NEW APPROACHES FOR CHARACTERIZING THE STRENGTH OF LUMBER BASED ON A SPATIAL DISTRIBUTION OF KNOTS

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Knots are common characteristics of lumber that impact its strength properties. Sawing practices for creating dimension lumber lead to the presence of distinct spatial patterns of knots visible on the lumber surfaces. Knots adjacent to each other have combined effects in strength reduction.

Many past studies have proposed models that relate the strength of lumber to its knots:
- E.g. Oh, Kim & Lee (2010); Fink & Kohler (2014); Wong, Lum, Wu & Zidek (2016); García and Rosales (2017)

Data has been limited by traditional grading practices (e.g., MSRC).
MOTIVATION FOR NEW APPROACHES

- High resolution scans of the four sides taken as a piece of lumber is being processed
  - Provides the necessary data for studying the impact of the spatial distribution of knots on strength

- Modern statistical computation based on Bayesian hierarchical models and Markov chain Monte Carlo (MCMC)
  - Provides the inferential techniques necessary to handle generative probabilistic models with many parameters and latent variables
IDENTIFYING AND MATCHING KNOT FACES

Fig. 1: The main varieties of knots

Fig. 2: Four sides of a sawn timber (2 Tops & 2 Sides)
IDENTIFYING KNOT FACES

- Knot localization – **object detection problem**.
- Bounding box detection: Single Shot MultiBox Detector (SSD)

![Figure 3: The true and predicted labels of image 340A_1609TLine17.jpg](Image 340A_1609TLine17.jpg)

Elliptical label is preferred than bounding box – “area over” for edge knots

![Figure 5: The plot of “tracheid data” for the areas shown by 340A_1609TLine18.jpg](Image 340A_1609TLine18.jpg)

![Figure 6: Detection of knots based on “tracheid data” for 340A_1609TLine17.jpg](Image 340A_1609TLine17.jpg)

“tracheid data” for 340A_1609TLine17.jpg
Planning to **adapt** the existing object detection methods to localize elliptical objects:
- R-CNN; Fast R-CNN; YOLO; SSD

**Data Preparation:**
- Elliptical Label made using the VGG Image Annotator
- Fix the image partial distortion in the “side” images
KNOT MATCHING

- Determine which knot faces belong to the same tree branch

- Sequential Monte Carlo (SMC) algorithm (Jun, S. H., Wong, S. W., Zidek, J., & Bouchard-Côté, A. 2017) for matching the knot faces:
  - based on the sizes, shapes, and locations of the fitted ellipses
  - fast runtime: can be applied real-time during lumber grading

- Matched knot faces permit re-construction of knot properties
  - E.g., volume and percentage cross-section displaced
Goal: Develop new strength prediction model, and fit to data with these features:

- Given all knot sizes and locations of a piece
- Accounts for spatial interaction of knots for strength-reducing effect
- Strength value and failure location recorded from destructive testing
- Model should be extensible to a variety of destructive test setups
MODEL SETUP

- Conceptually sub-divide each piece into $m$ cells
- Each cell has its own strength value

- Strength value in a cell depends on:
  - The underlying strength of the piece
  - The effect of the knots – size and location
With the knot faces identified and matched, the physical knot is then modelled in 3-D as convex hulls – with the smallest convex volume that encloses the different knot faces corresponding to a knot.

The spatial distribution of knots is captured by the distance matrix calculated from the knot and cell centroids.
(1) **KNOT-FREE SPECIMEN STRENGTH**

- Use a hierarchical process by assuming a process model $X$ nested within a measurement model $Y$.

