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Technical Note

Review of existing approaches for modelling wood properties models

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Summary: This review of existing modelling approaches has shown that none of the approaches reviewed are on their own adequate as inputs for product quality simulation. The requirements for next generation models will be presented separately.

Introduction

Wood property models describe the variation in one or more traits (e.g. basic density) based on one or more conditioning variables (e.g. height in tree, site altitude). Traditionally they are developed separately from growth and architectural (branching models) even though these different aspects of tree growth are inextricably linked via physiological processes, particularly those occurring in the cambium.

Some wood property models describe variation inside a stem (i.e. at material points) based on qualitative descriptions of location (e.g. 'breast height'). Others use 1-, 2-, or 3-dimensional descriptions of material point location based on either spatial coordinates ($r\theta z$) or temporal ($t_r\theta t_z$). The traits being described are often continuous variables (e.g. density) but may also be categorical (heartwood, branch), in the latter case it is common to partition space into discrete regions.

The problem of representing stochastic spatial variation is not confined to wood science. Other biological tissues, natural and artificial materials, geology and even cosmology all benefit from being able to characterise and recreate 'realistic' patterns of variation. The development of statistical models that perform these functions are variously motivated, and have a variety of outcomes. This review is focussed on identifying modelling approaches that are capable, wholly or in part, of delivering the requisite input to product quality simulations.

Product Quality Prediction Requirements

To drive product quality simulations, any candidate modelling methodology must be capable of meeting the following requirements:

1. Estimate distributions of trait values at each material point (i.e. each point inside a tree) rather than just mean values.
2. Estimate all traits needed to predict a performance measure, for instance density, microfibril angle and grain angle for predicting timber stiffness or these plus chemical composition for warp.
3. Respect covariance structures, both spatial and cross-trait and both intra- and inter stem.
4. Respect constraints (conditioning variables) supplied either from measured data (e.g. observed exterior log geometry, breast height outerwood density) or as part of the generation request (give me 200 trees of genotype G representative of those that would be grown on site S with environment E and silvicultural regime S).

Essentially these requirements boil down to the model output being statistically indistinguishable from measurements of actual trees.

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Existing Approaches

There are a large number of pubications describing wood property models and along with comprehensive reviews of wood property modelling strategies written e.g. (Grace 2003) and Grace jointly with Finnish researchers (Mäkelä et al. 2010). Wood property models can be classified as statistical, mechanistic, and hybrid for growth, yield, and wood quality attributes (Weiskittel 2014; Weiskittel et al. 2011). Empirical/statistical models are often focused on single wood property traits and often based on either mean value of the property at breast height or at few different heights of the tree. Models have been developed to predict wood properties on either stem, stand or site level. Empirical models should not be used outside the range of conditions used in developing the model. Hence models are likely to have a finite life-time and there is a need to be continually collecting good quality data relevant to current forestry practices (Grace 2003). These models can be useful additions in the product quality prediction arsenal but are insufficient on their own.

One of the earliest wood density models was developed by (Harris 1965) based on a regional survey of outerwood (10 rings) density. This study reported a strong relationship for density to mean annual temperature and density also decreased with increasing altitude and latitude. Other wood density models related to environmental factors such as mean annual temperature and soil nutrition have also been published (Beets et al. 2001; Beets et al. 2007; Cown et al. 1991; Palmer et al. 2013). Beets et al. (2007) used wood survey data from throughout New Zealand to construct a model using growth sheaths and including effects for latitude, sand country, and C/N ratio to explain regional density differences. The National Density model (Kimberley et al. 2015) was a meta analysis using many previous wood density datasets. Models were developed to fit stand averaged tree data from throughout NZ at a range of stand stockings. A “local site effect” was introduced to adjust output values to local conditions, and ring width was used as an optional surrogate for stocking rate. Density at breast height for a given ring is calculated using a local site effect, ring number from pith, and stocking (or ring width). Disc density at other heights is calculated using tree relative height positions. Previous research has also investigated the effects of forest management practices, such as thinning, pruning and rotation age, and genetic differences on wood properties (Carson et al. 2014; Cown and Ball 2001; Moore et al. 2015; Moore et al. 2018).

Other wood property attributes have also been modelled. (Moore et al. 2014) examined MFA variation measured by SilviScan in 26 regions throughout New Zealand. MFA variation was modelled as a function of cambial age and relative height. The differences between sites were small. Radial profiles indicated large tree-to-tree variation in MFA at low heights. Carson et al.(2014) also found tree-to-tree variation was also large in outerwood density and also for standing stress wave velocity for a study comparing seedlots and silvicultural treatments at five sites. Watt et al. (2013) compared spiral grain at 5 mm radial increments and 4 heights in 7 young radiata pine clones finding small clonal differences, large between ramet variation and consistent patterns with radial position and height. Moore et al. (2015) did an analysis of spiral grain measurements made throughout New Zealand. Large differences between individual stems were measured and there were only very small regional differences. Other wood traits that impact on product performance such as branch knot distribution (Grace et al. 2006) and compression wood (Leban et al. 2002) have also been incorporated into three dimensional models. A model of basic density (and ring width) was developed as part of an MSc thesis (Pont 2003), and the model was designed to be linked to branch growth models.

In models such as STANDQUA attempts were made to describe the two-dimensional distribution of wood density and spiral grain for radiata (Tian et al. 1995a; Tian et al. 1995b) and Norway spruce (Leban et al. 1996) by summarising properties at both radial and height positions. They can be presented as 3D models by assuming rotational symmetry around a vertical axis and alignment of pith on the vertical axis. The downside of this is that they are derived from a limited number of trees and few sites, averages were calculated at the stand level (vs individual tree level). The model implies that wood density in a given ring from the pith will be independent of silvicultural treatment.

(Fernández et al. 2011) has developed a structural-functional model for radiata pine that increments growth at one monthly periods. This model includes several functionalities relevant to wood quality. Wood density is estimated by partitioning carbohydrates into ring growth or density according to conductive requirements. Another property modelled is heartwood formation. Branch internode length is driven by year-to-year to year temperature and water deficits.

An interesting virtual tree generation approach is the PipeQual Simulator. PipeQual is a yearly step growth simulator for trees at different dominance positions which uses crown length to determine how photosynthesis is affected by neighbour shading. Annual growth, heartwood /sapwood zones, and stem branch knots are predicted (Mäkelä and Mäkinen 2003). Virtual trees of Scots pine (*Pinus sylvestris*) with various initial stocking and thinning treatments from this approach have been used in sawing simulation to predict grade yield and compared to real stems (Lyhykainen *et al.* 2008).

Outside of wood science considerable effort has gone into characterizing and reconstructing random microstructures (Frantziskonis, 1998; Ballani and Stoyan, 2015; Liu and Shapiro, 2015; Hull *et al.*, 2018;). Recently, as in so many other applications, neural networks and deep learning techniques have been showing considerable promise (Li *et al.*, 2018; Losch *et al.*, 2019; Chun *et al.*, 2020; Gayon-Lombardo *et al.*, 2020).

Conclusion

Numerous wood property models exist, but the fundamental approaches are similar and insufficient. Outside of wood there are promising approaches that should be further explored in partnership with domain experts and along with more representative data.

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