing cost of this short lumber would be the same as that of the long lumber unless further value-added operations are performed on the short boards to improve their marketability.

Another means of obtaining short length lumber from long logs involves remanufacturing material that has already passed entirely through the sawmill. Boards whose value could be increased through remanufacturing would be designated by the grader. They would be separated and sent to a remanufacturing operation or reintroduced into the sawmill for additional processing at an appropriate time. The board evaluation procedure would be similar to that proposed for the in-mill production trim saw, however the short versus long value comparison would have to include consideration of remanufacturing costs. A computer program named HaRem has been developed that can be used as a training tool to help the grader and other mill personnel recognize value-added remanufacturing opportunities (Schwehm et al. 1990). This program has been designed to tie in with automatic defect detection and grading systems being developed within the ALPS research program (McMillin et al. 1984).

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AN ANALYSIS OF VARIOUS LUMBER ATTRIBUTES THAT AFFECT THE PRODUCTION AND UTILIZATION OF SHORT LENGTH LUMBER

Section 2

Abstract

Opportunities for producing higher grade short length lumber by value-trimming lower grade, longer length lumber were investigated. Fifteen percent of the 8 and 9 foot long, 1 Common, red oak lumber and 49 percent of the 8 and 9 foot long, 2A Common lumber inspected could be trimmed to a higher grade, higher value short board (< 8 feet long). The average value increase for the short boards produced by end-trimming was 38 cents for boards upgraded from 1 Common to Selects, and 45 cents for boards upgraded from 2A Common to 1 Common.

A data bank of defect-mapped red oak boards was used to compare short length lumber with long length lumber with regard to various defect characteristics that are important in lumber utilization. The two defect categories which showed the most significant variation between lumber length groups were crook and wane. The average crook deviation for 16 foot long boards was over one-half inch while the average deviation for 4 and 5 foot long boards was less than one-tenth inch. Wane made up a higher percentage of the total defect area for short boards than for long boards.

The yield of clear-face cuttings of required minimum sizes as specified by the National Hardwood Lumber Association grade rules was examined using the same data bank. This information gives an indication of the relative yield of longer parts which a

secondary processor might expect to obtain from the lumber. For all three lumber grades examined the grade cutting yield was higher for short boards than for long boards and the number of cuttings required to obtain the yield increased with board length.

Introduction

Short length lumber (SLL; lumber shorter than 8 feet long) can be generated by various means within present sawmilling operations. These means include: value-trimming boards, recovering a short board from logs with swollen butts by making an extra pass on the headrig, and saving short boards which are presently being generated but are being diverted to the chipper. Value-trimming of lumber can occur in one of three ways: 1 - the grader may be positioned in front of the trim saw in order to make value-added trimming decisions and marks on the boards as is common practice in the softwood lumber industry, 2 - the trimmer operator may be trained in the grade rules and have responsibility for making value-added trimming decisions which are fairly clearcut, or 3 - remanufacturing operations may be performed on the board based on post-trimming decisions made by the grader. If the value-added trimming is performed as the board passes through the sawmill trimmer the first time there are no remanufacturing costs associated with the operation.

A computer program called HaRem (Hardwood lumber Remanufacturing program) has been developed which is designed to interface with computer vision systems to grade a board then determine value-added edging and trimming remanufacturing solutions (Schwehm et al. 1990). While the grading module which this program employs is not the most accurate and reliable version of the grading program (conversation with Klinkhachorn et al. 1990) in existence today, it does highlight the value-added opportunities which lumber remanufacturing can offer.

Short length lumber production opportunities such as value-added trimming are not pursued by most hardwood sawmills due to a lack of demand for short hardwood lumber by secondary wood products manufacturers. While there is a basic problem associated with the handling of short length lumber which needs to be understood and overcome before short length lumber markets will open up on a large scale, lumber manufacturers should be able to produce and market smaller quantities of short lumber. Information regarding the lumber quality attributes demanded by several high-value hardwood lumber market segments is available (Bush 1989). If lumber manufacturers can deliver a short length board product that is accurately graded with consistent thickness and moisture content, well-dried with minimum surface checks and end splits, clean, straight, and competitively priced, they will be much more likely to find markets for any short length lumber which they are capable of producing at present.

Information about any differences that might exist between short and long length lumber with regard to defect occurrence could be used in planning a short length lumber marketing strategy. A recently completed study of defect occurrence in red oak lumber looks at defect counts and areas by lumber grade group but not by lumber length (Harding 1991).

Methodology

The analyses within this study were performed on data collected by the U.S. Forest Service, Northeastern Forest Experiment Station, Forestry Sciences Laboratory in Princeton, West Virginia. The data consists of board defect information collected on more than 1200, 4/4-inch thickness, red oak boards. The boards which comprise the sample were collected from three mills; two of the mills were grade sawmills which sawed to a center cant (Gatchell and Wiedenbeck 1992). Green lumber was obtained from these mills. The lumber was dried using a mild kiln schedule at the Princeton Forestry Sciences Laboratory. Kiln-dried lumber was obtained at the third mill. All boards were graded using the National Hardwood Lumber Association's (NHLA 1991) Special Kiln Dried Rule. This grading method was chosen because the resulting grades more accurately predict furniture cutting yields than do the grades assigned using the Standard Kiln Dried Rule (Gatchell 1992).

The sample was randomly chosen with regard to defects but was designed to assemble 1 Common and 2A Common data banks with predetermined board width and length distributions (Gatchell and Wiedenbeck 1992). An attempt was made to fill cells of given length and width combinations with a predetermined number of boards. The size of each cell was based on sampling information provided by Lucas and Catron (1973) which was designed to represent the size distribution of the red oak lumber resource. In collecting this sample the narrow width cells filled up quite quickly but wider boards were harder to find (Gatchell and Wiedenbeck 1992).

All boards within the data bank were initially graded by an NHLA grader. When the mapped board data was input into the HaRem program (Schwehm et al. 1990) to assess remanufacturing opportunities the grades returned by HaRem differed on many boards from those assigned by the NHLA grader. The board data was then input into the HaLT program which contained the same grading module but also contained explanations of the grading process for each board (Schwehm 1989). The HaLT program, designed as a lumber grading tutorial, was unable to handle certain grade and defect considerations which were encountered during the grading of the several hundred boards in the data bank. The HaLT2 revision (Klinkhachorn et al. 1991) of the HALT program, which contains a more accurate grading module, was used in combination with to-scale plots of each board, to assign the final grades.

The potential for producing short length lumber of a higher grade and value by end-trimming lower grade/value longer boards was investigated initially using the HaRem program (Schwehm et al. 1990). It was discovered that HaRem missed some remanufacturing opportunities, in particular opportunities to upgrade 2A Common boards to 1 Common. The same to-scale plots which were used for grading the lumber were used to evaluate value-added trimming opportunities missed by the HaRem program.

Value-added trimming decisions may vary depending on the assumed manufacturing costs and lumber prices employed in the analysis. Lumber prices employed in the analysis were taken from a November, 1991 Weekly Hardwood Review (Anonymous). The prices used were: $300 per thousand board feet (mbf) for No. 2A Common, $545 per mbf for No. 1 Common, and $775 per mbf for Selects. It was assumed that any trimming operation resulting in higher value boards could be performed as the boards passed through the trimmer the first time. Given this assumption no remanufacturing costs were applied in the analysis. Value-added solutions which involved edging were not included in this analysis. The visual identification of boards with upgrade potential was generally much easier for the 1 Common boards than the 2A Common boards.

Defect distributions for short and long boards (short boards being less than 8 feet long) were tabulated using one of two FORTRAN programs written to sum and average individual board defect data. The yield of clear-face cuttings of required minimum sizes and the average number of cuttings taken to obtain the specified yield were obtained from the HaLT2 program (Klinkhachorn et al. 1991).

Results

Value-added Trimming to Produce Short Length Lumber

A large percentage of the 1 Common and 2A Common, 8 and 9 foot long boards surveyed would be more valuable if they were end-trimmed to produce a higher grade/value board. This is the case for 49 percent of the 41, 8 and 9 foot long 2A Common and 15 percent of the 102, 8 and 9 foot 1 Common boards inspected (Table 7). All of the 8 and 9 foot boards so trimmed yielded short length lumber. Examples of 1 Common boards that could be trimmed to short Selects boards of higher value are shown is Figures 1, 2, and 3. Examples of 2A Common boards that could be trimmed to short 1 Common boards of higher value are presented in Figures 4, 5, and 6. In each of these figures, side 2 of the boards shows the defects as they would appear if one could see them by looking through side 1 (as if side 1 were transparent). The poorer side of the original board (the grading face) is designated as Side 1.

For the 10 and 11 foot long lumber, 11 percent of the 107, 1 Common boards examined could be value-trimmed but only 17 percent of the trimming solutions (2 of 12) would yield lumber shorter than 8 feet long. Thirty-nine percent of the 38, 10 and 11 foot

Table 7. Short lumber obtainable by value-trimming red oak boards.

Original Lumber Grade: 1 Common	Original Board Length			
	8'-9'	10'-11'	12'-16'	Total
# of Boards Surveyed	102	107	166	375
# of Boards Value-Trimmed[a]	15	12	13	40
% of Boards Value-Trimmed	15	11	8	11
Average Value Increase Per Board ($/mbf)				399
# of Short Boards Produced	15	2	0	17
% of Boards That Yielded a Higher Value Short Board	15	2	0	5
Average Value Increase Per Short Board Produced	38¢			
Original Lumber Grade: 2A Common	**8'-9'**	**10'-11'**	**12'-16'**	**Total**
# of Boards Surveyed	41	38	51	130
# of Boards Value-Trimmed[b]	20	15	21	56
% of Boards Value-Trimmed	49	39	41	43
Average Value Increase Per Board ($/mbf)				596
# of Short Boards Produced	20	8	1	29
% of Boards That Yielded a Higher Value Short Board	49	21	2	22
Average Value Increase Per Short Board Produced	45¢			

a- Trimming decision based on assumed prices of $545/mbf for 1 Common and $775/mbf for Selects.

b- Trimming decision based on assumed prices of $300/mbf for 2A Common and $545/mbf for 1 Common.

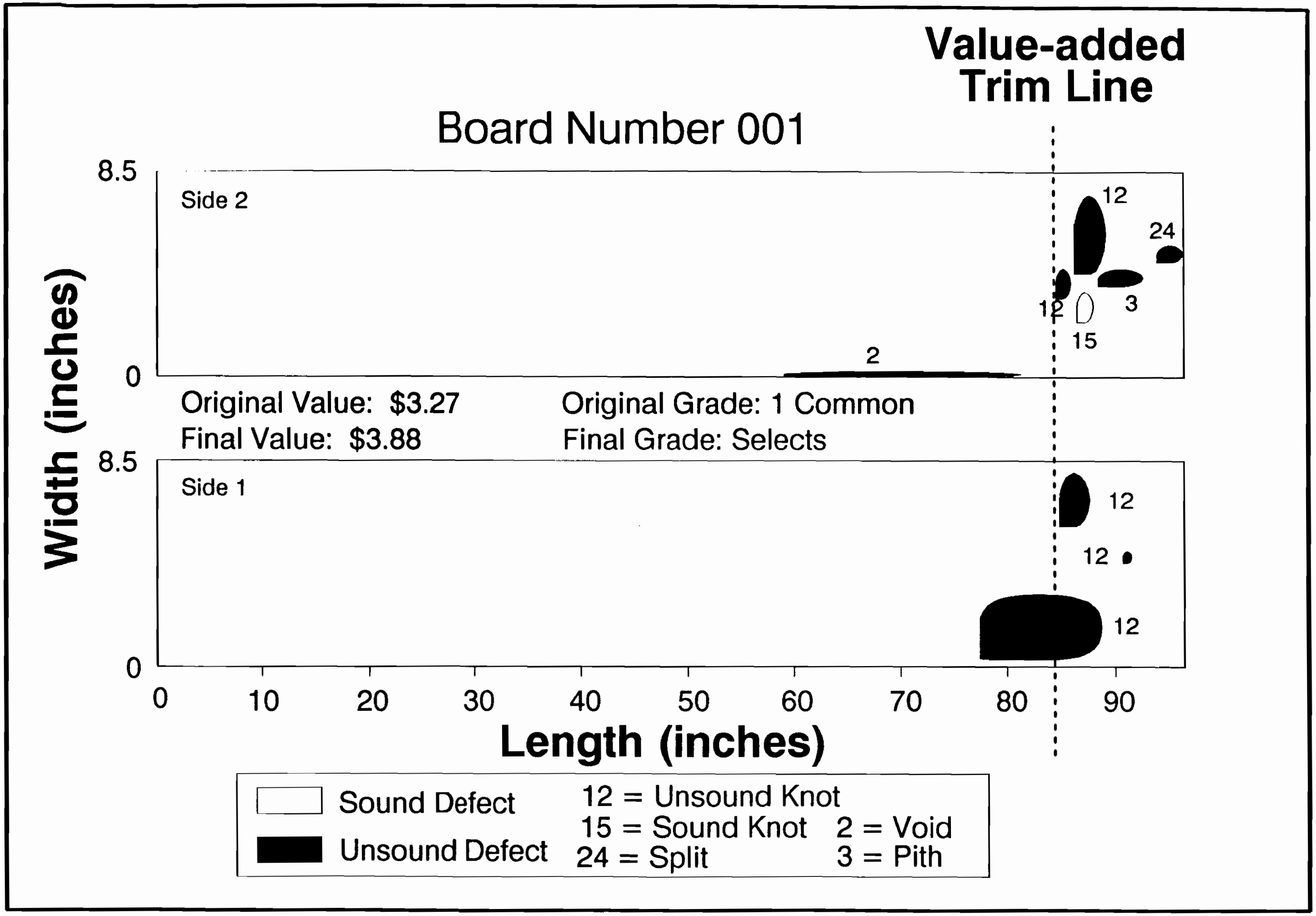

Figure 1. Example of a 1 Common board that can be value-trimmed.

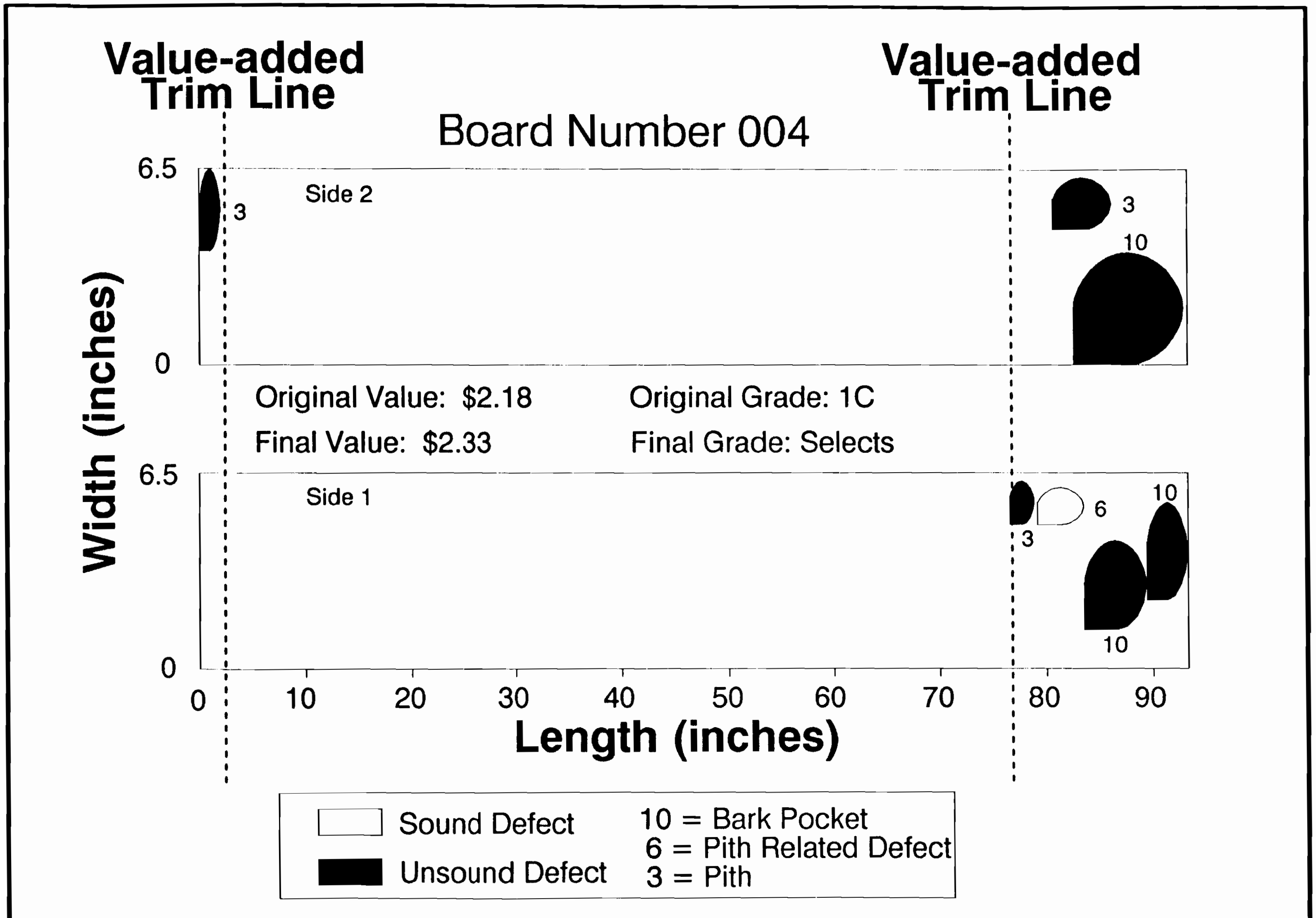

Figure 2. Example of a 1 Common board that can be value-trimmed.

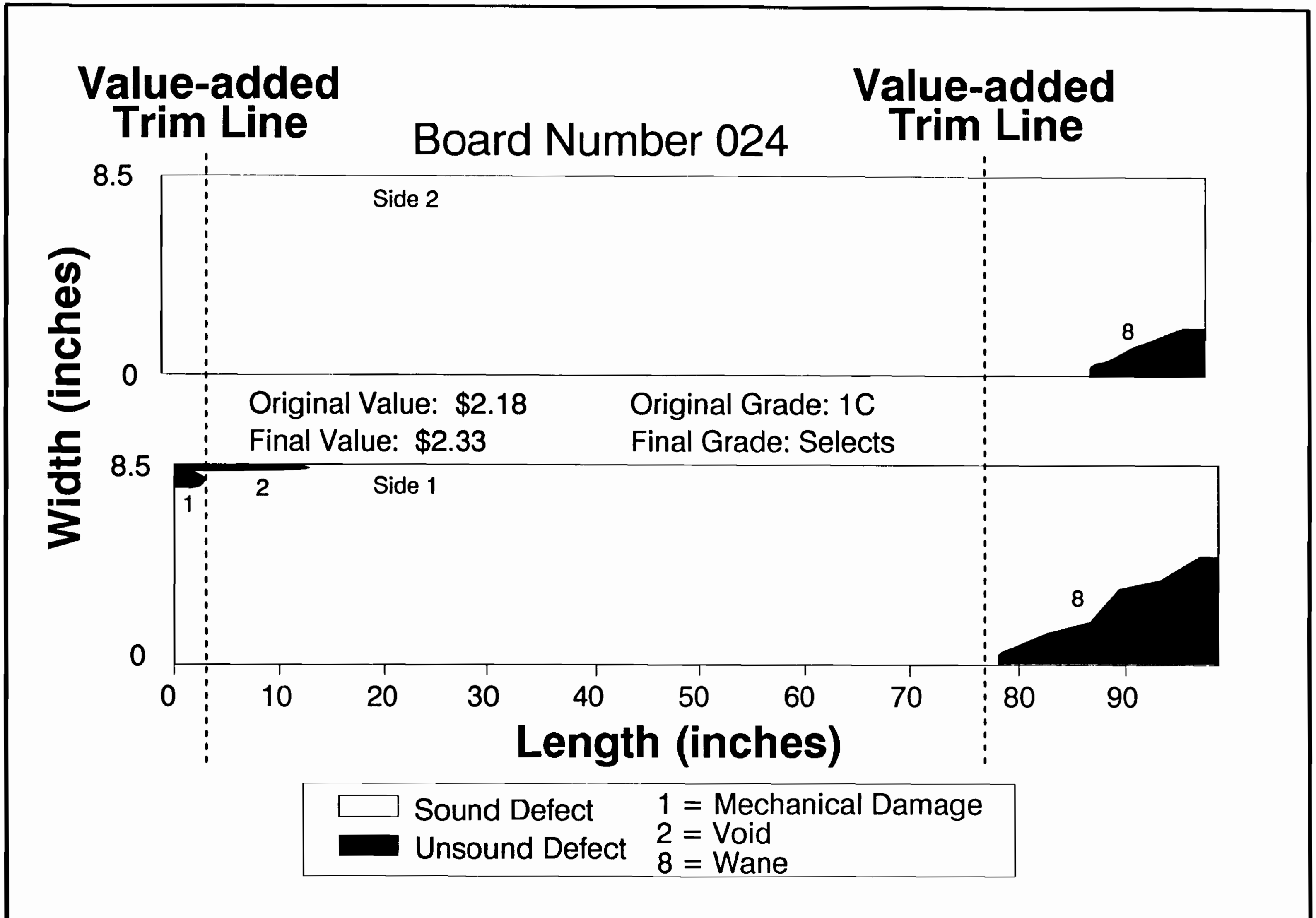

Figure 3. Example of a 1 Common board that can be value-trimmed.

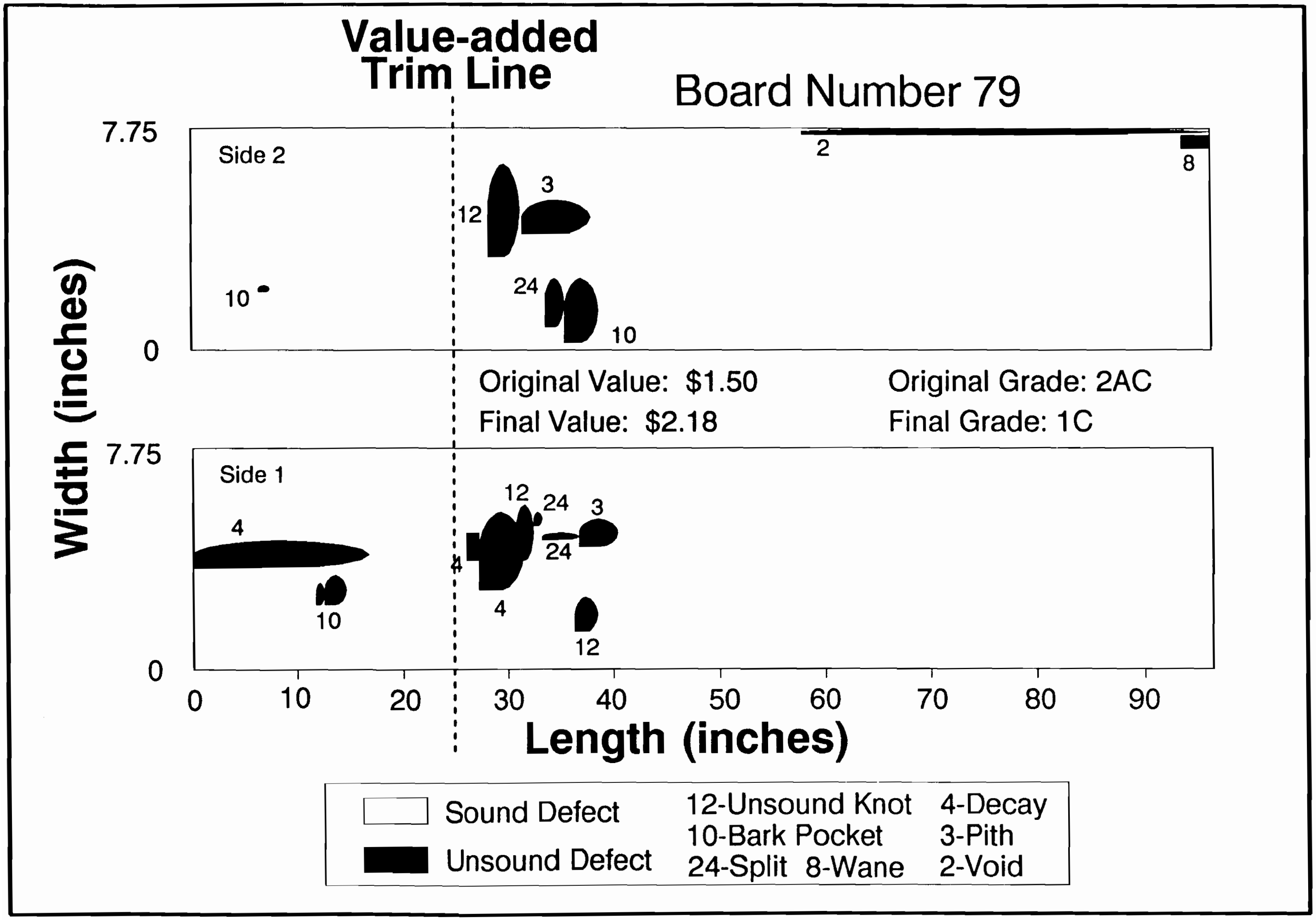

Figure 4. Example of a 2A Common board that can be value-trimmed.

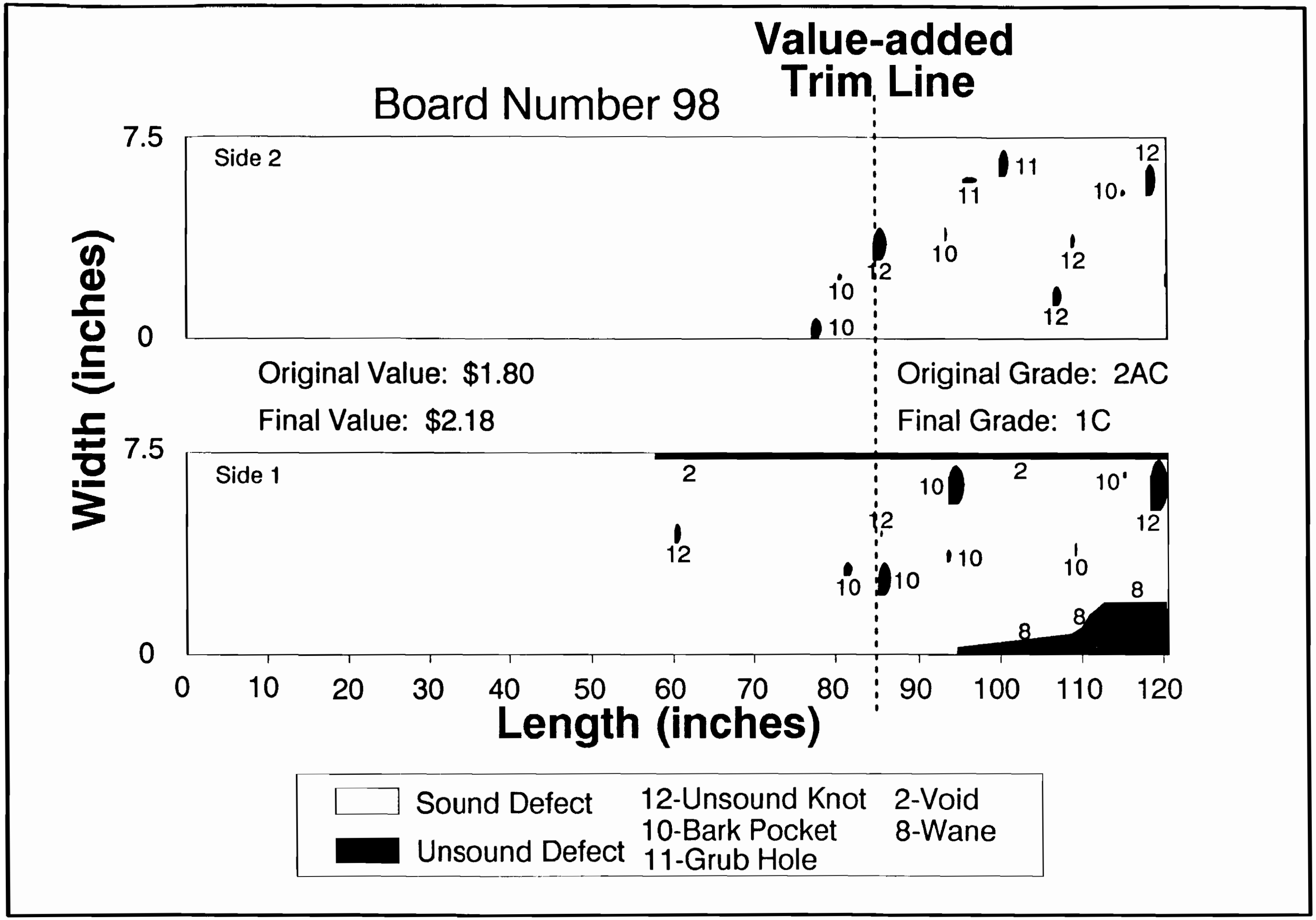

Figure 5. Example of a 2A Common board that can be value-trimmed.

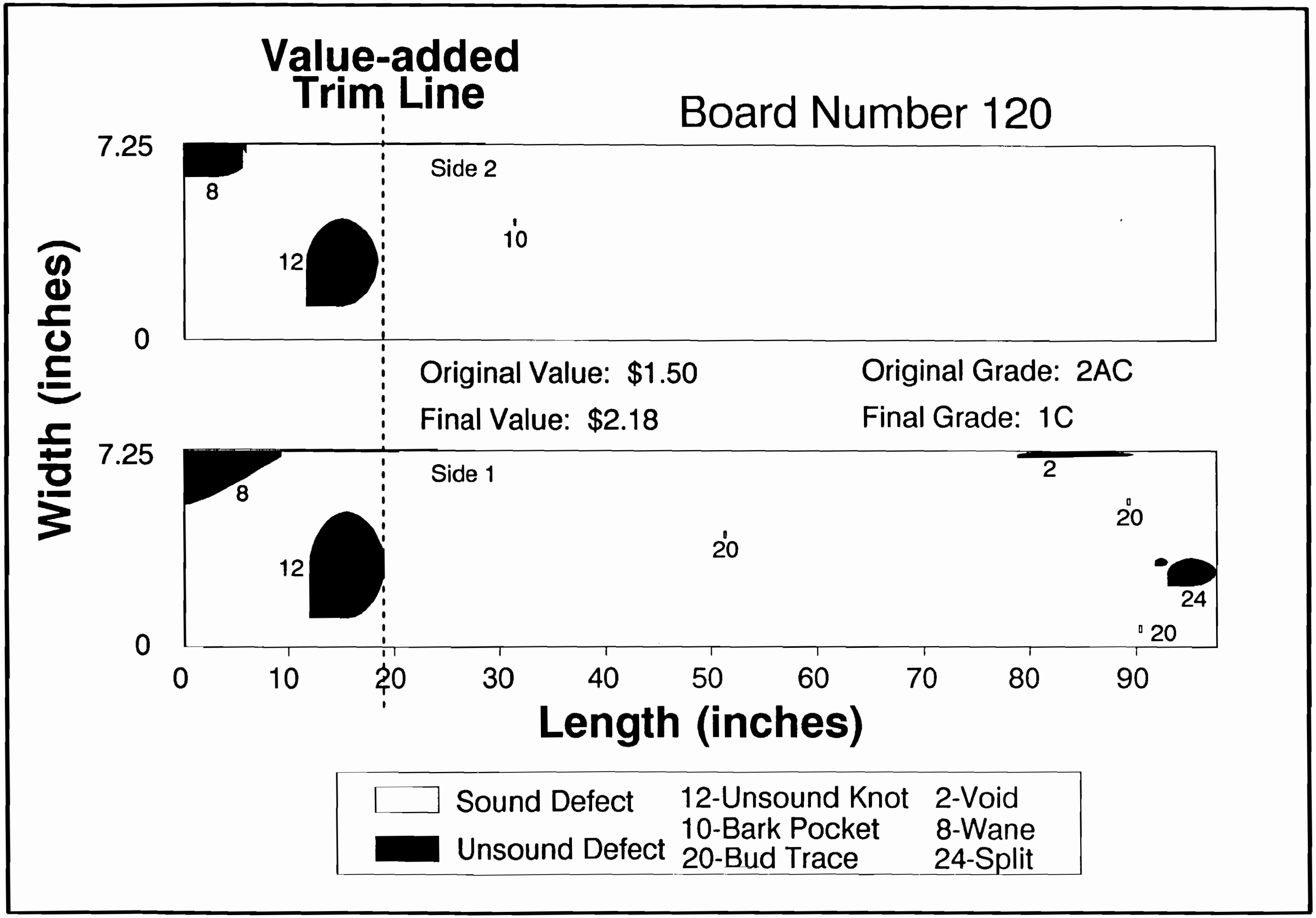

Figure 6. Example of a 2A Common board that can be value-trimmed.

2A Common boards surveyed could be trimmed to produce a higher value board. Fifty-three percent of these 2A Common trimming solutions (8 of 15) would yield short length lumber. None of the 166, 12 to 16 foot long 1 Common boards surveyed would yield short length lumber when value-trimmed and only 1 of 51, 2A Common 12 to 16 foot long boards surveyed would yield short lumber.

For the short boards produced by trimming 1 Common lumber to obtain a Selects grade board, the average value increase per board would be 38 cents (Table 7). The average value increase per short board produced by value-trimming the 2A Common lumber would be 45 cents. These figures are based on the assumption that short length lumber prices are the same per mbf as long length lumber prices. Average breakeven prices for the short length boards produced by trimming longer length boards were calculated. The breakeven price for the short length Selects lumber generated by value-trimming is $693 per mbf. This compares to the current price for green, Selects grade, 4/4, Appalachian red oak of approximately $775 per mbf (adapted from the Weekly Hardwood Review 1991). The breakeven price for the short length 1 Common lumber generated by value-trimming 2A Common longer lumber is $423 per mbf. The current price for 1 Common, 4/4, Appalachian red oak is approximately $545 per mbf (Weekly Hardwood Review 1991).

Defect Characteristics of Short Versus Long Lumber

For both 1 Common and 2A Common lumber crook (a.k.a. sidebend) deviation per board increases with increasing board length. Figures 7 and 8 show plots of crook

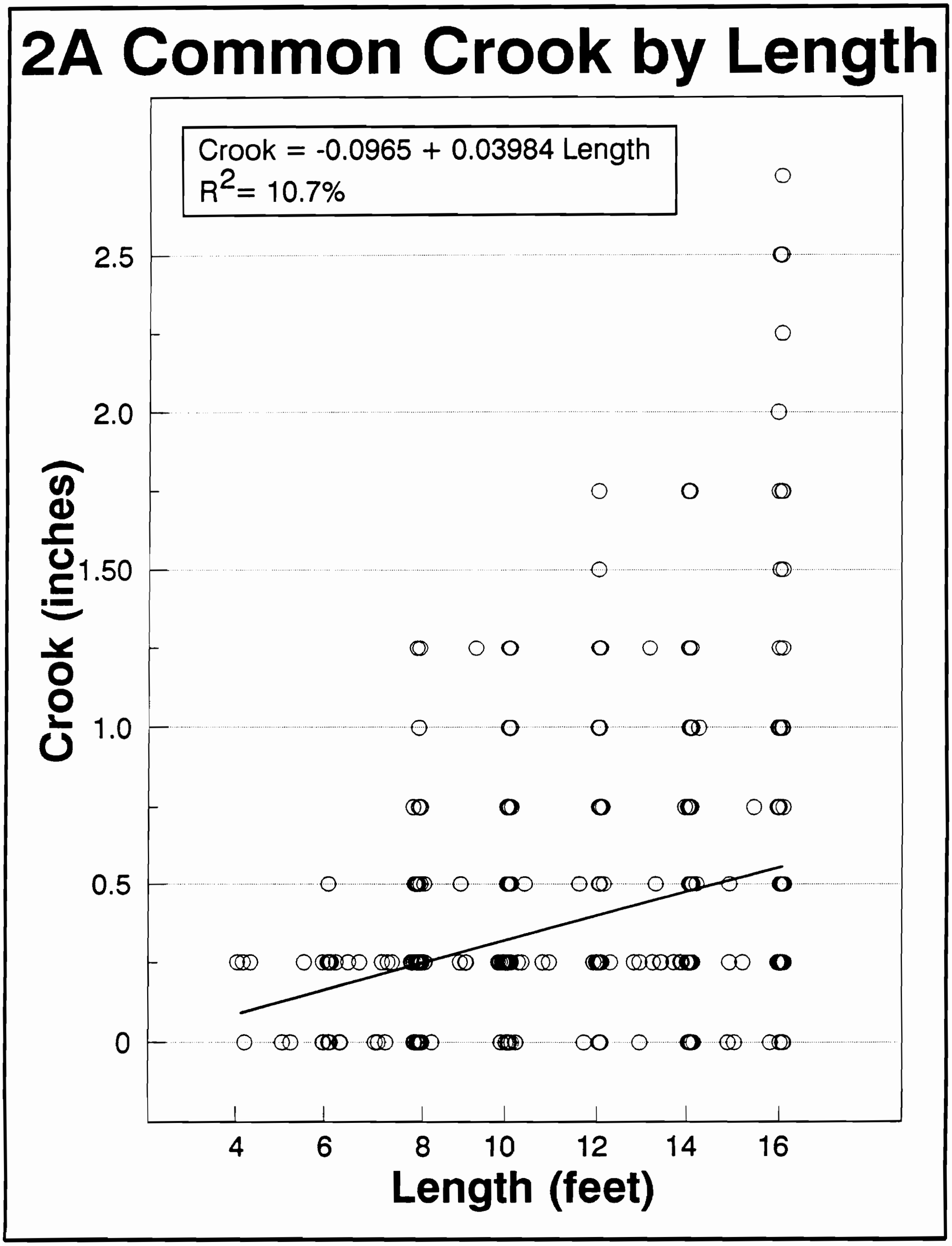

Figure 7. Crook deviation versus lumber length; 2A Common lumber.

