IMPACT OF FOREST BIOTECHNOLOGY ON THE ECONOMICS OF CORRUGATED BOX PRODUCTION

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Abstract

The impact of wood quality on pulp and paper manufacture is underemphasized by mills, but provides important potential for improving mill economics, product quality and product differentiation. Increases in pulp yield due to higher specific gravity, decreased lignin content, and reductions in basis weight due to lower cellulose microfibril angle (MFA) represent opportunities for wood quality improvements to positively impact pulp and paper manufacturing. To estimate the economic potential we determined the value to a kraft linerboard mill of changes in tree properties – in particular, decrease in microfibril angle - with a multidimensional cash flow model that includes loblolly pine plantation forestry and pulp and paper mill costs. We have now extended the economic impact of wood quality changes in linerboard to a box plant, using a newly developed cash flow model of a box plant. The box plant model makes a total of 36.5 million medium, large, and jumbo (1:2:1) boxes per year.

There is a significant impact on box plant economics as a result of reducing linerboard basis weight. Sensitivity analysis of the box plant model with reduced linerboard basis weight shows that for each 2 lb decrease, box plant production cost decreases by 1.2%. Based on empirical data obtained with young loblolly pine trees, we predict that when the average MFA is decreased from 30 to 18 degrees the basis weight of 42 lb/msf linerboard can be reduced to 36 lb/msf and still meet the short span STFI requirements. Such a reduction in basis weight would increase annual box plant net income by 9%. The details of our approaches, assumptions, estimated cost savings and potential impacts of biotechnology on box plant profitability are presented.

Introduction

The United States produces the most corrugated boxes in the world. Products in this area are divided between combined board, folding cartons and set-up boxes. In recent years, these products have accounted for slightly more than half of the industry's total paper and paperboard production (1). In 1999, 30.1 percent of the total world corrugated was produced in the United States but overall pulp and paper industry production has declined since the second half of 2000. During 2002 and 2003, the paper and paperboard sector faced the same obstacles as in 2001, including a soft U.S. economy, weak prices, continued downtime and higher manufacturing costs in the developed countries (1).

In recent years there has been significant merger activity attempting to counteract overcapacity to better match supply and demand to help stabilize price fluctuations and thereby improve global competitiveness of linerboard and box makers. Specifically, the market picture for the corrugated container industry has changed in the last five years. As a result of mergers, acquisitions and consolidations, the industry's "Big 5" producers – Smurfit Stone Container Corp., International Paper, Georgia-Pacific, Weyerhaeuser, and Temple-Inland in 2002, had a 72% market share compared with only 45% in 1993 (2). With this larger market share, these companies have reviewed their overall operations, closed some mills, and shut down inefficient machines to bring supply more in line with demand. But as industry removed capacity, demand dropped, exports declined, and imports increased such that overcapacity in the United States still exists (3).

It is clear that paper companies in the United States are at a point where they must find new ways to increase their profitability. The present research focuses on one of the most important branches of this industry: corrugated containers. Since up to 60% of the total cost of corrugated container manufacturing is the raw material, an approach for evaluating the impact of wood and fiber traits on the production costs of this product was developed (Figures 1 and 2) (4). A potential long-term solution to decreasing raw material costs is to apply biotechnological methods to improve trees for pulp and paper production. By using this approach companies can not only cut costs in the production of combined board but also, generate better quality products. For example, if compressive strength were increased (e.g., by decreasing wood microfibril angle), significantly less fiber could be used in the finished box since compressive strength defines the ability of a container to sustain the loads imposed from stacking boxes in warehouses. The cost modeling presented was accomplished with a forest cost model for loblolly pine plantations based on the growth and yield equations developed by the University of Georgia, an integrated kraft pulp and linerboard mill model and a box plant model developed by Jaakko Pöyry Management Consulting (JPC) under contract to the Institute of Paper Science and Technology (IPST).

Approach

Linerboard properties.

The objective of this project is to predict wood and fiber traits that, when altered, provide the lowest production costs while meeting all the structural quality standards required for corrugated board in the market. Three fiber traits were selected for economic analysis of genetic alteration: specific gravity (SG), wood lignin content (WCN) and microfibril angle (MFA) (5,6). Only the microfibril angle results will be reviewed here. Microfibril angle is the orientation angle of the cellulose fibrils in the S2 layer of the fiber cell wall to the long axis of the fiber cell. A base case scenario was defined consisting of linerboard made from loblolly pine wood that on average has a 30 degree MFA, 0.46 specific gravity, and 29% wood lignin content. Overall the linerboard furnish in this analysis was 80% virgin fiber (70:30 softwood:hardwood) and 20% recycle.

In the case of MFA, it is assumed that lower MFA fibers increase the strength properties of the linerboard in such a way that the basis weight (BW) of the linerboard can be reduced while still maintaining (or increasing) the strength properties of the container. This reduction in linerboard BW results in cost reduction in the container because the box plant is now able to produce the same amount of boxes from fewer tons of linerboard purchased from the paper mill, because, the roll supplied by the paper mill will give more area for the same mass of linerboard purchased.

In this analysis, it is important to consider:

1. How linerboard properties are related to the selected wood and fiber traits?
2. How values for compressive strength of linerboard with different basis weights and MFA's can be assigned in order to predict the top-to-bottom compressive strength of a container and, as a result, compare these predicted strengths with the market strength requirements?

For the first issue, the discussion below will describe the relationship between the selected fiber trait and some important properties of the linerboard, as well as the relationship between the combined board components and the stacking strength of a corrugated container. For the second issue, later discussion will provide the approach used to determine the compressive strength of the linerboard as a function of basis weight and its relation to microfibril angle.

How Wood and Fiber Traits Affect Linerboard Properties

It is well known that wood and fiber traits play an important role in the performance characteristics of paper and linerboard. In this analysis, the fiber trait microfibril angle was selected for analysis of the impact of alteration either by breeding or genetically.

The tensile strength of fibers reaches its maximum at the lowest microfibril angle possible and will decrease with increases in the angle of microfibrils (7). The primary effect of a high microfibril angle is on fiber tensile strength whereas tear and bulk are only slightly affected by microfibril angle (7). The strength characteristics, stress and strain, of pulp fibers also depend upon the microfibril angle. Low strain at failure and high breaking stress correspond to a low fibril angle while a high microfibril angle gives greater strain at failure and lower breaking stress. In addition, elastic modulus is inversely correlated to the microfibril angle in kraft pulps, when MFA is high elastic modulus is low (7, 8).