- The process model is conceptualized by first assuming a “clear” specimen

  $$ X = \{X_j\} \quad j = 1, \ldots, m $$

  $$ X_j = \alpha + \rho X_{j-1} + \epsilon_j \quad 0 < \rho < 1, \quad \epsilon_j \sim N(0, \sigma^2) $$

- It is assumed to have a reversible Markovian structure; follows a first-order autoregressive $AR(1)$ process on $X$

- Covariates can be included by defining the model that satisfies:

  $$ E[X_j|X_{j-1} = x_{j-1}, y_j] = = \alpha + \rho x_{j-1} + y_j' \eta $$

  Where $y_j$ denotes a vector of covariates at cell j.
The underlying strength $Y_j$ is then defined using the spatial distribution of knots and their strength-reducing effects.

$$Y_j = X_j - \gamma_{\{0,1\}} \cdot \sum_{k=1}^{K} h(d_{jk}) \cdot Z_k$$

- $k = 1, 2, ... K$, is the number of knots on the piece
- $\gamma_0$ if $k^{th}$ knot is not an edge knot, $\gamma_1$ if $k^{th}$ knot is an edge knot
- $Z_k$ is the effect of $k^{th}$ knot, which is characterized as the percentage of wood displaced by the knot volume in that cell
- $h(d_{jk})$ is a decreasing function of $d_{jk}$, the distance between $k^{th}$ knot centroid and $j^{th}$ cell centroid. An exponentially decaying function is used: $h(x) = e^{-\beta x}$
(3) OBSERVED STRENGTH FROM DESTRUCTIVE TESTS

• The observed strength corresponds to the “weakest” cell

• The observed strength is defined as the minimum of the underlying strength

• With the location of failure being observed, the cell index of the minimum will also be identified from the test

\[ Y_{\text{obs}} = \min\{Y_1, \ldots, Y_m\} \]
**INFERENCE**

\[
X_j = \alpha + \rho X_{j-1} + \epsilon_j \quad 0 < \rho < 1, \quad \epsilon_j \sim N(0, \sigma^2)
\]

\[
E[X_j|X_{j-1} = x_{j-1}, MOE] = \eta_0 + \rho x_{j-1} + \eta_1 \cdot MOE
\]

\[
Y_j = X_j - \gamma_{\{0,1\}} \cdot \sum_{k=1}^{K} e^{-\beta \cdot d_{jk}} \cdot Z_k \quad j = 1, 2, \ldots, m
\]

\[
Y_{\text{obs}} = \min\{Y_1, \ldots, Y_m\}
\]

- The unknown parameters are: \(\theta: = \{\eta_0, \eta_1, \rho, \sigma^2, \beta, \gamma_0, \gamma_1\}\)
- The unobserved \(\{X_j\}\) and \(\{Y_j\}\) are latent variables.
- We adopt a Bayesian approach to infer the joint posterior distribution of the model parameters.
Recent advances in statistical computation allow the analytically intractable posterior to be sampled using Markov chain Monte Carlo (MCMC) techniques.

The fitted model provides the predictive distribution of timber strength that accounts for the spatial distribution of knots.

The priors for the unknown parameters are chosen to be weakly informative

\[
\begin{align*}
\eta_0 & \sim N(0, 10) & \eta_1 & \sim N(0, 10) & \beta & \sim N(0, 1) \\
\rho & \sim N(0.5, 0.5) & \sigma & \sim Cauchy(0, 5) \\
\gamma_0 & \sim N(0, 1) & \gamma_1 & \sim N(0, 1)
\end{align*}
\]
SCANNING AND DESTRUCTIVE TESTING EXPERIMENT

- Douglas Fir lumber are being scanned and tested to fit and calibrate model parameters

- Currently, we have fitted the model based on a preliminary sample of 20 pieces

- Many thanks to FPInnovations for providing the equipment, test samples, and staff to assist with data collection
Inference results for preliminary data

Posterior samples of the parameters


**DISCUSSION AND FURTHER WORK**

- Data processing to be finished for the experiment of 12ft Douglas Fir lumber, and model fitted to the full dataset

- Provides strength prediction rule for scans of future pieces

- Framework is extensible
  - can incorporate multiple strength measurements on a single piece to improve estimates of autoregressive parameters
  - incorporate other covariates such as density