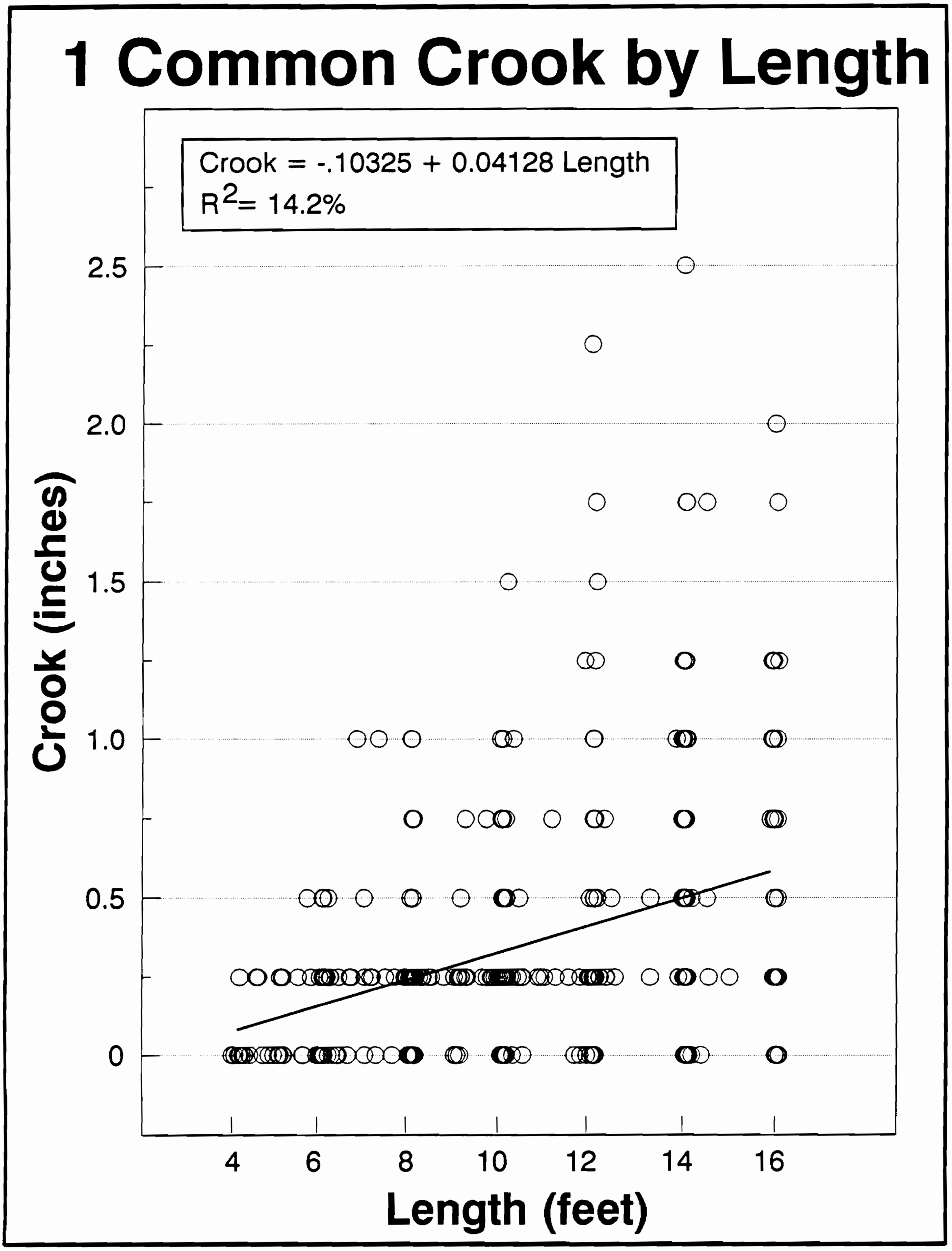

Figure 8. Crook deviation versus lumber length; 1 Common lumber.

deviation versus lumber length for the two grades. For both lumber grades the amount of board crook is significantly, and positively related to lumber length.

The regression relationship between the degree of crook per lineal foot of lumber and lumber length was not significant for either lumber grade. The probability values associated with the F-statistics for the 1C and 2AC regression tests were .069 and .075, respectively. Figures 9 and 10 show the normalized plots of crook versus lumber length. The regression equations are not given since they have very low R^2-values and thus lack predictive significance. For both grades the regression equations indicated a tendency for normalized crook (inches of crook per foot of lumber) to increase with increasing lumber length.

Table 8 shows the average crook deviation for boards grouped into 2 foot length categories. For 1 Common and 2A Common 4 and 5 foot long boards, the average crook deviation is .08 and .10 inches, respectively. Only 3 percent of the 1 Common 4 and 5 foot boards have more than one-quarter inch of crook. Zero percent of the 2A Common boards in this shortest lumber length category have more than one-quarter inch of crook. For 1 Common and 2A Common 16 foot long boards, the average crook deviation is .55 and .64 inches respectively. Forty-four percent of the 1 Common and 46 percent of the 2A Common 16 foot long boards have crook deviation in excess of one-quarter inch. An analysis of variance test indicated that length category has a highly significant effect on a board's degree of crook deviation.

Of the seven defect types other than crook which are most prevalent on an area basis, only wane varies consistently between short and long length lumber groups (Table 9). For both the Selects and 1 Common grades, t-test results indicate that short length

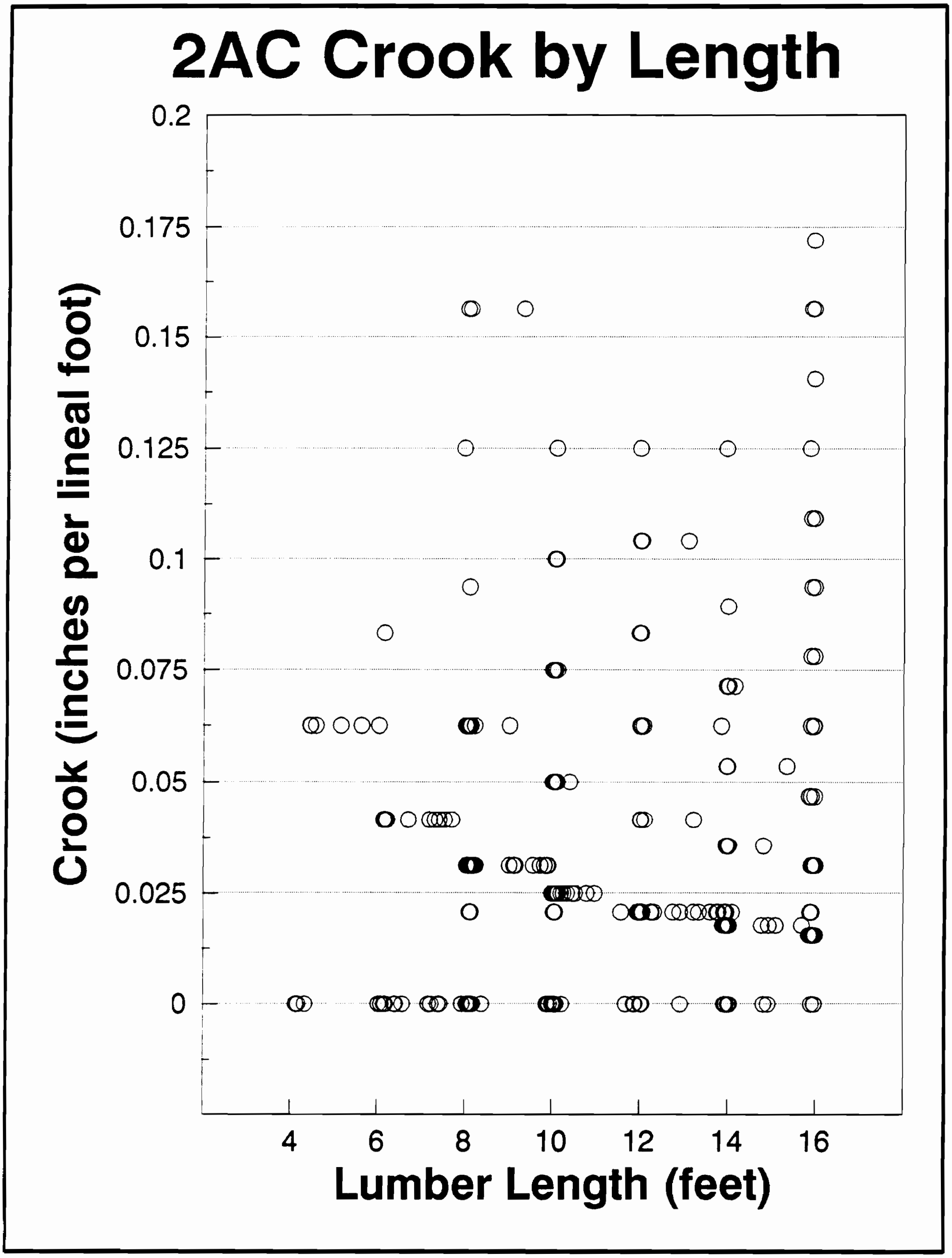

Figure 9. Normalized crook versus lumber length; 2A Common lumber.

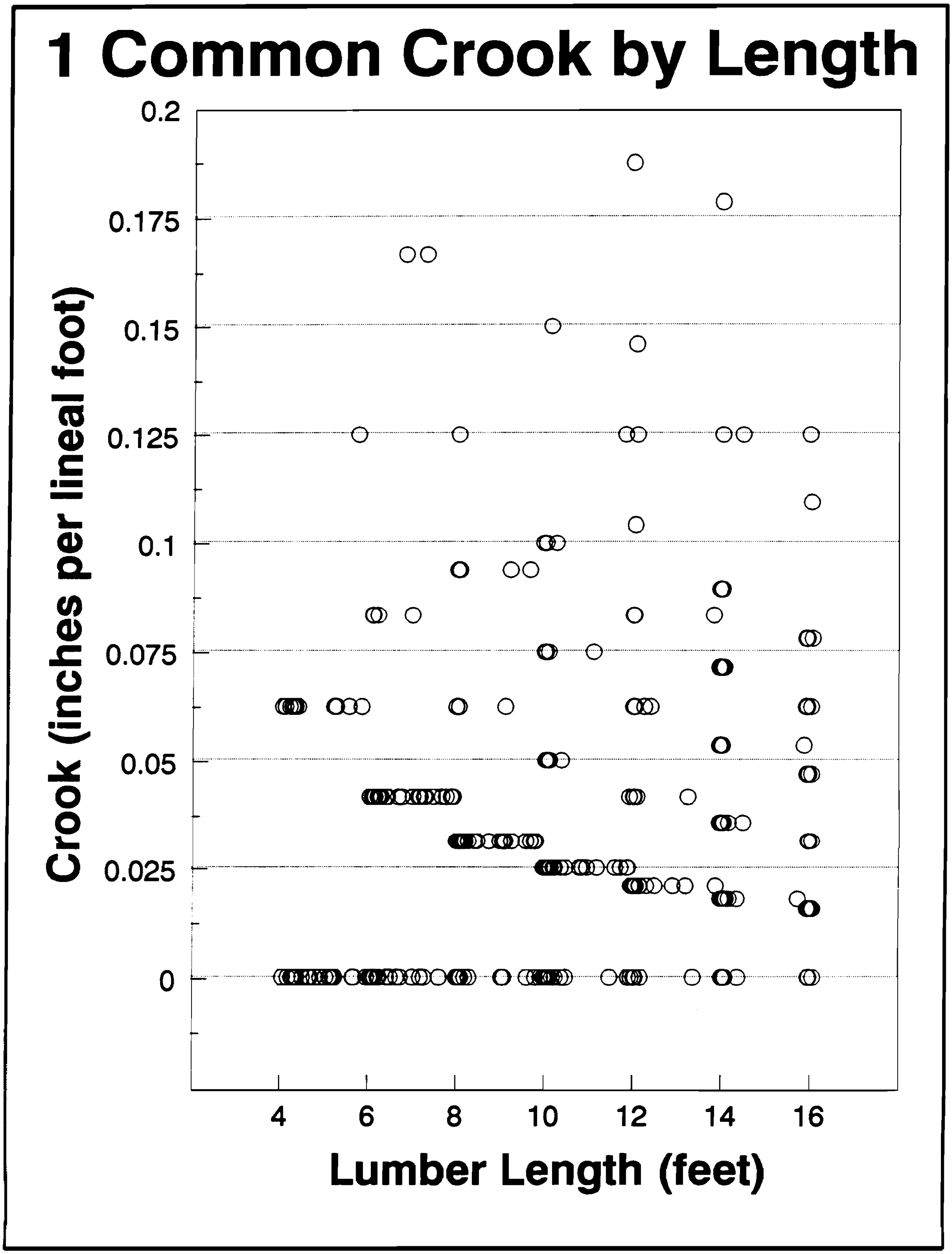

Figure 10. Normalized crook versus lumber length; 1 Common lumber.

Table 8. Average crook deviation and percentage of boards exceeding one-quarter inch of crook by length and grade.

Board Length	1 Common		2A Common	
	Average Crook Deviation Per Board (inches)	Percent of Boards With More Than One-Quarter Inch of Crook	Average Crook Deviation Per Board (inches)	Percent of Boards with More Than One-Quarter Inch of Crook
4'-5'	.08	3	.10	0
6'-7'	.18	8	.18	5
8'-9'	.26	12	.25	15
10'-11'	.30	21	.30	18
12'-13'	.38	30	.37	27
14'-15'	.51	48	.40	34
16'	.55	44	.64	46
Significance	ANOVA of Crook Deviation by Length Category is Significant at α=.05		ANOVA of Crook Deviation by Length Category is Significant at α=.05	

Table 9. Short and long length lumber defect comparison and t-test results.

	Selects			1 Common			2A Common		
	Short[a] Value	Long Value	Short VersusLong T-Test Result	Short[a] Value	Long Value	Short Versus Long T-Test Result	Short[a] Value	Long Value	Short Versus Long T-Test Result
# Defects	6.1	11.7	SIG **	9.4	17.4	SIG **	13.9	23.7	SIG **
# Defects Per Lineal Foot	.9	1.1	NS	1.6	1.6	NS	2.3	2.1	NS
% Clear Area	97.6	97.5	NS	95.7	95.6	SIG **	94.1	94.0	NS
Ave Split Lngth per Board (in)	1.1	8.2	SIG **	4.7	7.1	SIG **	5.2	8.3	SIG **
Percent of Defect Area that is									
Mechanical Damage	13.1	10.5	NS	3.7	3.5	NS	1.4	1.6	NS
Decay	.8	1.9	NS	2.2	2.4	SIG **	3.6	3.4	NS
Wane	33.4	31.1	SIG **	23.6	22.9	SIG **	24.0	23.5	NS
Bark Pocket	6.5	9.9	SIG **	14.1	13.7	NS	11.4	11.5	NS
Unsound Knot	2.5	3.5	SIG **	23.8	23.7	NS	20.1	20.0	NS

a- Short lumber is defined as lumber shorter than 8 feet in length.

SIG **- Significant at the α=.05 level.

NS- Not significant.

lumber defect area is made up of a significantly higher (α = .05) percentage of wane than is long length lumber defect area. The same trend appears in the 2A Common sample but the relationship is not significant.

The splits category includes checks which would not surface out (Gatchell and Wiedenbeck 1992). The average length of splits per board varied between the short and long length lumber categories for all three grades (Table 9). For the short Selects lumber approximately 1.4% of the lineal footage of the lumber contained splits. For the long Selects lumber 6.1% of the lineal footage of the board contained splits. For the 1 Common and 2A Common grades however, splits occupied a higher percentage of the lineal footage of the short length boards than of the long length boards: 5.3 percent versus 4.7 percent for 1 Common, and 7.1 percent versus 6.1 percent for 2A Common. The split tallies for the 1C and 2AC grades exhibit the expected trend: splits occupy a higher percentage of the lineal footage on the short boards than on the long. However, the effect of end splitting and checking on short lumber does not appear to be as large as might be predicted. For example, a 6 inch long end split affects 12.5 percent of the length of a 4 foot long board but only 4.2 percent of the length of a 12 foot long board.

Clear-face Cutting Yield Differences Between Lumber Length Groups

HaLT generated clear-face cutting yields of required minimum cutting sizes as specified under National Hardwood Lumber Association grade rules (1990) were significantly related to lumber length for the Selects, 1 Common, and 2A Common grade categories in regression tests conducted at the α = .05 significance level (Table 10). For each grade the relationship was negative: as nominal board length increased, the yield of clear-face cuttings decreased. In this study the regression analyses and resulting equations are based on nominal length categories as specified by the NHLA (e.g. 4, 5, 6, etc.; 1990). The degree of influence which nominal board length has on clear-face cutting yield as indicated by the R^2 value is 13.7% for the Selects, 5.6% for the 1 Common, and 3.1% for the 2A Common. These very low R^2-values indicate that the relationship between board length and clear-face grade cutting yield explains only a small fraction of the variation in clear-face grade cutting yield.

The number of cuttings required to get the clear-face cutting yield for each board shows a significant, positive relationship to nominal board length for each of the three grades examined (Table 10). The R^2 values for the relationships between number of cuttings and nominal length were 14.1%, 34.9%, and 31.1% for the Selects, 1 Common, and 2A Common grades respectively.

Discussion

In the value-added trimming analysis summary table (Table 7), the percentages contained within the column labelled "Total" may be only marginally credible. This is because the sampling scheme for the boards was not based on the width and length of the available lumber resource but rather on a predefined sample cell structure that seemed to oversample wide and to a lesser degree, long boards. If the available lumber resource is somewhat shorter than the distribution of boards obtained in the sample, the

Table 10. Yield of clear-face cuttings of required minimum sizes obtained in grading boards by length and lumber grade.

Length Group	Selects[a]		1 Common		2A Common	
	Grade Cutting Yield	Cuttings To Get Yield	Grade Cutting Yield	Cuttings To Get Yield	Grade Cutting Yield	Cuttings To Get Yield
4'-5'	n/a[b]	n/a[b]	79.8%	1.14	62.8%	1.00
6'-7'	95.3%	1.00	76.9%	1.52	59.6%	1.48
8'-9'	90.6%	1.09	73.8%	1.84	57.5%	1.78
10'-11'	88.4%	1.22	73.4%	2.22	57.5%	1.97
12'-13'	84.1%	1.44	74.2%	2.27	57.0%	2.42
14'-15'	93.2%	1.25	72.3%	2.67	56.0%	2.68
16'	97.5%	1.50	72.2%	2.82	55.5%	3.12
Regression	Yield = 99.7 - .943 Length Group		Yield = 79.5 - .518 Length Group		Yield = 61.1 - .358 Length Group	
R^2	13.7%		5.6%		3.1%	
Significance	P = .002		P = .000		P = .000	
Regression	Cuttings= .683 + .0526 Length Group		Cuttings= .648 + .143 Length Group		Cuttings= .399 + .165 Length Group	
R^2	14.1%		34.9%		31.1%	
Significance	P = .002		P = .000		P = .000	

a- The Selects sample was small, consisting of only 59 boards, compared to the 1 Common sample (492 boards) and the 2A Common sample (590 boards).

b- Not applicable because the Selects grade has a minimum board length requirement of 6 feet.

percentage of long length boards that could be value-trimmed back to short length lumber would likely be higher.

The difference between the breakeven lumber prices calculated in the value-added trimming analysis and the current market prices for non-discounted red oak lumber, represents a margin within which certain costs associated with manufacturing short length lumber through value-added trimming would have to fall in order to justify the practice. For example, for the boards upgraded to 1 Common from 2A Common by trimming, the breakeven 1 Common price for these boards was calculated to be $423 per mbf. The 1 Common market price used in the analysis was $545 per mbf. The difference between these two figures ($122/mbf) is the maximum amount which any additional costs associated with manufacturing short length lumber or any price discounts offered on short length lumber should sum to. Clearly, the sum of such costs should be less than this price margin for there to be any value associated with the practice of trimming for grade.

One issue related to value-added trimming is whether remanufacturing changes the yield distribution of cuttings within the grade. For example, a producer of lumber that remanufactures 2A Common to obtain 1 Common probably removes from their 2A Common bundles many of the boards that were high quality, high yield 2A Commons (Gatchell 1989). By the same token, the number of boards in the 1 Common grade that just make the grade may be increased by the practice of remanufacturing.

The effect of crook on furniture cutting yields in rip-first rough mills is a major problem (Gatchell 1990; Gatchell 1991). Due to the fact that the edges of boards with crook are not parallel to the rip saw's fence, boards with crook yield fewer full-width strips in a rip-first operation. An inordinately large percentage of the yield obtained from crooked boards in a rip-first rough mill comes from salvage operations. Pieces generated in a salvage cutting stage are much more costly than those generated in the initial rip and crosscut stages. Since short length lumber is generally straighter than longer lumber, the negative impact of crook on yields and costs will be a much larger concern when processing long length lumber in a rip-first rough mill. In crosscut-first rough mills the effect of crook on yield is not significant but crooked boards may pose handling problems in more highly automated systems.

In marketing short length lumber its straightness is one characteristic which buyers should find appealing. Bush's (1989) survey of five major hardwood lumber market segments indicated that lumber straightness was considered one of the most important lumber attributes by industrial hardwood lumber buyers.

Since the red oak lumber contained in the crook study sample was carefully dried using a mild kiln schedule the number of boards with crook and the size of the crook deviation were minimized. In many industrial drying operations with limited kiln capacity, good drying practices may not be as rigorously adhered to. One might expect that the difference is crook occurrence between lumber length groups measured in this study would be more pronounced in these cases.

Just as Bush's (1989) survey of five major hardwood lumber market segments indicated that lumber straightness was very important to lumber buyers, it also indicated that absence of wane was important. The fact that a greater percentage of the defect area in short boards is wane defects would be expected if a higher percentage of short boards are being produced from jacket boards coming off the log. Since logs with swollen butts are considered to be a prime, but greatly under-utilized source of short length lumber, short lumber coming off the headrig will probably seldom be square-edged.

Wane is a less costly defect for rough mills to remove than are other defects. For furniture parts which require a high-quality edge a ripping operation will need to be conducted parallel to the edge of the board regardless of whether wane is present or absent. Thus, the removal of wane on the edge of the board, unlike most other types of defects, seldom requires any additional milling operations.

Clear-face cutting yields and the number of cuttings needed to obtain the yield should be predictive of relative rough mill yields. The relationships noted for each grade in which yield decreases and the number of cuttings required to obtain the yield increases as the nominal board length increases are reflective of the NHLA (1990) grade rules. These relationships will be tested for their predictive value in the next section of this paper.

Summary

Studies were conducted on 4/4 thickness, red oak lumber collected from three Appalachian sawmills and defect-mapped at the Forestry Sciences Laboratory in Princeton, West Virginia. Plots of the boards were used to grade the material and to determine value-added remanufacturing opportunities. It was determined, based on current Appalachian red oak prices, that 15 percent of the 8 and 9 foot long 1 Common boards surveyed and 49 percent of the 2A Common, 8 and 9 foot boards could be trimmed to produce a short board of higher value. Due to the price difference between 1 Common and 2A Common red oak lumber some upgrade opportunities were also found for longer 2A Common boards. Unfortunately, 2A Common upgrade opportunities seem to be somewhat more difficult to recognize on quick inspection than 1 Common upgrade opportunities.

Straightness and absence of wane are both characteristics that are important to lumber buyers. Crook was found to be less of a problem with shorter lumber and wane was found to be more prevalent. While crook causes real problems in a furniture rough mill, wane is one of the easier defects to deal with in the parts manufacturing process.

The yield of clear-face cuttings of required minimum size obtained in grading the board was found to be inversely related to lumber length. The corresponding number of cuttings taken to make the grade is directly related to lumber length. The relationship between furniture cutting yield (as opposed to clear-face cutting yield to make grade) and lumber length will be discussed in the next section. The yield obtained in grading the board should be correlated with rough mill yields within each grade.

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THE EFFECT OF LUMBER LENGTH ON RANDOM WIDTH DIMENSION YIELDS: CORY SIMULATION RESULTS

Section 3

Abstract

The CORY lumber cut-up program was used to evaluate the effect of lumber length on several rough dimension yield variables. Multiple runs of the cut-up program were conducted with each run incorporating a different combination of cutting bill lengths, cutting priorities, and first-operation specifications (rip or crosscut-first).

For 10 of the 18 cutting bill combinations processed, the regression between total part yield and lumber length was significant. In the significant crosscut-first simulations yield increased with increasing lumber length. In the rip-first tests yield decreased as lumber length increased.

Average cutting length and average cutting value per board foot (bf) of lumber input exhibited significant positive regression relationships with lumber length for many of the cutting bill combinations analyzed. The yield of parts shorter than 20 inches long demonstrated a significant inverse relationship to lumber length in only 3 of the 18 cut-up scenarios. The yield of the longest length part on the cutting bill was notably higher for the longer length lumber in only 5 of the 18 cut-up scenarios. The variable which showed the strongest and most consistently significant relationship to lumber length was the bf production of parts per sawline; a significant, inverse relationship was detected for 14 of the 18 cutting bill combinations.

Investigations into the effect of crook on yield indicated that as crook decreases, yield, average cutting length, bf per sawing operation, and average value per board foot of lumber input tend to increase for both the rip-first and crosscut-first models.

Introduction

Potential Use of Short Length Lumber

One of the obstacles which must be overcome before the furniture industry will accept larger volumes of short length lumber (< 8 feet long) is the uncertainty which exists about the yield potential of short length lumber (Wengert et al. 1986). In order to make reliable estimates of the value of short length lumber to the furniture and cabinet industry, yield estimates must be combined with processing cost estimates.

It has been estimated that a one percent increase in part yield will result in a decrease in rough part manufacturing costs of approximately 2 percent (Wengert and Lamb 1990). This generalization applies if the parts produced are both readily obtainable and readily usable. If the yield increase is obtained through intensive machining activities that tie up equipment that could otherwise be used in higher value and volume production efforts, the underutilization of the equipment will negatively affect profits. If the parts are of quality or size that are not needed, their value is reduced by inventory carrying costs, opportunity costs, and risks associated with damage and pilferage.

Concerns about yields from short length lumber are often more appropriately expressed as concerns about the yield of longer length parts from short length lumber. Studies by Bingham and Schroeder (1976/1977) and Araman (1982) in which the cutting needs of various sectors of the furniture and cabinet industries were surveyed indicate that a large percentage of the cutting needs for all industry segments are shorter than 42 inches. Despite these findings, most rough mill managers believe that they generate an excess of short length parts from their present lumber length-quality mix. They fear that if they increased their use of short length lumber, a costly surplus of short length parts would develop.

Information on the relationship between lumber length and the yield of various length parts is very limited. In one study the yield of the longest length cutting (31") in a cutting bill was found to be independent of lumber length over a very narrow range of lumber lengths (4 to 6 feet; Ringer 1975). In a second study, the yield of short (less than 40") versus long parts obtained in a non-conventional gang-rip rough mill was only 10 percent for 4 foot lumber but ranged between 30 and 40 percent for the 5 to 8 foot long lumber (Reynolds and Schroeder 1978).

Information on the relationship between lumber length and total cutting yield is also very limited. In one tally maintained at a mill that produced short length, unedged lumber on a bolter saw, the yield from the bolter-sawn lumber was higher than the yield from longer length, 2A Common lumber in six of the seven quarters for which records were kept (North Carolina Division of Forest Resources 1979). The results of a more controlled study at this same mill provided a grade-based breakdown of the yield from short length lumber (4, 5, 6 feet long; Ringer 1975). The yields of clear two-face cuttings were 69.4 percent for the No. 1 Common, 58.4 percent for the No. 2A Common, and 48.4 percent for the No. 3A Common lumber. No yield differences were detected between the 4, 5, and 6 foot length groups within each grade. These short length yields were compared with expected yields from standard length lumber given in the Forest Products Laboratory's nomograms (Englarth and Schumann 1969). Cutting yields from the short length lumber were higher in each grade category but the differences were not statistically significant.

Computer Simulation of Yield

By using a cut-up simulation program to evaluate dimension yields, multiple cutting bill combinations can be tested. In addition, detailed information on the yield and cuttings obtained from individual boards can be obtained. These two features represent the major advantages in conducting computer-based yield studies rather than in-mill yield studies.

One of the disadvantages associated with computer-based yield studies is the time and effort required to map the location of defects on each board for input into the yield program. A more critical concern is that the algorithms contained in the cut-up simulation programs are quite different from the decision-rules used by rough mill saw operators. Computer-based yield study results are theoretically sound but operational changes based on these studies must be approached with caution. Since rough mill sawing decisions are likely to become computer-driven at many mills in the near future, this issue will become less important.

Developmental efforts in the microcomputer-based cut-up programming arena in the last five years have resulted in two programs that are more flexible and that execute faster than the previous generation of cut-up programs. One of these programs, CORY (Computerized Optimization of Recoverable Yield; Brunner et al. 1989) can perform either rip-first or crosscut-first heuristic-based optimizations. The other program, GR-1ST (Hoff et al. 1991) is designed to optimize a wide variety of gang-rip-first cut-up configurations.

A comparison of CORY's performance with program YIELD's (Wodinski and Hahm 1966) for identical boards and cutting bills indicated CORY was more effective (9 percent higher total yield) and more efficient (reduced execution time by 98 percent) than YIELD (Brunner et al. 1989). A comparison of the heuristic-search CORY algorithm with an exhaustive-search version demonstrated that the exhaustive version obtained only slightly higher total yields (less than 2 percent) but required on average 623 times longer to execute (Brunner and Anderson 1991). An analysis of CORY's performance versus that of a crosscut-first rough mill showed that CORY's yields was not statistically different from the mill's yield but the value of the cuttings produced by CORY was significantly higher (with higher value attached to longer cuttings; Yun 1989). Different versions of the CORY program have been used and visually validated at Virginia Polytechnic Institute and State University (Yun 1989; Kline et al. 1992).

The GR-1ST program can handle gang-rip saw configurations with fixed, variable, and fixed plus floating saw spacings (Hoff et al. 1991). It is not designed to perform crosscut-first analyses. The GR-1ST program has been used extensively by Gatchell (1990; 1991). The GR-1ST program does not incorporate an input specification for prioritizing part lengths nor does it have an output option that will write individual board data to a file in a format that can be readily imported into spreadsheet or statistical programs (Hoff et al. 1991).

Objective and Hypothesis

The purpose of this study was to identify and describe lumber length-dependent relationships for several rough mill yield variables. The basic hypothesis underlying this research is that for a variety of cutting bills, short length lumber dimension yields are comparable to those of longer lumber.

The specific form of the series of statistical hypotheses under investigation is:

1. $\text{Yield Variable}_4 = \text{Yield Variable}_6 = \ldots\ldots = \text{Yield Variable}_{16}$
2. $\text{Yield Variable}_{SLL} = \text{Yield Variable}_{LLL}$
3. $\beta_1 = 0$ in the equation: $\text{Yield} = \beta_0 + \beta_1 \times \text{Length} + E$

The tests associated with the type 1 hypothesis test analysis of variance procedures to search for differences in a given yield variable for seven lumber length groups (4, 6, 8, 10, 12, 14, and 16 feet). The tests associated with the type 2 hypothesis employ t-test techniques to search for differences in yields between two lumber length groups (SLL or short lumber: 4-7 feet long; LLL or longer lumber: 8-16 feet long). The type 3 hypothesis testing procedures involve an evaluation of the degree of linear association between the yield variable and lumber length (regression analysis).

Methodology

Red Oak Board Data

The analyses within this study were performed on data collected by the U.S. Forest Service, Northeastern Forest Experiment Station, Forestry Sciences Laboratory in Princeton, West Virginia. The data consists of board defect information collected on more than 1200, 4/4-inch thickness, dry, red oak boards. The boards which comprise the sample were collected from three mills; two of the mills were grade sawmills which sawed to a center cant (Gatchell and Wiedenbeck 1992). The boards in the sample ranged from 4 to 16 feet in length. Green lumber was obtained from these mills. The lumber was dried using a mild kiln schedule at the Princeton Forestry Sciences Laboratory. Kiln-dried lumber was obtained at the third mill. All three mills were in the Appalachian region. All boards were graded using the National Hardwood Lumber Association's (NHLA 1990) Special Kiln Dried Rule. This grading method was chosen because the resulting grades more accurately predict furniture cutting yields than do the grades assigned using the Standard Kiln Dried Rule (Gatchell 1992).

The sample was randomly chosen with regard to defects but was designed to assemble 1 Common and 2A Common data banks with predetermined board width and length distributions (Gatchell and Wiedenbeck 1992). An attempt was made to fill cells of given length and width combinations with a predetermined number of boards. The size of each cell was based on sampling information provided by Lucas and Catron (1973) which was designed to represent the size distribution of the red oak lumber resource. In collecting this sample the narrow width cells filled up quite quickly but wider boards were more difficult to obtain (Gatchell and Wiedenbeck 1992).

All boards within the data bank were initially graded by an NHLA grader. The boards from two of the mills were inspected by the NHLA grader for upgrade opportunities that would increase the value of the lumber (Gatchell and Wiedenbeck 1992). Approximately 12 percent of the boards from these two mills were trimmed to more valuable, shorter, higher grade boards as specified by the grader.

When the mapped board data was input into the HaRem program (Schwehm et al. 1990) to assess remanufacturing opportunities the grades returned by the grading module within HaRem differed on many boards from those assigned by the NHLA grader. The board data was then input into the HaLT program which contained the same grading module but also contained explanations of the grading process for each board (Schwehm et al. 1989). The HaLT program, designed as a lumber grading tutorial, was unable to handle certain grade and defect considerations which were encountered during the grading of the several hundred boards in the data bank. The HaLT2 revision (Klinkhachorn et al. 1991) of the HaLT program, which contains a more accurate grading module, was used in combination with to-scale plots of each board, to assign the final grades.

After regrading, the Selects, 1 Common, and 2A Common data banks contained 123, 651, and 783 boards, respectively. The 1 Common data bank had the most uniform distribution of boards by length and had the largest number of boards shorter than 8 feet long - 111. Of the 123 boards in the Selects data bank, 35 were shorter than 8 feet long. Only 6 percent (47 boards) of the 2A Common boards were short length lumber.

The Selects boards were not collected as Selects at the mills. They are boards that were originally in the 1 Common or 2A Common sample and were upgraded during the regrading process. Thus, tests conducted on the Selects sample must be interpreted with caution. The quality distribution of the Selects sample may or may not be representative of the quality distribution of red oak Selects boards manufactured at the three sawmills from which the sample was collected.

CORY Cut-up Program

The microcomputer-based CORY program was used to simulate both the rip-first and crosscut-first cut-up on all boards in the data bank. The random width version of the CORY program was used rather than the fixed width since the majority of Eastern U.S. furniture and cabinet rough mills produce a large percentage of their cuttings in random widths. Initial runs were conducted using the 3-stage version of CORY. A stage is defined as series of cutting operations on a given piece of equipment (Anderson et al. 1991). In a 3-stage, crosscut-first operation the board is crosscut into several full width pieces during the first stage. Each full width piece is ripped into multiple narrower pieces in the second stage. A salvage crosscut operation, if needed, would represent the third stage. The CORY 3-stage model generated cutting solutions in which a high percentage (20 to 30 percent) of the cutting yield was produced in the third, or salvage stage. The third stage also produced a substantial percentage of the longer length cuttings which is not typically the case in a rough mill operation. Since the results of this work are meant to be applicable to present-day furniture and cabinet rough mill operations, a 2-stage version of the random width model was obtained from Brunner and Anderson (1991) for testing. In the 2-stage model no salvage cuttings are produced. A 2-stage cutting sequence is sometimes found in rough mills producing random width parts. The 2-stage crosscut-first model yields a cutting surface area that is approximately 4 percent lower than that obtained using the 3-stage model.

The value of each length cutting in the cutting bill relative to the other cutting lengths can be assigned within CORY. In earlier versions of CORY a weighting factor (wf) was entered that indicated the relative value to attach to a cutting based on the relationship: width x length ^{wf}. A weighting factor of 1 generates the maximum yield solution as no cutting length is favored over another. A weighting factor of 2 attaches high value to the longest cutting in the cutting bill but results in cutting solutions that have lower total yields. Volume yield decreases attributable to increases in the weighting factor are larger for crosscut-first simulations than for rip-first (Maristany et al. 1991). The differences between CORY's weighting factor = 1 yields and weighting factor = 2 yields also vary by lumber grade with lower grades showing a bigger effect (Maristany et al. 1990). The maximum yield difference observed between these two weighting factors was seen when No. 2A Common lumber was processed with the crosscut-first option.

The yield difference was 7.37 percent (Maristany et al. 1990). The minimum yield difference observed in the comparison of the two weighting factors resulted when FAS lumber was ripped-first. For this scenario the total yield for the weighting factor = 2 option was 2.93 percent lower than for the weighting factor = 1 option (Maristany et al. 1990).

The solutions generated by both the rip and crosscut-first versions of the model were verified by drawing out the kerf lines on to-scale plots. Eighteen boards were verified for each of the versions. Verification of the CORY solutions involved determining that none of the cuttings contained defects and that no large clear areas were omitted from cuttings.

Cut-up Analysis Framework

Two cutting bills were used in the analyses. Both were adopted from a theoretical study performed by Wengert et al. (1986). The cutting quality used for each of the cutting bills was clear two-face. The shorter of the two cutting bills contained seven cutting lengths ranging from 12 to 48 inches. This cutting bill is fairly representative of both a short furniture case goods and a cabinet operation's cutting requirements. The second cutting bill contained eight cutting lengths ranging from 18 to 70 inches. This cutting bill could also be found in a furniture case goods operation.

For the crosscut-first alternative three lumber grades, Selects, 1 Common, and 2A Common were processed with weighting factors of 1 and 2 through each of the cutting bills. For the rip-first alternative each of the lumber grades was processed through the shorter cutting bill (cutting bill A) with weighting factors of 1 and 2. The longer cutting bill was not used for the rip-first tests since rip-first configurations are predominantly found in the cabinet industry. The shorter cutting bill better represents cabinet industry cutting lengths. This design matrix for the CORY simulation runs is displayed in Table 11.

CORY can provide individual board information on total yield and on the yield and number of cuttings per cutting length. Average cutting lengths, average cutting volumes per sawing operation, total cutting yield in cuttings shorter than 20 inches, total cutting yield in the longest length cutting class, and average relative cutting value per board foot of raw material were calculated then analyzed with the Minitab and SAS statistical software packages. All yields given are based on dry lumber dimensions.

Rough Part Valuation

Average cutting values are highly variable both between operations and from one day to the next within a given operation. Since value is a measure of relative profit and profit is the difference between income and cost, the relative value of parts is a very complex calculation. Yun (1989) employed a program designed to determine the optimum grade mix of lumber to use to fill a given cutting bill, to estimate the raw material cost component of the value equation for each cutting length. These relative cost per board foot figures were arbitrarily referenced to a base value of 1000 (unitless) per board foot for a 23.25" cutting. Yun's equation for the linear regression of "cost per board foot" versus "cutting length" was used to calculate relative part length-based values in this

Table 11. Design matrix for CORY simulation runs.