Methodology for Calculating the Stacking Strength of a Corrugated Container

Box compressive strength. Corrugated containers are often subjected to high compressive loads during their service life, making the stacking strength or compressive strength of the container one of its most important properties. McKee et al showed that this top-load compressive strength of a container depends on two properties of the combined board, edgewise compressive strength (ECT) and flexural stiffness. Their work revealed that ECT is the most important property (9).

Because of this, McKee et al. developed an equation retaining only those factors dominant in box compression behavior (10). The result was the following box compression formula

$$P = 2.028 P_m^{.746} \left(\sqrt{D_x D_y}\right)^{.254} Z^{.492} \qquad \text{Eq. (1)}$$

where P = box compression (lb)
P_m = Edgewise compressive strength of the combined board (lb/in)
$D_x D_y$ = combined board flexural stiffnesses in MD (x) and CD (y) (lb/in)
Z = Loaded perimeter in inches (2*Box Length + 2*Box Width)

The simplified box formula revealed that the top-load compression strength of vertical flute boxes depended on two types of combined board properties (cross machine edgewise compression strength and flexural stiffness in both directions) and on box perimeter. Still, this formula was not practical to use since it relied on using combined board properties that are not easily measured in a corrugating plant. This led to further simplification of the box compression formula.

During development of the previous box formula, McKee et al. found the material and geometric properties of the combined board were correlated, allowing further simplification of the box formula (10). Correlation was made between composite flexural stiffness, $\sqrt{D_x D_y}$, and edgewise compression strength times caliper squared, $P_m h^2$ (24). The correlation allows replacing $\sqrt{D_x D_y}$ in the box formula by $P_m h^2$. Subsequently, the following simplified version of the McKee box compression formula is obtained:

$$P = 5.87 P_m h^{.508} Z^{.492} \approx 5.87 P_m \sqrt{hZ} \qquad \text{Eq. (2)}$$

Where P = box compression (lb)
P_m = Edgewise compressive strength of the combined board (lb/in)
h = caliper of combined board (in)
Z = Loaded perimeter in inches (2*Box Length + 2*Box Width)

After this simplification, box strength is expressed in terms of combined board caliper, h, rather than composite flexural stiffness, $\sqrt{D_x D_y}$. The accuracy of the new equation was nearly as high as that obtained previously for the sixty-three samples under study (10). Equation 2 is very attractive for estimating box compression because it eliminates the need of measuring the flexural stiffnesses of the combined board which requires longer time, equipment and skills compared with the measurement of the combined board caliper. In summary, the work performed by McKee et al., reveals that the edgewise compressive strength of the combined board is the most important property in determining box strength.

Combined board strength. Edgewise Compressive Strength (ECT) of the combined board can be determined by performing the Edge Crush Test and can be predicted by considering that it is primarily dependent on the edgewise compressive strengths of the components used in making the board. The edgewise compressive strength of a combined board can be defined as the maximum load, parallel to the flutes, which a sample with specific dimensions can withstand before failure (or specified deformation) under standard test conditions. ECT is the edgewise strength of a small representative section of the corrugated board. When used with other container characteristics (caliper and perimeter), it can predict the average maximum load it can support before it fails (11).

The edgewise compressive strength of a combined board depends on the properties of the components (linerboard and medium) used in combined board manufacture and on the quality of the conversion and finishing operations. The relation between ECT and component characteristics has been analyzed by Whitsitt et al. (9). The well-correlated measurements of ECT and STFI done by Whitsitt (12) can lead to the development of a linear equation of the form:

$$ECT = A + B\,(2L + DM) \qquad \text{Eq. (3)}$$

Where:
A = intercept (lbf/in), constant = 2.2 lbf/in
B = slope of graph, dimensionless constant = 0.72
L = CD linerboard compressive strength (lbf/in)
D = Take-up factor for the medium, 1.44 for a C-flute medium
M = CD medium compressive strength (lbf/in)

Good approximations for the corresponding values of A and B can be obtained, which in this case are = 2.2 lbf/in and B = 0.72.

Linerboard strength. In general, the maximum load and strain in compression of paper is about one-third of that in tension (13, 14). This observations led to the conclusion that the edgewise compression strength of linerboard can be estimated using the known tensile strength values for the CD direction. The relationship between these two properties then, is approximately:

$$CS = TS / 3 \qquad \text{Eq. (4)}$$

where
CS = Linerboard CD compressive strength
TS = Linerboard CD tensile strength

Applying Eq (4) allows us to convert microfibril angle:tensile data to microfibril angle:compressive strength results, giving us a way to evaluate the effect of microfibril angle on box compressive strength using Eq. (2)-(4).

Cost Modeling – Mill Model

The value of changes in wood and fiber properties for linerboard production costs and mill profitability were estimated with a multidimensional cash flow model, consisting of:

- A forest cost model for a loblolly pine plantation (developed with a grant from the Sloan Foundation-funded Center for Paper Business and Industry Studies at IPST and Georgia Tech)
- A greenfield, vintage 1995, integrated kraft pulp and linerboard mill cost model developed by Jaakko Pöyry Management Consulting (JPC) under contract to the Institute of Paper Science and Technology (IPST) (15). The approach to model these wood and fiber properties is shown in Figure 2 (15).
- An IPST box plant model, also developed under contract with Jaakko Pöyry

The mill model was enhanced by addition of a module to calculate energy recovered when black liquor amount and composition change (15). To minimize errors due to fluctuations in spot prices for all forest, mill and box plant inputs and for the sale price of linerboard, real prices obtained from trend price regressions were used. The linerboard costs and mill and box plant profits were projected for the year 2020, where the real price of linerboard is expected to drop from current values. Trait modeling predictions were based on empirical pulping and papermaking relationships obtained from the literature and, when not available, on mass and energy balances. All modeling was conducted with the following basic assumptions (15):

1) The mill owns the forestland reflected in the lack of transfer pricing for softwood logs
2) Softwood logs are loblolly pine trees grown clonally
3) All softwood logs for the mill come in as roundwood from company owned land
4) Hardwood (roundwood and chips) and recycled paper are purchased on the open market
5) Linerboard production is held constant. Basis weight is 42 lb/msf.