CROSSCUT-FIRST TEST STRUCTURE	RIP-FIRST TEST STRUCTURE
3 Grades (Selects, 1C, 2AC) **X** 2 Cutting Bills (A, B) **X** 2 Weighting Factors (1, 2)	3 Grades (Selects, 1C, 2AC) **X** 1 Cutting Bill (A) **X** 2 Weighting Factors (1, 2)
TOTAL: 12 CORY simulation runs	TOTAL: 6 CORY simulation runs
Cutting Bill A lengths (inches): 12, 14, 17, 20, 28, 44, 48. Cutting Bill B lengths (inches): 18, 20, 24, 28, 36, 44, 60, 70.	

study. The relationship arrived at by Yun (1989) is:

$$\textbf{Relative Value} = 19.69 * \textbf{Cutting Length} + 542.11$$

For cutting bill A relative part values ranged from 778 per board foot for the 12 inch cutting to 1487 for the 48 inch cutting. For cutting bill B relative part values ranged from 897 per board foot for the 18 inch cutting to 1960 for the 72 inch cutting. Alternatively, the tests performed on yield also represent tests on relative value for the scenario where all parts are valued equally per board foot regardless of length.

Statistical Treatments

All statistical tests were performed with board width included as either a covariate (in the analysis of covariance and t-tests) or an independent regression variable. This was deemed necessary since the sampling procedure had attempted to fill length by width cells rather than sampling at random such that the dimensions of the sample boards reflected the dimensions of the population of Appalachian red oak boards.

Tests performed included analysis of covariance tests of the yield variables for seven lumber length categories (LCAT): 4, 6, 8, 10, 12, 14, 16. The means of each variable, adjusted for width were calculated for each LCAT. The adjusted scores represent the predicted values for the yield variable under consideration, at the assumed common mean width (Kleinbaum et al. 1988). The means were submitted to various statistical separation procedures (multiple comparison tests) but these tests do not account for covariate adjustments. The means for the statistically significant tests were visually examined for a tendency to increase or decrease with increasing LCAT.

Yield variables for the boards which had been inspected for their remanufacturing potential were compared with those which had not been so inspected in a series of t-tests. The remanufactured or non-remanufactured designation was not included as a grouping variable in the analysis of covariance tests since the boards came from different mills (no true control group) and thus any differences could not be clearly attributed to the remanufacturing activity.

Regression analysis was used to investigate the effect of crook on the yield variables. Since the degree of crook has previously been shown to be significantly and positively related to lumber length (Section 2), length based differences in the yield variables might be considered to be in part, a function of crook.

Results

Covariance Test Results

Analysis of covariance tests were performed with lumber width treated as a covariate. In this analysis procedure adjustments are made to the dependent yield variable under consideration that are based on the assumption that the distribution of lumber widths in each group is similar. The adjustments remove confounding effects associated with the influence of width on yield. The covariance model is of the form:

$$Y_{ij} = \mu + \alpha_i + \beta_0 X_{ij} + \epsilon_{ij}.$$

Y_{ij} = yield value for observation j in treatment i,

μ = population mean,

α_i = effect of treatment (lumber length),

$\beta_0 X_{ij}$ = effect of covariate (lumber width), and

ϵ_{ij} = error term ... unexplained variation.

Covariance Test Results: Selects

Analysis of covariance test results in which the continuous variable lumber width was treated as the covariate are compiled in Table 12. For the Selects grade the variation in total yield between length categories (6, 8, 10, 12, 14, 16) was not statistically significant at α = .05 for 5 of the 6 cutting bill combinations tested. Similarly, the variation in average part value per input board foot of lumber was not significant for 5 of the 6 cutting bill combinations. Covariance tests on the percent yield of parts less than 20 inches long and the percent yield of the longest part in the cutting bill (48" for cutting bill A, 72" for cutting bill B) were not significant for 4 of the 6 cutting bill combinations within the Selects grade.

Results of the test on the hypothesis that the average cutting length for each length category is equal were highly significant (α = .01; i.e. the hypothesis was rejected) for 4 of the 6 cutting bill combinations: A2X, B2X, A1R, and A2R. Similarly, for 4 of the 6 cutting bill combinations significant differences between length categories for the variable board feet of cuttings produced per sawing operation were detected. Only the two rip-first cutting bills did not exhibit a statistically significant difference for this variable. Visual inspection of the adjusted means for each length category for this variable indicated that for each of the four crosscut-first cutting bills the board feet of cuttings produced per sawing operation showed a tendency to decrease with increasing LCAT

Table 12. Analysis of covariance results for comparisons of rough part yield variables versus LCAT (lumber length category) using lumber width as a covariate.

Dependent Variable Tested Against LCAT	Cutting Bill [a]					
	A1X	A2X	B1X	B2X	A1R	A2R
SELECTS						
Yield	NS[b]	NS	NS	NS	**	NS
Ave Cutting Length	NS	**	NS	**	**	**
BF/Sawline	**	*	**	**	NS	NS
% Yld lt 20 Inches	NS	NS	NS	*	**	NS
% Yld Longest Part	*	NS	NS	**	NS	NS
Ave Value/Input Bf	NS	NS	NS	**	NS	NS
1 COMMON						
Yield	**	*	**	**	NS	NS
Ave Cutting Length	NS	**	NS	**	**	**
BF/Sawline	**	**	**	**	NS	NS
% Yld lt 20 Inches	NS	*	NS	NS	**	**
% Yld Longest Part	NS	NS	NS	**	**	**
Ave Value/Input Bf	NS	**	NS	**	*	**
2A Common						
Yield	*	NS	**	CR	CR	CR
Ave Cutting Length	**	*	NS	*	**	NS
BF/Sawline	CR	NS	CR	*	*	CR
% Yld lt 20 Inches	*	NS	NS	NS	**	NS
% Yld Longest Part	NS	NS	NS	**	**	**
Ave Value/Input Bf	NS	*	CR	NS	CR	CR

a- Cutting bill designations indicate cutting lengths (cutting bill A has shorter lengths than B), simulation weighting factors used (1 or 2), and the first operation (X = crosscut-first, R = rip-first).

b- Abbreviations used: NS - not significant at α=.05, CR - complex relationship involving interaction, * - significant at α=.05, ** - highly significant at α=.01.

(Table 13). Visual inspections of the means for the other variables that produced significant covariance test results did not show a consistent tendency to either increase or decrease with increasing LCAT.

Covariance Test Results: 1 Common

For the 1 Common boards the variation in total yield between length categories was statistically significant after factoring out the effect of lumber width, for 4 of the 6 cutting bill combinations tested. The only non-significant tests for the variable total yield were the two rip-first tests: A1R and A2R (Table 12). For three of the four significant analysis of covariance tests on total yield, visual inspection of the group means revealed a distinct tendency for yield to increase with increasing LCAT (Table 14; Figure 11). Figure 11 shows that there is a high degree of unexplained variability in these models.

For the yield variables "average cutting length", "board feet of cuttings per sawing operation", and "average part value per board foot of lumber", significant differences between LCAT's were detected for 4 of the 6 cutting bill combinations. For both average cutting length and average part value per board foot of lumber, significant differences were associated with the A2X, B2X, A1R, and A2R cutting bill combinations (Table 12). Inspection of the means revealed a tendency for each of these variables to increase with increasing lumber length (Table 14). For the variable "board feet of parts per sawing operation", significant covariance test results were associated with the A1X, A2X, B1X, and B2X cutting bill combinations (Table 12). The adjusted group means for two of these four tests indicated a tendency for the board feet of cuttings per sawing operation to decrease with increasing LCAT (Table 14).

Table 13. Rough mill yield variable means by length category for those variables that demonstrate length-based trends: Selects grade.

SELECTS	**Lumber Length Category**					
	6	**8**	**10**	**12**	**14**	**16**
n =	(27)	(8)	(15)	(25)	(21)	(27)
Variable - Cutting Bill [a]	**Mean Values**					
Board Feet per Sawline - A1X	.26	.19	.22	.20	.18	.17
Board Feet per Sawline - A2X	.39	.41	.38	.38	.34	.32
Board Feet per Sawline - B1X	.36	.30	.29	.28	.23	.23
Board Feet per Sawline - B2X	.64	.45	.50	.49	.45	.42

a- Cutting bill designations indicate cutting lengths (cutting bill A has shorter lengths than B), simulation weighting factors used (1 or 2), and the first operation (X = crosscut-first, R = rip-first).

Table 14. Rough mill yield variable means by length category for those variables that demonstrate length-based trends: 1 Common grade.

1 COMMON	Lumber Length Category						
	4	6	8	10	12	14	16
n =	(38)	(73)	(121)	(138)	(119)	(95)	(67)
Variable - Cut. Bill [a]	**Mean Values**						
Yield - A1X	76.0	77.3	77.6	77.9	78.9	79.6	80.0
Yield - B1X	72.8	73.4	73.4	74.7	75.6	76.1	77.1
Yield - B2X	63.8	60.0	63.9	64.8	65.6	65.2	66.2
Ave Cut Length - B2X	45.1	57.2	47.7	47.4	51.9	51.2	51.9
Ave Cut Length - A1R	21.7	22.8	24.0	25.3	26.2	25.6	26.4
Bf/Sawline - A1X	.24	.23	.22	.21	.21	.18	.20
Bf/Sawline - B1X	.31	.30	.29	.27	.27	.26	.26
% Yld lt 20 inches - A2X	6.1	6.1	5.4	5.5	3.8	4.4	2.8
% Yld lt 20 inches - A1R	32.9	27.5	22.8	20.6	19.4	19.3	18.3
% Yld longest part - B2X	0.2	21.7	25.2	21.3	26.6	29.0	32.4
% Yld longest part - A1R	14.9	16.8	23.6	20.8	25.4	22.5	25.7
Ave Value/Input Bf-A2X	896	857	880	872	920	903	945
Ave Value/Input Bf-B2X	914	990	940	956	1019	1009	1037
Ave Value/Input Bf-A1R	735	757	763	777	790	778	790

a- Cutting bill designations indicate cutting lengths (cutting bill A has shorter lengths than B), simulation weighting factors used (1 or 2), and the first operation (X = crosscut-first, R = rip-first).

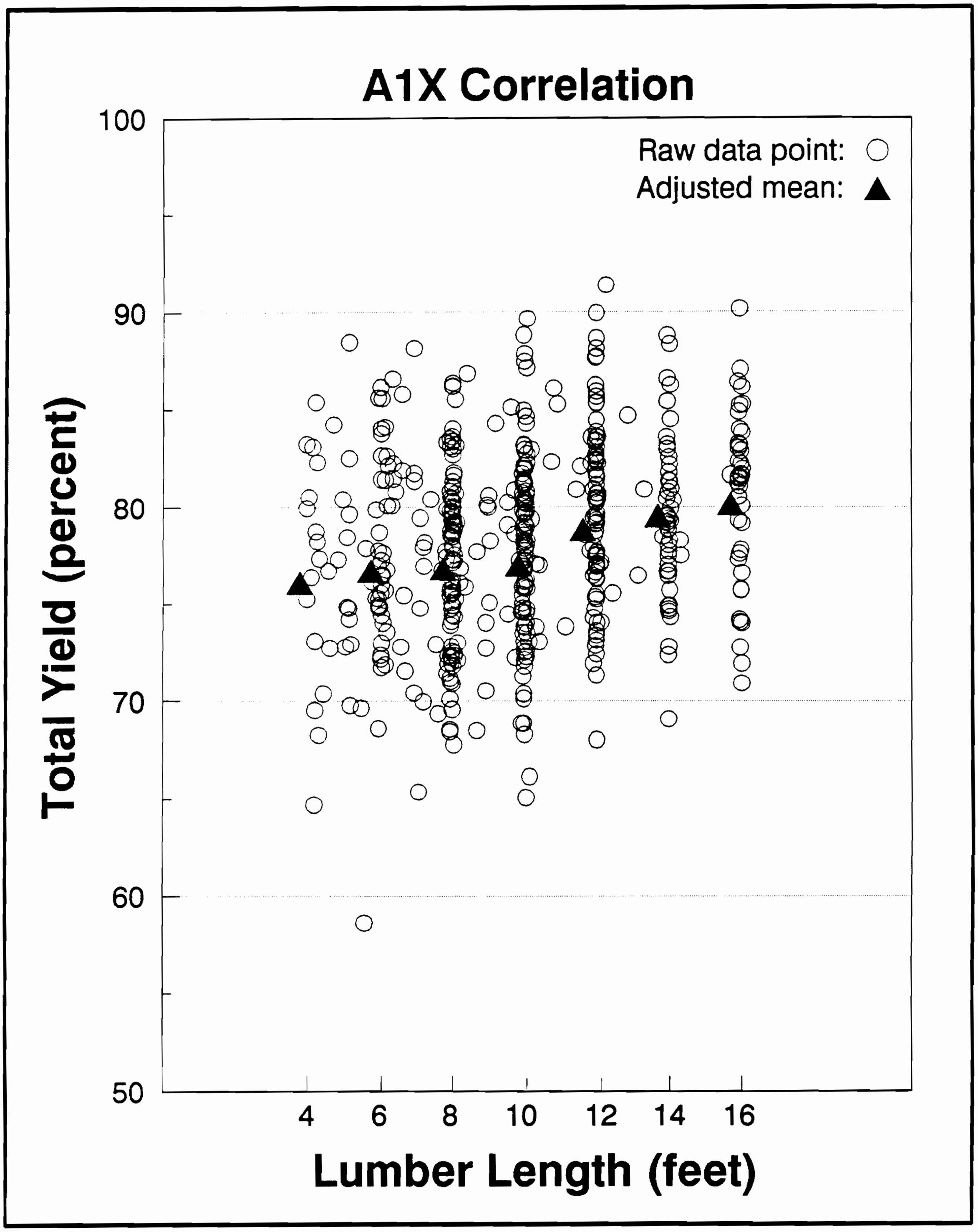

Figure 11. Total yield versus lumber length; crosscut-first, 1 Common, intermediate length cutting bill analysis.

Covariance tests on the percent yield of parts less than 20 inches long and the percent yield of the longest part in the cutting bill were significant for 3 of the 6 cutting bill combinations (Table 12). For the variable "percent yield of parts less than 20 inches", visual inspection of the adjusted group means pointed to a tendency for the variable to decrease with increasing LCAT (Table 14). For the variable "percent yield of the longest part in the cutting bill", a tendency for the group means to increase with increasing LCAT was observed.

Covariance Test Results: 2A Common

For several of the 2A Common tests a significant interaction effect between lumber length and width was detected. The presence of a significant interaction indicates that the effect of width on the variable being tested is different at various levels of the grouping variable LCAT. For these cases the analysis of covariance test is not a valid test. For the variables "total yield", "board feet of parts per sawing operation", and "average part value per board foot of lumber" three of the six tests indicated the presence of interaction (Table 12). In addition, two covariance tests were significant for the variable "total yield", two were significant for the variable "board feet per sawing operation", and 1 covariance test was significant for the variable "average part value per board foot of lumber" (Table 12). Again, inspection of the adjusted mean values for these variables for each of the length categories indicates that yield and average value per board foot of lumber tend to increase with increasing LCAT while board feet of parts per sawing operation tends to decrease (Table 15).

Table 15. Rough mill yield variable means by length category for those variables that demonstrate length-based trends: 2A Common grade.

2A COMMON	Lumber Length Category						
	4	6	8	10	12	14	16
n =	(10)	(37)	(171)	(174)	(154)	(139)	(98)
Variable - Cut. Bill [a]	**Mean Values**						
Yield - A1X	67.9	72.6	72.6	73.1	73.3	73.3	74.3
Yield - B1X	62.6	66.7	67.7	68.6	68.7	68.6	70.0
Ave Cut Length - A2X	28.9	32.5	34.3	34.1	34.6	34.9	35.7
Ave Cut Length - B2X	41.0	50.9	44.8	44.9	45.7	45.1	46.4
Ave Cut Length - A1R	19.2	20.7	22.1	21.9	22.2	22.9	22.7
Bf/Sawline - B2X	.36	.40	.34	.34	.34	.33	.32
% Yld lt 20 inches - A1R	37.0	31.2	25.9	25.9	25.4	23.7	23.1
% Yld longest part - B2X	0.2	10.3	18.1	19.6	17.6	18.7	19.0
% Yld longest part - A1R	2.9	10.6	15.0	14.2	15.6	16.3	15.8
% Yld longest part - A2R	24.2	29.6	35.1	36.6	35.5	33.7	33.5
Ave Value/Input Bf - A2X	687	719	752	756	765	768	778

a- Cutting bill designations indicate cutting lengths (cutting bill A has shorter lengths than B), simulation weighting factors used (1 or 2), and the first operation (X = crosscut-first, R = rip-first).

Results of the test on the hypothesis that the average cutting length for each lumber length category is equal were significant for 4 of the 6 cutting bill combinations: A1X, A2X, B2X, and A1R (Table 12). For the variable "percent yield of parts less than 20 inches long" only 2 of the 6 cutting bill combinations showed significant differences between length categories. For 3 of the 6 cutting bill combinations significant differences between length categories for the variable "percent yield of the longest length part" were detected. Evaluation of the adjusted mean values for these variables at each level of LCAT indicates that average cutting length and the percent yield of the longest part tend to increase with increasing LCAT while the percent yield of parts less than 20 inches long tends to decrease (Table 15). These trends are similar to those which were seen in the analyses of the Selects and 1 Common grades.

Regression Test Results

The models tested in these regression analyses are of the form:

$$\text{Yield} = \beta_0 + \beta_1 \times \text{Length} + E.$$

The E-term gives a measure of how far an individual yield value is from the regression line. The regression is significant if the inclusion of the β_1 x Length term in the model gives a better prediction of individual responses than would the mean yield value by itself.

Regression Test Results: Selects

Table 16 lists those regression tests between the four variables, "total yield", "average cutting length", "board feet of parts per sawing operation", and "average cutting value per board foot of lumber" and lumber length which were significant at the α=.05 level. Of the 24 associations investigated (4 variables x 6 cutting bill combinations), 12 were significant. In several cases the multiple regression which included width as well as length as independent variables is listed since both the width and length effects were significant and when combined contributed to a significantly increased R^2 measure for the variable.

Regression tests of the association between the variable "total yield" and length were significant for two of the six cutting bill combinations, A1R and A2R. For these tests yield decreases with increasing lumber length. The R^2-values are quite low, indicating that the major effects are due to random variability.

Regression tests of the association between the variable "average cutting length" and lumber length were significant for three of the six cutting bill combinations. In one of these associations lumber width is also a significant component of the regression equation. For the two significant crosscut-first regression associations, B1X and B2X, average cutting length decreases with increasing lumber length. For the significant rip-first regression association, A2R, average cutting length increases with increasing lumber length.

Tests of the association between the variable "board feet of parts per sawing operation" and lumber length were significant for five of the six cutting bill combinations. In three of these five cases the multiple regression including width contributes

Table 16. Significant regressions between rough mill yield variables and lumber length and width.

Dependent Variable and Cutting Bill [a]	Effect of Length	Effect of Width	P-Value	R^2
SELECTS				
Yield - A1R	-	n/a	.000	12.3%
Yield - A2R	-	n/a	.004	5.3%
Ave Cutting Length - B1X	-	n/a	.011	4.1%
Ave Cutting Length - B2X	-	-	.000	15.4%
Ave Cutting Length - A2R	+	n/a	.001	7.9%
BF/Sawline - A1X	-	n/a	.000	15.3%
BF/Sawline - A2X	-	+	.000	12.0%
BF/Sawline - B1X	-	+	.000	21.5%
BF/Sawline - B2X	-	+	.000	20.6%
BF/Sawline - A2R	-	n/a	.014	3.8%
Av Value/Input BF - B2X	-	-	.000	18.1%
Av Value/Input BF - A1R	-	n/a	.033	2.7%
1 COMMON				
Yield - A1X	+	-	.000	8.5%
Yield - A2X	+	-	.000	5.6%
Yield - B1X	+	-	.000	8.4%
Yield - B2X	+	-	.000	3.6%
Yield - A1R	-	n/a	.010	0.9%
Ave Cutting Length - A2X	+	n/a	.009	0.9%
Ave Cutting Length - A1R	+	n/a	.000	6.8%
Ave Cutting Length - A2R	+	n/a	.033	0.5%
BF/Sawline - A1X	-	+	.000	6.9%
BF/Sawline - A2X	-	+	.000	9.1%
BF/Sawline - B1X	-	+	.000	8.3%
BF/Sawline - B2X	-	+	.000	4.2%
Av Value/Input BF - A2X	+	-	.000	6.8%
Av Value/Input BF - B1X	+	-	.000	7.1%
Av Value/Input BF - B2X	+	-	.000	10.1%
Av Value/Input BF - A1R	+	n/a	.001	1.4%

Table 16. (continued from previous page).

Dependent Variable and Cutting Bill	Effect of Length	Effect of Width	P-Value	R^2
2A Common				
Yield - A1X	+	-	.000	7.0%
Yield - B1X	+	-	.000	7.7%
Yield - A1R	-	n/a	.001	1.4%
Ave Cutting Length - A2X	+	n/a	.001	1.3%
Ave Cutting Length - A1R	+	n/a	.000	1.7%
BF/Sawline - A1X	-	+	.000	8.9%
BF/Sawline - B1X	-	+	.000	9.1%
BF/Sawline - B2X	-	+	.000	3.6%
BF/Sawline - A1R	-	n/a	.017	0.6%
BF/Sawline - A2R	-	n/a	.000	1.6%
Av Value/Input BF - A2X	+	-	.000	8.2%
Av Value/Input BF - B1X	+	-	.000	10.8%

a- Cutting bill designations indicate cutting lengths (cutting bill A has shorter lengths than B), simulation weighting factors used (1 or 2), and the first operation (X = crosscut-first, R = rip-first).

n/a- The effect of width is not significant ... only the single variable model with length as the independent variable is significant.

significantly to the prediction of the variable. For all five of the significant regression associations, board feet of parts per sawing operation decreases with increasing lumber length.

For two of the five cutting bill combinations the association between the dependent variable "average part value per board foot of lumber" and the independent variable "lumber length" were significant. In both of these cases value decreases with increasing length. For the B2X values width is also included in the regression equation.

Regression Test Results: 1 Common

Of the 24 associations between the same four yield variables and lumber length investigated in the 1 Common grade, 16 were significant (Table 16). Five of these significant associations were between total yield and lumber length. All four crosscut-first cutting bill combinations had significant, positive associations between yield and lumber length (and negative associations with lumber width). For the significant rip-first association, yield decreased with increasing lumber length.

Regression tests of the association between the variable "average cutting length" and lumber length were significant for 3 of the 6 cutting bill combinations (Table 16). For each of these significant tests, which included one crosscut-first and both rip-first cutting bills, lumber length had a positive effect on average cutting length. The R^2-values for these tests are all below 10%. This indicates that, while lumber length contributes to the prediction of average cutting length, the unexplained variability in the model is several times larger than the variability explained by lumber length.

The cutting length distributions for the 6, 12, and 16 foot long, 1 Common lumber groups are detailed in Figures 12 and 13. For the crosscut-first cut-up simulations using cutting bill A and a low priority for cutting length (wf=1), the 6 foot long lumber has a higher yield of the longest cutting (48") and of the three longest cuttings combined, than does either the 12 or 16 foot long lumber groups (Figure 12). The total yield for the 6 foot lumber is 2½-3 percent lower than the yields of the other groups. When a higher cutting length priority is used (wf=2) the 6 foot long lumber group produces a lower percentage of the longest cuttings but a higher total yield (2½-3 percent higher) than do the longer length lumber groups.

For each of the cutting bill A, rip-first simulations the 6 foot long lumber's total yield is higher than the yields obtained from the 12 and 16 foot lumber (Figure 13). For the weighting factor = 1 iterations, the 6 foot lumber's yield of the longest cutting (48") is about 2/3's that of the longer length lumber groups. When the higher cutting length priority is used the rip-first cut-up simulation returns a more similar cutting length distribution for the different lumber lengths.

The variable "board feet of cuttings produced per sawing operation" showed a significant, negative association with lumber length and a significant, positive association with lumber width for each of the crosscut-first cutting bills (Table 16). The variable "average cutting value per board foot of lumber" showed a significant, positive association with lumber length for four of the six cutting bill combinations including three crosscut-first and one rip-first cutting bill.

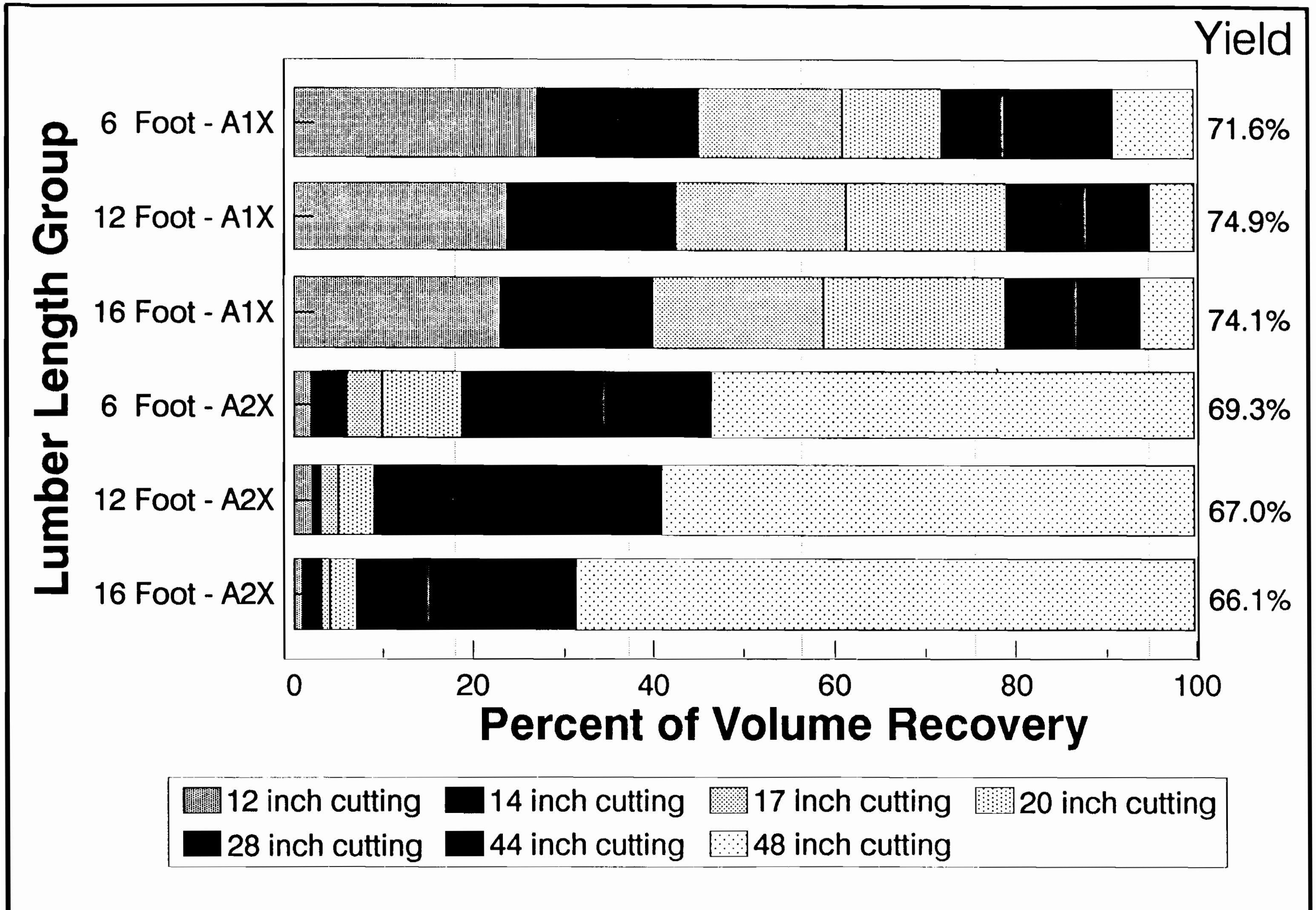

Figure 12. Crosscut-first cutting length distributions for the 6, 12, and 16 foot long lumber length groups; cutting bill A (7 lengths; 12-48 inches).

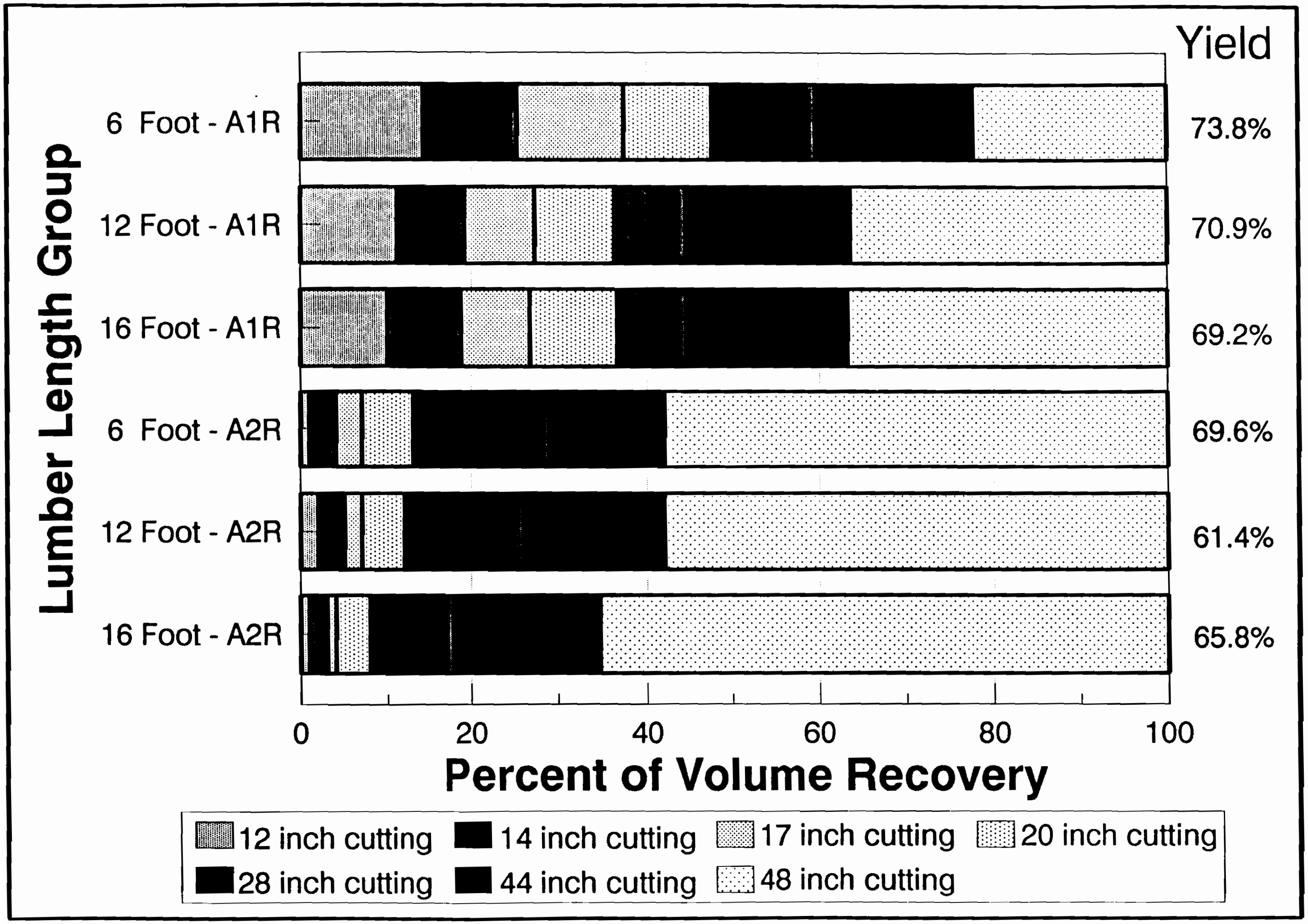

Figure 13. Rip-first cutting length distributions for the 6, 12, and 16 foot long lumber length groups; cutting bill A (7 lengths; 12-48 inches).

Regression Test Results: 2A Common

Of the 24 associations between the four yield variables and lumber length investigated in the 2A Common grade, 12 were significant (Table 16). The nature of the significant regression associations were very similar to those seen for the 1 Common tests. There were three significant yield-length regressions. Of these, two were for crosscut-first cutting bills. In these two relationships the association between yield and length was positive. A significant negative association between yield and lumber width was also included in the prediction equation. For the significant rip-first regression, yield decreased with increasing lumber length.

For two of the six cutting bill combinations "average cutting length" demonstrated a significant, positive relationship to lumber length (Table 16). For 5 of the 6 cutting bill combinations the variable "board feet of cuttings per sawing operation" decreased as lumber length increased. For the significant crosscut-first relationships, width is included in the regression relationship. Only two of the six regression relationships between "average value per board foot of lumber" and lumber length were found to be significant. The nature of the regression relationships for the two crosscut-first cutting bills which produced significant test results is similar to that which was described for the 1 Common grade: average part value shows a positive association with lumber length and a negative association with lumber width.

T-Test Results: Short versus Long Lumber

The variables "total yield", "average cutting length", "board feet of parts per sawing operation", and "part value per board foot of lumber" for each of the cutting bill combinations were compared between short and long length lumber groups. All lumber shorter than 8 feet long was classified as short length lumber. The continuous variable "lumber width" was treated as a covariate in these tests. All tests were two-sided tests. The results of all of these tests are detailed in Table 17.

Considering the results from the crosscut-first runs for all three lumber grades:

1. The difference in "total yield" between lumber length groups was significant for 6 of the 12 t-tests - in 5 of the 6 significant tests the mean yield value for long length lumber exceeded the mean value for short length lumber - the difference between the means was on the order of 2 percent.
2. The difference in "average cutting length" between lumber length groups was significant for 8 of the 12 t-tests - in 5 of the 8 significant tests the mean value for the short length lumber group exceeded the mean value for the long length lumber.
3. The difference in "board feet of parts per sawing operation" between lumber length groups was significant for 10 of the 12 t-tests - in all these cases the mean value for the short length lumber group exceeded the mean value for the long lumber group.

Table 17. Rough mill yield variable t-test results between short and long length lumber groups.

CB[a]	T-Test Variable	SELECTS SIG	SELECTS Means SLL	SELECTS Means LLL[b]	1 COMMON SIG	1 COMMON Means SLL	1 COMMON Means LLL	2ACOMMON SIG	2ACOMMON Means SLL	2ACOMMON Means LLL
A	Yield	NS			**	76.9	78.6	NS		
1	Av Cut L	*	19.2	17.5	NS			NS		
X	BF/SawIn	**	.26	.19	**	.23	.20	*	.18	.17
	Val/In BF	*	759	724	NS			NS		
A	Yield	*	77.5	74.4	NS			NS		
2	Av Cut L	**	33.9	39.8	**	35.4	37.3	**	31.7	34.6
X	BF/SawIn	NS			*	.37	.35	NS		
	Val/In BF	*	939	986	*	870	899	**	712	762
B	Yield	NS			**	73.2	75.2	**	65.9	68.6
1	Av Cut L	*	27.9	25.1	NS			NS		
X	BF/SawIn	**	.36	.26	**	.31	.27	**	.25	.22
	Val/In BF	NS			NS			*	659	683
B	Yield	NS			**	61.3	65.0	*	53.2	56.3
2	Av Cut L	**	68.7	52.7	**	53.0	49.7	*	48.8	45.3
X	BF/SawIn	**	.64	.46	**	.52	.44	**	.39	.34
	Val/In BF	**	1294	1107	NS			NS		
A	Yield	**	76.8	65.8	*	76.2	74.7	NS		
1	Av Cut L	**	25.0	29.7	**	22.4	25.4	**	20.4	22.3
R	BF/SawIn	NS			NS			NS		
	Val/In BF	NS			**	749	779	NS		
A	Yield	**	76.5	72.1	NS			NS		
2	Av Cut L	**	35.2	39.9	**	36.6	38.0	*	33.6	34.9
R	BF/SawIn	NS			NS			NS		
	Val/In BF	NS			NS			NS		

a- Cutting bill designations indicate cutting lengths (cutting bill A has shorter lengths than B), simulation weighting factors used (1 or 2), and the first operation (X = crosscut-first, R = rip-first).

b- Abbreviations used: SLL = short length lumber, LLL = long length lumber; NS = not significant at α = .05; * = significant at α = .05, ** = highly significant at α = .01.

4. The difference in "part value per board foot of lumber" between lumber length groups was significant for 6 of the 12 t-tests - in 4 of the 6 significant tests the mean value for the long length lumber group exceeded the mean value for the short length group.

Considering the results from the rip-first runs for all three lumber grades:

1. The difference between lumber length groups for the variable "yield" was significant for 3 of the 6 t-tests - in all three cases the mean yield value for the short length lumber group exceeded the mean value for the long length group.
2. The difference between lumber length groups for the variable "average cutting length" was significant in all 6 rip-first t-tests - in all cases the mean value for the long length lumber group exceeded the mean value for the short length group.
3. The difference between lumber length groups for the variable "board feet of parts per sawing operation" was not significant for any of the rip-first t-tests.
4. The difference between lumber length groups for the variable "average value per board foot of lumber" was only significant for 1 rip-first category (1 Common; A1R) - the mean value for the long length lumber group was higher than the mean value for the short length lumber group.

Regression Test Results: The Influence of Crook

Simple linear regressions in which the degree of association between the same four yield variables and the independent variable "crook deviation" were investigated for all three lumber grades. The association between crook deviation and lumber length was also analyzed. Tables 18, 19, and 20 detail the results of these regression analyses for the Selects, 1 Common, and 2A Common grades, respectively.

All significant regressions within each of the grades indicate a negative association between crook and the yield variable. Of particular note is the fact that the R^2-value for the strength of the association between total yield and crook deviation is considerably higher for the rip-first results than for the crosscut-first results. Figure 14 shows a plot of total yield versus crook for 1 Common lumber processed using the rip-first, weighting factor equals one cut-up routine (A1R). The most consistently significant relationship across grades and cutting bill combinations is the relationship between "board feet of parts per sawing operation" and "crook deviation".

Yield Correlations

Tables 21, 22, and 23 show for the Selects, 1 Common, and 2A Common grades respectively, the correlation between cutting bill combinations for the variable "total yield". The yield of clear-face cuttings of required minimum size which is obtained in grading the boards with program HaLT was also correlated with the "total yield" obtained using each of the six cutting bill combinations.

Table 18. Significant regressions between rough mill yield variables and the degree of lumber crook: Selects grade.

Dependent Variable and Cutting Bill [a]	Effect of Crook	P-Value	R^2
SELECTS			
Yield - A2X	-	.000	10.7%
Yield - B1X	-	.004	5.5%
Yield - B2X	-	.002	6.4%
Yield - A1R	-	.000	13.8%
Yield - A2R	-	.000	18.9%
Ave Cutting Length - A1X	-	.004	5.6%
Ave Cutting Length - B1X	-	.001	7.4%
Ave Cutting Length - B2X	-	.001	7.3%
BF/Sawline - A1X	-	.000	28.2%
BF/Sawline - A2X	-	.000	24.4%
BF/Sawline - B1X	-	.000	28.1%
BF/Sawline - B2X	-	.000	22.7%
BF/Sawline - A1R	-	.000	13.5%
BF/Sawline - A2R	-	.000	15.6%
Av Value/Input BF - A1X	-	.001	7.2%
Av Value/Input BF - A2X	-	.000	9.2%
Av Value/Input BF - B1X	-	.000	12.7%
Av Value/Input BF - B2X	-	.000	15.1%
Av Value/Input BF - A1R	-	.000	11.5%
Av Value/Input BF - A2R	-	.000	12.8%
Regression of Crook on Length	**+**	**.000**	**28.4%**

a- Cutting bill designations indicate cutting lengths (cutting bill A has shorter lengths than B), simulation weighting factors used (1 or 2), and the first operation (X = crosscut-first, R = rip-first).

Table 19. Significant regressions between rough mill yield variables and the degree of lumber crook: 1 Common grade.

Dependent Variable and Cutting Bill [a]	Effect of Crook	P-Value	R^2
1 Common			
Yield - A2X	-	.019	0.7%
Yield - B2X	-	.043	0.5%
Yield - A1R	-	.000	10.1%
Yield - A2R	-	.000	7.2%
Ave Cutting Length - A1X	-	.000	2.0%
Ave Cutting Length - B1X		.000	0.5%
Ave Cutting Length - A1R	-	.002	1.4%
BF/Sawline - A1X	-	.000	18.2%
BF/Sawline - A2X	-	.000	12.5%
BF/Sawline - B1X	-	.000	15.2%
BF/Sawline - B2X	-	.000	10.3%
BF/Sawline - A1R	-	.000	2.8%
BF/Sawline - A2R	-	.000	3.9%
Av Value/Input BF - A1X	-	.002	1.3%
Av Value/Input BF - A2X	-	.034	0.5%
Av Value/Input BF - B1X	-	.032	0.6%
Av Value/Input BF - A2X	-	.001	0.6%
Regression of Crook on Length	**+**	**.000**	**14.9%**

a- Cutting bill designations indicated cutting lengths (cutting bill A has shorter lengths than B), simulation weighting factors used (1 or 2), and the first operation (X = crosscut-first, R = Rip-first).

Table 20. Significant regressions between rough mill yield variables and the degree of lumber crook: 2A Common grade.

Dependent Variable and Cutting Bill [a]	Effect of Crook	P-Value	R^2
2A Common			
Yield - A1R	-	.000	4.7%
Yield - A2R	-	.000	3.9%
Ave Cutting Length - B1X		.000	1.9%
BF/Sawline - A2X	-	.000	7.2%
BF/Sawline - B1X	-	.000	16.1%
BF/Sawline - B2X	-	.000	5.7%
BF/Sawline - A1R	-	.000	2.7%
BF/Sawline - A2R	-	.000	2.1%
Av Value/Input BF - A1X	-	.000	2.0%
Av Value/Input BF - A2X	-	.000	2.4%
Regression of Crook on Length	**+**	**.000**	**10.1%**

a- Cutting bill designations indicate cutting lengths (cutting bill A has shorter lengths than B), simulation weighting factors used (1 or 2), and the first operation (X = crosscut-first, R = Rip-first).

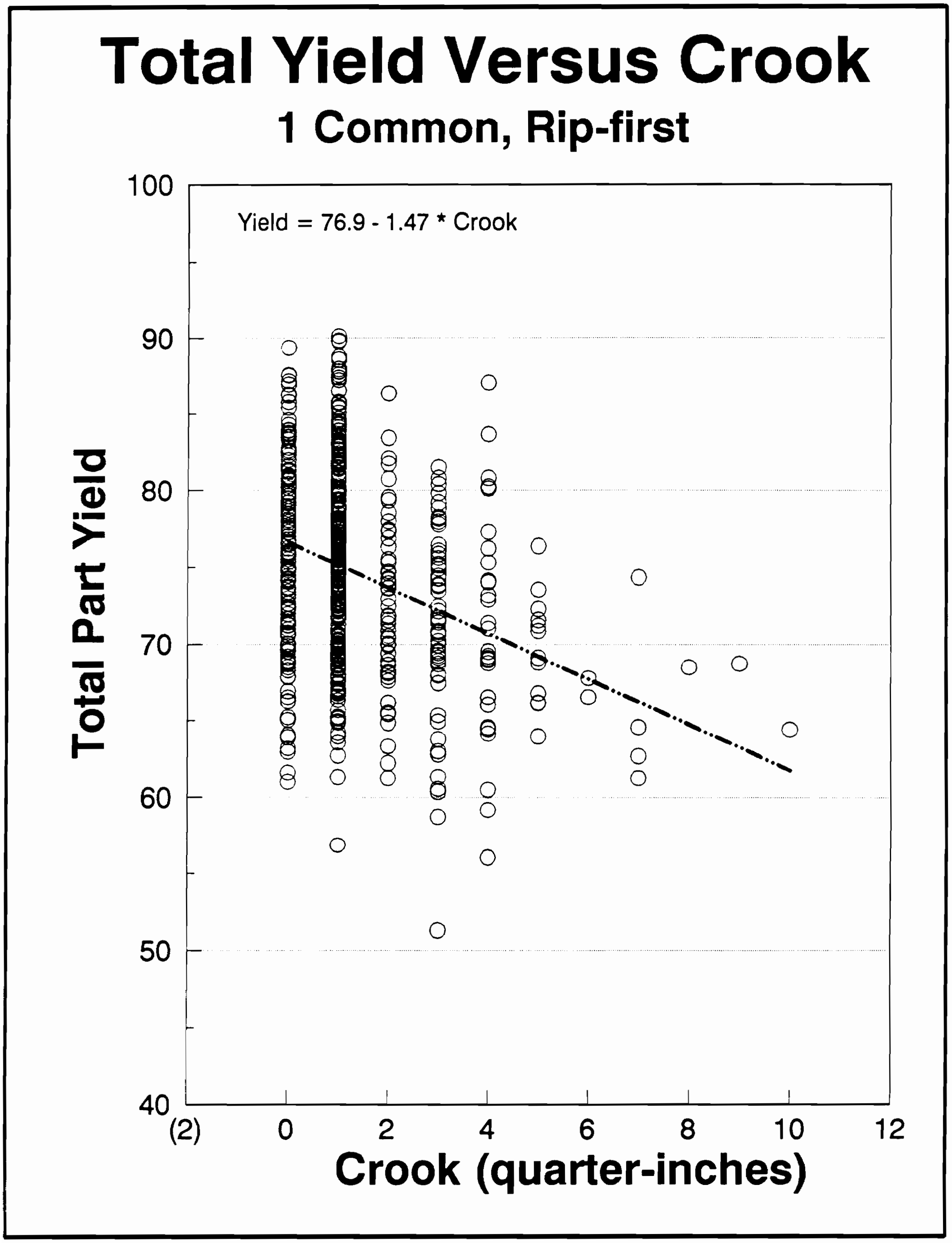

Figure 14. Total yield versus crook; rip-first, 1 Common, intermediate length cutting bill analysis.

Table 21. Cross-correlations between simulated yields for 6 cutting bill combinations and the grade cutting yield generated by the program HaLT: Selects grade.

Cutting Bill (a)	A1X Yield	B1X Yield	A2X Yield	B2X Yield	A1R Yield	A2R Yield
A1X Yield	1					
B1X Yield	.605	1				
A2X Yield	.656	.529	1			
B2X Yield	.486	.443	.557	1		
A1R Yield	.394	.242	.388	.216	1	
A2R Yield	.426	.473	.545	.392	.458	1
Grading Yld	.320	.147	.207	-.067	.125	.136

a- Cutting bill designations indicate cutting lengths (cutting bill A has shorter lengths than B), simulation weighting factor used (1 or 2), and the first operation (X = crosscut-first, R = rip-first).

Table 22. Cross-correlations between simulated yields for 6 cutting bill combinations and the grade cutting yield generated by the program HaLT: 1 Common grade.

Cutting Bill (a)	A1X Yield	B1X Yield	A2X Yield	B2X Yield	A1R Yield	A2R Yield
A1X Yield	1					
B1X Yield	.803	1				
A2X Yield	.676	.628	1			
B2X Yield	.510	.561	.476	1		
A1R Yield	.648	.609	.497	.393	1	
A2R Yield	.623	.592	.511	.422	.847	1
Grading Yld	.204	.212	.269	.100	.147	.115

[a] Cutting bill designations indicate cutting lengths (cutting bill A has shorter lengths than B), simulation weighting factor used (1 or 2), and the first operation (X = crosscut-first, R = rip-first).

Table 23. Cross-correlations between simulated yields for 6 cutting bill combinations and the grade cutting yield generated by the program HaLT: 2A Common grade.

Cutting Bill (a)	A1X Yield	B1X Yield	A2X Yield	B2X Yield	A1R Yield	A2R Yield
A1X Yield	1					
B1X Yield	.843	1				
A2X Yield	.631	.647	1			
B2X Yield	.524	.552	.538	1		
A1R Yield	.723	.656	.505	.375	1	
A2R Yield	.692	.607	.496	.373	.852	1
Grading Yld	.093	.116	.141	.049	.060	.025

a- Cutting bill designations indicate cutting lengths (cutting bill A has shorter lengths than B), simulation weighting factor used (1 or 2), and the first operation (X = crosscut-first, R = rip-first).

For the Selects grade the three highest correlations for the variable "total yield" are between cutting bill combinations A1X and A2X (.656), A1X and B1X (.605), and A2X and B2X (.557; Table 21). The correlation between the HaLt yield or "grading yield: and the yields from the six cutting bill combinations is consistently low. The highest correlation for the "grading yield" variable is .320 with A1X yield.

For the 1 Common grade the three highest correlations for the variable "total yield" are between cutting bill combinations A1R and A2R (.847), A1X and B1X (.803), and A1X and A2X (.676; Table 22). The correlation between the variable "grading yield" and the yields from the six cutting bill combinations ranges from a low of .100 to a high of .269 for the correlation between "grading yield" and A2X yield.

For the 2A Common grade the three highest correlations for the variable "total yield" are between cutting bill combinations A1R and A2R (.852), A1X and B1X (.843), and A1X and A1R (.723; Table 23). The correlation between the variable "grading yield" and the yields from the six cutting bill combinations is extremely low for the 2A Common comparisons. The highest correlation for the variable "grading yield" is with A2X yield and is only .141.

Discussion

The data bank of mapped red oak boards which was input into the CORY cut-up program is the most extensive red oak data base of its kind in existence. It must be noted however, that the boards in the data base came exclusively from three Appalachian region mills. If the sample had been collected from a larger number of more widely dispersed mills the results of these tests could be more broadly interpreted.

The Selects boards in the sample were not collected as Selects, but rather were collected as 1 Common (or more rarely 2A Common) boards and upon regrading were classified as Selects. Thus, the Selects sample might be expected to contain a higher percentage of lower quality Selects (just better than 1 Common) than would normally be found within the Selects grade at the three mills from which the sample was collected. In addition, the Selects sample consists of a total of only 123 boards compared to 651, 1 Common boards and 783, 2A Common boards.

The 1 Common board data was the most balanced as to length. The minimum number of boards in any one of the length categories was 38 (in the 4-5' group). In addition the relative percentage of non-remanufactured boards (boards from mill 1) to remanufactured boards (boards from mills 2 and 3) was similar from one LCAT to the next in the 1 Common data bank. The results of the analysis of covariance tests (Table 12) for the 1 Common grade likely reflects the degree to which the data set is balanced: the A1X and B1X test results are similar to one another as are the A2X and B2X and the A1R and A2R. For the Selects and 2A Common grades the covariance test results are not comparable between like weighting factors and first operation scenarios.

Some of the more consistent covariance test results which can be noted in looking at Table 12 are that:

1. For those cutting bill combinations in which "average part value per board foot of lumber" is significantly different between lumber length groups,

"average rough part length" is also significant; since the part valuation equation attaches more value to longer parts this is an intuitive result.

2. The variable "board feet of parts per sawing operation" is significantly different between length groups for all but one of the executable crosscut-first covariance tests.

3. The variable "average cutting length" is significantly different between length groups in all of the weighting factor = 2, crosscut-first covariance tests; with a weighting factor of 2, heavy emphasis is put on recovering the longest part in the cutting bill - for cutting bill B the longest length, 70 inches, is impossible to retrieve from 4 and 5 foot long lumber.

The nature of the relationship between the various yield variables and lumber length is most easily visualized by looking at Table 16. The fact that the Selects test results are not always consistent with the 1 Common and 2A Common results becomes obvious when looking at this table. Whether these differences are attributable to sample size differences is not clear. Basic differences between the Selects grade rule and the 1 Common and 2A Common grade rules might also affect the test results. Selects are graded on the good face of the board and can either be: 1 - Selects quality on the grading face with sound backs on the cuttings, or 2 - Selects quality on the grading face and 1 Common quality on the back face with no regard for the quality of the backside of the Selects cuttings. In contrast, for both 1 Common and 2A Common boards the grading face is the worst face of the board and the backside of the cuttings must be of sound quality. To interpret how this difference between the grades might contribute to the divergent test results would require board by board analysis.

Significant differences in "total yield" that show up in covariance, t-test and regression results indicate that the yield from longer lumber is higher than the yield from shorter lumber when processing certain crosscut-first cutting bills. In contrast, differences in "total yield" that show up for the rip-first cut-up simulations indicate that the yield from shorter lumber is higher than the yield from longer lumber. In a crosscut-first operation the long lumber may have slightly higher yield since there are more combinations of lengths which can be placed on a long length board and thus less potential yield loss associated with crosscut waste (Wengert et al. 1986). The higher yield from short length lumber obtained in the rip-first simulations can largely be attributed to the effect of crook. Longer boards have greater average crook deviation and crooked boards suffer an inherent yield loss in a rip-first operation. The loss occurs as the rip operator tries to create a straight edge on the board. These results lend further support to the work performed by Araman (1979) and Gatchell (1990; 1991) from which they concluded that crooked boards should always be crosscut before being ripped.

The tendency for the variable "board feet of cuttings per sawing operation" to decrease as lumber length increases is not surprising given the nature of the NHLA grade rules. To make the same grade a short board generally needs to have a higher clear-face cutting yield than does a longer board, and that yield must be obtained in fewer cuttings. The influence of "board feet per sawline" should be captured as a component of throughput rate in the rough mill.

The low R^2-values in combination with plots of the data indicate that the random error associated with all of these models in high. The probability value (p-value) associated with the F-statistic (which corresponds to the alpha level at which the test would be rejected) for many of these tests indicates that lumber length (or crook) has an influence on the yield variables. Further analysis of the significance of the lumber length-yield relationship could be done by incorporating the length-based relationship into a simulation model, executing the model, then executing the model again using the mean and standard deviation from the entire sample as predictors. The sensitivity of the decision variables in the model (e.g. production volume per hour) to the change in the estimate of the yield variable would indicate the importance of the lumber length-based relationship.

The correlation tests between "grading yield" and each of the simulated yields indicate that "grading yield" is of very little value in predicting potential cut-up yields. This can be explained in part by the fact that in grading the board once a minimum acceptable yield solution for the grade is found the search for better, higher yield solutions is interrupted.

The correlation tests between the different cutting bill combinations for the variable "total yield" indicate that there is a strong association between A1X and B1X yields for each grade. The correlation tests were performed to estimate how safe it would be to extrapolate the results obtained in these studies to other cutting bills. For the crosscut-first, low cutting length priority (wf=1) iterations the associations are substantially high that extrapolation should be feasible.

Summary

Studies were based on 4/4 thickness, red oak lumber collected from three Appalachian sawmills and defect-mapped at the Forestry Sciences Laboratory in Princeton, West Virginia. Board data was entered into the CORY lumber cut-up simulation program. Several yield measures were generated for each board from each of six CORY runs in which different combinations of cutting bill lengths, weighting factors, and first-operation specifications were entered.

The hypothesis that "total yield" is equal between length groups was rejected in the majority of crosscut-first cases. Regression results and group means analysis indicated that "total yield" tends to be slightly higher for longer lumber than it is for shorter lumber when crosscut-first. In contrast, the significant rip-first results indicated that "total yield" is higher for short lumber than for long for many rip-first cutting bills. This difference can be largely attributed to yield losses associated with ripping boards with crook.

Average cutting length and average cutting value per board foot of lumber exhibited significant positive regression relationships with lumber length for many of the cutting bill combinations analyzed. The variable which showed the strongest and most consistently significant relationship to lumber length was the "average board feet of parts per rough mill sawing operation". The value of "board feet of parts per sawing operation" tended to decrease with increasing lumber length.

The effect of crook on these same yield variables was examined in a series of regression tests. Results indicate that as crook decreases, yield, average cutting length,

board feet per sawing operation, and average value per board foot of lumber tend to increase.

The correlation between "grading yield" and the various CORY-generated cut-up yields was studied to see if "grading yield" is predictive of rough mill cut-up yields. The correlations for each of these comparisons were very low.

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THE EFFECT OF LUMBER LENGTH ON CROSSCUT-FIRST AND RIP-FIRST ROUGH PART YIELDS AND PROCESSING RATES: MILL STUDY RESULTS

Section 4

Abstract

Mill studies were conducted at a rip-first cabinet parts plant and at a crosscut-first case goods parts plant. Both yield and processing rate data was collected for five length-based board groups (4, 6, 8, 10, and 12 feet long) in each of two grades: 1 Common and 2A Common.

Regression analyses indicated that for both mills and grades the relationship between the total yield figure for each length group and the average length of the boards in each group was not significant. Neither were regressions of the yield of the longest length cutting in each length group versus average lumber length significant for any of the four mill-grade combinations tested. The percentage of total yield made up of the longest length cutting does show one consistent trend for each mill - grade combination: the yield of the longest length parts from the 6 and 7 foot lumber group is distinctly higher than the yields from the other length categories (LCAT'S). The percentage of total yield made up of the three longest length cuttings on the cutting bill is significantly and inversely related to average lumber length in the crosscut-first, 2A Common grade analysis.

Regression tests between average cutting length and average lumber length, the percent of fixed width cuttings (for the rip-first test) and average lumber length, and the

crosscut time per cutting or per board foot of lumber and average cutting length were not significant. For the rip-first mill study, the ripsaw rate per board foot of lumber did have a significant linear association with average lumber length for both the 1 Common and 2A Common grades.

Introduction

Short Lumber Yield

Information about the effect of lumber length on rough part dimension yields is scarce. Uncertainty about the yield potential of short length lumber has been identified as one of the major obstacles to be overcome before the furniture and cabinet industries will accept larger volumes of short length lumber (Wengert et al. 1986).

In addition to total rough part yield, the yield of the longer length parts in the cutting bill is a critically important yield measure. Concerns about the yield of short length lumber are often more appropriately expressed as concerns about the yield of longer parts from short lumber. Studies by both Bingham and Schroeder (1976/1977) and Araman (1982) in which the cutting needs of various sectors of the furniture and cabinet industries were surveyed indicate that a large percentage of the cutting needs for all industry segments are shorter than 42 inches. Despite these findings, most rough mill managers believe that they generate an excess of short length parts from their present lumber length-quality mix. They fear that if they increased their use of short length lumber a costly surplus of short length parts would develop.

Information on the relationship between lumber length and the yield of various length parts is very limited. In one study, the yield of the longest length cutting (31") in a cutting bill was found to be independent of lumber length over a very narrow range of lumber lengths (Ringer 1975). In a second study, the yield of short (less than 40") versus long parts obtained in a non-conventional gang-rip rough mill was only 10 percent for 4 foot lumber but ranged between 30 and 40 percent for the 5 to 8 foot long lumber (Reynolds and Schroeder 1978).

Information on the relationship between lumber length and total cutting yield is also very limited. In one tally maintained at a mill that produced short length, unedged lumber on a bolter saw, the yield from the bolter-sawn lumber was higher than the yield from longer length, 2A Common lumber in six of the seven quarters for which records were kept (North Carolina Division of Forest Resources 1979). The results of a more controlled study at this same mill provided a grade-based breakdown of the yield from short length lumber (4, 5, 6 feet long; Ringer 1975). The yields of clear two-face cuttings were 69.4 percent for the No. 1 Common, 58.4 percent for the No. 2A Common, and 48.4 percent for the No. 3A Common lumber. No yield differences were detected between the 4, 5, and 6 foot length groups within each grade. These short length yields were compared with expected yields from standard length lumber given in the Forest Products Lab's nomograms. Cutting yields from the short length lumber were higher in each grade category but the differences were not statistically significant.

Yield Studies

Yield studies conducted in the mill are logistically complex. Attempts to minimize the disruption and impact of the test on the operation and operators must be balanced against the need to obtain as much data as possible. A partial review of the literature on human factors considerations that impact on mill studies is presented by Yun (1989).

Without using highly specialized tools it is not possible to collect individual board data on yield, cutting length distribution, etc. in a mill study. This represents one of the major disadvantages associated with mill studies versus cut-up program-based yield studies. The other major disadvantage is the fact that a given group of boards can only be processed through one mill and cutting bill. Thus, the effects of such factors as mill design, operator performance, and cutting bill lengths cannot be readily compared. To perform multiple yield studies to obtain this type of information would be very time consuming and costly.

A major advantage associated with performing a mill study rather than a cut-up program-based yield study is that mill studies incorporate the detection abilities and decision rules of the operator while cut-up programs use defect data obtained via board scrutiny and incorporate optimization-based decision rules. Since many rough mills use back gages to assist operators in making the crosscut (chop) decision, the differences between the decision rules used by one operator at one mill and another operator at a second mill bear some similarity. Differences between how two different operators approach cutting up a board may be smaller than differences between how the computer and an operator approach cutting up a board. For rough mill managers who may not be familiar with computer modeling and optimization methods, mill study results are likely to be more understandable and believable than computer cut-up program results.

Methodology

Red Oak Lumber Sample

The short length red oak lumber included in the mill study samples was made up of 4 to 7 foot long lumber acquired from four different sawmills. The lumber from two of the mills was received kiln dried. The material from the other two mills was received in the green condition and was dried in one of the rough mill operator's kilns. The lumber was regraded after drying by the graders at the participating rough mills using the National Hardwood Lumber Association's (NHLA 1990) Standard Kiln Dried Rule.

The long length red oak lumber that was part of the mill study samples was made up of 8 to 13 foot long lumber which was part of the participating rough mills' inventory. This lumber was also regraded by the company graders using the NHLA's Standard Kiln Dried Rule. The long length boards were then numbered and their lengths and widths were measured.

The total number of boards in the sample was based on an estimate of the time requirements for processing the boards compared to the time constraints of the participating rough mills. This estimate was based on knowledge gained from participation in a mill study conducted by Yun (1989). The number of boards within each length category for the two samples was based on a combination of factors. Since the short lumber is the material which is least familiar to the furniture/cabinet industry, most of the available short boards were included in the sample. An attempt was made to place approximately equal numbers of 4 and 5 foot and 6 and 7 foot lumber in each sample. However, there was a shortage of 6 foot long 2A Common lumber. The longer length lumber samples were limited by the sizes of lumber made available by the mills. In assembling the long length lumber samples the available boards in each length category were included or excluded based on their width. An effort was made to have the width distributions of each of the longer length lumber categories match the width distribution of the short length lumber categories. The number and sizes of boards in each of the two mill study groups are given in Tables 24 and 25.

Mill Study Design

For both mill studies the rough mill supervisors were asked to pick out a cutting bill that they thought would match up well with shorter lumber. For the crosscut-first mill study the cutting bill had the following cutting lengths: 14, 22, 28, 30.375, 34, and 40.375 inches. Each cutting length included both fixed and random width part needs. For the rip-first mill study the fixed width cutting lengths in the cutting bill were: 8.25, 13.25, 15.75, 22.25, and 25.875 inches. These cuttings are not unusually short for the rip-first cabinet parts operation.

Crosscut-first Mill Study Methods

The crosscut-first mill study was run during a slow week when the rough mill was essentially shut down except for supervisors and a few key personnel. The rough mill supervisor operated the crosscut saw in the study. By having only one of the mill's three crosscut saws running during the study, it was possible to get crosscut saw timings on a large percentage of the boards. It also eliminated the logistical nightmare of having to

Table 24. Crosscut-first mill study sample size and average board size information; by grade and length category.

Lumber Grade		Lumber Length Category				
		12	10	8	6	4
1 Common	Sample Size	69	34	17	64	57
	Average Width	6.58"	7.38"	6.57"	6.37"	7.13"
	Average Length	149"	126"	108"	74"	57"
2A Common	Sample Size	29	29	36	28	66
	Average Width	7.29"	6.41"	6.42"	7.40"	6.44"
	Average Length	149"	126"	105"	75"	54"

Table 25. Rip-first mill study sample size and average board size information; by grade and length category.

Lumber Grade		Lumber Length Category				
		12	10	8	6	4
1 Common	Sample Size	40	39	31	55	55
	Average Width	6.23"	6.19"	6.07"	6.25"	6.25"
	Average Length	144"	124"	101"	75"	53"
2A Common	Sample Size	40	38	32	31	79
	Average Width	6.57"	6.42"	6.55"	6.82"	6.56"
	Average Length	145"	124"	101"	75"	54"

assure, given multiple operators, that the same percentage of the boards in each length category would be processed by each. After all of one grade of lumber was processed through the crosscut saw, several rip saws were run simultaneously with the help of additional personnel. The rip saw operators were constant for all but the very last lumber batch which was completed after the eight hour shift was over (so only supervisors were left at the end of the study).

The first group of boards processed consisted of half of the longest length (12 and 13 foot) 1 Common boards. The other half of the 12 and 13 foot (LCAT 12) long 1 Common lumber group was saved for processing at the very end of the study to help detect if there were any time-dependent effects present. This is the group of boards that was processed through the rip saws by different operators in some cases. All of the 1 Common boards were run first in reverse length order (LCAT 12, LCAT 10, LCAT 8, LCAT 6, LCAT 4) then the 2A Common boards were processed, again in reverse length order. As the usable crosscut pieces were conveyed away from the crosscut saw a colored mark was made across the face of each piece that corresponded with the length of the lumber from which it was cut. This color code was later used in tallying the part yields by length category after ripping.

The fixed width cuttings produced were counted and the random width cuttings produced were measured for width in batches. In the analysis fixed and random width cutting areas were combined. Previous discussions with the rough mill supervisor had indicated that the fixed width parts were not of distinctly higher value than the random width parts. Since this study was conducted on a day when the mill was essentially shut down, there were insufficient personnel available to operate the salvage saw. No salvage yields were measured.

Rip-first Mill Study Methods

The rip-first mill study was run at the beginning of the first shift of the day (6 AM) in full production mode. A larger group of data collectors was needed for this study since the boards were being processed on parallel pieces of equipment simultaneously. The rip-first mill sends fixed width strips, which make up close to 80 percent of the rip saw strip volume, through a moulder then to a chop saw line. There are eight parallel chop saws on this fixed width production line. The random width strips go directly to a random width chop saw line which includes three parallel chop saws.

In the rip-first mill study the boards were processed in the same order: 1 Common long to short then 2A Common long to short with the 1 Common, LCAT 12 group broken up into pre and post-test groups to investigate the presence of time dependent effects. During the mill study the rip saw operators and moulder operator were asked to pause between lumber length groups to make obvious to the data collectors the changeover to the next lumber length. A communication breakdown between the moulder operator and the two markers/talliers on the fixed width line caused the length changeovers to be missed between the 1 Common LCAT 12, LCAT 10, AND LCAT 8 lumber groups. Thus, these groups are pooled together in most of the analyses. The average lumber length of this combined group of boards is 120 inches.

Rough Part Valuation

Average cutting values are highly variable both between operations and from one day to the next within a given operation. Since value is a measure of relative profit and profit is the difference between income and cost, the relative value of parts is a very complex calculation. Yun (1989) employed a program designed to determine the optimum grade mix of lumber to use to fill a given cutting bill, to estimate the raw material cost component of the value equation for each cutting length. These relative cost per board foot figures were arbitrarily referenced to a base value of 1000 (unitless) per board foot for a 23.25" cutting. Yun's equation for the linear regression of "cost per board foot" versus "cutting length" was used to calculate relative part length-based values in this study. The relationship arrived at by Yun (1989) is:

$$\textbf{Relative Value} = 19.69 \times \textbf{Cutting Length} + 542.11$$

Data Analysis

The analyses performed on the data collected in these two mill studies were predominantly descriptive in nature. The lumber length group design of the studies allowed for regression analyses to be performed on the relationship between the average yield value for each lumber group and the average lumber length of the group. Since the results of CORY simulation cut-up studies indicated that lumber width may have an effect on yield for some cutting bills, and the average widths of the length-based groups varied by as much as one inch in some cases, regressions between the average yield value of the lumber length group and the average lumber width for the group were also investigated. For both the crosscut-first and rip-first mill studies individual board data on the first cut-up operation was recorded and analyzed using analysis of covariance procedures (with width as the covariate).

The regression analyses were conducted on the mean values for each lumber length group. For the majority of the regression analyses there were only five data points. Since there was only one data point per lumber length level the variance associated with the difference between an individual observation and the group mean is not present in the regression model.

Results

Crosscut-first Mill Study Results

The total rough part yield for each length category and grade for the crosscut-first mill study is shown in Figure 15. The linear association between the average yield figure for each length category and the average length of the lumber of each category was not significant for the 1 Common boards. For the 2A Common test this regression was not significant at $\alpha = .05$ but was significant at $\alpha = .10$ (Figure 16; Table 26). Total yield for the 2A Common crosscut-first test tended to increase with increasing average lumber length. The regression relationship that included only average length as the independent variable had an R^2-value of 55.3 percent. When average width was added to the regression relationship as a second independent variable the R^2-value increased to 83.4 percent. Individual board data collected at the crosscut saw during the mill study did not indicate any significant differences between LCAT's for crosscut saw yield. For the

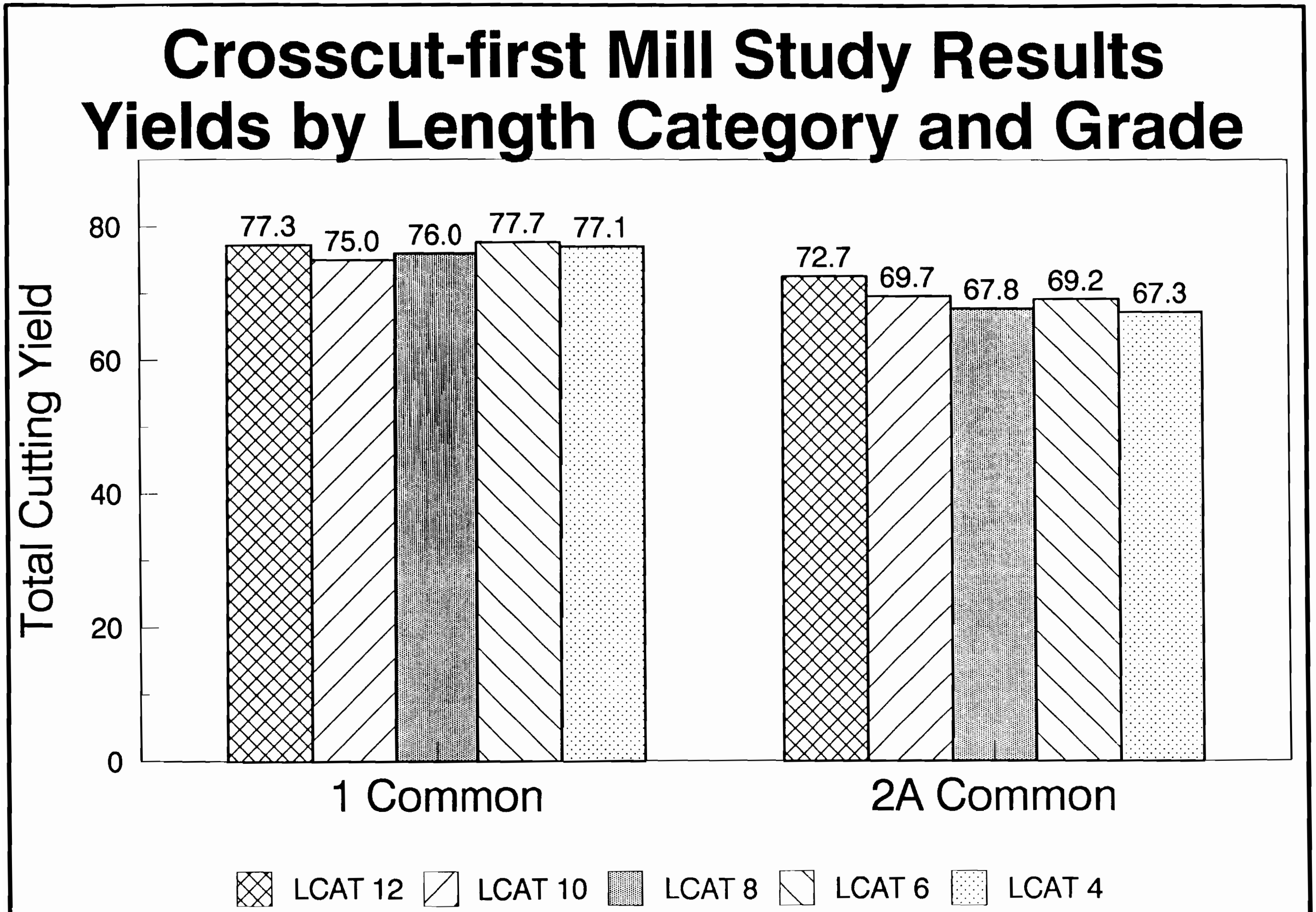

Figure 15. Crosscut-first mill study results: total rough part yield; by length category and grade.

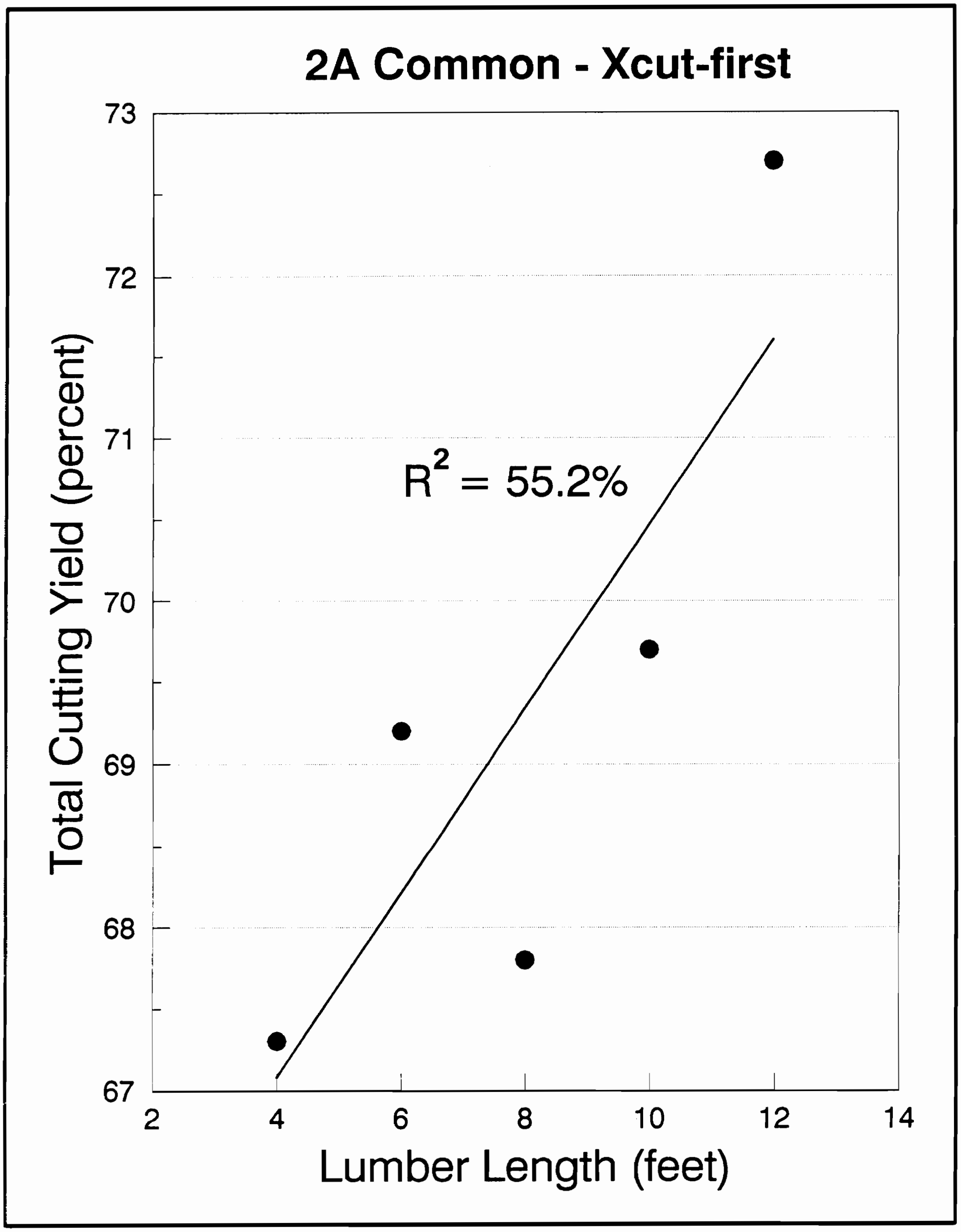

Figure 16. Crosscut-first mill study results: total cutting yield versus lumber length; 2A Common lumber.

Table 26. Significant regressions between the average value of various yield variables for each length category and the average lumber length for the length category.