6) Linerboard furnish is 80% virgin fiber (70:30 softwood:hardwood) and 20% recycle.)

Primary input data for the box plant model is the linerboard transfer price obtained under different proposed scenarios (different microfibril angles) by using the modeling approach previously described. The range of microfibril angles investigated is assumed to be obtainable through breeding, clonal selection or genetic engineering.

The economic impact of the MFA in the price of linerboard was modeled by reduction in basis weight because a decrease in cellulose MFA increases the tensile strength of fibers. In this analysis up charges on lower basis weight linerboard sale prices commonly given to high performance linerboard grades were used along with base case wood prices and mill parameters. As expected when total annual production is fixed, a decrease in basis weight increases mill profitability. Although there is an upcharge in the linerboard price for reduced basis weights, it will be shown later that the box plant also receives its own additional advantage. The box plant is now able to produce the same amount of boxes with less linerboard (tons) supplied by the paper mill, because the roll supplied by the paper mill will give more area for the same mass of linerboard supplied. The range of basis weight values considered during the modeling went from the base case of scenario of 42 lb/msf to a minimum of 32 lb/msf.

Cost Modeling – Box Plant Model

The value of changes in linerboard properties for corrugated container's production costs and plant profitability were estimated with a box plant cost model developed by Jaakko Pöyry Management Consulting (JPC) under contract to the Institute of Paper Science and Technology (IPST). The equipment and processes modeled are typical for a facility that would have been built in 1995 and the plant is located in the southeastern United States. The geographical location specified affects many variables including labor rates, energy consumption and shipping costs considered as part of the analysis. The box plant economic model, provided in a Microsoft Excel program, consists of a series of worksheets that link together all the input data along with the process and product specifications in order to calculate the production costs of the finished corrugated containers for a particular scenario. A logic flow diagram showing the course of the information within the program's worksheets is shown in Figure 3.

The base case scenario in this project consists of combined board that has 42 lb/msf linerboard and 26 lb/msf C-flute medium. For the rest of the scenarios modeled, all unit costs and prices are kept the same except for the linerboard prices. To minimize errors due to fluctuations in costs for all box plant inputs and for the sale price of corrugated containers, real values obtained from trend price regressions were used. The box plant costs and prices were projected for the year 2020.

In the box plant, a single, 110-inch corrugator operates along with four flexo-folder-gluers selected to be representative of the normal industry mix (i.e. 1 medium, 2 large, and 1 jumbo). The corrugator is considered to operate at an average speed of 600 fpm and an efficiency of 86%. The corrugator is designed to run at 600 fpm, 8 hours per shift, 2 shifts per day, and 5 days a week, for a total of 4160 hours per year. Labor at the Flexo-folder gluers and cutters, which produce knocked-down flats, similarly work 4160 hours per year.

Results and Discussion

Linerboard CD Compressive Strength Determination

It was mentioned that reducing MFA in the fibers will increase the strength properties of linerboard in such a way that the basis weight of this component can be reduced while the strength properties of a corrugated container are maintained or increased. As a result, the following question needs to be addressed: How can values for the edgewise compressive strength (CD) of linerboard with different basis weights and MFA's be assigned in order to predict the top-to-bottom compressive strength of a container (Eq. 2) and, as a result, to compare these results with the market strength requirements?

A literature search was run to identify values of edgewise compressive strength of linerboard as a function of basis weight and MFA; unfortunately, no specific literature on this subject was identified. Hence, the approach to this problem was to use information reported by Courchene (16) and Litvay (17) on paper sheet properties of loblolly pine trees with low and high microfibril angles. In their study, ten trees were selected for relatively constant high, mid or low MFA from breast height cores. After pulping, microfibril angle measurements of the pulps were taken to relate these variances in microfibril angle to the corresponding physical tests that were to be performed. Some of the tests performed used three representative pulps that were the high, mid, and low microfibril angles. Two different methods were used for each of the three representative pulps resulting in six different conditions for physical testing. The different methods consisted of making unrefined handsheets according to TAPPI T 205 sp-95 "Forming handsheets for physical tests of pulp", and refined handsheets after refining of the pulp at 2500 rev in a PFI mill (17).

Figure 4 shows the tensile index vs. pulp MFA for both the refined and unrefined pulps (16). As expected when MFA increases, the tensile index decreases. A total of five different measurements were done for each of the six different physical testing conditions. The tensile measurements corresponding to the refined pulps have wider ranges than those corresponding to the unrefined pulps (Table I). A possible reason for this is that the refining process was not uniform for all the fibers within each of the different MFA populations.

To estimate the linerboard compressive strength at different basis weights and its relation to fiber MFA, the refined pulp tensile index data from Figure 4 were used, as represented in Equation (5) and Table II. The refined data more closely reflect commercial linerboard production.

$$TI = MFA*(-1.0152) + 103.05 \qquad \text{Eq. (5)}$$

A relationship was established between the properties of the prepared handsheets and those of linerboard to take MD/CD ratio into account. In the case of linerboard, a typical MD/CD ratio is around 2:1 due to the fiber orientation and drying restraints. Random handsheets on the other hand are "square" (1:1 MD/CD ratio) due to lack of oriented shear during forming and the ability to dry with uniform restraint. Hence, the handsheet geometric mean tensile data were converted to oriented tensile data.

In summary:

- For a given microfibril angle, determine tensile index (Figure 4, Equation (5)).
- Calculate tensile strength as a function of basis weight (assuming that it is possible to reduce BW in the manufacturing process from the base case of 42 lb/msf down to 32 lb/msf and still meet the strength requirements). (Tensile strength is obtained from the product of tensile index and basis weight.)
- Calculate CD tensile assuming the 2:1 MD:CD tensile ratio
- Knowing the tensile strength values for the linerboard in the CD direction, estimate the edgewise compressive strength of the linerboard using Equation 4 above (Table III, Figure 5).