Regression Equation	P-Value	R^2
CROSSCUT-FIRST; 1 COMMON		
NO SIGNIFICANT REGRESSIONS AT $\alpha = .10$		
CROSSCUT-FIRST; 2A COMMON		
Yield 3 Longest Cuttings = 81.7 - .184 * Av. Lumber Length	.046	71.1%
Total Yield = 64.7 + .0452 * Av. Lumber Length	.093	55.2%
Total Yield = 50.7 + .0403 * Av. Length + 2.14 * Av. Width	.083	83.4%
RIP-FIRST; 1 COMMON		
Rip Rate Per BF of Lumber = 4.35 - .0213 * Av. Lumber Length	.020	83.0%
RIP-FIRST; 2A COMMON		
Total Yield = 56.2 - .130 * Av. Lumber Length	.076	60.4%
Fixed Width Cutting Yield = 44.1 - .124 * Av. Lumber Length	.068	62.9%
Fixed Width Percent of Yield = 79.8 - .0645 * Av. Length	.080	59.0%
Rip Rate Per BF of Lumber = 3.55 - .0151 Av. Lumber Length	.048	70.5%
Chop Rate Per Bf of Strips = 11.7 - .0320 * Av. Lumber Length	.057	66.8%

1 Common and 2A Common crosscut-first tests, the percent of the total cutting volume that is made up of the three longest cuttings in the cutting bill (40.375", 34", and 30.375") is shown in Figures 17 and 18. The regression association between the average percent of total cutting volume made up of the three longest length cuttings and the average lumber length of each length group was not significant for the 1 Common grade but was significant for the 2A Common grade (α = .05; Table 26). The 2A Common regression equation indicates that the percent of cutting volume made up of the three longest length cuttings tends to decrease with increasing average lumber length (Figure 19). The R^2-value for this regression relationship is 71.1 percent. The cutting volume breakdown by cutting length is shown in Table 27.

Both Figures 17 and 18, and Table 27 show that the yield of the longest length cutting from the 6 and 7 foot long boards is distinctly higher than for the other lumber length groups. The average cutting lengths for each of the lumber length categories also reflect the preponderance of long length cuttings obtained from the LCAT 6 lumber in the crosscut-first mill study (Table 28). The regressions between average cutting length and average lumber length and average cutting value and average lumber length were not significant for either lumber grade.

The percent of the total cutting volume made up of the shortest length cutting (14") in the cutting bill is highest for the LCAT 4 group for both grades. The percent recovery of the shortest cutting is lowest for the LCAT 6 group.

The average crosscut time per cutting produced for each of the length categories is presented in Table 29. For each grade the average crosscut rate for LCAT 6 is high relative to the average value for the other length categories combined. The regression

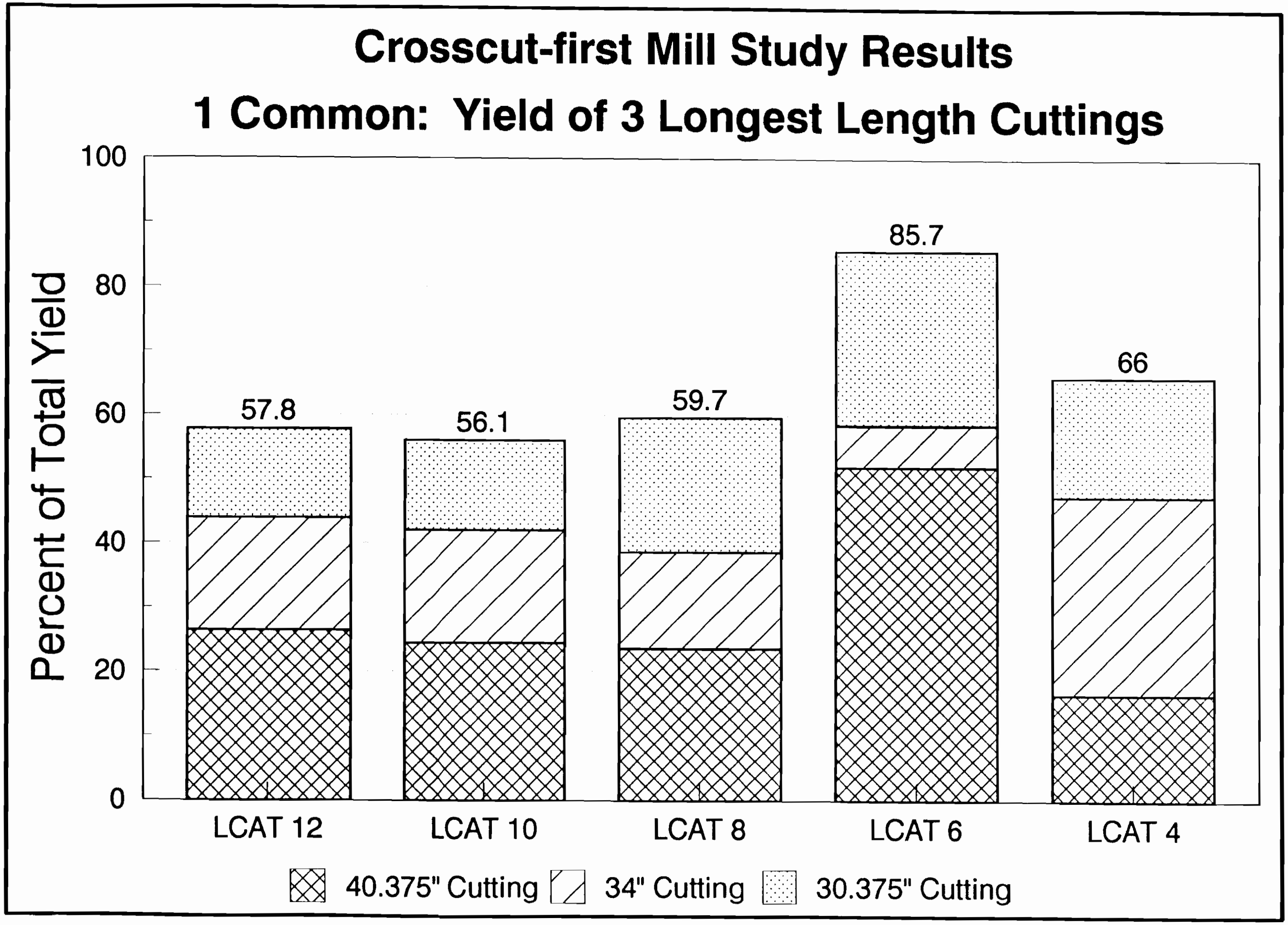

Figure 17. Crosscut-first mill study results: yield of 3 longest length cuttings; 1 Common lumber.

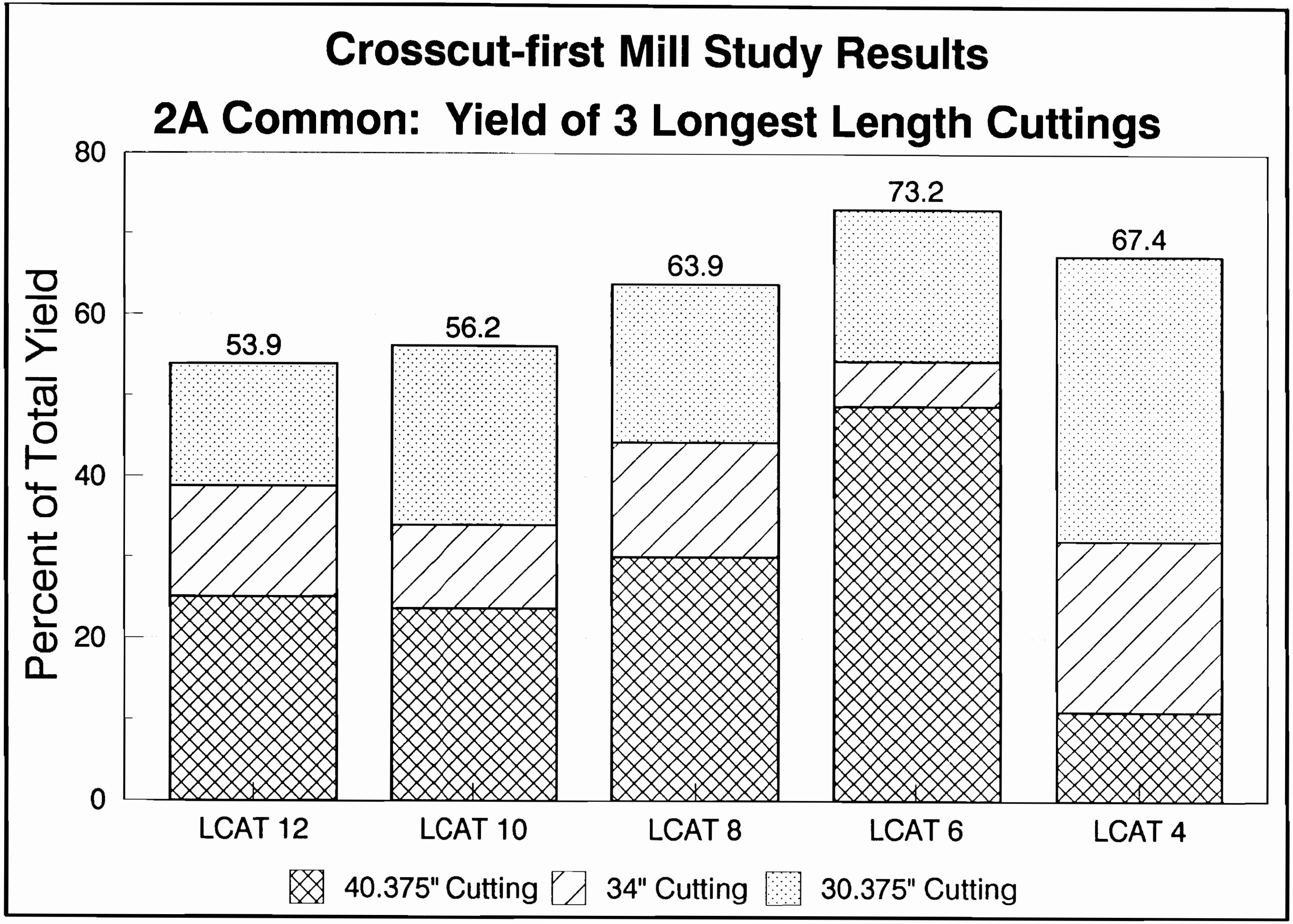

Figure 18. Crosscut-first mill study results; yield of 3 longest length cuttings; 2A Common lumber.

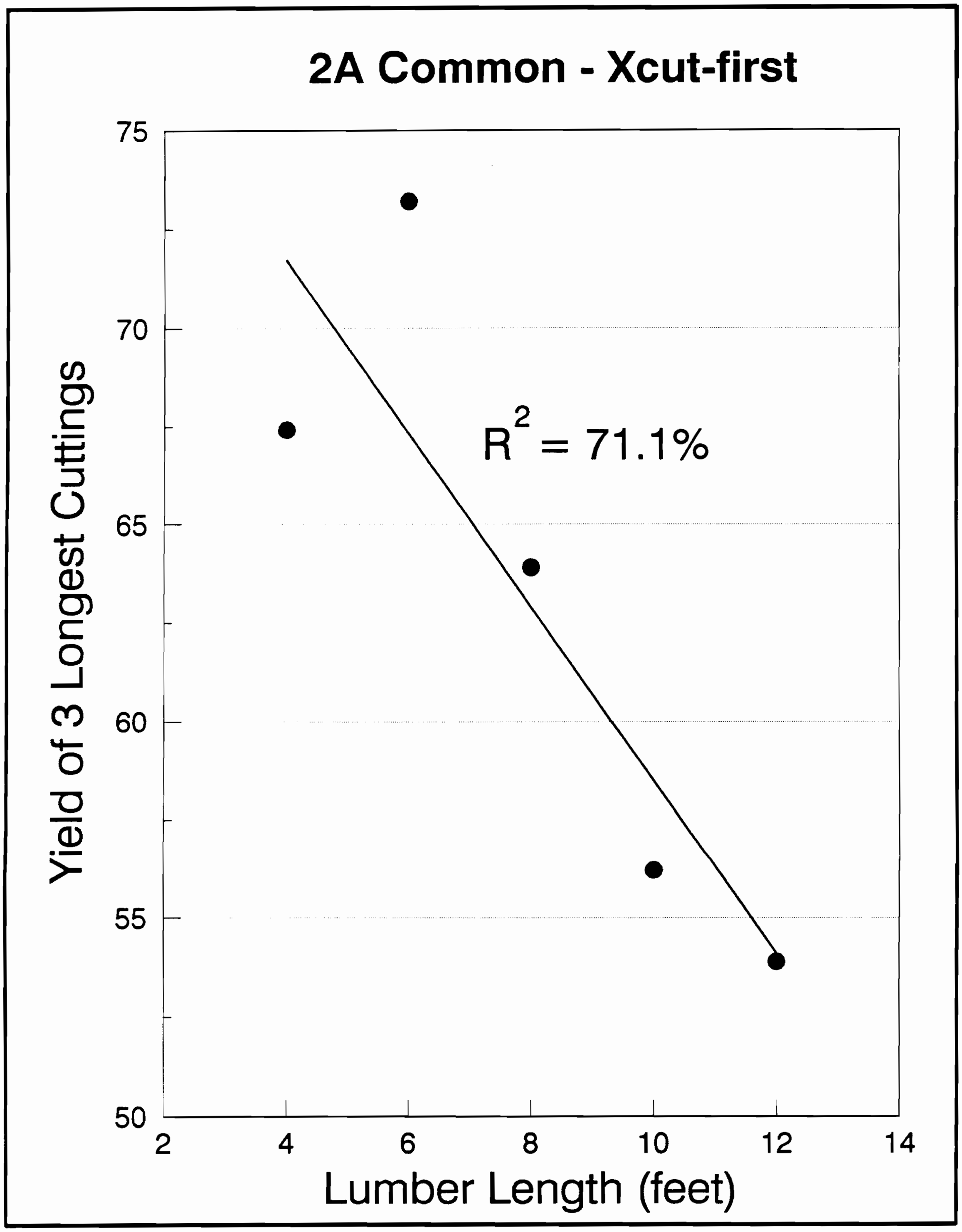

Figure 19. Crosscut-first mill study results: yield of 3 longest length cuttings versus lumber length; 2A Common lumber.

Table 27. Crosscut-first volume-based cutting length distribution by grade and lumber length category (LCAT).

Grade and Lumber Length Category	Cutting Length (inches)					
	14	22	28	30[a]	34	40[a]
1C - LCAT 12	5.3%	8.6%	28.2%	13.9%	17.5%	26.4%
1C - LCAT 10	5.1%	10.4%	28.4%	14.1%	17.5%	24.5%
1C - LCAT 8	8.3%	10.4%	21.5%	21.0%	15.1%	23.6%
1C - LCAT 6	2.3%	2.0%	9.9%	27.2%	6.5%	52.0%
1C - LCAT 4	13.7%	8.1%	12.2%	18.6%	30.9%	16.5%
2AC - LCAT 12	8.3%	17.2%	20.5%	15.1%	13.7%	25.1%
2AC - LCAT 10	10.3%	17.2%	16.3%	22.2%	10.3%	23.7%
2AC - LCAT 8	7.9%	16.5%	11.6%	19.6%	14.2%	30.1%
2AC - LCAT 6	5.2%	7.1%	14.4%	18.8%	5.6%	48.8%
2AC - LCAT 4	17.4%	6.7%	8.6%	35.3%	21.1%	11.0%

[a]- Actual cutting lengths were 30.375 inches and 40.375 inches.

Table 28. Crosscut-first mill study average cutting lengths and values by grade and length category.

Lumber Grade		Lumber Length Category				
		12	10	8	6	4
1 Common	Average Length	31.4"	31.1"	30.5"	35.1"	29.9"
	Average Value	1161	1155	1143	1233	1131
2A Common	Average Length	30.1"	29.6"	30.9"	33.7"	28.6"
	Average Value	1135	1125	1151	1206	1105

Table 29. Crosscut-first mill study average crosscut time per cutting and average lumber throughput rate; by grade and length category.

Lumber Grade		Lumber Length Category				
		12	**10**	**8**	**6**	**4**
1 Common	Input BF/Sec	0.19	0.20	0.19	0.19	0.20
	Seconds Per Cutting	7.2	7.7	7.1	8.1	7.3
2A Common	Input BF/Sec	0.19	0.16	0.16	0.22	0.23
	Seconds Per Cutting	5.2	4.5	8.3	8.1	6.5

associations between the average crosscut rate values for each length category and average lumber length values were not significant.

The two, 1 Common, LCAT 12 board groups which were processed first and last in the mill study had relatively similar average cutting lengths with the end-of-test group's average cutting length value being slightly higher (31.7 inches versus 31.1 inches). The total yield values for the two groups showed the reverse trend: the average yield for the end-of-test group was lower than the beginning-of-test group's yield (76.03 percent versus 78.51 percent).

Rip-first Mill Study Results

The total rough part yield for each length category and grade for the rip-first mill study is shown in Figure 20. The test of the association between the average yield figure for each length category and the average length of the lumber in each category was not significant for the 1 Common grade. For the 2A Common test this regression was not significant at $\alpha = .05$ but was significant at $\alpha = .10$ (Table 29; Figure 21). The regression equation indicates a negative linear association between total yield and average lumber length for the 2A Common lumber groups. The R^2-value for the relationship was 60.4 percent.

For the 1 Common and 2A Common rip-first studies, the percent of the total fixed width cutting volume that is made up of the three longest cuttings in the cutting bill (25.875", 22.25", and 15.75") is shown in Figures 22 and 23. The regression association between the average percent of total cutting volume made up of the three longest length

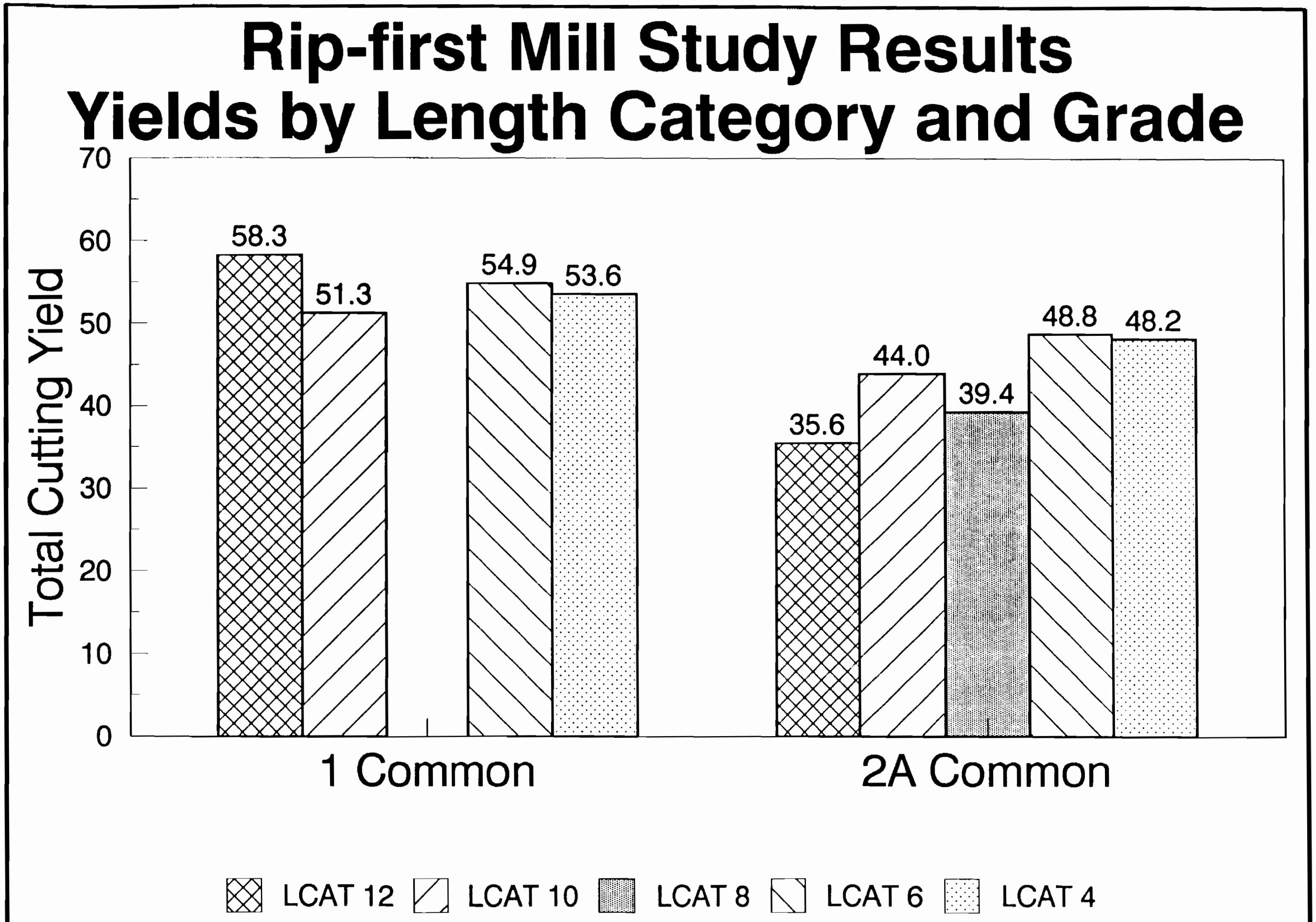

Figure 20. Rip-first mill study results: total rough part yield; by length category and grade.

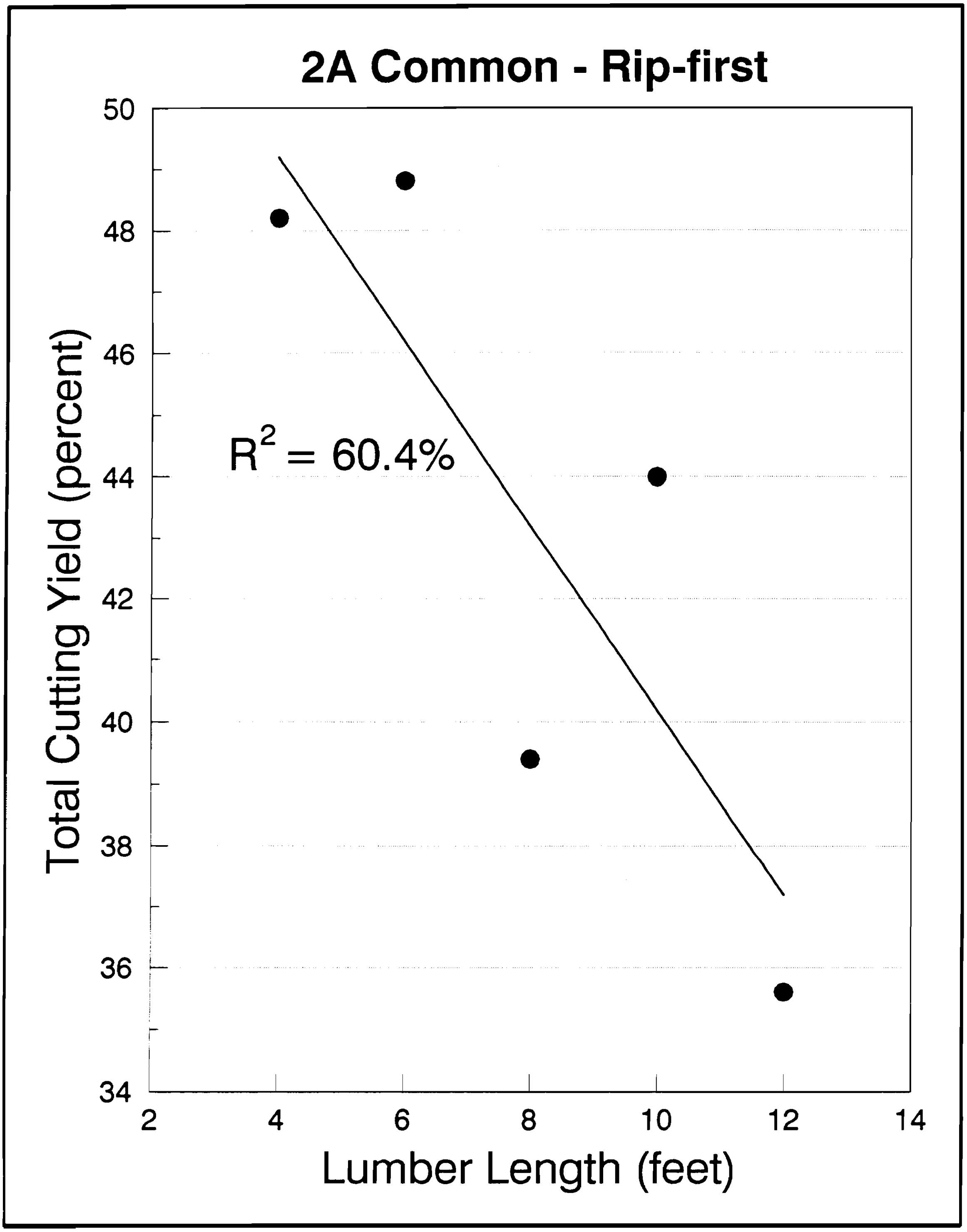

Figure 21. Rip-first mill study results: total cutting yield versus lumber length; 2A Common lumber.

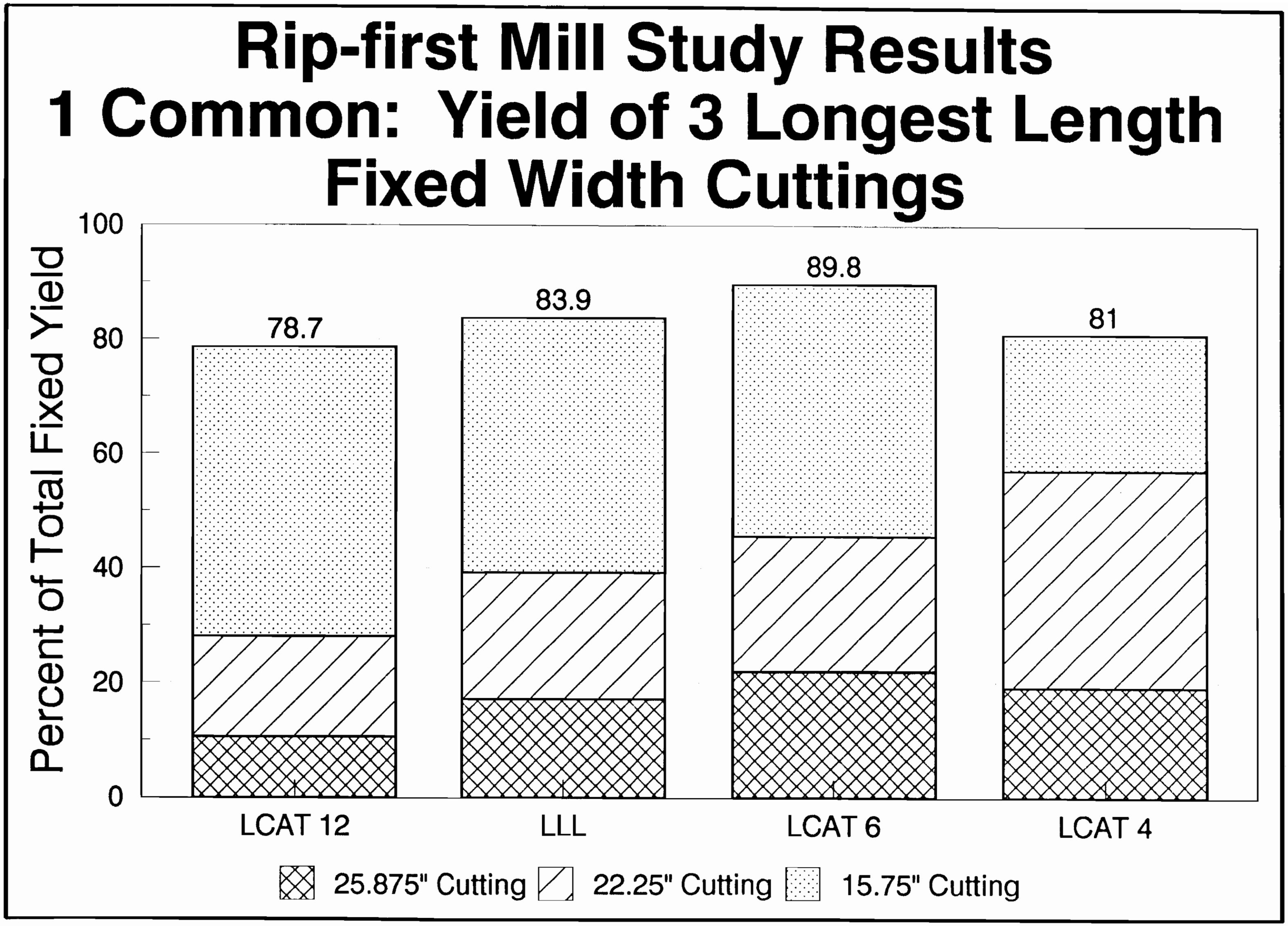

Figure 22. Rip-first mill study results: yield of 3 longest length cuttings; 1 Common lumber.

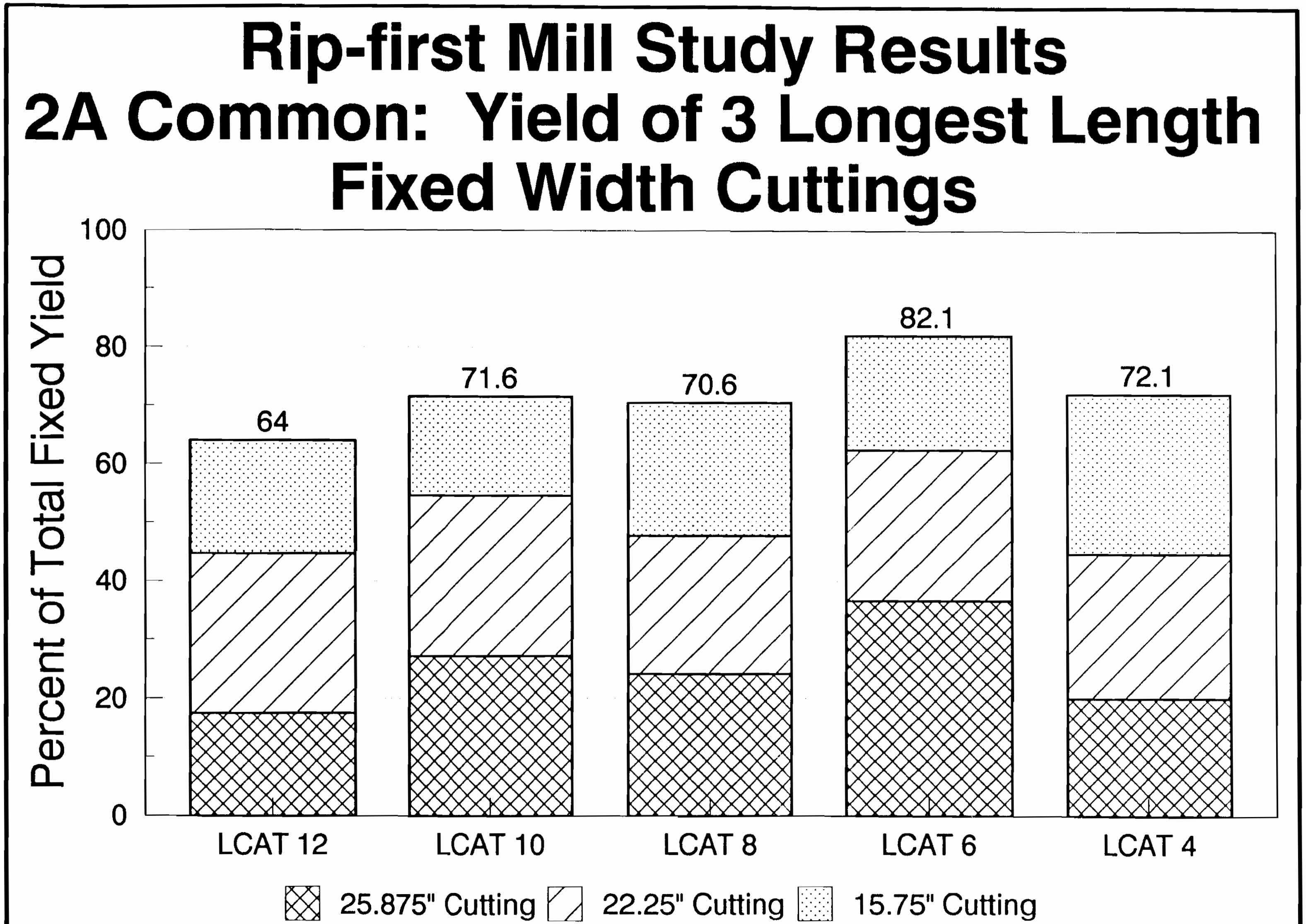

Figure 23. Rip-first mill study results: yield of 3 longest length cuttings; 2A Common lumber.

cuttings and the average lumber length of each length group was not significant for either grade. A trend similar to one seen in the crosscut-first study can be seen here as well: Figures 22 and 23, and Table 30 show that the yield of the three longest length cuttings from LCAT 6 boards was distinctly higher than for the other length categories. This is the case for both lumber grades. In addition, the percent of the total cutting volume made up of the longest length cutting (25.875") is 10 percent higher for the 2A Common, LCAT 6 board group than for any of the other 2A Common groups (Table 30).

The percent of the total cutting volume made up of the shortest length cutting (8.25") in the cutting bill is highest for the LCAT 12 group for both grades. The percent recovery of the shortest cutting is lowest for the LCAT 6 group.

In the rip-first operation at which the mill study was conducted the emphasis is placed on producing as many fixed-width, 2½" strips as possible. The random-width chop saw line is considered the "salvage line". Data collected in the 1 Common mill study was insufficient to detect any significant differences in percent of total yield comprised of fixed-width cuttings (Table 31). The 2A Common test for linear association between the fixed-width percent of total yield for each lumber group and the average length of the lumber in the group was not significant at $\alpha = .05$. The P-value for this test (equivalent to the α value for which the test would be significant) was .08. The regression equation, with a R^2-value of 59.0 percent, indicated a tendency for the fixed-width percent of total yield to decrease with increasing average group lumber length (Table 26). In the 2A Common study the absolute fixed-width cutting yield also showed a slight tendency to decrease with increasing average group lumber length (P-value = .068, R^2 = 62.9 percent; Table 26).

Table 30. Rip-first volume-based cutting length distribution by grade and lumber length category (LCAT).

Grade and Lumber Length Category	Cutting Length (inches)				
	8[a]	13[a]	15[a]	22[a]	25[a]
1C - LCAT 12 (post)	7.0%	14.3%	10.6%	17.5%	50.6%
1C - LCAT 12/10/8	4.5%	12.9%	15.5%	20.9%	46.2%
1C - LCAT 6	2.6%	7.6%	22.0%	23.6%	44.2%
1C - LCAT 4	3.3%	15.7%	19.2%	38.0%	23.8%
2AC - LCAT 12	9.7%	26.2%	19.3%	27.2%	17.5%
2AC - LCAT 10	7.6%	20.7%	17.0%	27.4%	27.2%
2AC - LCAT 8	6.3%	23.1%	22.8%	23.6%	24.2%
2AC - LCAT 6	2.5%	15.4%	19.6%	25.8%	36.7%
2AC - LCAT 4	6.4%	21.4%	27.4%	24.7%	20.0%

a- Actual cutting lengths were 8.25 inches, 13.25 inches, 15.75 inches, 22.25 inches, and 25.875 inches.

Table 31. Rip-first mill study percentage of cuttings that are fixed width and average cutting lengths and values by grade and length category.

Lumber Grade		Lumber Length Category				
		12	10	8	6	4
1 Common	Fixed-width %	---------	73.4%	---------	73.2%	78.3%
	Average Length	---------	21.1"	---------	21.4"	20.0"
	Average Value	---------	958	---------	964	936
2A Common	Fixed-width %	70.5%	73.4%	70.7%	75.6%	76.8%
	Average Length	17.9"	19.2"	18.7"	20.6"	18.3"
	Average Value	895	920	910	948	903

The regressions between cutting length and lumber length and cutting value and lumber length were not significant for either lumber grade. The highest value for average cutting length was the LCAT 6 group value reflecting the cutting length distributions that were discussed previously (shown in Figures 15 and 16 and Table 30).

The average rip saw throughput rate (lumber volume per second) for each length category is significantly and positively related to lumber length. The R^2-value for the 1 Common regression is 83.0 percent. The strength of the association for the 2A Common grade is not as high (R^2 = 70.5 percent; Table 26). The rip saw rates for the five lumber length groups are presented in Table 32.

The average chop saw rate per board foot of strips processed on the fixed-width chop saw line was not significantly related to lumber length for the 1 Common group (α = .05). For the 2A Common lumber group the regression test had a P-value of .057 and an R^2-value of 66.8 percent. As was true for the rip saw rates, both the group averages and regression equation indicated a tendency for the chop saw throughput rate to increase with increasing average group lumber length (Table 33; Table 26).

Analysis of covariance tests conducted on individual board data collected at the rip saws during the mill study did not detect any significant differences in rip saw yields for boards from the different length categories. Average rip saw yield figures, adjusted for the covariate "lumber width", are given in Table 34. The width-adjusted average differences between the actual measured board width and the width of the of the usable board as determined by the rip saw operators when they set the laser lines are also given in Table 34. For the 1 Common study, the analysis of covariance test conducted at an α-level of .05 did not detect a significant difference in this rip saw width difference

Table 32. Rip-first mill study average rip time per board and average lumber throughput rate; by grade and length category.

Lumber Grade		Lumber Length Category				
		12	**10**	**8**	**6**	**4**
1 Common	Seconds Per Board	9.6	9.0	8.5	7.9	8.2
	Input BF/Sec	0.67	0.59	0.50	0.42	0.28
2A Common	Seconds Per Board	10.5	9.0	8.4	7.4	7.8
	Input BF/Sec	0.62	0.62	0.55	0.48	0.32

Table 33. Rip-first mill study average chop time per strip and per board foot of strips; by grade and length category.

Lumber Grade		Lumber Length Category				
		12	**10**	**8**	**6**	**4**
1 Common	Seconds Per Strip	16.2	17.2	12.9	9.3	8.3
	Seconds Per BF	6.5	8.0	7.4	7.1	9.1
2A Common	Seconds Per Strip	18.0	8.0	7.4	7.1	9.1
	Seconds Per BF	7.1	7.5	9.0	8.2	10.5

Table 34. Rip-first mill study rip saw yields and average difference between actual width and laser line width; by grade and length category (lumber width the covariate).

Lumber Grade		Lumber Length Category				
		12	10	8	6	4
1 Common	Rip Saw Yield	78.7%	81.5%	81.8%	81.7%	81.2%
	Width[a] Difference	.89"	.74"	.65"	.77"	.73"
2A Common	Rip Saw Yield	81.5%	82.7%	83.5%	79.7%	82.1%
	Width[a] Difference	.87"	.63"	.72"	.88"	.76"

a- Includes wane, glue-line edges, kerf, and operator error.

between length categories. A significant difference was detected for the 2A Common grade but the average values for each length category do not indicate the presence of either an increasing or decreasing trend based on length (Table 33).