Combined Board's Edgewise Compressive Strength Estimation

The next step to model the strength of a corrugated container at different basis weights is to estimate the edgewise compressive strength of the combined board (via Equation 3) used to produce the container. This requires (1) CD linerboard compressive strength for different basis weights and MFA (Table III) and (2) medium compressive strength.

To calculate the CD medium compressive strength, the short span Compression Index can be used. Extensive studies have shown that this index for a semi-chemical fluting is 19.5 kNm/kg (18). Therefore, knowing that for this case the medium basis weight will be kept constant at 26 lb/msf (127 g/m^2), the medium compressive strength can be obtained with Equation 6:

$$CompressiveStrength = \frac{CompressiveIndex * BW}{1000} \qquad \text{Eq. (6)}$$

Where: Compressive Strength (=) kN/m
Compressive Index (=) kNm/kg
BW: Basis Weight (=) gr/m^2

The calculation gives medium compressive strength of 2.47 kN/m (or 14.14 lbf/in for use in Eq. 3).

The edgewise compressive strength of combined board was estimated for the established ranges of both linerboard basis weight and MFA using Equation 3 (Table IV, Figure 6).

Top-to-to-Bottom Compressive Strength Estimation for a Corrugated Container

The last step to model the strength of a corrugated container at different basis weights is to estimate the top-to-bottom compression strength using the McKee box compression formula (Equation 2), with combined board edgewise compressive strength values from Table IV. The type of container modeled is the Regular Slotted Container (RSC). The McKee box compression formula can only be applied to RSCs, and only those with a perimeter-to-depth ratio no greater than 7:1 (19).

In the box plant model different box sizes are considered as part of the cost analysis. It is necessary to first determine the box dimensions, to calculate the top to bottom compressive strength with the McKee formula (Table V) (20). Subsequently, box strength is calculated, e.g. the jumbo box size results are tabulated in Table VI and graphed in Figure 7.

Earlier, it had been discussed that the alteration of MFA will modify the strength properties of the linerboard in such a way that the basis weight of this component can be reduced while the strength properties of the container are maintained or increased. It had also been mentioned that this reduction in basis weight will lower the cost of container manufacture because the box plant would be able to produce the same amount of boxes with fewer tons of linerboard supplied by the paper mill. After analyzing the corresponding compressive strength data for each box, it can be concluded that for the base case container of 42 lb/msf and 30 degree MFA, linerboard basis weight reduction to about 36 lb/msf is possible if the MFA of the pulp used to manufacture the linerboard were decreased to 18 degrees (Figure 7). This new proposed scenario will give the same compressive strength characteristics as those given by the base case container. However, before analyzing the economic impact of reducing the linerboard basis weight, it is necessary to determine if the different compressive strengths estimated for each box meet the market requirements.

ECT Requirements for Corrugated Containers

In 1991, the rail (Rule 41) and truck (Item 222) carrier classifications were revised to provide an alternative set of requirements that uses stacking strength as the primary performance attribute instead of the typical Mullen burst test. This alternate classification is based on the edgewise compression strength (ECT) of the combined board and recognizes its relationship to the compression or stacking strength of the finished box (Table VII) (21). ECT had been defined as the edgewise compressive strength, parallel to the flutes of a short column of combined fiberboard (22). Since the present work is focused in modeling the alteration of fibers to improve the compressive characteristics of the combined board and hence, those of the container, the judgment on the modeled containers will be done by comparison with the alternate set of requirements, ECT.

Once the maximum outside dimensions of the three different box sizes are determined, then the minimum corresponding ECT values for the three different boxes can be obtained (Table VIII). Recalling the edgewise compressive strength values previously estimated for combined board (Table IV), and comparing with the minimum ECT values listed in Table VIII, the following can be concluded:

- The base case scenario for each one of the three box sizes meet the minimum ECT value established by the alternate rule requirements.
- For the complete range of basis weights and MFA modeled in this project, the ECT estimated values of combined board meet the minimum rule requirements (Table VIII) of the medium and large size boxes (20).
- For the jumbo size box, there are some BW-MFA scenarios in which the combined board's estimated compressive strength is below the minimum rule requirement. These scenarios are marked in Table IX.

Therefore, in terms of the market requirements, only the jumbo box has some restrictions for basis weight reduction over the range of basis weights and MFA's evaluated.

It can be concluded now that the basis weight–MFA scenario to select for a box will depend mainly on the requirement to be met. For example, recall the analysis in which under terms of box compressive strength the base case scenario of 42 lb/msf linerboard could be reduced to 36 lb/msf as long as the MFA was decreased from 30 to 18 degrees for the three box sizes. In terms of the alternate rule requirements, it can be observed that the same base case scenario of 42 lb/msf linerboard could be reduced to 34 lb/msf and still be in good shape even for the jumbo box if the MFA were decreased from 30 to at least 20 degrees. The basis weight of linerboard for medium and large boxes can be reduced down to 32 lb/msf and still meet the ECT rule requirements.

If the ECT rule requirements were the only ones to be met (and not the box compression strength requirements) for the three box sizes, a bigger economic benefit could be obtained in the box plant model by means of linerboard basis weight reduction. However, in order to be on the safe side, the economic impact analysis considers that the linerboard basis weight is reduced to a minimum of 36 lb/msf as long as the MFA is altered from 30 to 18 degrees. With this consideration, both the box compressive strength and the alternate rule requirements will be met for the three box sizes.

In the market, jumbo size boxes are regularly manufactured with 69 lb/msf linerboard. Therefore, meeting the ECT requirements with 42lb/msf linerboards as it was shown along the present section shows the opportunity that jumbo manufacturers have in terms of reducing the basis weight to their standard linerboard for jumbo size boxes. Obviously, some additional considerations on the properties of the container should be taken into account in order to have a more complete analysis. Such properties include flat crush test, flexural rigidity and burst strength.

Linerboard Cost to Box Plant

Table X shows the linerboard cost to the box plant, as a result of the modeling assumptions, in combination with change in basis weight (15, 20). The value in bold ($416.7/ton) is the base case scenario for this project. These data are input to the box plant model as part of the raw materials costs. These values will ultimately define the best scenario for the box plant model in terms of the economic benefits that could be obtained after altering basis weight.

Box Plant Economic Model Results

Considering the total number of hours and the production capacity at the end of the line, the amount of boxes per year for each size was calculated (Table XI). The substitution of linerboard prices for different basis weight into the box plant model resulted in corresponding corrugated container production costs (Table X). Starting at the base case scenario of 42 lb/msf (and 29% wood lignin composition and 0.46 specific gravity), the impact in production costs due to basis weight reduction is seen.

It was stated above that the economic impact analysis should consider a linerboard basis weight reduction to a minimum of 36 lb/msf and a MFA alteration from 30 to 18 degrees. With this consideration, both the box compressive strength and the alternate rule requirements would be met for the three box sizes considered in the box plant model. The production costs by reducing basis weight from 42 to 36 lb/msf range from $34.05/msf to $32.77/msf (Table X), Figure 10 shows the trend on finished box costs and net income for the box plant as basis weight is reduced.

Table XII shows a summary of the proposed changes on the linerboard and its favorable impact in the economic aspects of the box plant. Reducing the basis weight and altering the fiber traits results in production of a container that meets both compressive strength and alternate rule requirements, while increasing the net income of the production facility by more than 1 million dollars per year due to the lower cost of linerboard per fixed area (Table XII). The economic benefit for the box plant after linerboard basis weight is reduced is due mainly to production of the same amount of boxes using less linerboard (tons). In other words, the roll supplied by the paper mill will give more area for the same mass of linerboard supplied. The previous assertion has been taken in consideration during the economic modeling by keeping constant the area of knocked-down flats produced on a time basis.

Another approach that can be taken in the modeling of this box plant is to consider supplying the same amount of linerboard (tons) and hence, producing more knocked-down flats (boxes). This scenario is realistic if the box plant can increase the productivity (speed) of their equipment. Also, this scenario is more attractive economically since not only will the cost per area of the roll supplied be lower, but also an additional cost reduction will be obtained by producing more boxes at a higher machine speed with the same fixed costs such as labor.

Conclusions

- With the approaches used we predict that the STFI compressive strength requirements established for shipping in terms of ECT of a container of 42 lb/msf linerboard with an average MFA of 30 degrees, are met by a container made with 36 lb/msf linerboard and average MFA of 18 degrees.
- By reducing the linerboard basis weight from 42 (base case) to 36 lb/msf and decreasing MFA from 30 to 18 degrees, the result is an increase in the net income of a corrugated container facility by more than 1 million dollars per year, even though the linerboard price is elevated.

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TABLES

Table I: Tensile Index results at each microfibril angle.

	MFA		
	Avg. = 22.2 ° (σ = 6.6 °)	**Avg. = 30.6 °** (σ = 8.0 °)	**Avg. = 39.3 °** (σ = 6.5 °)
Refined Tensile Index	79.1 Nm/g (σ = 4.0)	74.8 Nm/g (σ = 4.2)	61.7 Nm/g (σ = 4.3)
Unrefined Tensile Index	52.4 Nm/g (σ = 2.1)	46.3 Nm/g (σ = 2.0)	40.8 Nm/g (σ = 3.8)

Table II: Tensile Index values at different MFA calculated from Equation 5.

MFA	**Tensile Index**
degrees	**Nm/g**
18	84.8
20	82.8
22	80.7
24	78.7
26	76.7
28	74.6
30	72.6

Table III: Estimated CD compressive strength (lbf/in) for linerboard.

	BW						
	lb/msf	**42**	**40**	**38**	**36**	**34**	**32**
MFA	g/m2	205.2	195.5	185.7	175.9	166.2	156.4
degrees							
18		23.4	22.3	21.2	20.1	19.0	17.8
20		22.9	21.8	20.7	19.6	18.5	17.4
22		22.3	21.2	20.2	19.1	18.0	17.0
24		21.7	20.7	19.7	18.6	17.6	16.6
26		21.2	20.2	19.2	18.2	17.1	16.1
28		20.6	19.6	18.7	17.7	16.7	15.7
30		20.1	19.1	18.1	17.2	16.2	15.3

Table IV: Estimated CD edgewise compressive strength (lbf/in) for combined board.

	BW						
	lb/msf	**42**	**40**	**38**	**36**	**34**	**32**
MFA	g/m2	205.2	195.5	185.7	175.9	166.2	156.4
degrees							
18		50.6	49.0	47.4	45.8	44.2	42.6
20		49.8	48.2	46.6	45.1	43.5	41.9
22		49.0	47.4	45.9	44.4	42.9	41.3
24		48.2	46.7	45.2	43.7	42.2	40.7
26		47.4	45.9	44.4	43.0	41.5	40.1
28		46.5	45.1	43.7	42.3	40.9	39.5
30		45.7	44.4	43.0	41.6	40.2	38.9

Table V: Dimensions for the 3 box sizes considered in the box plant model.

Box size	**Avg. sheet size (in^2)**	**W (in)**	**L (in)**	**D (in)**	**Perimeter, 2(L+W) (in)**
Medium	1,730	9.8	19.6	19.6	58.8
Large	4,680	16.12	32.24	32.24	96.72
Jumbo	6,235	18.61	37.22	37.22	111.66

Table VI: Top-to-bottom compressive strength (lb) estimation for the jumbo sized container.

	BW						
	lb/msf	**42**	**40**	**38**	**36**	**34**	**32**
MFA	g/m2	205.2	195.5	185.7	175.9	166.2	156.4
degrees							
18		1,293.7	1,252.6	1,211.5	1,170.4	1,129.4	1,088.3
20		1,273.0	1,232.9	1,192.8	1,152.7	1,112.7	1,072.6
22		1,252.3	1,213.2	1,174.1	1,135.0	1,095.9	1,056.8
24		1,231.7	1,193.6	1,155.5	1,117.3	1,079.2	1,041.1
26		1,211.0	1,173.9	1,136.8	1,099.6	1,062.5	1,025.4
28		1,190.4	1,154.2	1,118.1	1,081.9	1,045.8	1,009.6
30		1,169.7	1,134.6	1,099.4	1,064.2	1,029.0	993.9