The two, 1 Common, LCAT 12 board groups which were processed first and last in the mill study could not be used to detect time-dependent differences in the mill study variables. Since the LCAT 12 board group that was processed at the beginning of the study was not successfully separated from the LCAT 10 and LCAT 8 groups by the rough part talliers, these three groups had to be pooled.

Discussion

Few statistically significant relationships were detected between the lumber length-based groups assembled for these mill studies. Since statistical tests were based predominantly on regression tests conducted on the five group mean values for the different lumber lengths, only very strong associations could be distinguished.

The two studies both detected a weak association between total yield and average lumber length for the 2A Common grade. The nature of this association, in which yield increased with increasing average lumber length for the crosscut-first study and decreased with increasing average lumber length for the rip-first study, is similar to results obtained previously using the CORY cut-up program.

For the crosscut-first study, the two LCAT 12 groups that were run at the very beginning and very end of the mill study, produced varied total yield and average cutting length figures. The end-of-test group's average cutting length was higher, and its total yield was lower, then the beginning-of-test group's. It is normal for total yield to decrease as an emphasis is placed on obtaining longer cutting lengths. The end-of-test LCAT 12 group was run late in the day after several interruptions in the mill study. It was noted that the crosscut saw operator seemed to process the lumber more hurriedly toward the end of the shift. By cutting longer cuttings on the crosscut saw, fewer cutting operations needed to be performed.

The exact point at which the operator's mode of operation changed could not be pinpointed. For the first half of the study, during which the 1 Common boards were being processed, the crosscut saw operator seemed to move at a more constant pace. The effect of the speed-up probably occurred at some point during the processing of the 2A Common lumber. The 2A Common relationships detected between average group lumber length and the percent of total cutting volume made up of the three longest cuttings and between average group lumber length and total yield were probably influenced by the time-dependent effect.

Total yield showed a tendency to decrease and the yield of the longest cuttings showed a tendency to increase as the average group lumber length decreased. Since the shorter lumber was run later in the study these results cannot be separated from the apparent effects of the crosscut saw operator's speedup. These linear associations, which were not significant at $\alpha = .05$, would probably not be significant in less powerful tests were it possible to separate out the influence of the operational change.

In the rip-first test the two LCAT 12 groups could not be compared. Since the rip-first mill study was run in full production mode it took less than 1½ hours to complete. No time-dependent differences in any elements of the rip-first operation were observed over the short time span of the test.

The average crosscut rate per cutting produced is influenced by several factors. The time to crosscut a board includes time associated with reloading the crosscut saw's table, inspecting the board, positioning it, and taking the standard ½" entering end clean-up cut. This time is spread over the number of cuttings taken when rate per cutting is calculated. For a shorter board, from which fewer cuttings are taken, this series of timing elements tends to increase the crosscut rate per cutting. A less significant factor which has the opposite effect, is the relative ease/speed with which shorter or narrower boards can be moved and positioned relative to longer or wider boards. Finally, the lengths of the cuttings taken from a board has a significant influence on the crosscut rate per cutting. Positioning a board for a longer cutting takes longer than does positioning a board for a shorter cutting. For the crosscut-first study, the average crosscut-rate per cutting was particularly high for both grades. This is probably attributable in large part to this last observation; the average cutting for the LCAT 6 lumber was higher than that of the other lumber length-based groups.

For the rip-first chop saw rates, the same factors are present, but data on the number of cuttings produced per strip was not recorded. The chop saw rate analyses are based on input strip volume rather than cuttings produced. Since information on the number of cuttings produced per strip is not available these rates cannot be readily explained.

The average values for the percent of the average cutting volume made up of the three longest cuttings, average cutting length values, and average values for the percent of recovery made up of the shortest length cutting, all indicate that the cutting length distribution obtainable from short lumber should not be a problem. This ability of the rough mill supervisor to match short length lumber with relatively short cutting bills could be an important part of this relationship. The significant, positive, linear associations between average cutting length and lumber length which the CORY data produced for several of the cutting bill iterations, are not supported by the mill study data analyses. These contrasting results provide evidence that mill operators cannot as effectively optimize for cutting length and value as can the CORY model. This is a conclusion previously arrived at by Yun (1989).

The significant, negative linear associations between average rip saw rate per board foot of lumber and average lumber length can be attributed largely to the time which elapses during the repositioning of the rip saw setworks after the previous board has cleared the saws. For short boards, this non-productive time occurs more frequently during the processing of like volumes of lumber. The rates for the LCAT 4 lumber are disproportionately higher than the rates for the LCAT 6 lumber. This is especially true for the 1 Common lumber. The rate difference for this length group is due to not only the setworks delay, but also a rip saw hardware limitation. One of the electronic eyes on the rip saw was not registering the 4 foot long lumber. This eye controls when the board that is waiting at the laser station can be released onto the rip saw infeed conveyor. Once this problem was discovered the operator kept things moving relatively smoothly by triggering the limit switch with his hand. However, this process did cause a slowdown.

In the rip-first mill study the "width difference" variable was recorded for each board at the rip saws. This represents the difference between measured width and laser line width. Laser lines are placed by rip saw operators so that the rip saws remove most wane and crook from the boards. Previous tests have indicated that short lumber tends to have more wane than long length lumber. Alternatively, the regression between lumber length and crook is significant and positive: longer boards have a greater degree of crook deviation.

Differences between length-based groups for the variable "width difference" were not significant for the 1 Common grade. For the 2A Common lumber a difference in the level of this variable did exist between LCAT groups. Examination of the group means did not expose any tendency for the variable to either decrease or increase with increasing lumber length.

The relationship of "width difference" to lumber length is confounded by the fact that not all of the lumber was dried by the same operator (half of the short lumber was not dried at the rough mill operator's kilns). Thus, the relationship between lumber length and crook may have been suppressed. For each grade there does appear to be a tendency for the "width difference" to decrease with decreasing lumber length for the LCAT 12, 10, and 8 groups. Length-based differences in rip-first cut-up yields have previously been attributed to differences in rip saw volume recovery that were attributable to the effect of crook (Gatchell 1990, 1991; Section 3).

Summary

The results of mill studies conducted at a crosscut-first case goods parts plant and at a rip-first cabinet parts plant revealed few significant associations between yield and timing variables and lumber length category. Examination of the mean yield values and the cutting distributions values for each length category and lumber grade (1 and 2A Common) indicate that short length lumber yields and distributions can be comparable to longer length lumber yields and distributions. In these tests the cutting bills which were used contained medium to short cutting lengths.

Regression analyses indicated that for both mills and grades the relationship between the total yield figure for each length group and the average length of the boards in each group was not significant. Neither were regressions of the yield of the longest length cutting in each length group versus average lumber length significant. The percentage of total yield made up of the longest length cutting does show one consistent trend for each mill - grade combination: the yield of the longest length parts for the LCAT 6 lumber group is distinctly higher than the yields from the other length categories. The percentage of the total yield made up of the three longest length cuttings on the cutting bill is significantly and inversely related to average lumber length in the crosscut-first, 2A Common grade analysis. This relationship may have been confounded by time-dependent mill study effects.

Regression tests between average cutting length and average lumber length, the percent of fixed width cuttings (for the rip-first test) and average lumber length, and the crosscut time per cutting (per board foot in the rip-first test) and average lumber length were not significant. For the rip-first mill study, the ripsaw rate per board foot of lumber did have a significant linear association with average lumber length for both the 1 Common and 2A Common grades.

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A FEASIBILITY STUDY: USING SHORT LENGTH LUMBER TO MANUFACTURE FURNITURE AND CABINET DIMENSION PARTS

Section 5

Abstract

Handling rates and costs associated with the use of short length lumber (less than 8 feet long) in furniture and cabinet industry rough mills have been assumed to be prohibitive. Discrete-event systems simulation models of both a crosscut-first and rip-first rough mill were built to measure the effect of lumber length on equipment utilization and the volume and value of the rough parts produced. The output from these models was entered into a series of rough part production alternatives which incorporated variable production, part value, and cost assumptions. The net present worth of after-tax cash flows and the breakeven short length lumber price of these alternatives were calculated and compared.

For the crosscut-first mill model the volume and value of parts produced from short length lumber compared favorably with the volume and value of parts produced from the medium (8-13 feet long) and long (14-16 feet long) length lumber. A "pessimistic case" short lumber scenario was also simulated in which the distribution of cutting lengths was varied. The short lumber volume and value yields for this model version were somewhat lower than the medium and long lumber yields.

For 14 of the 16 crosscut-first production alternatives tested, the present worth of the after-tax cash flows was higher for the short length lumber ("most-likely case") than for the medium and long length lumber. The net present values (NPV'S) of the "pessimistic case" short lumber alternatives were lower than the NPV's of the medium and long lumber. The breakeven short lumber purchase price for dry, 1 Common, red oak lumber for these alternatives ranged between $671 and $753 per thousand board feet (mbf). These prices are only $47 to $129 less than the going market price.

For the rip-first mill model the volume and value of parts produced from short lumber was equal to approximately 60 percent of the production from the medium and long length lumber. The unstacker/planer were unable to provide sufficient material to the rip saws which in turn were unable to process the short lumber fast enough to keep the chop saws busy. The breakeven short length lumber prices calculated for this model ranged between $373 and $653 per mbf.

Introduction

Obstacles to the Use of Short Lumber

Before the furniture and cabinet industries will accept short length (< 8 feet) hardwood lumber several obstacles must be overcome. These obstacles include: cutting yield uncertainties (addressed in Section 3 and Section 4), handling problems and costs, and the furniture industry's lack of experience with short lumber (Wengert et al. 1986). If short length lumber processing rate and cost estimates were available, the value of short length lumber to the furniture and cabinet industries could be evaluated.

Several negative opinions and experiences related to the utilization of short length hardwood lumber by the furniture and cabinet industries were printed in the Weekly Hardwood Review (Anonymous 1989):

1. "In our plant the usage of short lumber indicated an increase in labor cost of 15%."
2. "Handling costs were increased not only on the green stacker but throughout the plant from unloading, drying and unstacking."
3. "Capital costs to change entire handling system would not justify change."
4. "We have a problem in running short lumber through the planer."

These statements indicate both that there are very real problems associated with processing short length lumber in the rough mill and that the economic impact of these problems is largely unknown.

The number of problems associated with handling short lumber in any operation depends on the number of processing steps which the lumber goes through, the degree of system automation, and the level of specialization of the system's equipment for longer lumber. In a rip-first furniture or cabinet rough mill the length of the lumber remains an issue until the lumber gets to the chop saw. In a crosscut-first rough mill, all operations that follow the crosscut operation are adapted to handling short, cut-to-length boards; lumber length distinctions are lost as soon as the crosscut operation has been performed.

Visits to various drying and rough mill operations have suggested that the following equipment limitations may be commonplace:

1. Planer/surfacer hold down systems not designed for short material lead to problems with boards skewing and stalling in the machine and may represent a safety hazard to operators in some cases.
2. Stacking and unstacking hoists have supports (knees) that are spaced to handle lumber longer than 8 feet.
3. Stick guides on automatic stacker may not be optimally spaced to allow placement of sticks within the last couple inches of short boards.
4. Limit switches (electronic eyes) on some pieces of equipment are unable to detect short lumber which can lead to misfeeds and handling problems.
5. Stops on accumulating conveyors that are widely spaced can cause short boards to skew when pressure, resulting from accumulation, is applied.

It is the general consensus of industry process control experts who have studied the feasibility of short length lumber utilization, that in most cases these equipment problems could be fixed quite readily (Reynolds 1976; Bingham and Schroeder 1976/1977). In some cases the equipment manufacturer might have to be brought in to make the necessary modifications. However, in the majority of cases the problems could be remedied with a few weekends of shop and maintenance work.

The effect of short length lumber on rough mill production rates and costs should be regarded as a much more important factor than equipment modification costs in assessing the feasibility of using short length lumber in the rough mill. In processing short lumber, more boards must be handled to obtain a given volume of parts. This has the effect of increasing production costs per unit of output volume (Bingham 1976; Wengert et al. 1986).

One offsetting factor to consider when looking at handling rates and costs, is that the manual handling of short pieces can be performed more quickly and with less fatigue and strain than would be required in handling long lumber (Bingham 1976). Another factor which may be hard to assess but which could be very valuable in high production rough mills is the potential for using short length lumber at times when long length lumber is causing material to back up at various machine centers. For example, the insertion of a pack of 4 or 5 foot lumber when the rip saws in a crosscut first rough mill are backing up the system, could serve to smooth production flow.

The Systems Simulation Modeling Tool

Systems simulation modeling provides a means of experimenting with a system that cannot be directly manipulated. Systems modeling links individual elements of a process together so that the effect of a change in one of the elements on the other elements in the system and on total system performance can be assessed. With simulation modeling new production methods can be analyzed for their effect on important output variables, alternative systems can be compared, bottlenecks can be isolated and possibilities for removing the bottlenecks can be studied, and sensitivity analysis can be performed.

Several systems simulation models have been developed for the furniture industry. One of these models was developed to look at issues related to production scheduling throughout a furniture plant up to, but not including the assembly stage (Townsend et al. 1988). Another model was built to simulate the operation of a proposed gang rip-first rough mill to demonstrate the usefulness of simulation modeling in system design and bottleneck analysis (Araman 1977). Another of these models was designed to assess the effect on processing costs of placing a newly developed defect detection device in the rough mill system (Harpole and McDonald 1981). A rough mill model built by Anderson (1983) was designed to estimate the costs of manufacturing various rough parts based on the number and type of machining operations which were required to generate the part. Kline et al. (1992) developed a rough mill demonstration model to illustrate the basic concepts and decisions involved in the modeling process and the overall utility of systems simulation modeling.

The systems simulation modeling solution technique offers a powerful tool for evaluating the effect of input lumber length on furniture rough mill volume and value yields. Opportunities to observe first-hand, the processing of short lumber in furniture/cabinet rough mills are extremely limited. Rough mill experiments designed to collect throughput and part value data would be very disruptive to the rough mill operation (to collect the more limited data discussed in Section 4, ten people were required). In addition, short length lumber handling problems which might exist in an actual rough mill would complicate the experimental procedure and bias the results. In a simulation model the assumption that handling problems would be remedied can be implemented and the potential production rates of short length lumber can be obtained.

Methodology

Once the furniture and cabinet industry's disinterest in short length lumber was understood to be predominantly associated with material handling and flow issues, it became apparent that systems simulation modeling should be applied to this problem. A PC-based simulation software programming language, SIMAN, was chosen as the development tool. The program's animation facility (CINEMA) provides a means of verifying and validating the model. The animation feature was also valued as a means of demonstrating the model to industry personnel in order to build credibility in the results. A flow chart of the modeling process is given in Figure 24.

System Definition

The first step in the system definition phase was to identify crosscut-first and rip-first rough mill cooperators. A crosscut-first case goods dimension plant and a rip-first cabinet parts plant agreed to become involved in this modeling project. Each of these mills produced red oak parts in their rough mills on a fairly regular basis. Red oak was selected for this study because it is the highest volume species in the eastern furniture industry. Both access and information were contributed on a continual basis by these

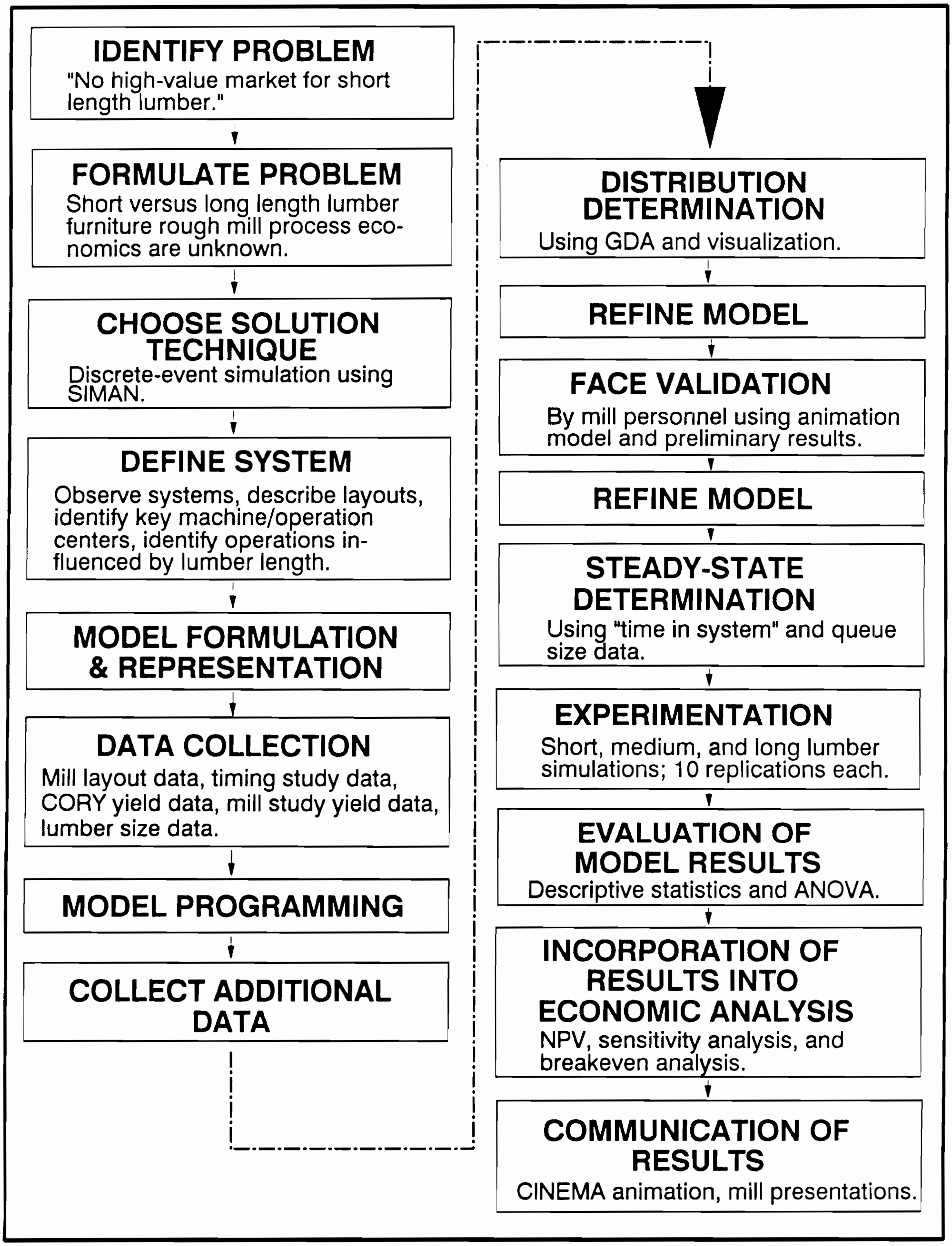

Figure 24. Flow chart of simulation modeling process.

cooperators during the year-long modeling process. Other elements of the system definition phase included: drawing the mill layouts (Figures 25 and 26), measuring conveyor distances, talking with production management personnel about lumber length-based issues, and observing the systems in operation.

Data Collection

After completion of the system definition phase of the modeling process, exploratory timing studies on various operations were conducted. It soon became clear which operations were most affected by lumber length and piece counts. These operations became the focus of subsequent timing studies. An attempt was made to capture between-operator variability by gathering data on multiple operators per operation.

Both mills ran a grade mix of lumber that consisted of 70-80 percent 1 Common and 10-15 percent each "uppers" (FAS, FAS1F, and Selects) and 2A Common. The grades were mixed within the kiln packages such that grade distinctions in this timing data could not be made. Data was also collected on the size distribution of the kiln dried lumber in dry storage at each of the mills. Timings, counts, and board measurements were more readily obtained from one mill than the other due to the difference in the frequency with which each of the mills processed 4/4 red oak, the species of interest in this study.

Additional data was collected during the mill studies which were discussed in detail in Section 4 of this paper. This data consisted of single operator timings by lumber length group and grade (1 Common and 2A Common) at the crosscut/chop and rip saws at each

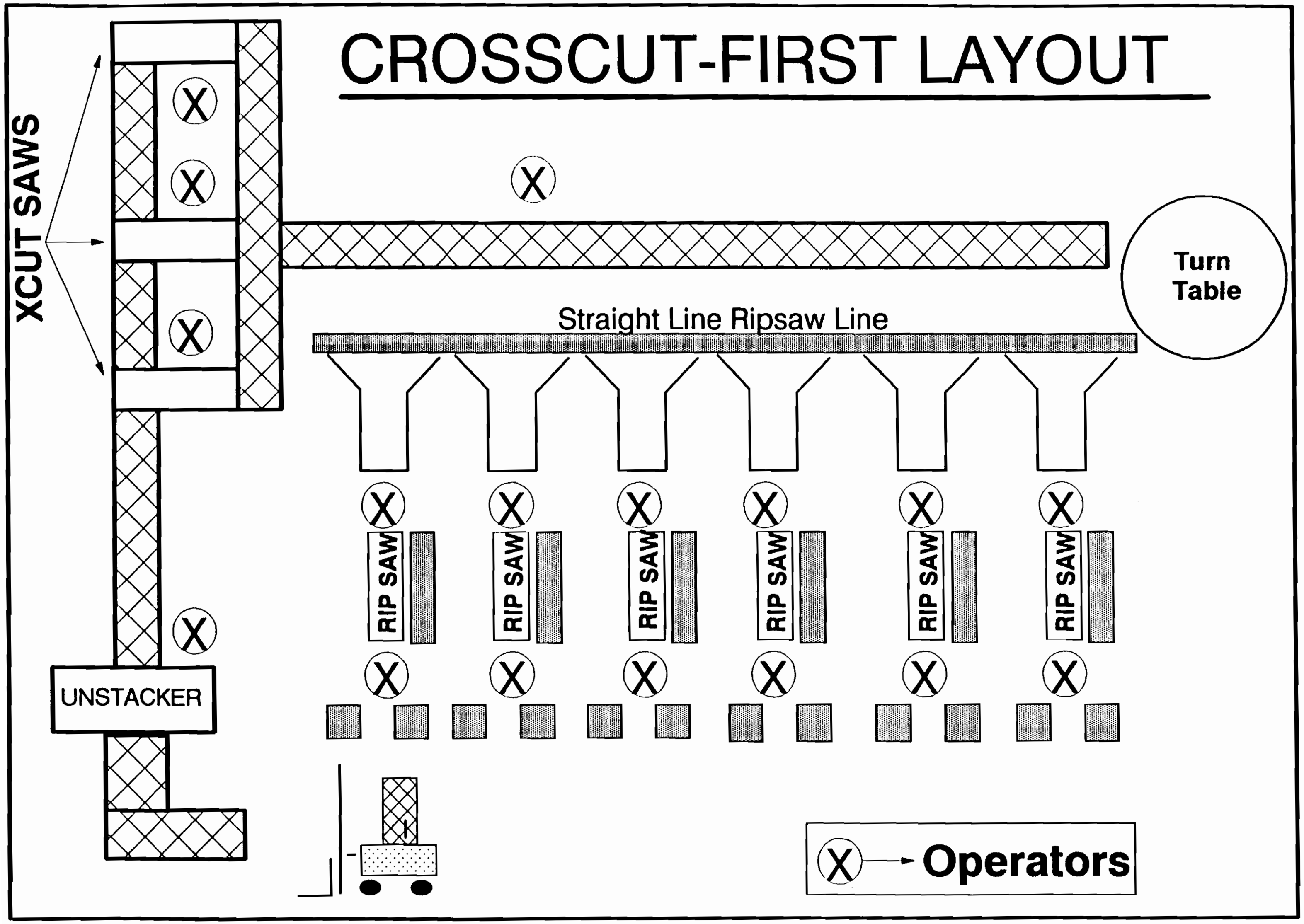

Figure 25. Crosscut-first rough mill layout used in simulation model.

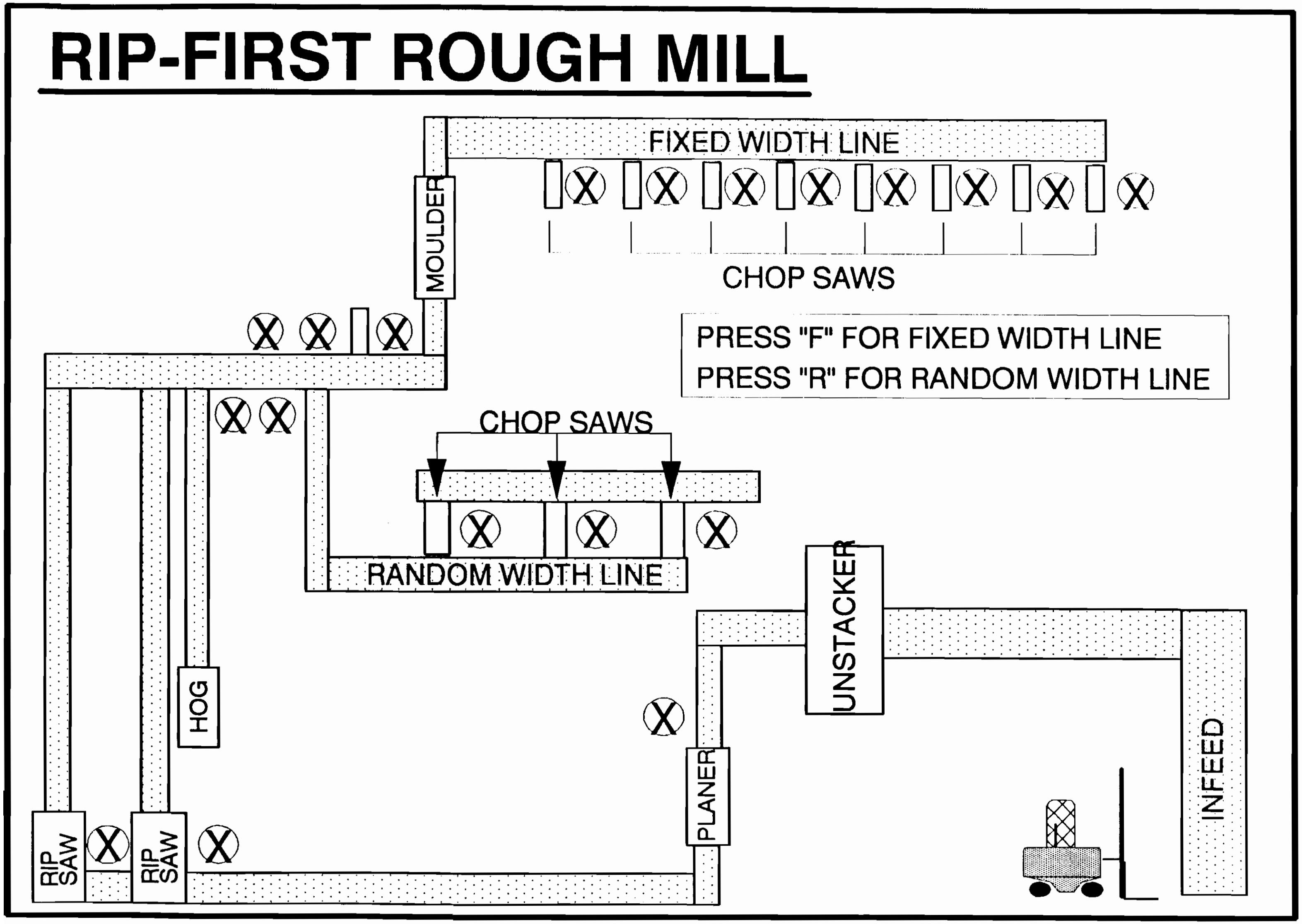

Figure 26. Rip-first rough mill layout used in simulation model.

of the mills. Data on the distribution of final part lengths and the number of parts generated at the first lumber breakdown operation was also collected. The cutting bills used in the mill studies were selected by the rough mill supervisor (Table 35). An attempt was made to choose a cutting bill that would match up well with the short length lumber input. However, simulated crosscut test results (Section 3) indicated that the cutting length distribution from short lumber is often comparable to that from longer lumber for longer cutting bills. The piece rates and cutting length distributions associated with these cutting bills formed the basis for the simulation models.

Model Programming

The translation of this information into the simulation programming language was attempted first with the rip-first model. During the programming process it was discovered that certain of the timing elements which had previously been defined were inadequate. For example, in timing the rip saw throughput rates, several elements had been aggregated together. Some of these time consuming elements were very lumber length dependent (e.g. total conveyance time through the rip saw), some were somewhat length dependent (e.g. operator inspection and laser line alignment), and some had no length dependency (e.g. lumber conveyance from scan station to ripsaw infeed, setworks related delay on infeed). These elements had to be split and re-timed to adequately capture lumber length-based differences in rough mill processing rates.

During the initial stages of the programming process certain complex material flow relationships were simplified so as not to bring the programming process to a temporary

Table 35. Cutting bill specifications and cutting length-based value relationships used in the simulation models and economic analyses.

CROSSCUT-FIRST CUTTING SIZES AND VALUES					
Cutting Length	**Cutting Width**	**Cutting Quality**[a]	**Value 1**	**Value 2**	**Value 3**
inches	inches		$/bf	$/bf	$/bf
14	R/W[b]	C1F	2.00	1.64	0.93
22	R/W	C1F	2.00	1.95	1.86
28	R/W	C1F	2.00	2.18	2.55
30.375	R/W	C1F	2.00	2.28	2.82
34	R/W	C1F	2.00	2.42	3.24
40.375	R/W	C1F	2.00	2.67	3.98

RIP-FIRST CUTTING SIZES AND VALUES					
Cutting Length	**Cutting Width**	**Cutting Quality**	**Value 1**	**Value 2**	**Value 3**
8.25	2.50	C2F	2.00	1.41	0.27
13.25	2.50	C2F	2.00	1.61	0.85
15.75	2.50	C2F	2.00	1.70	1.14
22.25	2.50	C2F	2.00	1.96	1.88
25.875	2.50	C2F	2.00	2.10	2.30
14	R/W[c]	S2F	1.54	1.09	0.72
17	R/W	S2F	1.54	1.35	0.99
23	R/W	S2F	1.54	1.53	1.97
35	R/W	S2F	1.54	1.90	3.35

a- Cutting quality abbreviations: C1F - clear one-face cutting, C2F - clear two-face cutting, S2F - sound two-face cutting.

b- R/W stands for random width cuttings.

c- The random width cuttings in the rip-first rough mill model varied between .75 and 2.4375 inches.

halt. These flow relationships were studied on subsequent visits to the cooperating mills. They were then modeled to the necessary level of accuracy.

Different versions of both the crosscut-first mill model and the rip-first mill models were assembled for each of three lumber length groupings: short (4 through 7 feet nominal measure), medium (8 through 13 feet), and long (14 through 16 feet). The main difference between these versions was in the distribution parameters for the various service rates and lumber attributes. However, the differences between the distributions sometimes created queuing problems in one model that were nonexistent in the other models. In these cases, additional programming was required to establish a realistic form of flow control.

Several assumptions were made during the modeling process in order to simplify and shorten the models. For example, in the crosscut-first model it was assumed that no lumber length-based differences in throughput rates and part yields existed for like-sized pieces in the straight-line ripping operation. In the rip-first model it was assumed that the system would never be shut down due to back-ups caused by insufficient rough part inspection and sorting capacity; the rough mill supervisor would shift around personnel rather than stop production. Downtime was not modeled for either mill configuration. System observation and discussions with mill management lent support to these simplifying assumptions.

Even with these model simplifications the rip-first model contained approximately 1450 lines of code and utilized 98 percent of the available conventional memory on the PC during compilation and execution. The crosscut-first model contained approximately 850 lines of code.

Distribution Determination

After the first translation of the models was completed the task of determining the appropriate distributions to associate with the different service rates and material parameters was undertaken. The first decision that had to be made about the input data was which data to use for those operations which were timed in both the mill studies and timing studies. Timings that were taken during the mill studies (crosscut-saw rates during the crosscut-first mill study, rip saw rates and fixed width chop saw rates during the rip-first mill study) were limited in several regards: only one operator was timed, a limited number of observations per operation were recorded, and the grades were segregated rather than mixed as is the case with the normal lumber input into the rough mills modeled. The major advantage of having obtained these timings is that they provided some data on short length lumber service rates which was not available from the non-mill study-based timing studies. The mill study timings were used predominantly to check the short length lumber service rate values which were extrapolated from the large-scale timing studies. For each of the operations timed in the mill study, the mean value for the timings fell within the 95% confidence interval of the mean value obtained through extrapolation.

Timing study and board data collected at the cooperating mills was plotted in histogram form and candidate distributions were visually identified. Analysis of variance tests were conducted on those data sets that displayed lumber length-based tendencies. The data was grouped into three length categories for these analyses. The data was then analyzed with the Graphic Distribution Analysis program (GDA; Worley et al. 1990). The

GDA analyses were sometimes inconclusive in that the data for one of the length groups demonstrated one type of distribution while the data for another length group indicated a different candidate distribution was more appropriate. In these cases, and in cases where the amount of data collected was thought to be insufficient, a triangular distribution was also considered. The minimum and maximum points for the triangular distribution were chosen from the pooled mill study and timing study data. The "most likely" parameter estimate was based on histograms of the timing study data.

For both the crosscut-first and rip-first models the number of parts and the distribution of part lengths generated at the crosscut/chop saws were based primarily on the data that was recorded during the mill studies. However, the mill study did not include any long length lumber. Therefore, these distributions had to be estimated using other methods.

The long length lumber distributions were estimated using the two-stage version of the lumber cut-up program CORY (Brunner et al. 1989). Red oak board data files which were assembled the U.S. Forest Service's Forestry Sciences Laboratory in Princeton, West Virginia were segregated into short, medium, and long length groups for processing by CORY. The part length priorities assigned in the long length lumber CORY analysis were determined by running CORY on the medium length board data until a piece count-based cutting length distribution similar to that obtained from the medium length lumber in the mill study was obtained.

The short length board data was also processed by CORY using these same medium length lumber-based cutting length priorities. For the crosscut-first model the distribution of parts from the short lumber that was established in the mill study produced higher volume and value yields then did the distribution that was similar to the medium length lumber distribution. The difference in the total yields for these two short lumber cut-up iterations was 2.0 percent. In contrast, the cutting length distributions generated from short length lumber in the rip-first mill study were less optimal than those obtained by processing the short lumber into cutting lengths that more closely mirrored the medium length lumber's cutting length distribution. The mill study-based distribution resulted in a 1.5 percent lower total yield than did the alternate distribution (based on CORY analysis of both).

For both the crosscut and rip-first models the mill study-based cutting length distributions are incorporated into the models that are designated "SHORT1". The alternate cutting length distributions are incorporated into the models that are designated "SHORT2". The alternate distributions are included in order to offer an estimate of the variability that might be expected given a slightly different cutting bill or a slightly different cutting length demand schedule.

The distributions used in the final crosscut-first simulation model are listed in Table 36. The crosscut time per cutting for the crosscut-first mill is related to both the number of cuttings removed from the board, and the length of the board. The relationship varies for each of the three operators modeled. The equations which capture this relationship are shown in Table 36. Both variable terms in each of these equations were significant at $\alpha = .05$. The R^2-values for these equations were approximately 30 percent. The remaining variability, unexplained by these equations, was modeled by incorporating the rates predicted by these equations into normal distributions as the mean values. The standard deviation parameter, which also varied considerably between operators, was

Table 36. Listing of the more critical distributions and equations incorporated into the crosscut-first simulation model.

PARAMETER	LUMBER LENGTH GROUP	DISTRIBUTION / EQUATION *(lengths in inches, times in seconds)*
Unstacker Reload Rate	Length Independent	NORM (120,15)
Lumber Width	Length Independent	NORM (6.2,1.8) truncated at 2.5
Lumber Length	SHORT	DISC (.40,50,.50,62,.90,74,1,86)
	MEDIUM	DISC (.264,98,.33,110,.594,122,.666,134,.924,146,1,158)
	LONG	DISC (.421,170,1,194)
XCUT 1 Rate Per Cutting		Rate1 = 9.51 - (.997 * Xcut Pieces) + (.194 * Length/12)
XCUT 2 Rate Per Cutting		Rate2 = 7.71 - (.790 * Xcut Pieces) + (.174 * Length/12)
XCUT 3 Rate Per Cutting		Rate3 = 6.11 - (.613 * Xcut Pieces) + (.174 * Length/12)
XCUT Pieces Per Piece of Lumber	SHORT1	DISC (.025,1,.918,2,.992,3,1,4)
	SHORT2	DISC (.105,1,.686,2,1,3)
	MEDIUM	DISC (.146,3,.616,4,.972,5,1,6)
	LONG	DISC (.02,4,.41,5,.84,6,.97,7,.99,8,1,9)
Cutting Length Distribution From XCUT Pieces	SHORT1	DISC (.107,14,.149,22,.275,28,.532,30.375,.643,34,1,40.375)
	SHORT2	DISC (.142,14,.258,22,.538,28,.685,30.375,.844,34,1,40.375)
	MEDIUM	DISC (.133,14,.263,22,.542,28,.710,30.375,.826,34,1,40.375)
	LONG	DISC (.15,14,.27,22,.56,28,.69,30.375,.82,34,1,40.375)
Rip Operations Per XCUT Piece	Length Independent	DISC (.107,2,.776,3,.946,4,.979,5,1,6) Width-based ... adjustments based on piece width included in program.
Cuttings Ripped Out of Each Piece	Length Independent	DISC (.091,1,.834,2,.992,3,1,4) Width-based ... adjustments based on piece width included in program.
Rip Feed Rate	Short Pieces	TRIA (2.0,3.5,6.0)
	Long Pieces	TRIA (2.0,4.0,7.1)
Rip Refeed Rate	Short Pieces	TRIA (2.2,2.75,4.0)
	Long Pieces	TRIA (2.3,2.75,4.5)

[a] Distribution notations used are: TRIA - triangular, NORM - normal, DISC - discrete.

based on the *Error Mean Square* estimate of the population variance from the regression analysis.

The number of crosscut pieces cut out of the piece of lumber influences the crosscut time per piece due to the fact that there is a set-up time associated with the cutting of each piece of lumber. This time consists of time required to load the board on the crosscut saw's infeed table, to visually inspect the board, to take a clean-up cut on the lead end of the board, and to clear from the saw table the remaining wood block after the last cutting is taken. If more cuttings are removed from a board, this set-up time is reduced per cutting.

Longer boards take longer to process per cutting removed than do short boards because they are heavier, and thus harder to move. In addition, for some cutting bills the longest cuttings are more readily obtainable from long lumber than from short lumber; positioning the board for especially long cuttings is more difficult and time consuming (moving it out to the stop) than is positioning it for shorter cuttings.