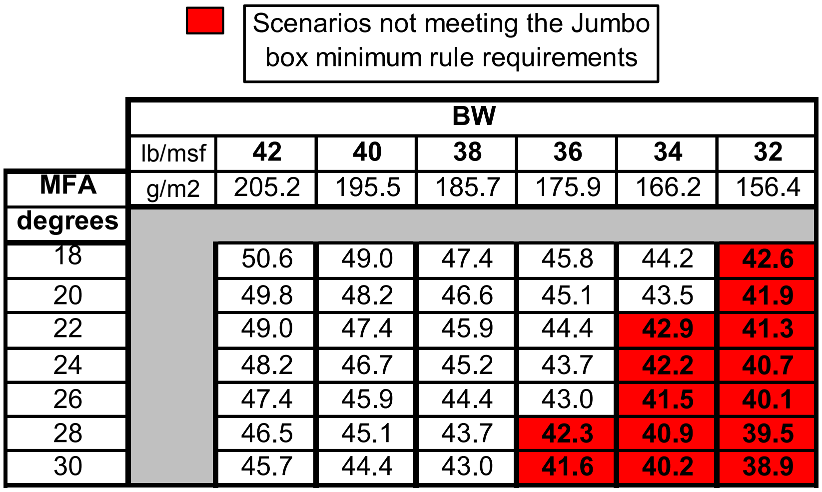
Table VII: Alternate Rule Requirements for corrugated containers (23).

Maximum outside dimensions (in.) (L+W+D)	**Minimum edge crush test – ECT (lbf/in)**
40	23
50	26
60	29
75	32
85	40
95	44
105	55

Table VIII: Rule requirements for the three box sizes considered in the box plant model.

Box Size	**Maximum outside dimensions (in.) (L+W+D)**	**Minimum edge crush test - ECT (lbf/in)**
Medium	49	25
Large	81	37
Jumbo	93	43

Table IX: Estimated combined board's ECT (lbf/in) and indication of those scenarios not meeting minimum rule requirements



🟥 Scenarios not meeting the Jumbo box minimum rule requirements

		BW					
	lb/msf	**42**	**40**	**38**	**36**	**34**	**32**
MFA	g/m2	205.2	195.5	185.7	175.9	166.2	156.4
degrees							
18		50.6	49.0	47.4	45.8	44.2	🟥 **42.6**
20		49.8	48.2	46.6	45.1	43.5	🟥 **41.9**
22		49.0	47.4	45.9	44.4	🟥 **42.9**	🟥 **41.3**
24		48.2	46.7	45.2	43.7	🟥 **42.2**	🟥 **40.7**
26		47.4	45.9	44.4	43.0	🟥 **41.5**	🟥 **40.1**
28		46.5	45.1	43.7	🟥 **42.3**	🟥 **40.9**	🟥 **39.5**
30		45.7	44.4	43.0	🟥 **41.6**	🟥 **40.2**	🟥 **38.9**

Table X: Linerboard cost to box plant ($/ton) as a function of basis weight (15).

	Basis Weight (lb/msf)	Basis Weight (g/m2)	Linerboard Cost to Box Plant ($/ton)	Corrugated Container Production Cost ($/msf)
Base Case	**42**	**205.2**	**416.7**	**34.05**
Lower BW Cases	40	195.5	426.8	33.64
	38	185.7	437.6	33.23
	36	175.9	448.4	32.77
	34	166.2	459.2	32.27
	32	156.4	470.0	31.72

Table XI: Production capacity for the box plant considered in the economic model

FFG	**% Capacity**	**Production capacity (ft^2/run hr)**	**Average sheet size (ft^2/sheet)**
Medium	18.4	40,655	*12.02*
Large	56.5	124,838	*32.50*
Jumbo	25.1	55,459	*43.30*
Total		**220,953**	

Considering → 1 sheet = 1 box

Production capacity (boxes/run hr)	**Production capacity (boxes/year)**
3,382	14,070,405
3,841	15,979,321
1,281	5,328,182
8,504	**35,377,908**

Table XII: Summary of economic impact with actions on linerboard properties.

Case	Basis Weight (lb/msf)	Microfibril Angle (degrees)	Cost ($/msf)	Cost (% reduction)	Net Income ($/yr)	Net Income (% increase)
Base	**42**	**30**	**34.05**	**-**	**8.857,830**	**-**
BW Reduction	**36**	**18**	**32.77**	**3.8**	**9,682,348**	**9.3**

Figures

Figure 1: Cost distribution for regular slotted container production in a corrugated container plant (4).

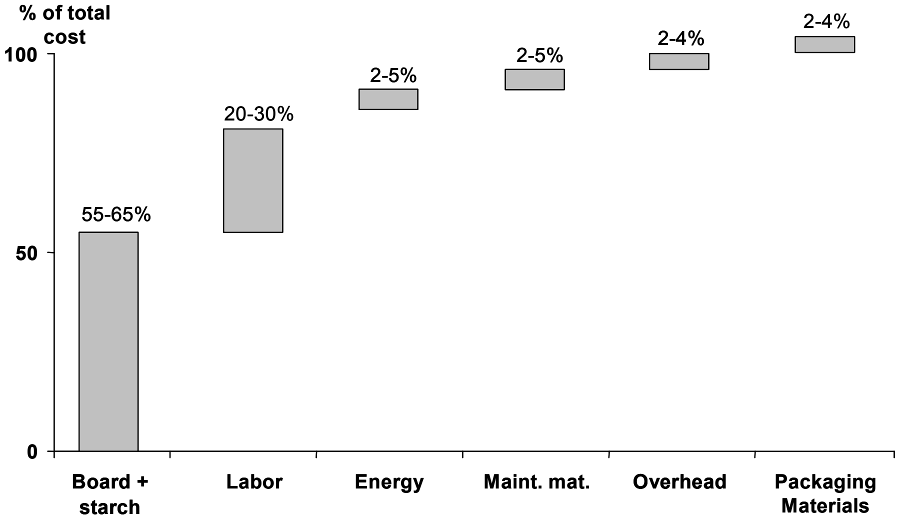


Figure 2: Approach to model wood and fiber properties on the cost of slush pulp, linerboard and mill profitability (15).

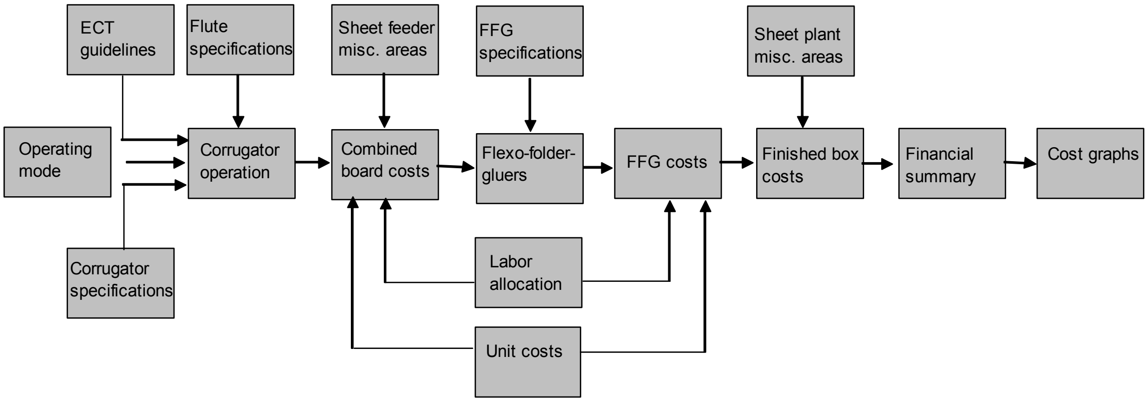


Figure 3: Logic flow diagram for the Excel program provided by Jaakko Poyry

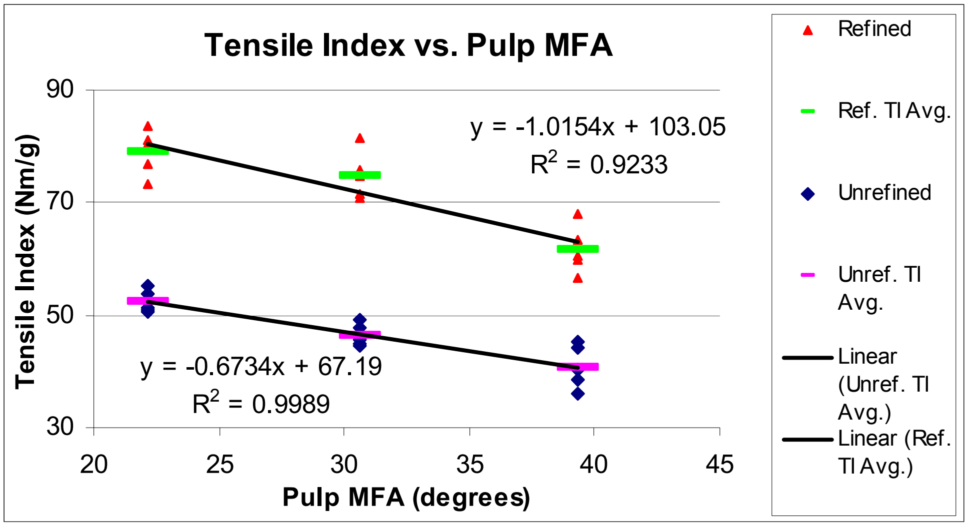


Figure 4: Handsheet Tensile Index vs. Pulp MFA for loblolly pine pulp (18).

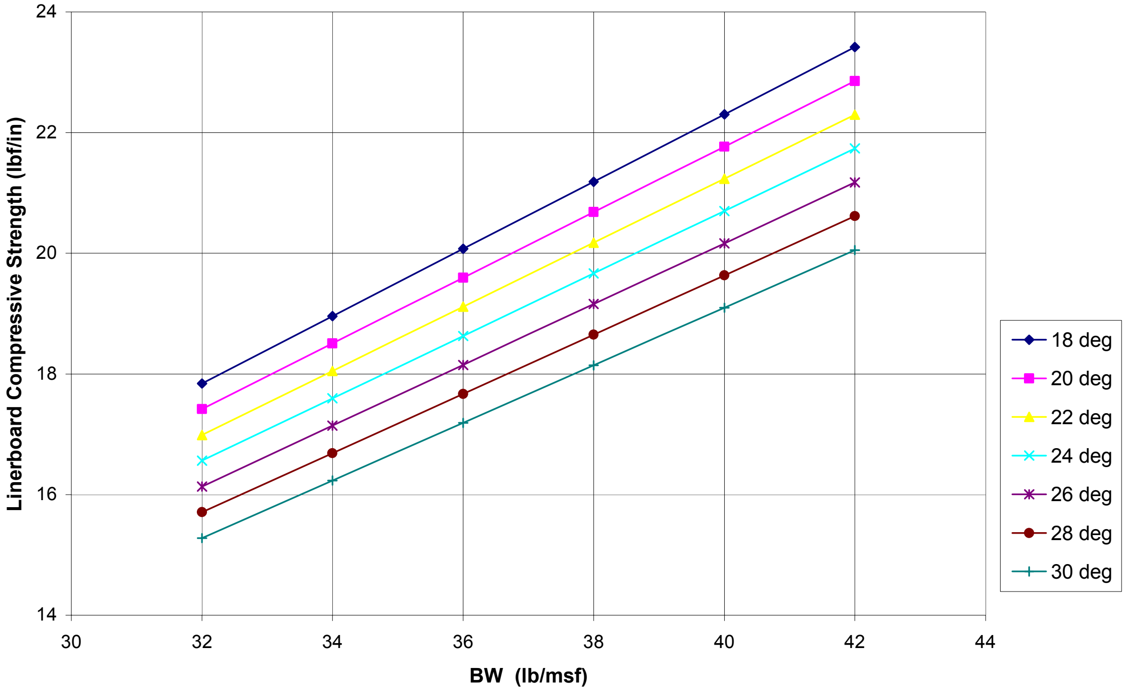


Figure 5: Estimated CD linerboard compressive strength vs. BW at different MFA.