For several of the more critical and less precise rip-first distribution estimates, the simulation model was run successively with first one, and then another of the distributions under consideration. Table 37 shows the distributions that were investigated in this manner. Ten replications of each of these distribution-check runs were executed. T-tests were conducted on some of the more critical simulation output results compiled from these runs. For a couple of the iterations some small differences were detected in one or two of the machine utilizations measured but none of the output volume and yield variables varied between runs. Triangular distributions were selected for the final experimentation runs for each of the parameters listed in Table 37. The distributions associated with the

Table 37. Rip-first rough mill simulation candidate distribution comparison based on part volume production per hour.

PARAMETER - Lumber Length Group	DISTRIBUTIONS COMPARED [a]	OUTPUT VOL PER HOUR (MEAN)	SIGNIFI-CANCE OF DIFFERENCE
		bf	
FIXED CHOP RATE PER CUTTING-Med.	NORM (16.99,4.62)	2804	NS [b]
	NORM (15.41,2.97)	2810	
FIXED CHOP RATE PER CUTTING-Med.	TRIA (7,15.5,29.5)	2816	NS
	NORM (15.41,2.97)	2810	
FIXED CHOP RATE PER CUTTING-Med.	TRIA (7,15.5,29.5)	2816	NS
	NORM (16.99,2.97)	2804	
RIP SAW LASER SCAN RATE-Long	TRIA (6.3,7.3,18.9)	2674	NS
	WEIB (6.3,3.2,1.1)	2688	
CHOP SAW BUFFER RELOAD RATE-Long	TRIA (2.5,2.8,4.8)	2674	NS
	WEIB (2.2,1.0,2.5)	2694	

a- Distribution notations used are: TRIA - triangular, NORM - normal, WEIB - three-parameter weibull.

b- NS stands for "not significant" ... t-tests conducted on the output from 10 replications of each model showed the groups were not significantly different (α =.05).

most critical parameters in the rip-first experimental model are listed in Table 38.

Model Verification and Validation

Model animations were built in parallel with the simulation models and proved to be very valuable in model debugging and verification activities. The models were shown to the cooperators using the animation feature, for purposes of structural validation. Results from the simulation runs were discussed and questions concerning various flow relationships were also posed. For the rip-first mill, several suggestions for improving the model were made and a couple more weeks of programming were required. The crosscut-first simulation model was found to be acceptable by mill personnel.

Steady-State Determination

The beginning of steady-state was determined for each of the models by collecting data on queue sizes and the length of time that an entity resided in the system. Data collection on these variables began at time zero and proceeded for several thousand seconds.

In both the crosscut-first and rip-first models the long length lumber group produced so many cuttings/strips at the first breakdown operation that the second stage cut-up operation's queues backed up steadily until a control mechanism within the models was triggered. In the crosscut-first model the control mechanism was the switching of a rip saw operator off a low volume cutting length onto the highest volume cutting length to help reduce the imbalance whenever the high volume rip saw's buffer accumulated more

Table 38. Listing of the more critical distributions and equations incorporated into the rip-first system simulation model.

PARAMETER	LUMBER LENGTH	DISTRIBUTION / EQUATION *(lengths in inches, times in seconds)*
Lumber Width	SHORT	NORM (6.21,1.93) truncated at 2.5
	MEDIUM	NORM (6.77,1.93) truncated at 2.5
	LONG	NORM (7.31,1.94) truncated at 2.5
Lumber Length	SHORT	DISC (.40,48,.50,60,.90,72,1,84)
	MEDIUM	DISC (.35,96,.37,108,.50,120,.51,132,1,144)
	LONG	DISC (.04,156,.35,168,.36,180,1,192)
Rip Saw Laser Scan Rate	SHORT	TRIA (1.5,2.92,4.8)
	MEDIUM	TRIA (1.8,3.25,11.9)
	LONG	TRIA (6.3,7.35,18.9)
Rip Saw Setworks	Length Independent	NORM (3.89,.24)
Setworks Delay		NORM (4.20,.33)
Rip Volume		Width - (TRIA (.2,.8,1.6))
R/W Strip Width		Width - (2.5 * # Fixed Strips) - (.19 * # Fixed Strips)
Fixed Chop Rate Per Cutting	SHORT	TRIA (5.25,8.50,21.00)
	MEDIUM	TRIA (7,15.5,29.5)
	LONG	TRIA (17,23,46)
Cuttings Per Fixed Width Strip	SHORT1	DISC (.03,0,.09,1,.50,2,.90,3,.99,4,1,5)
	SHORT2	DISC (.03,0,.09,1,.43,2,.89,3,.99,4,1,5)
	MEDIUM	DISC (.01,2,.05,3,.31,4,.62,5,.87,6,.98,7,1,8)
	LONG	DISC (.01,5,.11,6,.36,7,.74,8,.91,9,.98,10,.99, 11,1,12)
Cutting Length Distribution From Fixed Width Strips	SHORT1	DISC (.07,8.25,.23,13.25,.48,15.75,.74,22.25,1,25.875)
	SHORT2	DISC (.15,8.25,.29,13.25,.46,15.75,.69,22.25,1,25.875)
	MEDIUM	DISC (.11,8.25,.23,12.25,.39,15.25,.58,22.25,1,25.875)
	LONG	DISC (.12,8.25,.23,13.25,.39,15.75,.56,22.25,1,25.875)
Chop Saw Buffer Reload Rate	SHORT	TRIA (1.0,1.93,3.76)
	MEDIUM	TRIA (1.25,2.0,4.8)
	LONG	TRIA (2.46,2.8,4.8)
R/W Chop Rate Per Cutting	SHORT	TRIA (5.0,8.5,17.1)
	MEDIUM	TRIA (5.5,10.5,22.2)
	LONG	TRIA (10.8,14.0,24.7)
Cuttings Per R/W Strip	SHORT	DISC (.02,0,.05,1,.42,2,.82,3,1,4)
	MEDIUM	DISC (.02,2,.25,3,.56,4,.87,5,.98,6,.99,7,1,8)
	LONG	DISC (.04,4,.14,5,.59,6,.86,7,1,8)
Cutting Length Distribution From R/W Strips	SHORT1	DISC (.28,14,.57,17,.89,23,1,35)
	MEDIUM	DISC (.18,14,.33,17,.56,23,1,35)
	LONG	DISC (.18,14,.37,17,.53,23,1,35)

than 175 entities. For the rip-first mill, the flow control mechanism used was the shut down of the rip saws when more than 50 entities were in the moulder queue. Steady-state was reached in both of these models at some point in time after the flow control mechanism was activated.

Figures 27 and 28 demonstrate the type of information used to determine steady-state for the crosscut-first rough mill. Time T_{7000} was chosen as the beginning of the steady-state period through visual inspection of these two graphs and similar graphs produced from other replications of the model. The "average steady-state value line" shown on the graph is the mean value for "time in system" (Figure 27) or "entities in 28-inch rip queue" (Figure 28) for the simulation run that was conducted beginning at T_{7000}. Since the steady-state beginning point chosen falls chronologically after the first several intersections of the mean value line with the plotted value line, the steady-state choice is substantiated. These two graphs are from the long length lumber version of the crosscut-first model. The same evaluation process was used to determine the end-point of the initial transient phase for the short and medium length lumber versions of the model.

Two steady-state estimation graphs for the rip-first model are presented in Figures 29 and 30. All of the versions of the rip-first model reached steady-state more rapidly then did the crosscut-first models. Since the bottlenecks in this system were the unstacker-planer (short lumber) and the moulder (medium and long lumber), each of which are high volume pieces of equipment that the lumber

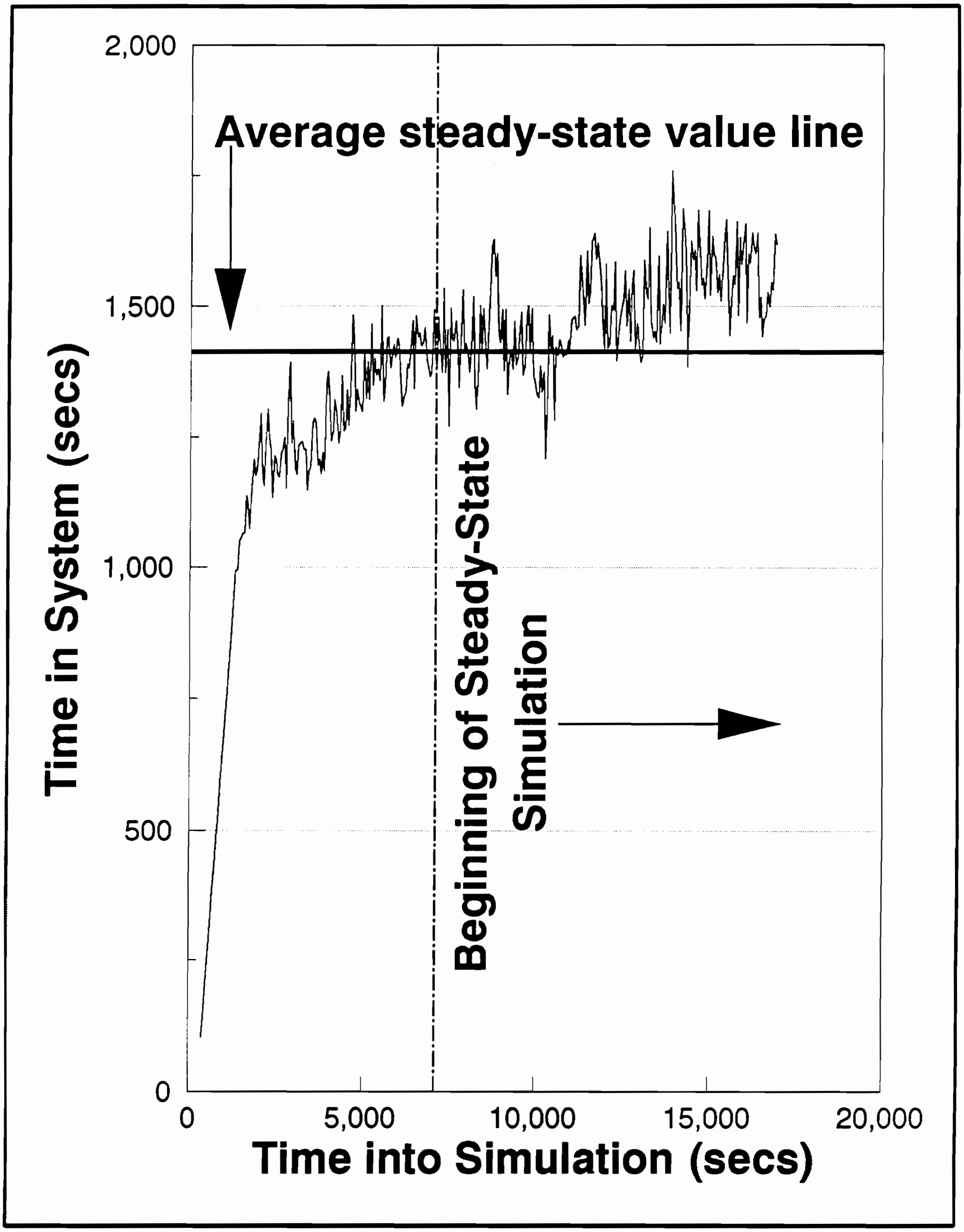

Figure 27. Crosscut-first model steady-state determination graph; entity time in system.

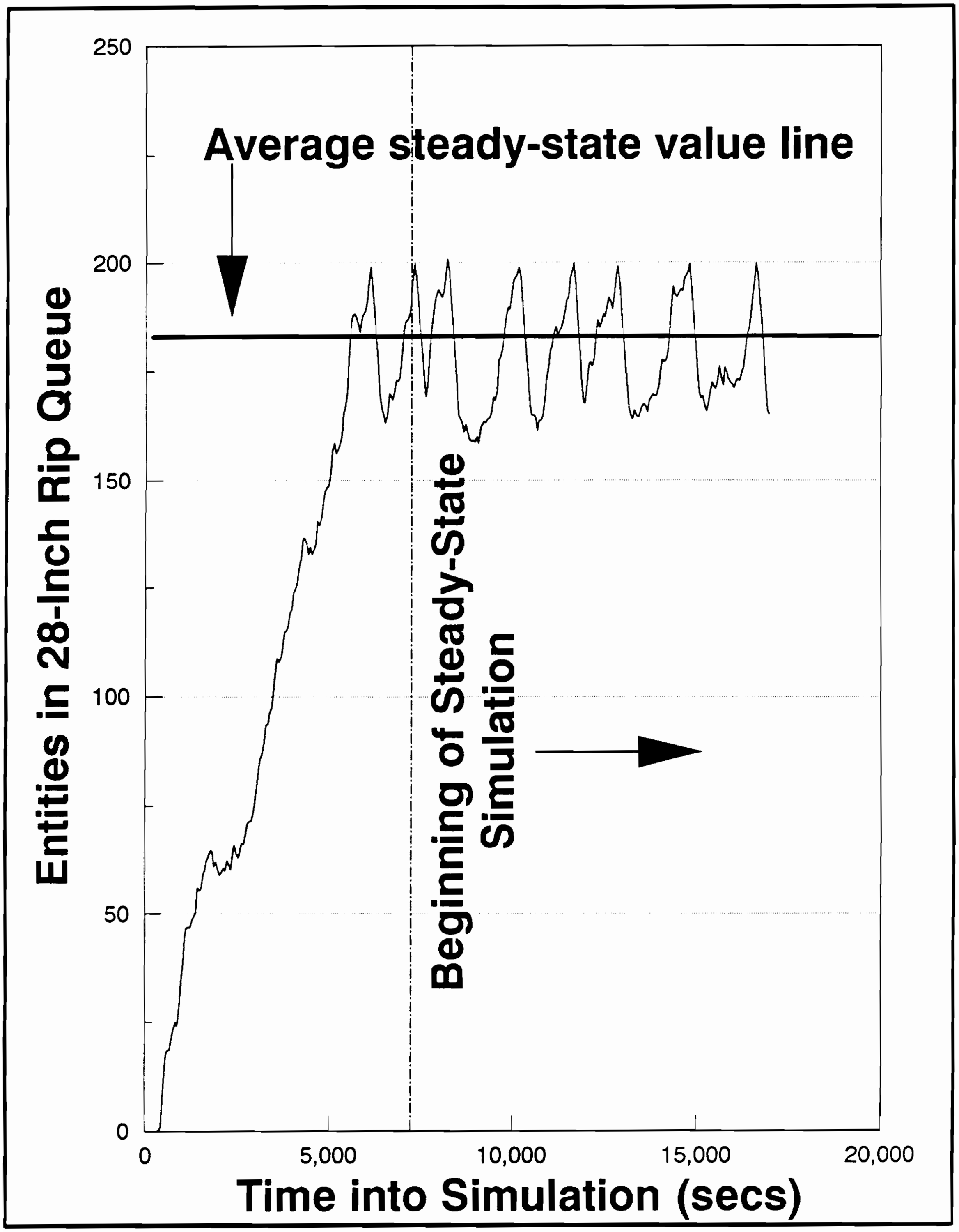

Figure 28. Crosscut-first model steady-state determination graph; entities accumulated in rip queue.

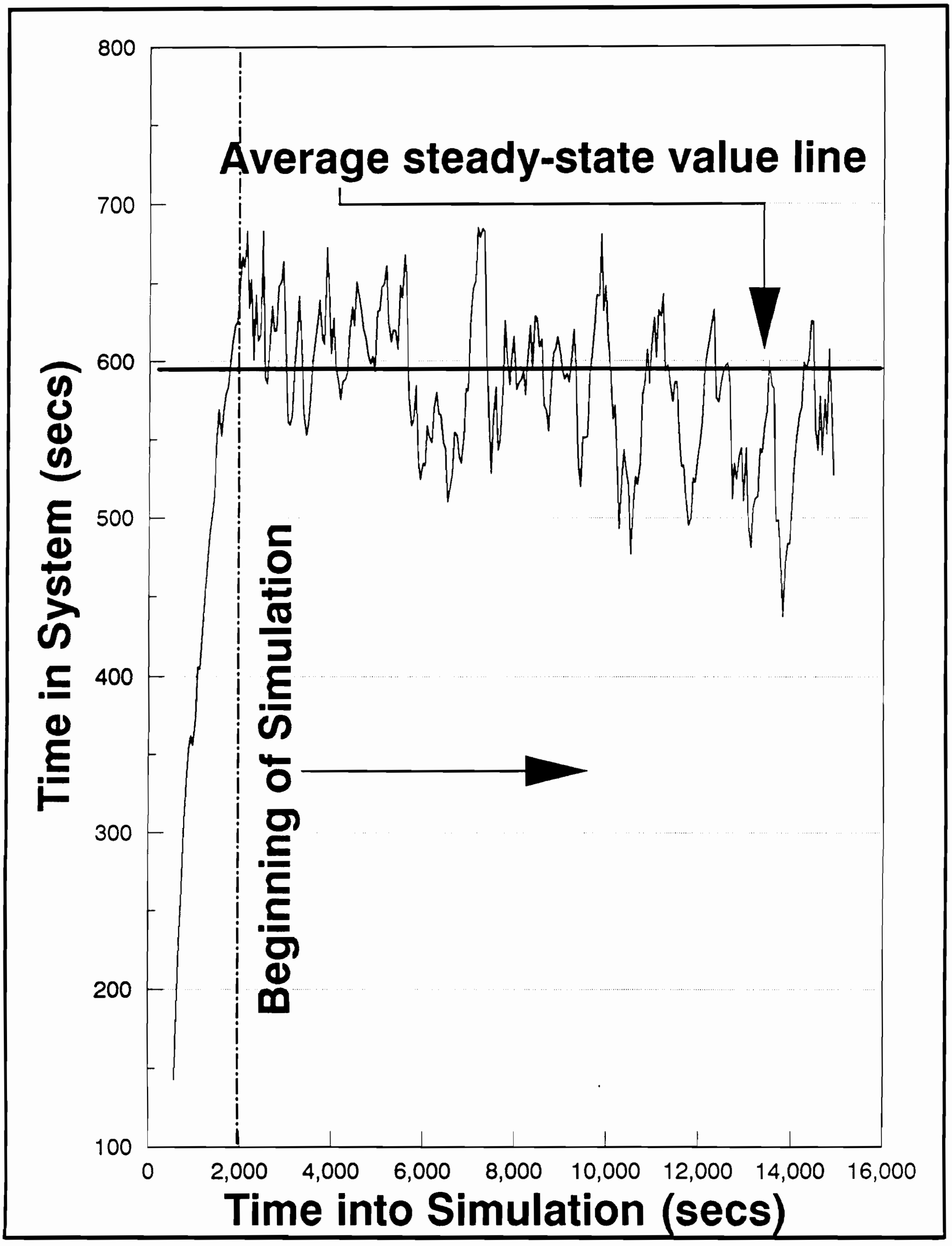

Figure 29. Rip-first model steady-state determination graph; entity time in system.

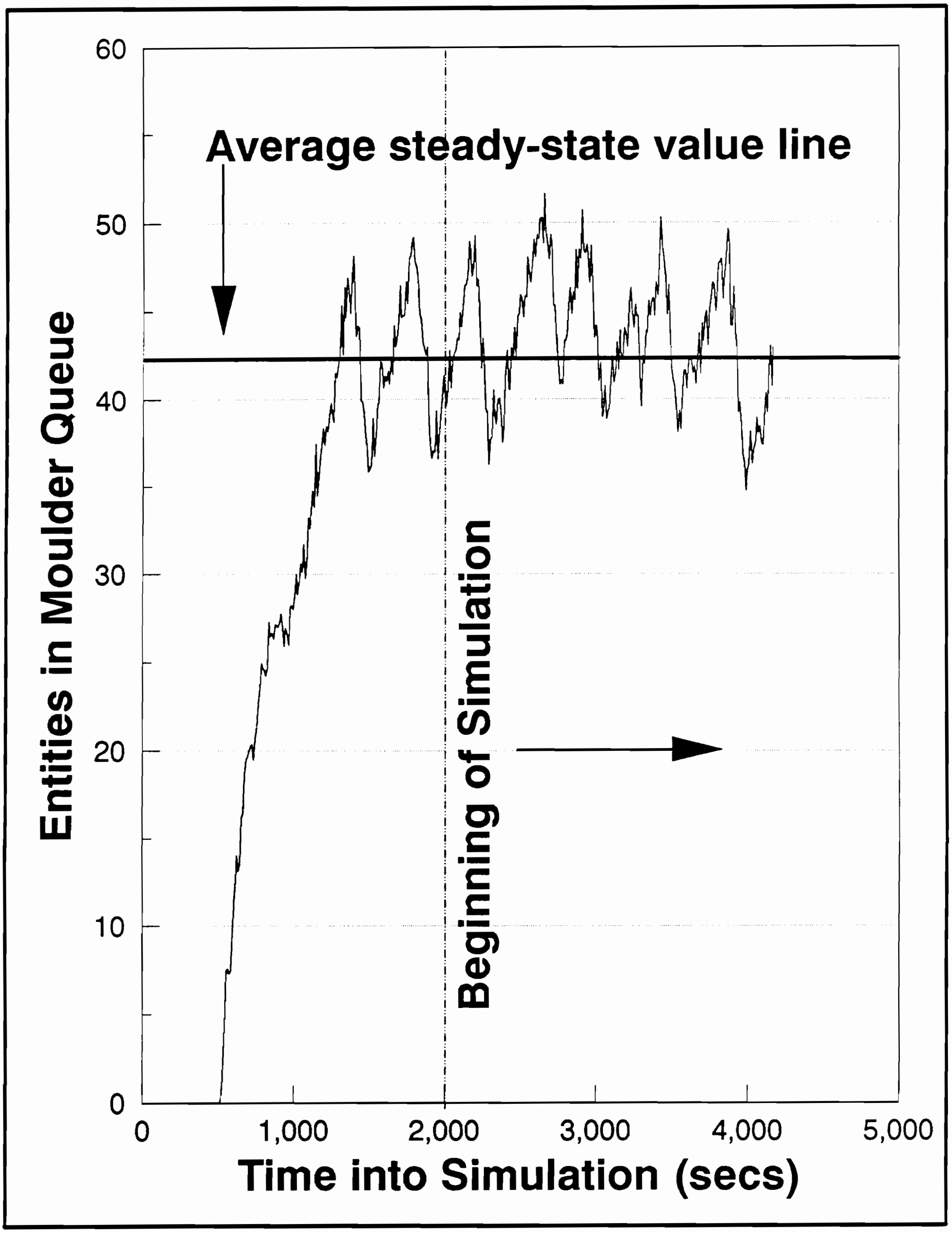

Figure 30. Rip-first model steady-state determination graph; entities accumulated in moulder queue.

gets to quickly, the flow control system was activated relatively early in the simulation.

Experimental Design

Before experimentation could begin decisions had to be made as to how to go about collecting the necessary data from the models. The use of replicates can be time consuming if a long, initial transient stage is discarded for each replication. This was not a major issue however, since a 486-computer was available for making the experimental runs. Memory limitations restricted the use of the SIMAN Output Processor's filtering tool which would have provided an alternative method of estimating the variance of the output values.

Ten replications were run of each of the versions of the two models. Statistics were collected on the rip-first model for 1800 seconds (½ hour) beginning at the predetermined transient phase truncation point. Test runs of a longer duration were conducted to ascertain that 1800 seconds was a sufficiently long simulation period. The output from the longer runs was not significantly different from the output of the 1800 second long simulation runs. The rip-first system is a non-terminating system that requires steady-state treatment. When cutting bill changes are made they frequently occur in a piecemeal fashion and they seldom affect any of the operations preceding the chop saws. The rip-first system is rarely emptied to the point that operators begin a shift or a cutting bill in the idle state with empty buffers.

For the crosscut-first simulation model both steady-state and start-up state replication sets were executed for each version. The start-up state simulation runs were considered more valid for the crosscut-first mill than were the steady-state runs. At the crosscut-first mill represented by this model, several wholesale cutting bill changes are made daily. During the new cutting bill set-up period the crosscut saws are shut down for several minutes while the operators change the jig positions on the front gauges. In almost all cases, the rip saw operators manage to clear their infeed buffers during this set-up period. This, in effect, creates a terminating system with a fixed starting condition (rip saws and sorting system idle and empty). The average length of time spent working on a given cutting bill at this mill is approximately 1½ hours. Thus, statistics were collected on the crosscut-first simulation runs for 5400 seconds.

Evaluation Procedures

Mean values for the simulation output variables were calculated from the 10 replications of each model version. Ninety-five percent confidence intervals for the means were also calculated. Analysis of variance tests were performed on each of the output variables to determine if differences existed between the four groups in each model (Short1, Short2, Medium, Long; $\alpha = .05$). Output variables which exhibited length group-based difference were further analyzed using the Tukey multiple comparison test (family error rate = .05).

Economic Analysis Procedures

The economic analysis matrix includes multiple levels of each of the following critical factors:

1. the cutting yield from short length lumber (2 levels: SHORT1 and SHORT2),
2. the relationship between cutting value per bf and cutting length (3 levels),
3. the annual volume of rough part production that could be assembled in "short cutting bills" (2 levels),
4. the costs associated with modifying a rough mill system to improve the handling of short length lumber (3 levels: none, moderate, extreme),
5. the percentage of total costs that consists of overhead (4 levels).

This proliferation of alternatives was established to get an indication of the sensitivity of the economic measures to changes in the levels of these various operations variables.

The present worth of the after-tax cash flows was calculated for each of the crosscut-first and rip-first production alternatives. These calculations were based on the mean value per hour figures calculated for each version of the two models. After, rather than before-tax cash flows were used because one of the mill modification cost alternatives includes the purchase of a depreciable asset. Many of the economic assumptions which were used in the analysis are listed in Table 39. A few of the assumptions require further explanation:

Table 39. Assumptions used in economic analyses of simulation output.

Economic Parameter	Assumption
o Dry red oak lumber price	$800 per mbf
o Fuel value of residue	$10 per ton; $20 per dry mbf
o Average rough mill labor rate	$6.75 per hour
o Fringe benefit rate	30 percent of wage rate
o # of operators; rip-first, medium and long lumber	27
o # of operators; rip-first, short lumber	24
o # of operators; xcut-first, med. and long lumber	15
o # of operators; xcut-first, short lumber	13
o Effect of inflation	No inflation factored in
o Minimum attractive after-tax rate of return	12 percent
o Overhead Costs	Used $/hour figure based on 30% of total medium length lumber costs
o Income tax rate	34 percent
o System conversion cost scenarios - rip-first mill	a - no changeover costs b - moderate costs ... $20,000 for equipment modifications c - extreme ... $50,000 for equipment modifications and $45,000 for purchase of small forklift
o System conversion cost scenarios - xcut-first mill	a - no changeover costs b - moderate costs ... $15,000 c - extreme costs ... $30,000 plus $45,00 for forklift
o Planning horizon	5 years
o Forklift depreciation schedule	5-year property; Accelerated Cost Recovery System applied
o Timing of conversion costs	Costs incurred during first year

1. The difference in the number of operators required for processing short lumber as compared to medium and long lumber was based on machine utilization rates.
2. The overhead rates which were applied were based on a $ per hour overhead cost figure which was calculated by multiplying the total medium length lumber cost by the overhead rate percentage and then dividing this total overhead cost by the number of medium length lumber production hours.
3. The cutting value - cutting length relationships, which are detailed in Table 35, were based on regression relationships developed by Yun (1989); the base value for the Value 2 and Value 3 relationships was $2.00 per board foot for a 23.25 inch long cutting.
4. The levels used for the *annual volume of rough part production that could be assembled in "short" cutting bills* (cutting bills with maximum cutting lengths similar to those listed in Table 35) are approximately equal to:
   a. 10 percent and 25 percent of the crosscut-first mill's potential annual production (one-shift basis), and
   b. 25 percent and 50 percent of the rip-first rough mills potential annual production (one-shift basis).

An economic measure which is more easily understood than the present worth value is the dry, short length lumber breakeven price. This is the dry lumber price which balances the discounted, after-tax cash flows for the short lumber and the medium length lumber alternatives. This price was calculated for each of the short lumber alternatives in which the present worth for the short lumber production system was lower than the present worth for the medium length lumber production system. The medium length lumber production and economics values were used as the baseline for comparison since the present distribution of lumber lengths processed by Appalachian region furniture rough mills is predominantly between 8 and 14 feet long.

Results and Discussion

Crosscut-first Model Simulation Results

For the crosscut-first model, the mean hourly production rate for the short1 simulations was not statistically different from the mean hourly production rates of the medium and long lumber groups in either the start-up or steady-state mode (Tables 40, 41, 42). The short1 version of the model incorporated mill study-based cutting length distributions and thus represents the "most-likely case" in this short lumber analysis. The short1 volumes are high because of the abundance of longer parts generated by this distribution (Table 36; "Cutting Length Distribution From XCUT Pieces").

Table 40. Crosscut-first rough mill simulation results - average values for 10 steady-state and 10 start-up runs.

	SIMULATION OUTPUT VARIABLE	SHORT 1[a]	SHORT 2[b]	MEDIUM	LONG
STEADY STATE	Time in System (secs)	502	848	1160	1508
	Input Vol (bf/hr)	2440	2254	2488	2552
	Production Vol (bf/hr)	1872	1781	1906	1955
	Part Value 1 ($/hr)	3739	3448	3812	3909
	Part Value 2 ($/hr)	4529	3958	4364	4488
	Part Value 3 ($/hr)	6073	4960	5456	5624
	Unstacker Op. Utilization	23.6%	23.3%	14.3%	8.0%
	Crosscut Saw Utilization	100%	100%	100%	100%
	Rip Saw Utilization	66.3%	68.0%	75.2%	77.7%
	Rip Queue Entities	15	165	191	200
START UP	Time in System (secs)	485	527	853	1072
	Input Vol (bf/hr)	2226	2100	2200	2240
	Production Vol (bf/hr)	1709	1567	1686	1716
	Part Value 1 ($/hr)	3418	3133	3371	3431
	Part Value 2 ($/hr)	4139	3599	3876	3948
	Part Value 3 ($/hr)	5555	4512	4870	4939
	Unstacker Op. Utilization	23.1%	22.6%	15.3%	11.7%
	Crosscut Saw Utilization	93.2%	93.7%	93.3%	94.1%
	Rip Saw Utilization	60.7%	61.8%	66.1%	68.1%
	Rip Queue Entities	9	24	61	73

a- Short1 simulation runs were based on the cutting length distribution from the 4 through 7 foot long lumber which was obtained in the mill study.

b- Short2 simulation runs used a cutting length distribution for short length lumber similar to the distribution for the 8 through 13 foot long lumber which was obtained in the mill study.

Table 41. Crosscut-first rough mill steady-state simulation results - confidence intervals and multiple comparison groupings for several variables.

Simulation Output Variable - Simulation Run			Mean ± 95% CI	Grouping [a]	
Output Volume (bf/hr) -					
	Low	**Short2**	1781.3 ± 119.7	A	
		Short1	1872.3 ± 22.2	A	B
		Medium	1905.9 ± 32.4		B
	High	**Long**	1955.2 ± 37.4		B
Part Value 1 ($/hr) -					
	Low	**Short2**	3448.2 ± 39.2	A	
		Short1	3738.6 ± 47.4	B	
		Medium	3811.8 ± 64.9	B	C
	High	**Long**	3909.4 ± 74.1		C
Part Value 2 ($/hr) -					
	Low	**Short2**	3957.7 ± 48.8	A	
		Medium	4363.8 ± 77.3	B	
		Long	4488.2 ± 89.5	C	
	High	**Short1**	4528.8 ± 61.9	C	
Part Value 3 ($/hr) -					
	Low	**Short2**	4960.3 ± 70.1	A	
		Medium	5456.1 ± 98.2	B	
		Long	5623.7 ± 120.0	C	
	High	**Short1**	6072.6 ± 90.6	D	
Rip Saw Utilization (%) -					
	Low	**Short1**	66.3 ± 0.7	A	
		Short2	68.0 ± 0.9	A	
		Medium	75.2 ± 1.3	B	
	High	**Long**	77.7 ± 1.4	C	

a- Groupings from Tukey multiple comparison tests using a family error rate of .05.

Table 42. Crosscut-first rough mill start-up simulation results - confidence intervals and multiple comparison groupings for several variables.

Simulation Output Variable - Simulation Run			Mean ± 95% CI	Grouping[a]
Output Volume (bf/hr) -				
	Low	**Short2**	1566.5 ± 20.3	**A**
		Medium	1685.5 ± 34.3	**B**
		Short1	1709.0 ± 15.0	**B**
	High	**Long**	1715.6 ± 24.2	**B**
Part Value 1 ($/hr) -				
	Low	**Short2**	3133.0 ± 40.6	**A**
		Medium	3371.0 ± 68.5	**B**
		Short1	3418.2 ± 30.3	**B**
	High	**Long**	3431.2 ± 48.5	**B**
Part Value 2 ($/hr) -				
	Low	**Short2**	3598.7 ± 53.0	**A**
		Medium	3876.2 ± 84.1	**B**
		Long	3947.9 ± 57.0	**B**
	High	**Short1**	4139.0 ± 39.6	**C**
Part Value 3 ($/hr) -				
	Low	**Short2**	4512.4 ± 79.0	**A**
		Medium	4869.8 ± 115.4	**B**
		Long	4939.4 ± 71.9	**B**
	High	**Short1**	5554.9 ± 51.6	**C**
Rip Saw Utilization (%) -				
	Low	**Short1**	60.7 ± 0.6	**A**
		Short2	61.8 ± 0.7	**A**
		Medium	66.1 ± 1.1	**B**
	High	**Long**	68.1 ± 0.9	**C**

a- Groupings from Tukey multiple comparison tests using a family error rate of .05.

The value of the parts produced in the short1 simulations was not different from the value of the parts produced in the medium length lumber simulations for the value relationship in which all parts are valued equally per bf (Tables 41 and 42). However, both the start-up and steady-state value figures were higher for the short1 group than for the medium group when the two value relationships in which longer parts are more highly valued per bf were used. In the start-up state simulation models part value relationships similar to those described for the short1 and medium models existed for the short1 and long models.

The average rip saw utilization calculated from the short1, start-up mode simulation runs was 60.7 percent (Table 40). The average values for the medium and long runs were 66.1 and 68.1 percent, respectively. The differences between these three utilization rates were statistically significant (Table 42). These utilization rates were used to determine how many rip saw operators would be included in the economic analysis of the alternatives. For the steady-state runs the difference between the average short1 rip saw utilization rate and the medium and long utilization rates were approximately 3 percent greater than in the start-up state models (Table 40).

In steady-state mode the long length lumber model's rip saw utilization rate was 77.7 percent (Table 40). An average of two-hundred entities were sitting in the rip saw buffers awaiting processing. Most of these entities were in a single rip saw queue. The simulation model's flow control mechanism was implemented multiple times during the long lumber iterations to prevent the build-up of entities at the rip saw from shutting down the system. Were the rip saws cutting out narrow fixed width parts rather than wider random width parts the bottleneck would be even more pronounced.

A feasible alternate flow control measure would be the introduction of short length lumber packages into the system when the rip saw buffers are backing up. The slower crosscut saw rate per cutting produced and the redistribution of cuttings into different length classes would smooth out production flow.

The mean crosscut saw utilization values were not significantly different for the different length groups for either the start-up mode or steady-state mode simulations. The mean values for the start-up simulation runs were approximately 93.5 percent. For the steady-state runs the mean crosscut saw utilization rate was 100 percent. Table 40 lists the mean crosscut saw utilization values and gives several other mean values not explicitly discussed in this section.

The mean hourly production volume for the short2 simulation runs (both start-up and steady-state) was significantly lower than the mean volumes for each of the other sets of runs (Tables 41 and 42). Similarly, the mean values for the short2 runs were significantly lower than the mean values for the short1, medium and long runs. The mean rip saw utilization percent for the short1 and short2 simulations were not significantly different from each other but were lower than the medium and long utilization rates.

Rip-first Model Simulation Results

For the rip-first models (only steady-state runs were conducted), the mean hourly production rate for both the short1 and short2 simulations were lower than the means of the medium and long simulation runs (Tables 43, 44). The hourly production rates for the short length lumber iterations were only sixty percent as high as the medium and long production rates. The short1 and short2 mean hourly production rates were not significantly different from one another.

In a rip-first system short length lumber maintains its identity throughout most of the processing steps. In a crosscut-first system the lumber length distinction is lost early when the crosscut saws cut the lumber in shorter parts. Any rip-first rough mill operation in which pieces move in a linear fashion and gaps between the pieces exist, will demonstrate lower throughput rates for shorter lumber. In the rip-first model the planer and rip saw rates, and to a lesser extent the moulder rates (a push-through moulder is modeled) are affected by lumber length. In addition, any operation for which a loading and setup time is required for each piece (e.g. the chop saws and rip saw laser scan station) will have lower volume-based throughput rates when short lumber is being processed.

A rip-first rough mill model which did not include an in-line planer and moulder would be likely to show less disparity between the short and medium length lumber production figures. For a rip-first mill having a rip saw which contains no moveable saws the setup time at the rip saw should be lower per piece. This model would also show less disparity between the short and medium length lumber production figures.

Table 43. Rip-first rough mill simulation results - average values for 10 steady-state simulations.

SIMULATION OUTPUT VARIABLE	SHORT 1 [a]	SHORT 2 [b]	MEDIUM	LONG
Time in System (secs)	262	261	539	916
Unstacker Reload Utilization	15.0%	12.9%	8.4%	5.9%
Forklift Utilization	16.1%	14.2%	8.7%	6.3%
Input Vol (bf/hr)	3023	2995	5142	4894
Production Vol (bf/hr)	1648	1677	2802	2668
Part Value 1 ($/hr)	3153	3214	5398	5147
Part Value 2 ($/hr)	2999	3114	5347	5105
Part Value 3 ($/hr)	2835	3083	5509	5281
Rip Saw Utilization	84.1%	85.1%	97.2%	90.5%
Rip Queue Entities	13	13	28	31
Planer Outfeed Entities	7	7	13	15
Fixed Width Strip Percent	74.9%	74.8%	77.5%	79.9%
R/W Chop Saw Utilization	55.7%	56.9%	46.2%	41.9%
F/W Chop Saw Utilization	68.7%	69.5%	83.7%	86.3%
Moulder Queue Entities	5	5	38	42
Fixed Chop Line Entities	35	37	37	103

a- Short1 simulation runs were based on the cutting length distribution from the 4 through 7 foot long lumber which was obtained in the mill study.

b- Short2 simulation runs used a cutting length distribution for short length lumber similar to the distribution for the 8 through 13 foot long lumber which was obtained in the mill study.

Table 44. Rip-first rough mill steady-state simulation results - confidence intervals and multiple comparison groupings for several variables.

RIP-FIRST STEADY-STATE SIMULATION RESULTS			
Simulation Output Variable - Simulation Run		**Mean ± 95% CI**	**Grouping** [a]
Output Volume (bf/hr) -			
Low	**Short1**	1647.5 ± 66.8	A
	Short2	1677.0 ± 62.7	A
	Long	2667.5 ± 46.8	B
High	**Medium**	2802.4 ± 32.5	C
Part Value 1 ($/hr) -			
Low	**Short1**	3153.2 ± 127.4	A
	Short2	3213.7 ± 120.8	A
	Long	5146.9 ± 84.8	B
High	**Medium**	5398.1 ± 58.3	C
Part Value 2 ($/hr) -			
Low	**Short1**	2999.4 ± 122.6	A
	Short2	3113.7 ± 119.5	A
	Long	5105.3 ± 89.5	B
High	**Medium**	5347.4 ± 60.3	C
Part Value 3 ($/hr) -			
Low	**Short1**	2835.4 ± 118.6	A
	Short2	3082.6 ± 122.4	B
	Long	5280.5 ± 114.2	C
High	**Medium**	5509.2 ± 96.4	D

a- Groupings from Tukey multiple comparison tests using a family error rate of .05.

** Table continued on next page.

Table 44. (continued from previous page).

RIP-FIRST STEADY-STATE SIMULATION RESULTS			
Simulation Output Variable - Simulation Run		**Mean ± 95% CI**	**Grouping [a]**
Random Chop Utilization(%)-			
Low	**Long**	37.3 ± 1.9	**A**
	Medium	46.2 ± 1.8	**B**
	Short1	55.7 ± 2.1	**C**
High	**Short2**	56.9 ± 2.8	**C**
Moulder Queue (# entities) -			
Low	**Short1**	4.9 ± 0.2	**A**
	Short2	5.0 ± 0.1	**A**
	Medium	38.6 ± 1.0	**B**
High	**Long**	42.4 ± 0.6	**C**
Fixed Chop Saw Utiliz. (%) -			
Low	**Short1**	68.7 ± 2.6	**A**
	Short2	69.5 ± 2.2	**A**
	Medium	83.7 ± 0.7	**B**
High	**Long**	86.3 ± 0.9	**B**

a- Groupings from Tukey multiple comparison tests using a family error rate of .05.

The mean part values calculated using the Value 1 and Value 2 relationships were not significantly different between the two short lumber versions of the rip-first model. The mean values for both of these short lumber model iterations were lower than the mean hourly part values recorded for the medium and long length lumber simulations (Table 44). Multiple comparison test results indicate that a significant difference exists between each length group for the Value 3 relationship (in which part length is most highly valued).

The mean values of other simulation output variables are listed in Table 43. Of particular note are the mean values for fixed-width chop saw utilization (the fixed-width strip line processes approximately 80 percent of the strip volume). The short1 and short2 utilization rates average approximately 69 percent versus the medium model's average rate of 83.7 percent. In contrast, the random width chop saw utilization rates are highest for the short2 model (56.9 percent) and next highest for the short1 model (Tables 43, 44). A look at the moulder queue length data helps to explain these seemingly contrasting results. The moulder queue length is quite low for the short lumber simulation runs but significantly higher for the medium and long length lumber models (Tables 43, 44). When the moulder queue gets above 50 entities the rip saws shut down for at least 90 seconds. Since strips never back up at the moulder in the short length lumber models the rip saws never have to pause. This means the supply of strips to the random width chop saw line can continue uninterrupted.

A comparison of the machine utilization rates listed in Table 43 for the two short iterations of the rip-first model indicates that a small change in the chop saw distributions has essentially no effect on the production flow of the system. The fact that the difference in utilization rates is relatively unaffected by the change in cutting length distribution should mean that the utilization rates would also be relatively unaffected by changes in the cutting bill. The rip-first steady state model seems to be relatively robust in its prediction of short lumber throughput rates.

Crosscut-first Model Economic Analysis

All of the economic analyses performed on the crosscut-first model were based on the start-up versions of the model rather than the steady-state versions. An example of the array of before-tax cash flows accounted for in this analysis is presented in Table 45. This particular set of cash flows is for the alternative in which no conversion costs are required for the adoption of a short length lumber processing program. The major variable in each of these analyses is the number of hours that would be required to produce the particular volume of cuttings (325 mbf or 812.5 mbf). The major cost items are material and overhead costs (based on a 30 percent overhead rate for medium length lumber processing).

The sum of the revenues minus the sum of the costs minus any additional costs associated with equipment modifications minus any depreciation deduction associated with adapting the system to handle short lumber is equal to the taxable income in this incremental alternative analysis. Present net worths based on the after-tax cash flows (five year planning horizon; minimum attractive rate of return = 12 percent) for the "value relationship 1", "value relationship 2", and "value relationship 3" alternatives are given in Tables 46, 47, and 48, respectively.

Table 45. Crosscut-first before tax incremental cash flows for two short length cutting bill production output levels - all parts valued equally per board foot; by lumber length class.

M B F	Lumber Length Group	Part Revenue ($)	Chip Revenue ($)	Hours To Produce	Direct Labor Cost ($)	Overhead Cost ($)	Direct Material Cost ($)
3	Short1 [a]	650,000	1390	190.7	21,740	156,374	339,426
2	Short2 [a]	650,000	1549	207.4	23,644	170,068	348,525
5	Medium	650,000	1390	190.7	25,172	156,374	339,426
	Long	650,000	1390	190.7	25,172	156,374	339,426
8	Short1	1,625,000	3475	476.8	54,355	390,976	848,564
1	Short2	1,625,000	3873	518.5	59,109	425,170	871,314
2	Medium	1,625,000	3475	476.8	62,938	390,976	848,564
	Long	1,625,000	3475	476.8	62,938	390,976	848,564

a- The "Short1" and "Short2" groups represent two different short length lumber cut-up scenarios: the "Short1" analysis incorporates the cutting length distribution measured in the mill study while "Short2" uses a cutting length distribution similar to that obtained from the longer length boards and has a 2.0% lower total yield.

Table 46. Results of economic analysis for crosscut-first rough mill model with all rough parts valued equally per board foot; present worth of after-tax cash flows and breakeven lumber price levels.

CROSSCUT-FIRST PRESENT WORTH OF AFTER TAX CASH FLOWS AND BREAKEVEN LUMBER PRICE LEVELS *PNW ($) / **BE Price per mbf ($)***				
MBF	**LUMBER LENGTH GROUP**	**CONVERSION COST LEVEL[a]** NONE	MODERATE	EXTREME
325	SHORT1	318,452[b]	309,612	234,644 / **725**
	SHORT2	260,072 / **752**[c]	251,232 / **743**	176,263 / **671**
	MEDIUM	310,286		
	LONG	310,286		
812	SHORT1	794,208	785,368	710,400 / **776**
	SHORT2	648,894 / **752**	640,055 / **749**	565,085 / **720**
	MEDIUM	773,795		
	LONG	773,795		

a- Conversion cost levels to modify rough mill system to enable processing of short length lumber are: NONE - no modification costs, MODERATE - $15,000 to modify system, EXTREME - $30,000 to modify system plus $45,000 to purchase a small forklift.

b- Breakeven prices were only calculated for short length lumber in cases where the short length lumber alternative's present net worth was less than the medium length lumber's.

c- Breakeven dry lumber prices were calculated using the medium length lumber present worth value as the basis for comparison.

Table 47. Results of economic analysis for crosscut-first rough mill model using value relationship 2: present worth of after-tax cash flow and breakeven lumber price levels.

CROSSCUT-FIRST PRESENT WORTH OF AFTER TAX CASH FLOWS AND BREAKEVEN LUMBER PRICE LEVELS *PNW ($) / BE Price per mbf ($)*				
MBF	**LUMBER LENGTH GROUP**	**CONVERSION COST LEVEL[a]** NONE	MODERATE	EXTREME
325	SHORT1	649,886[b]	641,047	566,078
	SHORT2	489,502 / **752**[c]	480,662 / **744**	405,694 / **672**
	MEDIUM	538,753		
	LONG	538,753		
812	SHORT1	1,624,716	1,615,876	1,540,908
	SHORT2	1,223,380 / **752**	1,214,540 / **749**	1,139,572 / **720**
	MEDIUM	1,346,883		
	LONG	1,346,883		

a- Conversion cost levels to modify rough mill system to enable processing of short length lumber are: NONE - no modification costs, MODERATE - $15,000 to modify system, EXTREME - $30,000 to modify system plus $45,000 to purchase a small forklift.

b- Breakeven prices were only calculated for short length lumber in cases where the short length lumber alternative's present net worth was less than the medium length lumber's.

c- Breakeven dry lumber prices were calculated using the medium length lumber present worth value as the basis for comparison.

Table 48. Results of economic analysis for crosscut-first rough mill model using value relationship 3: present worth of after-tax cash flows and breakeven lumber price levels.

CROSSCUT-FIRST PRESENT WORTH OF AFTER TAX CASH FLOWS AND BREAKEVEN LUMBER PRICE LEVELS *PNW ($) / BE Price per mbf ($)*				
MBF	**LUMBER LENGTH GROUP**	**CONVERSION COST LEVEL**[a] NONE	MODERATE	EXTREME
	SHORT1	1,292,290[b]	1,283,451	1,208,482
3	SHORT2	940,209 / **753**[c]	931,369 / **745**	856,401 / **672**
2	MEDIUM	988,808		
5	LONG	988,808		
	SHORT1	3,230,726	3,221,886	3,146,602
8	SHORT2	2,350,523 / **753**	2,341,683 / **750**	2,266,715 / **721**
1	MEDIUM	2,472,021		
2	LONG	2,472,021		

a- Conversion cost levels to modify rough mill system to enable processing of short length lumber are: NONE - no modification costs, MODERATE - $15,000 to modify system, EXTREME - $30,000 to modify system plus $45,000 to purchase a small forklift.

b- Breakeven prices were only calculated for short length lumber in cases where the short length lumber alternative's present net worth was less than the medium length lumber's.

c- Breakeven dry lumber prices were calculated using the medium length lumber present worth value as the basis for comparison.

The highest present net worth value for the "value 1 relationship" (all parts valued equally per bf) set of alternatives is for the short1 production model with no conversion costs (Table 46). The lowest present net worth value for this set of alternatives is for the short2 alternative with the extreme mill modification cost assumption applied.

The breakeven short length lumber price is indicated in bold print in this series of tables. The breakeven short lumber price, as expected, decreases with increasing system conversion costs. The breakeven price is higher for the higher volume short lumber production alternatives than for the lower volume alternatives. The additional revenue generated by producing a higher volume of parts from short lumber helps offset the costs incurred to convert the system; the dollars spent in conversion are being more fully utilized. When no conversion costs are incurred the breakeven short lumber price is the same for the low volume and high volume production alternatives.

The short length, dry, red oak lumber breakeven prices for the "value 1 relationship" range from $671 per mbf to $800 per mbf. The dry red oak lumber price applied in the present worth calculations was $800 per mbf. The difference between the breakeven price and $800 per mbf represents the degree of price discount which would make short lumber utilization an equally attractive alternative.

The highest present net worth value for the "value 2 relationship" (longer parts valued more highly per bf than shorter parts) alternatives is for the short1 model with no conversion costs (Table 47). The lowest present net worth value for this set of alternatives is for the short2 alternative with the extreme modification cost assumption applied.

The breakeven short length lumber prices demonstrate the same trends as noted for the "value 1 relationship". The short length, dry, red oak lumber breakeven prices for the "value 2 relationship" range from $674 per mbf to $800 per mbf. The minimum breakeven price for this part valuation system and cutting bill is essentially the same as the minimum calculated for the "value 1 relationship" (all parts of equal value per bf).

The highest present net worth value for the "value 3 relationship" (longer parts valued much more highly per bf than shorter parts) set of alternatives is, once again, for the short1 model with no conversion costs (Table 48). The short2 alternative with the extreme modification cost assumption has the lowest present net worth of after-tax cash flows.

The breakeven price range for the "value 3 relationship" extends from $672 per mbf to $800 per mbf. The difference between the minimum breakeven price for this value system and the minimum for the system in which all parts are valued equally per bf is only $1 per mbf.

For a crosscut-first mill that switches cutting bills less frequently the steady-state model might be more appropriate. Calculations made on the part values contained in Table 40 indicate that the steady-state values for the two short lumber models are equal to approximately 110 percent of the start-up values. For the medium and long length models the steady-state part values are equal to approximately 113 percent of the start-up values. Since the medium length lumber's production output is relatively more valuable for the steady-state model than the start-up state model, the breakeven short length lumber prices for a steady-state operation should be somewhat lower than those shown in Tables 46, 47, and 48.

Rip-first Model Economic Analysis

An example of the array of before-tax cash flows accounted for in this analysis is presented in Table 49. The highest present net worth value for the rip-first model's "value 1 relationship" (all parts valued equally per bf) alternatives is for the medium length lumber production model (Table 50). The lowest present net worth value for this set of alternatives is for the short1 alternative with extreme mill modification costs. Higher mill modification costs were used for the "moderate" and "extreme" alternatives in the rip-first model than in the crosscut-first model (Table 39). In a rip-first operation in which the length of the original board is maintained throughout most of the processing steps, a system ill-designed to handle shorter boards and strips will have many material handling equipment modifications to make.

In this analysis, the short1 and short2 cash flows are based on the mean values for volume per hour and value per hour calculated from the simulation output. The short1 and short2 data was not pooled for those cases where the multiple comparison test failed to detect a difference between the data sets (bf per hour; Value 1-based $ per hour, Value 2-based $ per hour). By carrying out the calculations for each iteration, separately the breakeven price range is wider and thus represents a slightly more conservative estimate of the value of short length lumber.

The present worth figures calculated for the rip-first model are all negative. There are several plausible explanations for the rip-first model's negative cash flow profile. The cash flow profile is highly sensitive to the overhead rate percentage applied in the analysis. The breakeven overhead rate for the medium length lumber model's cash flows

Table 49. Rip-first before-tax incremental cash flows for two short length cutting bill production output levels - all parts valued equally per board foot; by lumber length class.

MBF	Lumber Length Group	Part Revenue ($)	Chip Revenue ($)	Hours To Produce	Direct Labor Cost ($)	Overhead Cost ($)	Direct Material Cost ($)
1	Short1 [a]	2,802,000	23,393	850.1	179,371	1,584,586	2,056,514
4	Short2 [a]	2,802,000	22,016	835.4	176,269	1,557,186	2,001,429
0	Medium	2,802,000	23,393	500	118,500	932,000	2,056,514
1	Long	2,802,000	23,393	525.1	124,449	978,786	2,056,514
2	Short1	5,604,000	46,786	1700.2	358,742	3,169,172	4,113,028
8	Short2	5,604,000	44,032	1670.8	352,538	3,114,372	4,002,858
0	Medium	5,604,000	46,786	1000	237,000	1,864,000	4,113,028
2	Long	5,604,000	46,786	1050.2	248,898	1,957,572	4,113,028

a- The "Short1" and "Short2" groups represent two different short length lumber cut-up scenarios: the "Short1" analysis incorporates the cutting length distribution measured in the mill study while "Short2" uses a cutting length distribution similar to that obtained from the longer length boards and has a 1.5% higher total yield.

Table 50. Results of economic analysis for rip-first rough mill model with all rough parts valued equally per board foot; present worth of after-tax cash flows and breakeven lumber price levels.

RIP-FIRST PRESENT WORTH OF AFTER-TAX CASH FLOWS AND BREAKEVEN LUMBER PRICE LEVELS

PNW ($) / BE Price per mbf ($)

MBF	LUMBER LENGTH GROUP	CONVERSION COST LEVEL[a] NONE	MODERATE	EXTREME
1401	SHORT1	-2,367,456/**522**[b]	-2,379,311 / **520**	-2,463,219 / **507**
	SHORT2	-2,167,108/**548**[c]	-2,178,958 / **547**	-2,262,858 / **532**
	MEDIUM	-670,024		
	LONG	-795,489		
2802	SHORT1	-4,734,916 / **522**	-4,746,840 / **522**	-4,830,846 / **515**
	SHORT2	-4,334,217 / **548**	-4,346,130 / **548**	-4,430,119 / **540**
	MEDIUM	-1,340,048		
	LONG	-1,590,979		

a- Conversion cost levels to modify rough mill system to enable processing of short length lumber are: NONE - no modification costs, MODERATE - $15,000 to modify system, EXTREME - $30,000 to modify system plus $45,000 to purchase a small forklift.

b- Breakeven prices were only calculated for short length lumber in cases where the short length lumber alternative's present net worth was less than the medium length lumber's.

c- Breakeven dry lumber prices were calculated using the medium length lumber present worth value as the basis for comparison.

is approximately 23 percent. The cash flow profile also is affected by the part value assignments. The estimate of the relative value of fixed width parts versus random width parts (Table 35) was based on the yield which is sacrificed at the rip saws in order to obtain a fixed width strip rather than a random width strip. If the fixed width part value is underestimated the effect on the cash flow profiles would be quite large. Another point is that the rip-first model had a significantly lower rough part yield than did the crosscut-first model. Yield is perhaps the major variable affecting profitability.

The operation of an "unprofitable" rough mill could be very profitable for a furniture mill. If the rough mill provides a timely supply of high quality parts to the rest of the operation which would not otherwise be assured, it may be very easy to economically justify the operation of an "unprofitable", non-profit center rough mill. Since it is the magnitude of the difference between the present net worth figures that affects the breakeven price calculation, the same analysis procedure that was used on the crosscut-first model's results was readily applied to the rip-first analysis.

The highest present net worth for the rip-first model's "value 1 relationship" (all parts valued equally per bf) alternatives is for the medium length lumber production model (Table 51). The lowest present net worth value for this set of alternatives is for the short1 alternative with extreme mill modification costs. Higher mill modification costs were used for the "moderate" and "extreme" alternatives in the rip-first model than in the crosscut-first model (Table 42). In a rip-first operation in which the length of the original board is maintained throughout most of the processing steps, a system ill-designed to handle shorter boards and strips will have many material handling equipment modifications to make.

Table 51. Results of economic analysis for rip-first rough mill model using value relationship 2: present worth of after-tax cash flows and breakeven lumber price levels.

RIP-FIRST PRESENT WORTH OF AFTER-TAX CASH FLOWS AND BREAKEVEN LUMBER PRICE LEVELS *PNW ($) / BE Price per mbf ($)*				
MBF	**LUMBER LENGTH GROUP**	**CONVERSION COST LEVEL**[a]		
		NONE	MODERATE	EXTREME
1401	SHORT1	-2,968,315/**474**[b]	-2,980,188 / **472**	-3,064,121 / **459**
	SHORT2	-2,644,283/**520**[c]	-2,656,147 / **517**	-2,740,066 / **504**
	MEDIUM	-975,747		
	LONG	-1,084,234		
2802	SHORT1	-5,936,633 / **474**	-5,948,593 / **473**	-6,032,649 / **466**
	SHORT2	-5,288,567 / **520**	-5,300,507 / **519**	-5,384,532 / **512**
	MEDIUM	-1,951,495		
	LONG	-2,168,467		

a- Conversion cost levels to modify rough mill system to enable processing of short length lumber are: NONE - no modification costs, MODERATE - $15,000 to modify system, EXTREME - $30,000 to modify system plus $45,000 to purchase a small forklift.

b- Breakeven prices were only calculated for short length lumber in cases where the short length lumber alternative's present net worth was less than the medium length lumber's.

c- Breakeven dry lumber prices were calculated using the medium length lumber present worth value as the basis for comparison.

One cost which is not assessed in the economic analyses, is the opportunity cost associated with producing a given volume of cuttings from one lumber length versus another. If a particular mill is operating at or very near capacity the opportunity cost associated with the time spent filling a particular cutting bill or set of cutting bills from a size or grade of lumber that produces at a relatively low volume per hour rate, may be quite high.

The medium length lumber model's present net worth is the yardstick against which the less valuable short length lumber processing alternatives are compared. The decision to use the medium length model's results rather than the long length model's in these comparisons is based on the fact that a much higher percentage of 8 through 13 foot long lumber is presently being run at most Appalachian area furniture rough mills than 14 through 16 foot long lumber. Another consideration is the fact that, given a limited long length lumber resource, the opportunity cost associated with cutting long lumber into medium and short length parts would be quite high. Thus, the medium length lumber model was considered the status quo model.

The breakeven prices for short length, dry, red oak lumber, indicated in bold print (Table 50), exhibit the same trends noted for the crosscut-first model results: the breakeven price decreases with increasing system conversion costs and increases with increases in the production volume cut from short length lumber. The breakeven prices for the rip-first, "value 1 relationship" range from $507 per mbf to $548 per mbf.

The highest present worth figure for both the "value 2 relationship" and "value 3 relationship" is for the medium length lumber production model alternative (Tables 51, 52). The lowest present worth value for both of these sets of alternatives is for the short1

Table 52. Results of economic analysis for rip-first rough mill model using value relationship 3: present worth of after-tax cash flows and breakeven lumber price levels.

RIP-FIRST PRESENT WORTH OF AFTER-TAX CASH FLOWS AND BREAKEVEN LUMBER PRICE LEVELS

PNW ($) / BE Price per mbf ($)

MBF	LUMBER LENGTH GROUP	CONVERSION COST LEVEL[a] NONE	MODERATE	EXTREME
1401	SHORT1	-3,300,011 /**388**[b]	-3,311,893 / **387**	-3,395,840 / **373**
	SHORT2	-2,705,900 /**477**[c]	-2,717,765 / **475**	-2,801,687 / **461**
	MEDIUM	-783,035		
	LONG	-864,359		
2802	SHORT1	-6,600,021 / **388**	-6,612,000 / **388**	-6,696,083 / **381**
	SHORT2	-5,411,800 / **477**	-5,423,744 / **476**	-5,507,778 / **469**
	MEDIUM	-1,566,069		
	LONG	-1,728,718		

a- Conversion cost levels to modify rough mill system to enable processing of short length lumber are: NONE - no modification costs, MODERATE - $15,000 to modify system, EXTREME - $30,000 to modify system plus $45,000 to purchase a small forklift.

b- Breakeven prices were only calculated for short length lumber in cases where the short length lumber alternative's present net worth was less than the medium length lumber's.

c- Breakeven dry lumber prices were calculated using the medium length lumber present worth value as the basis for comparison.

iteration with extreme modification costs.

The "value 2 relationship's" short lumber breakeven price range goes from $459 to $520 per mbf. The breakeven prices for the "value 3 relationship" range from $373 to $477 per mbf. The difference between the minimum breakeven price for the "value 3 relationship" and the "value 1 relationship" for this model is much larger than was the maximum difference for the crosscut-first model ($134 versus $1). This can be attributed to the fact that for the crosscut-first model, the short1, short2, medium, and long part values all vary consistently with changes in the part value relationship but this is not the case for the rip-first model. The value per hour figures for the different length-based iterations in the rip-first model demonstrate the following trends:

1. $Short1_{value3} < Short1_{value2} < Short1_{value1}$
2. $Short2_{value3} < Short2_{value2} < Short2_{value1}$
3. $Medium_{value2} < Medium_{value1} < Medium_{value3}$
4. $Long_{value2} < Long_{value1} < Long_{value3}$

Since the "value 3 relationship" produces the highest hourly part value for the medium length lumber model and the lowest for the short length lumber models, the breakeven price which balances these cash flows is considerably lower than for the other value systems.

Overhead Rate Sensitivity Analysis

The influence of overhead rate on the breakeven short length lumber price was investigated for both the crosscut-first and rip-first models. Only the "no conversion cost, low production volume" alternatives were included in the sensitivity analysis. Since, for the crosscut-first, short1 model iteration the present worth figures compared quite favorably with the medium model's present worth figures, this iteration was omitted from the sensitivity analysis.

For the rip-first model, changing the overhead rate from 30 percent of costs to 20 percent of costs (based on the medium length lumber cost schedule) resulted in an increase in the breakeven short length lumber price of $106 per mbf for the short1 production scenario and $105 per mbf for the short2 production scenario (Table 53). For the crosscut-first model, the effect of overhead rate on the breakeven price for dry, short length, red oak lumber was much less substantial: only a $12 per mbf increase was realized. This difference can be attributed to the difference in yields for the two models. Since the cutting yield for the rip-first model is quite a bit lower than the yield for the crosscut-first model, the impact of a reduction in absolute costs on the profitability per bf, is much greater for the rip-first model.

Hypothetical Rip-first Production Scenario

Utilization and productivity rates recorded for the short1 simulation runs were used to estimate the productivity and cash flows which might be realized if a reduced labor crew, assigned to an additional production shift, was engaged in producing rough parts from short length lumber. If the overhead costs for the additional shift were 20 percent or lower, this scenario might present a feasible production alternative (Table 54).

Table 53. Sensitivity analysis results for the influence of overhead rate on the breakeven short length lumber price using the rip-first and crosscut-first, low volume, no mill modification cost alternatives.

MODEL	SHORT LUMBER ITERATION [a]	OVERHEAD TREATMENT	BREAKEVEN LUMBER PRICE
RIP-FIRST			$ / mbf dry lumber
	SHORT1	30 percent	522
	SHORT1	25 percent	579
	SHORT1	23 percent	599
	SHORT1	20 percent	628
	SHORT2	30 percent	548
	SHORT2	25 percent	604
	SHORT2	23 percent	624
	SHORT2	20 percent	653
XCUT-FIRST			
	SHORT2	30 percent	756
	SHORT2	28 percent	759
	SHORT2	25 percent	763
	SHORT2	20 percent	768

a- The "SHORT1" and "SHORT2" groups represent two different short length lumber cut-up scenarios: the "SHORT1" analysis incorporates the cutting length distribution measured in the mill study while "SHORT2" uses a cutting length distribution similar to that obtained from the longer length boards.

Table 54. Estimate of feasibility of producing rough parts from short lumber by adding an additional production shift to the rip-first model.

GROSS ESTIMATE OF FEASIBILITY OF PROCESSING SHORT LENGTH LUMBER INTO FURNITURE PARTS BY ADDING AN ADDITIONAL PRODUCTION SHIFT
ASSUMPTIONS: 1 rip saw with 100 percent utilization - requires 2 random width chop saws and 4 fixed width chop saws; other shift(s) operating at capacity; 1,401 bf of short parts demanded.
LABOR REQUIREMENTS: 1 unstacker/planer operator, 1 rip saw operator, 4 fixed width chop saw operators, 2 random width chop saw operators, 2 waste handlers, 3 fixed width part sorters, 3 random width part sorters = 18 operators .... $158/hour (direct labor + fringe).
PRODUCTION - VALUE PER HOUR: 979 bf per hour ... parts valued equally per board foot - $1873 per hour.
Breakeven Short Length Lumber Price if extra shift's overhead rate is 10 percent: **$1022/mbf**
Breakeven Short Length Lumber Price if extra shift's overhead rate is 15 percent: **$964/mbf**
Breakeven Short Length Lumber Price if extra shift's overhead rate is 20 percent: **$899/mbf**

It should be expected that the incremental overhead rates incurred in the operation of an additional production shift would make up significantly less than 30 percent of total costs. Many overhead costs such as taxes, rentals, travel, training, clerical wages, fire protection, and depreciation should vary only minimally, if at all, with the start-up of an additional production shift. Of course, the feasibility of starting an extra shift is largely dependent on whether present production capacity can meet present and future rough part demand.

Summary

Handling rates and costs associated with the use of short length lumber (less than 8 feet long) in furniture and cabinet industry rough mills have been assumed to be prohibitive. Discrete-event systems simulation models of both a crosscut-first and rip-first rough mill were built to measure the effect of lumber length on equipment utilization and the volume and value of the rough parts produced. The output from these models was entered into a series of rough part production alternatives which incorporated variable production, part value, and cost assumptions. The net present worth of after-tax cash flows and the breakeven short length lumber price of these alternatives were calculated and compared.

For the crosscut-first mill model the volume and value of parts produced from short length lumber compared favorably with the volume and value of parts produced from the medium (8-13 feet long) and long (14-16 feet long) length lumber. A "pessimistic case" short lumber scenario was also simulated in which the distribution of cutting lengths was varied. The short lumber volume and value yields for this model version were lower than the medium and long lumber yields.

For 14 of the 16 crosscut-first production alternatives the present worth of the after-tax cash flows was higher for the short length lumber ("most-likely case") than for the medium and long length lumber. The net present values (NPV's) of the "pessimistic case" short lumber alternatives were lower than the NPV's of the medium and long lumber. The breakeven short lumber price for these alternatives ranged between $671 and $753 per thousand board feet (mbf).

The results obtained in the crosscut-first analysis should be broadly applicable since the mill model represents a reasonably representative crosscut-first operation. Rip-first rough mills tend to be much harder to characterize than crosscut-first. The rip-first mill modeled has more machining operations within the rough mill system than do many rip-first operations. The breakeven prices calculated for the rip-first model are lower than would be expected for many other rip-first mill configurations. For both the crosscut-first and rip-first models, the breakeven short length lumber prices for the best case and worst case iterations are listed in Table 55.

The production of rough furniture parts from short length lumber in a crosscut-first mill is economically feasible with careful matching of cutting bills and short length lumber input schedules. If mills can obtain the short lumber at a $100 to $150 per mbf price discount they can justify spending several thousand dollars on equipment modifications to improve the flow of the short lumber.

For the rip-first mill model the volume and value of parts produced from short lumber was equal to approximately 60 percent of the production from the medium and

Table 55. Comparison of breakeven short length lumber prices for the best and worst case short length lumber cut-up scenarios.

	ALTERNATIVE	**Breakeven Short Lumber Price**
		$/mbf dry lumber
CROSSCUT-FIRST BEST CASE	No conversion costs, SHORT1 yields.	800 or Current Market Price
CROSSCUT-FIRST WORST CASE	Extreme conversion costs, SHORT2 yields, low mbf annual output from short lumber.	671
RIP-FIRST BEST CASE	No conversion costs, 20% overhead rate, SHORT2 yields.	653
RIP-FIRST WORST CASE	Extreme conversion costs, 30% overhead rate, SHORT1 yields, low mbf annual output from short lumber.	373

long length lumber. The unstacker and planer were unable to provide sufficient material to the rip saws which in turn were unable to process the short lumber fast enough to keep the chop saws busy. The breakeven short length lumber prices calculated for this model ranged between $373 and $653 per mbf. The effect of overhead rate on the breakeven short length lumber price is quite substantial for the rip-first model. Application of an overhead rate equivalent to 30 percent of total costs results in a breakeven dry short lumber price of $522 or $548 per mbf (depending on yield scenario). At an overhead rate of 20 percent the breakeven short lumber price rises to $628 or $653 per mbf. The use of short length lumber in a rip-first rough mill operation would only be economically feasible if:

1- a means could be established to keep the rip saws and chop saws more fully utilized, and/or,

2- a partial production crew operating on an additional shift with a lower overhead rate per hour was employed to supplement production, and/or,

3- sharply discounted short length lumber prices per mbf could be negotiated.

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Dissertation Summary

The primary purpose of this study was to evaluate short length lumber (less than 8 feet long) utilization opportunities within the furniture and cabinet industries. If such a high-value market for short length lumber could be developed, the profit potential for many sawmills would increase and the forest resource management options in many areas would expand. Short length lumber furniture part yield and processing cost information were evaluated then combined in order to predict the potential value of short length lumber to the furniture and cabinet industries.

Short Lumber Characteristics and Sawmill Profit Potential

In the first part of the study, a data bank of mapped red oak lumber was used to search for differences in lumber characteristics between lumber length groups. The same data was used to evaluate opportunities for improving the value of a piece of lumber by trimming a lower grade, longer length piece to obtain a shorter, higher grade board. The defect data indicated that wane makes up a slightly higher percentage of the total defect area for short boards than for long boards but the degree of crook deviation for short boards is significantly less than for long boards. The analysis of value improvement opportunities indicated that fifteen percent of the 8 and 9 foot long, 1 Common, red oak lumber and 49 percent of the 8 and 9 foot long 2A Common lumber surveyed could be trimmed to a higher grade, higher value short board. The average value increase for short boards produced by end-trimming lower grade long length lumber was 38 cents for boards upgraded from 1 Common to Selects, and 45 cents for boards upgraded from 2A

Common to 1 Common. The profit potential for sawmills producing short lumber is contingent upon secondary processors becoming motivated to use short length lumber.

Short Lumber Yield

The effect of lumber length on random width dimension yields was examined using the CORY lumber cut-up program and the same red oak lumber data base. For 10 of the 18 cutting bill combinations processed, the regression between total yield and lumber length was significant. In the significant crosscut-first relationships, total yield decreased with increasing lumber length. In the significant rip-first relationships, total yield decreased as lumber length increased. The variable which showed the strongest and most consistently significant relationship to lumber length was the average volume of parts produced per furniture rough mill sawing operation; the regression of board feet per sawing operation was significantly and negatively related to lumber length in 14 of the 18 cutting bill combinations tested. Regression results for both the rip-first and crosscut-first cut-up models indicated that as crook decreases, total cutting yield, average cutting length, part volume per sawing operation, and part value tend to increase.

Short and longer length lumber yields were also compared in mill studies. The mill studies were conducted at a crosscut-first furniture rough mill and at a rip-first cabinet rough mill. Total yield, the yield of the longest length cutting on the cutting bill, the percentage of total yield made up of the three longest length cuttings, average cutting length, and crosscut and rip saw rates were investigated. The only significant regression relationships detected were: 1 - for the crosscut-first, 2A Common analysis the percentage of total yield made up of the three longest length cuttings was inversely related to lumber length, and 2 - for the rip-first, 1 Common and 2A Common analyses the ripsaw volume throughput rate improved with increasing lumber length.

When all of the evidence from the simulated cut-up experiments and mill studies is consolidated, the following tendencies are noted: 1 - crosscut-first yields tend to increase slightly with increasing lumber length, and 2 - rip-first yields tend to decrease slightly with increasing lumber length. However, studies showed that lumber length-based differences in yield are inconsistent between cutting bills.

The Feasibility of Short Lumber Utilization

In order to obtain credible estimates of the value of short length lumber to the furniture and cabinet industries dimension part yield estimates and processing cost estimates were combined. The combination was examined using the systems simulation modeling approach. The short lumber yield results obtained from both the cut-up simulation experiments and mill study experiment along with processing rate data comprised the major inputs to two systems simulation models. The rough mills modeled were the same two mills used in the mill studies.

The crosscut-first simulation study indicated that the volume and value of parts cut from short length lumber in a crosscut-first rough mill compares favorably with the volume and value recovery obtained from longer length lumber. In the "worst case" crosscut-first production alternative the breakeven short length lumber price was only $129 less per thousand board feet than the going market price for dry, 1 Common, red oak lumber. This "worst case" alternative incorporated a suboptimum cutting length distribution which resulted in a 2 percent lower cutting yield. This 2 percent yield difference is similar to the maximum yield variation between short and longer length lumber yields obtained in the computer cut-up studies.

The breakeven short lumber purchase price calculated using this pessimistic yield figure is 84 percent of market price. It is more than 1.6 times higher than the estimated breakeven lumber sales price for short lumber generated from material that would otherwise be chipped (Section 1, Table 6). It is 1.1 times higher than the breakeven price for short lumber generated by upgrading longer boards in the sawmill (section 2; $200 surcharge for dry lumber included).

For the rip-first model the volume and value of parts produced from short lumber was only 60 percent that of the longer length lumber. The breakeven short length lumber prices calculated for this model ranged between $427 and $147 per mbf less than the going market price for long length lumber.

The rip-first mill model's short lumber throughput rates were so low relative to the longer lumber throughput rates that the small scale yield advantage which might be achieved in processing short lumber does not compensate for the difference. The "best case" rip-first alternative incorporates a short lumber yield that is a 1.5 percent higher than the longer length yields. The breakeven short length dry lumber purchase price for this most optimistic scenario is still somewhat lower than the pessimistic crosscut-first scenario's breakeven price. Additional rip-first mill models should be built to determine if other rip-first mill configurations are more suited for running short length lumber.

Since the crosscut-first mill modeled is a very representative crosscut-first rough mill, the simulation and economic analysis results are applicable to a large percentage of crosscut-first operations. For crosscut-first mills that occasionally process "short" cutting bills, short length lumber should be part of the raw material mix. This is especially true if: 1 - short lumber price discounts of $100 to $150 per thousand board feet can be obtained or, 2 - in processing longer length lumber, stop-and-start flow develops due to rip saw bottlenecks, and 3 - the materials handling system is already well-adapted to handle shorter lumber.

While it is difficult to characterize a given rip-first mill configuration as being "representative", the rip-first model used in this study clearly demonstrates the fact that throughput rates for linear processing operations in which lumber passes through machines one-by-one in a lengthwise orientation, are generally higher for longer length lumber. Thus, a rip-first operation with fewer linear operations (e.g. rip saw only) would be less affected by lumber length than would one with more linear operations (e.g. planer, rip saw, moulder). The changeover costs for a rip-first rough mill to enable handling of short lumber are potentially higher than for a crosscut-first mill. Only under a very limited set of conditions would it be feasible for a rip-first mill such as the one modeled in this study (with 3 linear operations) to utilize short length lumber. Additional rip-first mill models should be built to determine if other rip-first mill configurations are more suited for running short length lumber.

As rough mills expand their lumber input mix to include a higher percentage of 4-7 foot lumber, higher value material (short lumber rather than chips or longer, lower grade lumber) can be produced by hardwood sawmills. Once a stronger market for short length hardwood lumber exists, short log processing systems will become more viable and the timber management options available to the resource manager will increase.

Curriculum Vitae

JANICE K. WIEDENBECK

Business Address:

USDA Forest Service
Southeastern Forest Experiment Station
1650 Ramble Road
Blacksburg, VA 24061
Phone: 703-231-8869

Education:

Ph.D.	**Virginia Polytechnic Institute and State University** Wood Science and Forest Products, May 1992
M.S.	**Virginia Polytechnic Institute and State University** Wood Science and Forest Products, June 1988
B.S	**University of Michigan** Forestry, December 1980

Industrial Experience

Quality Control Supervisor and Dry End Supervisor, Crown Zellerbach, Inc., McComb, MS, June 1984 - March 1986.

Quality Control Supervisor, Crown Zellerbach, Inc., Holden, LA, July 1983 - June, 1984.

Assistant Forester, Crown Zellerbach, Inc., Livingston, LA, February 1981 - July 1983.

Academic Experience

Graduate Research Assistant, Virginia Polytechnic Institute and State University, Blacksburg, VA, September 1986 - March 1992.