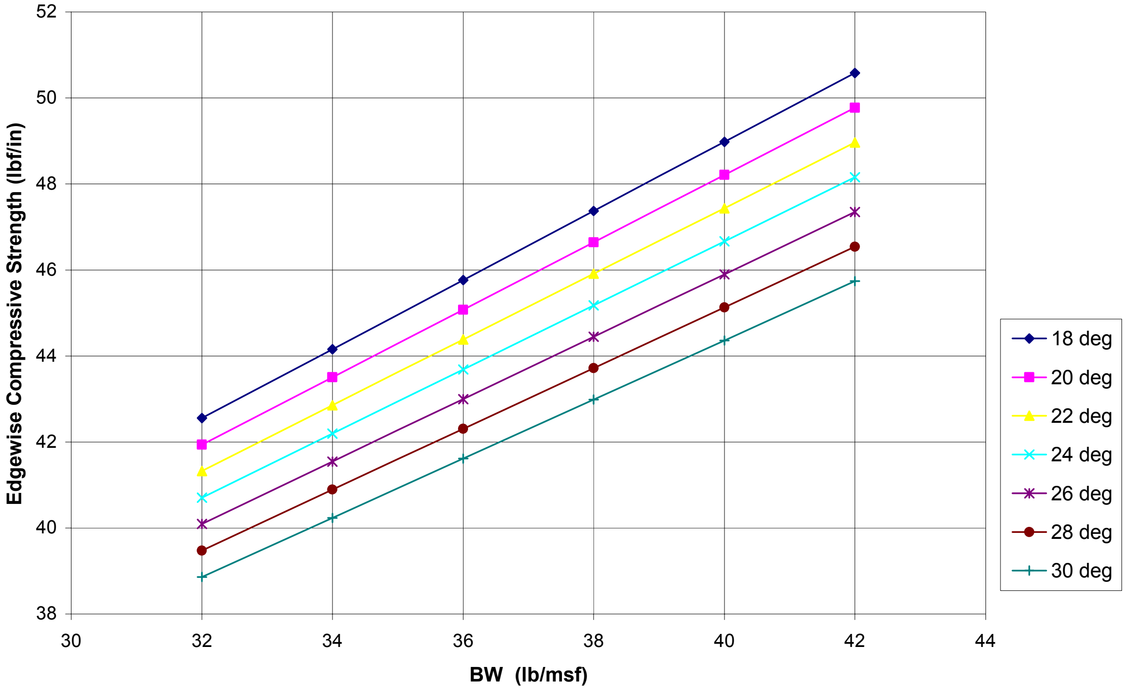


Figure 6: Estimated combined board CD compressive strength vs. BW at different MFA.

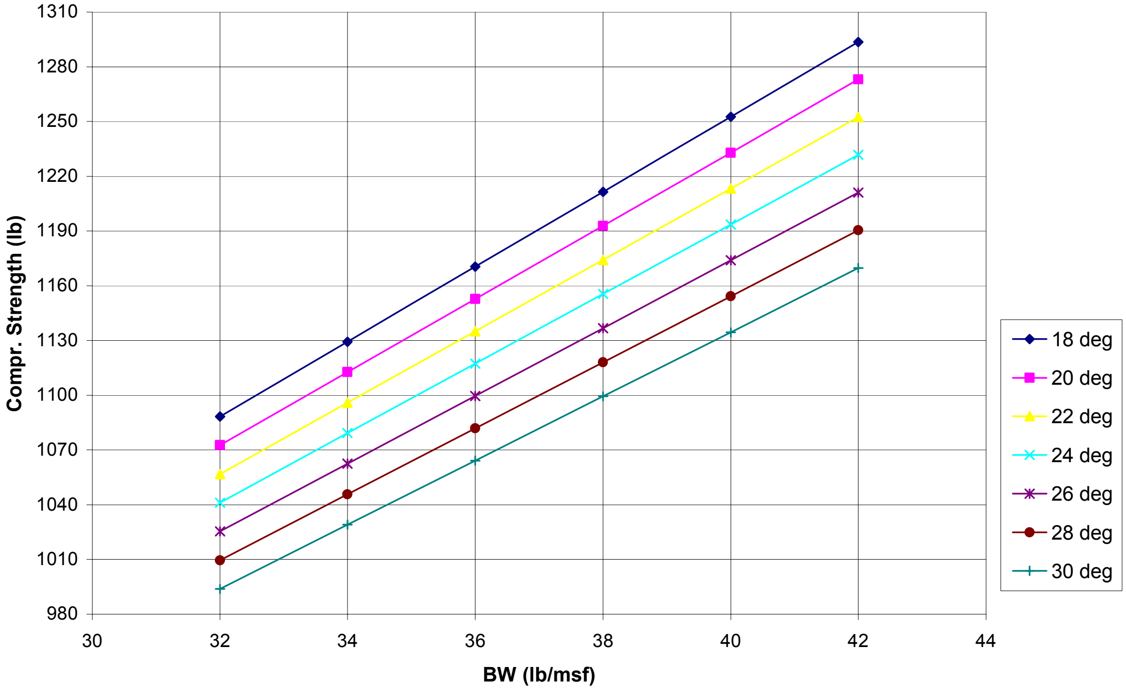


Figure 7: Estimated jumbo sized container compressive strength vs. BW at different MFA.

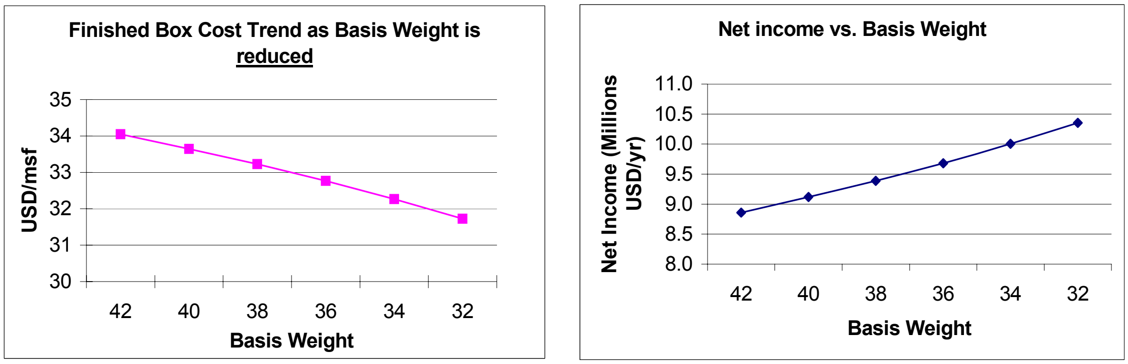


Figure 8: Finished box costs and net income for the box plant as a function of basis weight